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UNIFIED FACILITIES CRITERIA (UFC)

WELDING – DESIGN PROCEDURES AND INSPECTIONS

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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UNIFIED FACILITIES CRITERIA (UFC)

WELDING – DESIGN PROCEDURES AND INSPECTIONS

U.S. ARMY CORPS OF ENGINEERS (Preparing Activity)

NAVAL FACILITIES ENGINEERING COMMAND

AIR FORCE CIVIL ENGINEER SUPPORT AGENCY

Record of Changes (changes are indicated by **1**\ ... /**1**/)

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This UFC supersedes TI 809-26, dated 1 March 2000. The format of this UFC does not conform to UFC 1-300-01; however, the format will be adjusted to conform at the next revision. The body of this UFC is the previous TI 809-26, dated 1 March 2000.

TI 809-26
1 March 2000

US Army Corps
of Engineers®

Technical Instructions

Welding - Design Procedures And Inspections

Headquarters
US Army Corps of Engineers
Engineering and Construction Division
Directorate of Military Programs
Washington, DC 20314-1000

CEMP-E **TI 809-26**

1 March 2000

TECHNICAL INSTRUCTIONS

WELDING - DESIGN PROCEDURES AND INSPECTIONS

Record of Changes (changes indicated \1\.../1/)

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WELDING - DESIGN PROCEDURES AND INSPECTIONS

Table of Contents

Page

CHAPTER 1. GENERAL

CHAPTER 2. APPLICABLE DESIGN SPECIFICATIONS

CHAPTER 3. WELDING PROCESSES AND MATERIALS

CHAPTER 4. STRUCTURAL STEELS

CHAPTER 5. DESIGN FOR WELDING

CHAPTER 6. STUD WELDING

CHAPTER 7. WELDING TO EXISTING STRUCTURES

CHAPTER 8. QUALITY ASSURANCE AND INSPECTION

CHAPTER 9. OTHER WELDING SPECIFICATIONS AND STANDARDS

CHAPTER 10. SAFETY & ENVIRONMENTAL CONSIDERATIONS

APPENDIX C. WELDING PROCESSES

APPENDIX D. NONDESTRUCTIVE TESTING METHODS

CHAPTER 1

GENERAL

1. PURPOSE AND SCOPE. This document provides criteria and guidance for the design and specification of welded structural components and systems in accordance with current technology, standards and materials. This includes information on design approaches, use of technical manuals, guidance on the application of codes and industry standards, and the design and specification of welded details, inspection and quality. The scope of this document is welding for general building construction for military applications, and does not include underwater, piping, or cryogenic applications, bridges, sheet steels, or the welding of materials other than structural steel. A building is defined as any structure, fully or partially enclosed, used or intended for sheltering persons or property.

2. APPLICABILITY. These instructions are applicable to all USACE elements having military construction responsibilities.

3. REFERENCES. Appendix A contains a list of references pertaining to this document.

4. BIBLIOGRAPHY. A bibliography of publications that provides additional information and background data is in Appendix B.

CHAPTER 2

APPLICABLE DESIGN SPECIFICATIONS

1. GENERAL.

a. Specification Cycles. Building design and welding design are governed by a variety of specifications and standards, as listed. Because of the varying focus of each standard or specification, and the varying dates of adoption and publication, the standards and specifications are in a constant cycle of revision.

b. Specification Conflicts. Conflicts may arise between codes as new research and methods are adopted in one code before another. There are also specific exceptions one code may take with another, as the AISC *Specification* does with AWS *D1.1*, listing those exceptions in AISC *Specification* section J1.2.

c. New Materials. New steels and welding materials, adopted by the industry, may not be listed in the codes for periods of several years because of the adoption and printing cycles. Within AWS standards, the filler metal specifications are being revised for metrication. The AWS *D1.1* code is also being fully metricated for the year 2000, with independent dimensional units and values. Those values established as of the date of this document have been adopted. Others may change with the publication of the *D1.1*-2000 *Structural Welding Code - Steel*.

d. Preferred Design Methodology. The American Institute of Steel Construction provides two methodologies for the design of steel-framed buildings. The first method is Allowable Stress Design (ASD), which provides adequate strength based upon service load conditions. All loads are assumed to have the same variability. The second method, Load and Resistance Factor Design (LRFD), is a more modern probabilistic approach also known as limit states design. LRFD uses load factors and load combinations applied to service loads, and resistance (strength reduction) factors applied to the nominal resistance of the component to achieve a design strength. Both methods are in current practice. The use of the LRFD method is preferred over the use of the ASD method, but is not required.

e. Standards Evaluation. Users of this document should evaluate the various standards listed, and new standards that may be published, for suitable application. It may be necessary to take exceptions to various code provisions, or to expand the code provisions through the use of the project specifications, to resolve conflicting issues and to permit new materials.

2. USACE AND OTHER MILITARY DOCUMENTS.

a. TI 809-01 Load Assumptions for Buildings. This document provides minimum snow and wind loads plus frost penetration data to be used in the design and construction of buildings and other structures. Except as designated within the document, all loadings are based upon ASCE 7-95, *Minimum Design Loads for Buildings and Other Structures*. Buildings are categorized according to occupancy.

b. TI 809-02 Structural Design Criteria for Buildings. General structural design guidance for buildings, and for building systems constructed of concrete, masonry, steel and wood is presented in this TI document. The design requirements provided herein, or cited by reference, are based on national building codes, industry standards, and technical manuals developed by the Army, Navy, and Air Force.

Instructions necessary to provide serviceable buildings and to assure load path integrity and continuity is included. Requirements unique to Army, Navy, and Air Force facilities are indicated. Supplemental information to help engineers interpret and apply code provisions, and meet serviceability and strength performance objectives is also included in the TI.

c. TI 809-04 Seismic Design for Buildings. This document provides qualified designers with the criteria and guidance for the performance-based seismic analysis and design of new military buildings, and the non-structural systems and components in those buildings. Chapter 7 includes discussion of structural steel framing systems, but does not provide specific details for welded connections in those systems.

d. TI 809-05 Seismic Evaluation and Rehabilitation for Buildings. This document is intended to provide qualified designers with the necessary criteria and guidance for the performance-based seismic analysis and design of new military buildings, and the nonstructural systems and components in the buildings. The primary basis for this document is the 1997 edition of the NEHRP Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 302). This document provides guidance in the interpretation and implementation of the FEMA 302 provisions for the Life Safety performance objective for all buildings, and it provides criteria for the design and analysis of buildings with enhanced performance objectives.

e. TI 809-07 Design of Cold-Formed Load Bearing Steel Systems and Masonry Veneer / Steel Stud Walls. This document provides design guidance on the use of cold-formed steel systems for both load-bearing and nonload-bearing applications. Cold-formed steel members are generally of a thickness that welding is governed by AWS *D1.3 Structural Welding Code - Sheet Steel*, rather than AWS *D1.1 Structural Welding Code - Steel*, and therefore are not covered by TI 809-26.

f. TI 809-30 Metal Building Systems. This document provides guidance on the use of Metal Building Systems, defined as a complete integrated set of mutually dependent components and assemblies that form a building, including primary and secondary framing, covering and accessories. These types of structures were previously referred to as pre-engineered buildings. Paragraph 5.i addresses welding for manufacturers not AISC certified in Category MB.

g. TM 5-809-6 Structural Design Criteria for Structures Other Than Buildings. This document will become TI 809-03. Revise as needed.

3. AISC SPECIFICATIONS AND STANDARDS.

a. Metric Load and Resistance Design Specification for Structural Steel Buildings. The Metric LRFD *Specification* contains provisions regarding welding design and application. Section J contains design provisions, and Section M contains limited supplemental information regarding quality and inspection. The Metric LRFD *Specification*, published in 1994, is based upon AWS *D1.1*-92, and takes exception to certain provisions of that edition. This metric specification is a dimensional conversion of the December 1, 1993 customary units edition. The principles and concepts of these two specifications (metric and customary) are identical, only the units differ. It is anticipated that a new LRFD *Specification*, containing both SI and US Customary Units within one document, will be published by AISC in early 2000.

b. Load and Resistance Factor Design Specification for Structural Steel Buildings. The LRFD *Specification* contains provisions regarding welding design and application. Section J contains design provisions, and Section M contains limited supplemental information regarding quality and inspection.

The LRFD *Specification*, published in 1993, is based upon AWS *D1.1*-92, and takes exception to certain provisions of that edition. It is anticipated that a new LRFD *Specification*, containing both SI and US Customary Units within one document, will be published by AISC in early 2000.

c. Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design. The ASD *Specification* contains provisions regarding welding design and application. Section J contains design provisions, and Section M contains limited supplemental information regarding quality and inspection. The ASD *Specification*, published in 1989, is based upon the use of AWS *D1.1*-88, and takes exception to certain provisions of AWS *D1.1*. Publication of an updated or new ASD *Specification* is not being planned by AISC.

d. Seismic Provisions for Structural Steel Buildings. This AISC document addresses the design and construction of structural steel and composite steel / reinforced concrete building systems in seismic regions. It is applicable for use in either LRFD or ASD. The provisions are for the members and connections that comprise the Seismic Force Resisting System (SFRS) in buildings that are classified as Seismic Design Category D or higher in FEMA 302, NEHRP *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. These structures include all buildings with an S_{DS} >= 0.50g (S_{D1} >= 0.20g), and Seismic Use Group III when S_{DS} >= 0.33g (S_{D1} >= 0.133g). See TI 809-04, Chapter 4. The *Seismic Provisions* document cites AWS *D1.1*-96 as the reference welding standard. Part I, Section 7.3 is applicable to welded joints, containing provisions regarding Welding Procedure Specification approvals, filler metal toughness requirements, and special concerns for discontinuities in SFRS members.

e. Code of Standard Practice. The AISC *Code of Standard Practice* defines practices adopted as commonly accepted standards of the structural steel fabricating industry. In the absence of other contract documents, the trade practices of the document govern the fabrication and erection of structural steel. Within the document, Materials are discussed in Section 5, Fabrication in Section 6, Erection in Section 7, and Quality Control in Section 8.

f. Manual of Steel Construction, LRFD, Metric Conversion. The AISC *Manual of Steel Construction* contains informational tables and design aids, as well as the AISC Specifications themselves. The *Manual* contains welding design aids in Volume II - Connections. Chapter 8 includes prequalified joint details, AWS welding symbols, tables for eccentrically loaded fillet welds, design examples, and general information regarding welding. Design examples are contained within Chapter 9 for Simple Shear and PR Moment Connections, Chapter 10 for Fully Restrained (FR) Moment Connections, and Chapter 11 for Connections for Tension and Compression. One is cautioned that the welded prequalified joint tables are based upon AWS *D1.1*-92, and have been substantially revised in subsequent editions of AWS *D1.1*.

g. Manual of Steel Construction, LRFD. The AISC *Manual of Steel Construction* contains informational tables and design aids, as well as the AISC Specifications themselves. When using LRFD, the *Manual of Steel Construction, 2nd Edition*, is applicable, and is in two volumes. The *Manual* contains welding design aids in Volume II - Connections. Chapter 8 includes prequalified joint details, AWS welding symbols, tables for eccentrically loaded fillet welds, design examples, and general information regarding welding. Design examples are contained within Chapter 9 for Simple Shear and PR Moment Connections, Chapter 10 for Fully Restrained (FR) Moment Connections, and Chapter 11 for Connections for Tension and Compression. One is cautioned that the welded prequalified joint tables are based upon AWS *D1.1*-92, and have been substantially revised in subsequent editions of AWS *D1.1*.

h. Manual of Steel Construction, ASD. The AISC *Manual of Steel Construction* contains informational tables and design aids, as well as the AISC Specifications themselves. The 9th Edition of the *Manual* contains welding design aids in Part 4 - Connections, including prequalified joint details, AWS welding symbols, tables for eccentrically loaded fillet welds, and design examples. One is cautioned that the welded prequalified joint tables are based upon AWS *D1.1*-88, and have been substantially revised in subsequent editions of AWS *D1.1*. The 9th Edition ASD *Manual* is supplemented by a separate book, Volume II - *Connections*. Chapter 2 contains general information regarding welding, Chapter 3 contains design examples for Simple Shear Connections, Chapter 4 contains Moment Connections, and Chapter 6 contains Column Connections.

4. AWS SPECIFICATIONS AND STANDARDS.

a. *D1.1* Structural Welding Code - Steel. ANSI/AWS *D1.1* contains the requirements for fabricating and erecting welded steel structures. The *D1.1* Code is limited to carbon and low-alloy steels, of minimum specified yield strength not greater than 690 MPa (100 ksi), 3.2 mm (1/8 in.) in thickness or greater. It is not applicable to pressure vessel or pressure piping applications. *D1.1* contains eight sections: (1) General Requirements, (2) Design of Welded Connections, (3) Prequalification, (4) Qualification, (5) Fabrication, (6) Inspection, (7) Stud Welding, and (8) Strengthening and Repair. It also contains both mandatory and nonmandatory annexes, plus commentary. It is updated biannually, in even years.

b. *D1.3* Structural Welding Code - Sheet Steel. ANSI/AWS *D1.3* covers arc welding of sheet and strip steels, including cold-formed members that are equal to or less than 4.8 mm (3/16 in.) in nominal thickness. Arc spot, arc seam, and arc plug welds are included in the Code. The *D1.3* Code is applicable when welding sheet steels to other sheet steels, or when welding to other thicker structural members. With the latter application, the use of AWS *D1.1* is also required for the structural steel. The *D1.3* Code contents are similar to AWS *D1.1*, except Sections 7 and 8 are not included.

c. *D1.4* Structural Welding Code - Reinforcing Steel. ANSI/AWS *D1.4* covers the welding of reinforcing steel, as used in concrete construction. Welding of reinforcing steel to reinforcing steel, and reinforcing steel to other carbon and low-alloy steels, is covered. With the latter application, the use of AWS *D1.1* is also required for the structural steel. *D1.4* follows a different organizational structure than AWS *D1.1* and *D1.3*, and includes the following sections: (1) General Provisions, (2) Allowable Stresses, (3) Structural Details, (4) Workmanship, (5) Technique, (6) Qualification, and (7) Inspection, plus annexes.

d. A2.4 Standard Symbols for Welding, Brazing and Nondestructive Testing. ANSI/AWS A2.4 contains standards for the application of welding symbols on structural design and detail drawings, as well as examples of their use. Part A of the document covers Welding Symbols, Part B covers Brazing Symbols, and Part C covers Nondestructive Examination Symbols. The symbols and use specified in this document supersedes symbols that may be shown in other AWS and industry documents, as they may be incorrect or outdated in the other documents.

e. A5-series Filler Metal Related Specifications. ANSI/AWS A5-series documents establish the requirements for electrodes, fluxes, and shielding gases, as applicable, for given general types of electrodes and given welding processes. The requirements include, as applicable, chemical composition of the electrode, moisture content, usability, markings, packaging, storage, certifications, and the as-tested mechanical properties (strength, ductility, and toughness) and soundness of weld metal. An Appendix or Annex is provided to explain the provisions and provide additional information. The A5-

series specifications applicable to structural steel are listed in Appendix A - References, of TI 809-26.

5. FEDERAL EMERGENCY MANAGEMENT AGENCY.

a. FEMA 267 and 267B Steel Moment Frame Structures - Interim Guidelines. The *Interim Guidelines*, published in 1995, are applicable to steel moment-resisting frame structures incorporating fully restrained connections in which the girder flanges are welded to the columns, and are subject to significant inelastic demands from strong earthquake ground motion. Guideline recommendations are provided based upon research conducted under the SAC Joint Venture, Phase 1 project. The Guidelines include information regarding the pre-earthquake evaluation and inspection of existing buildings, post-earthquake evaluation and inspection of existing buildings, repairing damaged buildings, retrofitting existing damaged and undamaged buildings, and designing, constructing and inspecting new buildings.
FEMA 267A was published as an additional advisory to FEMA 267, based upon information available as of August 1996. A second advisory, FEMA 267B, was published in mid-1999, replacing FEMA 267A.

b. FEMA 267 Replacement. A series of five new documents are planned for publication in early 2000, based upon the results of the SAC Joint Venture Phase 2 project. These will supersede FEMA 267 and issued advisories. The documents will be as follows: (1) *Seismic Design Criteria for New Moment-Resisting Steel Frame Construction*, (2) *Post-Earthquake Evaluation and Repair Criteria for Welded Moment-Resisting Steel Frame Construction*, (3) *Seismic Evaluation and Upgrade Criteria for Existing Steel Moment-Resisting Frame Construction*, and (4) *Quality Assurance Guidelines for Moment-Resisting Steel Frame Construction*, and (5) *Recommended Specifications for Moment-Resisting Steel Frame Buildings*.

c. FEMA 273 NEHRP Guidelines for the Seismic Rehabilitation of Buildings. FEMA 273 provides guidelines for the seismic rehabilitation of buildings constructed of steel or cast iron, concrete, masonry, wood and light metal, including foundations and architectural, mechanical and electrical components. The document is oriented toward structural analysis procedures, with limited information regarding specific details for welding or inspection.

d. FEMA 302 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. FEMA 302 provides minimum design criteria for the design and construction of structures to resist earthquake motions. Included are provisions for foundations, steel structures, concrete structures, composite structures, masonry structures, seismic isolation, related building components, and nonbuilding structures such as racks, towers, piers and wharves, tanks and vessels, stacks and chimneys, electrical distribution structures, and several other structures. Not included in the provisions are certain classes of one-and two-family residential structures, agricultural structures, and structures in areas of low seismicity.

CHAPTER 3

WELDING PROCESSES AND MATERIALS

1. WELDING AND RELATED PROCESSES.

a. General - Welding. The proper selection of welding processes, materials, and procedures is vital to achieving the strength and quality necessary for adequate performance in the structure. The contract documents, prepared by the Engineer, should specify any special requirements for materials, inspection, or testing beyond that required by the codes and standards.

b. General - Heating and Thermal Cutting. The application of heat, whether for straightening, cutting, or welding, may have a significant effect upon the mechanical properties of the steel, weld, and heat-affected zones. Should any limitations in the use of heat be needed beyond those specified in the codes, the contract documents prepared by the Engineer should so state.

c. General - Weld Heat-Affected Zone. The heat-affected zone (HAZ) is the portion of steel immediately adjacent to the weld that has been metallurgically modified by the heat of the welding. The microstructure has been changed, and the mechanical properties typically have been degraded with reduced ductility and toughness, but with increased strength. Also, hydrogen from the welding operation will have migrated into the hot HAZ, then subsequently been trapped within the metallurgical structure, embrittling the steel. The hydrogen will eventually migrate out the HAZ, at rates dependent upon initial hydrogen levels, thickness and temperature. The HAZ is typically about 3 mm (1/8 in.) thick for common size welds, primarily depending upon welding heat input.

d. Project Specifications. In most cases, it is adequate to simply require compliance with the codes. The contractor may be allowed the full choice of welding processes and materials. The use of “matching” prequalified filler metals is encouraged. When SMAW is performed, the use of low-hydrogen electrodes is encouraged. Recently, the use of specified toughness levels for filler metals in specific seismic building applications has been added to standard practice. For further guidance in the use and selection of welding processes and materials, see Appendix C.

2. APPLICATION OF HEAT FOR WELDING.

a. Cooling Rate Control. Preheat is used primarily to slow the cooling rate of the heat-affected zone (HAZ). Because preheating slows the cooling rate, the steel remains at an elevated temperature longer, increasing the rate and time of hydrogen diffusion and reducing the risk of hydrogen-assisted cracking. Preheat also aids in the removal of surface moisture and organic compounds, if present, from the surface to be welded, reducing porosity and other discontinuities. Preheating may also reduce residual stresses and improve the toughness of the completed joint.

(1) High Cooling Rates. A high cooling rate may cause a hard, martensitic HAZ microstructure with a higher risk of cracking during cooling. The HAZ will also contain higher levels of hydrogen, also embrittling the steel and increasing the risk of cracking.

(2) Low Cooling Rates. Conversely, a very low cooling rate can detrimentally affect toughness because of grain growth. When preheat above approximately 300^{o}C (550^{o}F) is used, weld metal properties may be degraded as well. If the steel is manufactured using heat treatment processes, such as

quenched and tempered steels, too high a preheat may affect steel properties by retempering the steel. For quenched and tempered steels, preheat and interpass temperatures above 230°C (450°F) should be avoided.

b. Preheat for Prequalified Applications. The basic values for minimum preheat temperatures for prequalified structural steels are provided in AWS *D1.1* Table 3.2. A summary of this table is provided as Table 3-1, with suggestions in Table 3-2 for non-prequalified steels. With any non-prequalified steel, a competent welding advisor should be consulted. When steels of different categories are joined, use the higher preheat required for their respective thicknesses.

(1) Category A is applicable when non-low hydrogen SMAW electrodes are used. This is permitted as prequalified only for AWS Group I steels, but is not recommended practice. See Appendix C, Paragraph 1b. Because of the higher diffusible hydrogen present when non-low hydrogen electrodes are used, higher preheats are required to allow additional time for hydrogen to escape from the heat-affected zone. When low-hydrogen SMAW electrodes are used, the preheat can be reduced because of the reduced hydrogen levels present.

(2) Category D is applicable to A913 steel, a thermo-mechanically controlled processed (TMCP) steel that has low carbon and alloy levels. Weldability tests have been conducted to document that the steel may be welded without preheat, provided the steel temperature is above 0°C (32°F), and an electrode classified as H8 (tested under ANSI/AWS A4.3 for 8 mL or less of diffusible hydrogen per 100 g of deposited weld metal) or lower is used.

(3) Users are cautioned that the use of these minimum preheat tables may not be sufficient to avoid cracking in all cases. Increased preheat temperatures may be necessary in situations involving higher restraint, higher hydrogen levels, lower welding heat input, or with steel compositions at the upper end of their respective specification. Conversely, preheats lower than those tabulated may be adequate for conditions of low restraint, low hydrogen levels, higher welding heat input, and steel compositions low in carbon and other alloys. Additional guidance for these situations may be found in AWS *D1.1* Annex XI, *Guideline on Alternative Methods for Determining Preheat*. The Guide considers hydrogen level, steel composition, and restraint and allows for calculation of the estimated preheat necessary to avoid cold cracking. When higher preheats are calculated, it is advisable to use these values, provided maximum preheat levels are not exceeded. When lower preheat values are calculated, the AWS *D1.1* Code requires the WPS to be qualified using the lower preheat value. Such testing may not always adequately replicate restraint conditions, so caution is advised.

(4) Although not required for building applications under AWS *D1.1*, consideration for higher preheat and interpass temperature requirements may be made for critical applications where fracture would result in a catastrophic collapse. For these conditions, AWS *D1.5 Bridge Welding Code* Tables 12.3, 12.4 and 12.5 provide recommended values. Seismic applications with routine building structures is not considered appropriate for requiring higher levels of preheat and interpass temperatures, and AWS *D1.1* Table 3.2 should suffice.

Table 3-1. Minimum Preheat and Interpass Temperatures for AISC-Approved Structural Steels Prequalified under AWS D1.1

Category	Structural Steel	Material Thickness of Thickest Part at Point of Welding	Minimum Preheat and Interpass Temperature
A *When using SMAW with other than low-hydrogen electrodes*	Shapes and Plates A36 A529, grade 42 A709, grade 36 Round and Rectangular Sections A53, grade B (round) A500, grades A and B (round) A500, grades A and B (rectangular) A501 (round)	3 to 19 mm (incl.) (1/8 to 3/4 in.)	0°C (32°F)[1]
		over 19 to 38.1 mm (incl.) (3/4 to 1-1/2 in.)	66°C (150°F)
		over 38.1 to 63.5 mm (incl.) (1-1/2 to 2-1/2 in.)	107°C (225°F)
		over 63.5 mm (2-1/2 in.)	150°C (300°F)
B *When using SMAW with low-hydrogen electrodes, or FCAW, GMAW or SAW*	Shapes and Plates A36 A529, grade 42 A709, grades 36, 50 & 50W A572, grades 42 and 50 A588, 100 mm (4 in.) thick and under A913, grade 50 A992, grade 50 (shapes only) Round and Rectangular Sections A53, grade B (round) A500, grades A and B (round) A500, grades A and B (rectangular) A501 (round) A618, grades Ib, II, & III (round)	3 to 19 mm (incl.) (1/8 to 3/4 in.)	0°C (32°F)[1]
		over 19 to 38.1 mm (incl.) (3/4 to 1-1/2 in.)	10°C (50°F)
		over 38.1 to 63.5 mm (incl.) (1-1/2 to 2-1/2 in.)	66°C (150°F)
		over 63.5 mm (2-1/2 in.)	107°C (225°F)

Category	Structural Steel	Material Thickness of Thickest Part at Point of Welding	Minimum Preheat and Interpass Temperature
C *When using SMAW with low-hydrogen electrodes, or FCAW, GMAW or SAW*	Shapes and Plates A572, grades 60 and 65 A709, grade 70W[2] A852, grades 70[2] A913, grades 60 and 65	3 to 19 mm (incl.) (1/8 to 3/4 in.)	10°C (50°F)
		over 19 to 38.1 mm (incl.) (3/4 to 1-1/2 in.)	66°C (150°F)
		over 38.1 to 63.5 mm (incl.) (1-1/2 to 2-1/2 in.)	107°C (225°F)
		over 63.5 mm (2-1/2 in.)	150°C (300°F)
D *When using SMAW with low-hydrogen electrodes, or FCAW, GMAW or SAW, with electrodes of class H8 or lower*	Shapes and Plates A913, Grades 50, 60, and 65	all thicknesses	0°C (32°F)[1]

[1] - If the steel is below 0°C (32°F), the steel, in the vicinity of welding, must be raised to and maintained at a minimum temperature of 21°C (70°F) prior to and during welding.

[2] - Maximum preheat and interpass temperature of 200°C (400°F) for thicknesses up to 40 mm (1-1/2 inches) inclusive, and 230°C (450°F) for thickness greater than 40 mm (1-1/2 inches).

Table 3-2. Suggested Minimum Preheat and Interpass Temperatures for AISC-Approved Structural Steels Not Prequalified under AWS D1.1.
(Seek advice of competent welding consultant prior to use of this Table.)

Category	Structural Steel	Minimum Preheat and Interpass Temperature
NPQ-A	**Shapes and Plates** A529, grade 46 A283 (plates) **Round and Rectangular Sections** A500, grade C (round)	same as Table 3-1, Category A
NPQ-B	**Shapes and Plates** A242, all grades A529, grades 50 and 55 A588, over 4" thick **Round and Rectangular Sections** A500, grade C (rectangular) A618, grades Ib, II, and III (round) A847	same as Table 3-1, Category B

c. Preheat for Non-prequalified Applications. Preheat requirements for non-prequalified steels and applications may be determined using rational engineering judgement considering material composition, restraint, hydrogen levels, and experience. Table 3-2 provides suggested values for common structural steels not currently listed in AWS *D1.1*. Other steels should be evaluated by a competent welding consultant. The use of AWS *D1.1* Annex XI is suggested, with suitable qualification testing to be performed to verify the analytical results.

d. Preheat for Sheet Steel to Structural Steel. When the structural steel element is of a grade or thickness requiring preheat under the provisions of AWS *D1.1*, preheat must be provided to the structural steel element. The sheet steel itself need not be preheated.

e. Interpass Temperature. Interpass temperature is the temperature maintained during welding, until completion of the weld joint. Minimum and maximum interpass temperatures are typically the same as the minimum and maximum preheat temperatures, but may vary in specific WPSs.

(1) Thicker materials may absorb enough heat from the weld region that it is necessary to reapply heat to the weld region prior to resuming welding of the joint.

(2) With maximum interpass temperature considerations, it may be necessary to pause welding operations to allow the steel to cool to below the maximum interpass temperature before resuming welding. Accelerated cooling using water should not be permitted, but the use of forced air is acceptable. Cooling time may be necessary for larger multi-pass welds on thinner materials or smaller members.

(3) When necessary to shut down welding operations on a joint prior to joint completion, it should be verified that adequate welding has been completed to sustain any currently applied or anticipated loadings until completion of the joint. The joint may be allowed to cool below the prescribed interpass temperature, but must be reheated to the required preheat / interpass temperature before resumption of welding of the joint.

f. Postheat (PWHT). Postheating is the continued application of heat following completion of the weld joint. It is not required by specification, but may be used in some cases when conditions of high restraint, poor weldability steels, and poor hydrogen control exist. In most cases, when proper attention is applied to preheat and interpass temperatures, and adequate control of hydrogen levels is maintained, postheating is not necessary to avoid cold cracking. Under the difficult conditions mentioned, it may be adequate to slow cooling rates through the use of insulating blankets applied immediately after completion of welding. The PWHT described in AWS *D1.1* Section 5.8, is for the purpose of stress relief, not cracking control.

3. APPLICATION OF HEAT FOR STRAIGHTENING AND CAMBERING.

a. Principle. Heat applied from a heating torch may be used to straighten curved or distorted members, and also to camber or curve members when desired. The method is commonly called “flame shrinking”, because the heat is applied to the part of the member that needs to become shorter.

b. Cambering Procedure. Cambering a beam with positive camber requires heat to be applied to the bottom flange of the beam. It is recommended to first apply a V-heat to the web, starting with a point near the top, to soften the web and minimize web crippling that may occur if only the flange is heated.

c. Maximum Temperatures. The temperature to which the steel may be heated as a part of the straightening or cambering process is limited to 650^{o}C (1200^{o}F) for most structural steels, and to 590^{o}C (1100^{o}F) for quenched and tempered steels. See AWS *D1.1* Section 5.26.2. For TMCP steels, the manufacturer’s recommendations for maximum temperatures should be followed. It is recommended that accelerated cooling using water mist not be used until the temperature of the steel has dropped below approximately 300^{o}C (600^{o}F).

4. THERMAL CUTTING. Thermal cutting is used in steel fabrication to cut material to size and to perform edge preparation for groove welding. Thermal cutting is generally grouped into two categories - oxyfuel gas cutting, also commonly called flame cutting or burning, and plasma arc cutting.

a. Oxyfuel Cutting. With oxyfuel gas cutting (OFC), the steel is heated with a torch to its ignition temperature, then exposed to a stream of oxygen from the same torch. The oxygen causes rapid oxidation, or “burning” to occur, which itself creates additional heat to allow the process to continue. The force of the oxygen stream blows away the molten steel, leaving a cut edge. The fuel gas used in oxyfuel cutting may be natural gas, propane, acetylene, propylene, MPS, or other proprietary fuel gases.

b. Plasma Arc Cutting. Plasma arc cutting (PAC) is sometimes used in shop fabrication, and is generally limited to steels 25 mm (1 in.) thick or less. Similar to oxyfuel cutting, the steel is heated to the point of melting, only this function is performed using an electric arc. The molten steel is then removed by the high velocity stream of plasma (ionized gas) created by the arc itself, within the cutting torch. Gases used for PAC include nitrogen, argon, air, oxygen, and mixtures of nitrogen/oxygen and argon/hydrogen. With plasma arc cutting, the area of steel heated by the process is less, resulting in less steel metallurgically affected by the heat of cutting, as well as less distortion. PAC generates considerable fume and noise, and therefore a water table and water shroud is typically used to minimize these undesirable environmental effects.

c. Edge Quality. The quality of thermally cut edges is governed by AWS *D1.1* Section 5.15.4. Limits are placed on surface roughness, as measured using ANSI/ASME B46.1, *Surface Texture (Surface Roughness, Waviness and Lay*). A plastic sample, AWS C4.1-G, *Oxygen Cutting Surface Roughness Gauge*, is typically used for visual comparison in lieu of physical measurement of surface roughness. Limitations are also placed on the depth and sharpness of gouges and notches. AISC, in Section M2.2, takes a minor exception to AWS *D1.1* quality criteria.

5. AIR CARBON ARC GOUGING. Air carbon arc gouging (ACAG) is commonly used to perform edge preparation for groove joints (especially J- and U-grooves), to remove unacceptable discontinuities from weld deposits, and to remove temporary attachments such as backing bars or lifting lugs. It may also be used to remove entire welds when structural repairs or modifications are necessary.

a. Process. The process appears similar to SMAW, with an electrode holder and a single electrode, and is usually performed manually, however, the electrode is a carbon electrode covered with a copper sheath. The electrode creates a controlled arc, melting the steel, which is quickly followed by the focused application of compressed air from the electrode holder. The air provides continued rapid oxidation, as well as removes the molten steel from the area. For complete information, see ANSI/AWS C5.3, *Recommended Practices for Air Carbon Arc Gouging and Cutting*.

b. Surface Finishing. Following ACAG, the joint should be thoroughly cleaned by wire brushing. Grinding of surfaces prior to welding is not required. If not welded, light grinding of the ACAG surface is suggested.

CHAPTER 4

STRUCTURAL STEELS

1. AISC AND AWS LISTED STRUCTURAL STEELS.

a. AISC Approved Steels. For building-type structures, the AISC lists approved steels in Section A3.1 of the *Specification for Structural Steel Buildings*. Additional steels are listed in the AISC *Seismic Provisions for Structural Steel Buildings* because of a more recent publication date. New structural steel specifications have been developed and approved since publication, such as ASTM A992, and should also be considered for application in structures. Structural steels currently accepted by AISC in the LRFD *Specification*, or pending acceptance as noted, are as follows:

Shapes and Plates
- A36
- A242
- A283[1]
- A514
- A529
- A572
- A588
- A709
- A852
- A913[2]
- A992[4] (wide flange shapes only)

Rounds and Rectangular Sections
- A53
- A500
- A501
- A618
- A847[3]

Sheet and Strip
- A570
- A606
- A607

[1] - added in AISC *Seismic Provisions* (1997)
[2] -added in AISC LRFD Supplement (1998)
[3] - added in AISC *Hollow Structural Sections* (1997)
[4] - approved for next specification

b. AWS Prequalified Steels. AWS *D1.1* lists prequalified steels in Table 3.1, and other approved steels in Annex M. Prequalified steels have been determined to be generally weldable when using the AWS *D1.1* Code. For some steel specifications, only certain strength levels or grades are considered prequalified. This situation may be because certain grades have compositional levels outside the range considered readily weldable, because certain strength levels are less weldable, or because certain steels or grades recently came into production and inadequate information was known about their weldability at the time of printing.

c. AWS Approved Steels. The steels listed in Annex M are approved for use, but Welding Procedure Specifications (WPSs) must be qualified prior to use in welding these steels. These steels are generally quenched and tempered steels, which are sensitive to temperature changes from welding operations that may affect their strength, ductility, and toughness. They are also generally more sensitive to diffusible hydrogen and are at higher risk of hydrogen-assisted HAZ cracking.

d. Matching Filler Metals for Prequalified Steels. Table 4-1 provides a summary of structural steels that are both approved by AISC and listed by AWS as prequalified. For joint designs requiring “matching” filler metal, the “matching” filler metal for the given welding process is provided.

Table 4-1. AISC-Approved Structural Steels Prequalified under AWS D1.1 Table 3.1

AWS Group	Structural Steel	Prequalified “Matching” Filler Metal
I	Shapes and Plates A36 A529, grade 42 A709, grade 36 Round and Rectangular Sections A53, grade B (round) A500, grades A and B (round) A500, grades A and B (rectangular) A501 (round)	SMAW A5.1: E60XX, E70XX A5.5: E70XX-X[1] FCAW A5.20: E6XT-X, E6XT-XM E7XT-X, E7XT-XM (Except -2, -2M, -3, -10, -13, -14, -GS) A5.29: E6XTX-X[1], E6XTX-X[1]M E7XTX-X[1], E7XTX-X[1]M GMAW A5.18: ER70S-X, E70C-XC, E70C-XM (Except -GS(X)) A5.28: ER70S-X[1]XX, E70C-X[1]XX SAW A5.17: F6XX-EXXX, F6XX-ECXXX F7XX-EXXX, F7XX-ECXXX A5.23: F7XX-EXXX-X[1], F7XX-ECXXX[1]

II	Shapes and Plates A572, grades 42 and 50 A588, 100 mm (4 in.) thick and under A709, grades 50 and 50W A913, grade 50 Round and Rectangular Sections A618, grades Ib, II, and III (round)	SMAW A5.1: E70XX, low hydrogen A5.5: E70XX-X[1], low hydrogen FCAW A5.20: E7XT-X, E7XT-XM (Except -2, -2M, -3, -10, -13, -14, -GS) A5.29: E7XTX-X[1], E7XTX-X[1]M GMAW A5.18: ER70S-X, E70C-XC, E70C-XM (Except -GS(X)) A5.28: ER70S-X[1]XX, E70C-X[1]XX SAW A5.17: F7XX-EXXX, F7XX-ECXXX A5.23: F7XX-EXXX-X[1], F7XX-ECXXX[1]
III	Shapes and Plates A572, grades 60 and 65 A913, grades 60 and 65	SMAW A5.5: E80XX-X[1], low hydrogen FCAW A5.29: E8XTX-X[1], E8XTX-X[1]M GMAW A5.28: ER80S-X[1]XX, E80C-X[1]XX SAW A5.23: F8XX-EXXX-X[1], F8XX-ECXXX[1]

IV	**Shapes and Plates** **A709, grade 70W** **A852, grade 70**	**SMAW** **A5.5: E90XX-X[1], low hydrogen** **E9018M** **FCAW** **A5.29: E9XTX-X[1], E9XT-X[1]M** **GMAW** **A5.28: ER90S-X[1]XX, E90C-X[1]XX** **SAW** **A5.23: F9XX-EXXX-X[1], F9XX-ECXXX[1]**

[1] - except alloy groups B3, B3L, B4, B4L, B5, B5L, B6, B6L, B7, B7L, B8, B8L, B9

e. Matching Filler Metals for Non-prequalified Steels. Table 4-2 provides “matching” filler metal information for structural steels approved by AISC, but not listed as prequalified by AWS *D1.1*. Quenched and tempered steels are not listed in this table. With the exception of A992, the advice of a competent welding consultant should be used prior to welding these steels. A992 steel is a new steel specification which is essentially a more restricted A572, grade 50 steel.

Table 4-2. AISC-Approved Structural Steels Not Prequalified under AWS D1.1 Table 3.1

Group	Structural Steel	Suggested "Matching" Filler Metal (Not Prequalified)
NPQ-I	**Shapes and Plates** A529, grade 46 A283, grade D (plates) **Round and Rectangular Sections** A500, grade C (round)	same as Table 4-1, Category I
NPQ-II	**Shapes and Plates** A242, all grades A529, grades 50 and 55 A588, over 100 mm (4 in.) A992, (W shapes only) **Round and Rectangular Sections** A500, grade C (rectangular) A618, grades Ib, II, and III (round) A847	same as Table 4-1, Category II

f. Unlisted Steels.

(1) Steels not listed as approved by AISC must be evaluated for structural properties such as yield strength, tensile strength, ductility and toughness. AISC design specifications assume adequate strength and ductility. For seismic applications, an assumed minimum level of toughness is assumed inherent with the steels listed in AISC *Seismic Provisions*. Other steels may warrant CVN testing or other mill documentation of typical toughness properties.

(2) Steels not listed as prequalified by AWS *D1.1* must be evaluated for their weldability. Weldability may be evaluated using methods such as carbon equivalency, the performance of WPS qualification testing, or physical testing such as the Tekken test, Lehigh Restraint Cracking Test, or the Varestraint Test. The Tekken and Lehigh methods simulate restraint that may be present in the actual joint. See Appendix B, Weldability of Steels, Stout and Doty, for further information on these tests.

2. WELDABILITY OF STRUCTURAL STEELS.

a. Chemical Composition. The chemical composition of the steel affects weldability and other mechanical properties. Several elements are purposefully added in the production of structural steel, but other undesirable elements may be present in the scrap materials used to make the steel. Carbon and other elements that increase hardenability increase the risk of “cold” cracking, and therefore higher preheat and interpass temperatures, better hydrogen control, and sometimes postheat are necessary to avoid cold cracking.

(1) Carbon (C) is the most common element for increasing the strength of steel, but high levels of carbon reduce weldability. Carbon increases the hardenability of the steel, increasing the formation of undesirable martensite with rapid HAZ cooling. Higher preheats and higher heat input welding procedures may be needed when welding a steel with relatively high carbon contents. Typical steel specifications limit carbon below 0.27%, but some steel specifications have much lower limits.

(2) Manganese (Mn) is an alloying element that increases strength and hardenability, but to a lesser extent than carbon. One of the principal benefits of manganese is that it combines with undesirable sulphur to form manganese sulfide (MnS), reducing the detrimental effects of sulfur. With high levels of sulfur, however, numerous large MnS inclusions may be present, flattened by the rolling operation, increasing the risk of lamellar tearing when high through-thickness weld shrinkage strains are created. Manganese limits are typically in the order of 1.40% or lower. A steel such as A36 does not place limits on Mn content for shapes up to 634 kg/m (426 lb./ft.), or for plates and bars up to 20 mm (3/4 in.), inclusive.

(3) Phosphorous (P) is an alloying element that increases the strength and brittleness of steel. Larger quantities of phosphorous reduce ductility and toughness. Phosphorous tends to segregate in steel, therefore creating weaker areas. Phosphorous is typically limited to 0.04% to minimize the risk of weld and HAZ cracking.

(4) Sulfur (S) reduces ductility, particularly in the transverse direction, thereby increasing the risk of lamellar tearing, and also reduces toughness and weldability. Higher sulfur levels will form iron sulfide (FeS) along the grain boundaries, increasing the risk of hot cracking. Manganese is used to form MnS to reduce this tendency. A minimum Mn:S ratio of 5:1 to 10:1 is recommended. Typical steel specifications limit sulfur to 0.05%.

(5) Silicon (Si) is a deoxidizer used to improve the soundness of the steel, and is commonly used to “kill” steel. It increases both strength and hardness. Silicon of up to 0.40% is considered acceptable for most steels.

(6) Copper (Cu) is added to improve the corrosion resistance of the steel, such as in weathering steels. Most steels contain some copper, whether specified or not. When specified to achieve atmospheric corrosion resistance, a minimum copper content of 0.20% is required. Generally, copper up to 1.50% does not reduce weldability, but copper over 0.50% may affect mechanical properties in heat-treated steels.

(7) Nickel (Ni) is an alloying element used to improve toughness and ductility, while still increasing strength and hardenability. It has relatively little detrimental effect upon weldability. Where nickel is reported as a part of steel composition, it is generally limited to a maximum value between 0.25% and 0.50%.

(8) Vanadium (V) is an alloying element used for increasing strength and hardenability. Weldability may be reduced by vanadium. When vanadium is reported as a part of steel composition, vanadium is generally limited to a maximum value between 0.06% and 0.15%.

(9) Molybdenum (Mo) is an alloying element which greatly increases hardenability and helps maintain strength and minimize creep at higher temperature. When molybdenum is reported as a part of steel composition, it is generally limited to a maximum value between 0.07% and 0.10%.

(10) So-called “tramp” elements such as tin (Sn), lead (Pb), and zinc (Zn), may be present in steel from the scrap material melted for steel-making. They have a low melting point, and may adversely affect weldability and cause “hot” cracking. Other low-melting point elements that create a risk of hot cracking include sulfur, phosphorous, and copper. When welding with high levels of these elements, it may be necessary to use low heat input welding procedures to minimize dilution effects.

b. Carbon Equivalency. The weldability of a steel can be estimated from its composition, using a calculation system termed the carbon equivalent (CE). The most significant element affecting weldability is carbon. The effects of other elements can be estimated by equating them to an additional amount of carbon. The total alloy content has the same effect on weldability as an equivalent amount of carbon. There are numerous carbon equivalent equations available and in use.

(1) The following equation is used in AWS *D1.1* Annex XI.

$$CE = C + Mn/6 + Cr/5 + Mo/5 + V/5 + Ni/15 + Cu/15 + Si/6$$

Where
C = carbon content (%)
Mn = manganese content (%)
Cr = chromium content (%)
Mo = molybdenum content (%)
V = vanadium content (%)
Ni = nickel content (%)
Cu = copper content (%)
Si = silicon content (%)

A carbon equivalent of less than 0.48 generally assures good weldability.

(2) Another common carbon equivalent equation is:

$$CE = C + Mn/6 + Cr/10 + Ni/20 + Cu/40 - V/10 - Mo/50.$$

If the CE from this equation is below 0.40, the material is considered readily weldable, and AWS *D1.1* Table 3.2 guidance for the given steel strength should be adequate. For values between 0.40 and 0.55, the use of preheat and low-hydrogen electrodes is generally necessary, regardless of thickness. Carbon equivalent values above 0.55 indicate a high risk that cracks may develop unless special precautions are implemented.

(3) The Dearden and O’Neill equation, applicable for steels with C greater than 0.12%, is similar:

$$CE = C + Cr/5 + Mo/5 + V/5 + Mn/6 + Ni/15 + Cu/15$$

A CE of 0.35% or lower is considered a steel with good weldability

(4) For steels with C between 0.07% and 0.22%, the Ito and Bessyo equation may be used. The Ito-Bessyo equation is also termed the composition-characterizing parameter, P_{cm}.

$$CE = C + 5B + V/10 + Mo/15 + Mn/20 + Cu/20 + Cr/20 + Si/30 + Ni/60$$

Where B = boron content (%)

A CE of 0.35% or lower is considered a steel with good weldability.

(5) The Yurioka equation may also used to calculate CE for steel with C between 0.02% and 0.26%, as follows:

$$CE = C + A(C) * \{5B + Si/24 + Mn/6 + Cu/15 + Ni/20 + Cr/5 + Mo/5 + Nb/5 + V/5\}$$

Where Nb = niobium content (%)
$A(C) = 0.75 + 0.25 * \tanh [20 (C - 0.12)]$

Table 4-3. Chemical Requirements for Sample Structural Steels (heat analysis, %, maximum, unless range is provided)

(Refer to ASTM specifications for complete information, including applicable thickness ranges, grades, types, combinations of elements, etc.)

Steel / Composition	A36 (shapes)	A572 grade 50 (shapes) Type 1	A572 grade 50 (shapes) Type 2	A992	A588, grade B	A852
C	0.26	0.23	0.23	0.23	0.20	0.19
Mn	---	1.35	1.35	0.50-1.50	0.75-1.35	0.80-1.35
P	0.04	0.04	0.04	0.035	0.04	0.035
S	0.05	0.05	0.05	0.045	0.05	0.04
Si	0.40	0.40	0.40	0.40	0.15-0.50	0.20-0.65
Cu	#	#	#	0.60	0.20-0.40	0.20-0.40
V	---		0.01-0.15	0.11	0.01-0.10	0.02-0.10
Co	---	0.005-0.05	---	0.05	---	---
Ni	---	---	---	0.45	0.50	0.50
Cr	---	---	---	0.35	0.40-0.70	0.40-0.70
Mo	---	---	---	0.15	---	---

Shapes composition limits are listed for sections up to 634 kg/m (426 plf).
 # minimum 0.20% when specified

3. PROPERTY ENHANCEMENTS FOR STRUCTURAL STEELS.

a. Yield to Ultimate Strength Ratio. AISC design equations assume some margin in structural steel from the point of yielding to the point of fracture to allow for the redistribution of stress. Some structural steels have been produced with F_y:F_u ratios as high as 0.95, considerably higher than that considered by

AISC in developing design methodologies.

(1) ASTM A572, grade 50, manufactured to the supplemental requirements of AISC Technical Bulletin #3, provides a requirement for a maximum F_y:F_u ratio of 0.85. This same value is a requirement for ASTM A992 steels. Although not considered critical in low-seismic applications, this requirement is advisable for members in the lateral load resisting systems in high-seismic applications.

(2) Structural steels providing this maximum F_y:F_u ratio are readily available from mill sources. Such a requirement can be met by special mill order requirements, the specification of A572, grade 50 meeting AISC Technical Bulletin #3, the specification of A992 shapes, or through the review of mill test reports of existing steels in inventory that are traceable to the mill heat number. There is currently no premium in steel mill cost to specify such properties, but some minor delays may be encountered in purchasing until the inventory of such materials is predominant.

b. Killed Steel. Killed steel has been processed to remove or bind the oxygen that saturates the molten steel prior to solidification. ASTM A6 / A6M defines killed steel as “steel deoxidized, either by addition of strong deoxidizing agents or by vacuum treatment, to reduce the oxygen content to such a level that no reaction occurs between carbon and oxygen during solidification.” Semi-killed steel is incompletely deoxidized, and may also be specified.

(1) The benefit of killing is to reduce the number of gas pockets present in the steel, which can adversely affect the mechanical properties of the steel, including ductility and toughness, as well as reduce the number of oxide-type inclusions in the steel.

(2) Most mills provide some form of deoxidation, in the form of semi-killed steel, as a part of routine production practices. AISC does not require killed steel for any specific applications.

(3) Most commonly, killing is done using additions of silicon, but may also be done with aluminum or manganese. Killed steels often have silicon levels in the range of 0.10% to 0.30%, but may be higher.

(4) Project requirements for killed steel should be considered when using wide-flange sections in Groups 4 or 5, and plates when over 50 mm (2 inches) in thickness, in tension applications, which have special AISC requirements for toughness in AISC *Specification* section A3.1c. ASTM A992 requires the steel to be killed.

(5) Specifying killed or semi-killed steel may carry a slight cost premium, except in the case of A992 steel. Because killed steel is typically a cost-premium mill order item, the inventory of killed structural steels available at steel service centers and in steel fabricating plants is less than that of regular steels. Mill orders typically require longer production lead times than service center or stock items.

c. Fine Grain Practice. Fine grain practice is the method of achieving Fine Austenitic Grain Size, defined by ASTM A6 / A6M as grain size number 5 or higher, measured using test methods prescribed by ASTM E112. Aluminum is typically used to achieve fine grain practice, which binds oxygen and nitrogen. When aluminum content is above 0.20%, by heat analysis, the steel is considered fine-grained, without the need for testing.

(1) Fine grain practice is beneficial in improving ductility and toughness. Consideration of requirements for fine grain practice should be made when using wide-flange sections in Groups 4 or 5, and plates when over 50 mm (2 inches) in thickness, in tension applications, which have special AISC

requirements for toughness in AISC *Specification* section A3.1c. When specifying steel to fine grain practice, ASTM Supplementary Requirement S91 should be consulted for the specific steel grade.

(2) Because fine grain practice is typically a cost-premium mill order item, the inventory of structural steels available at steel service centers and in steel fabricating plants manufactured to fine grain practice is less than that of regular structural steel. Mill orders typically require longer production lead times than service center or stock items.

d. Toughness. Steel toughness, also commonly referred to as “notch toughness”, is the resistance to brittle crack initiation and propagation. For this resistance, the steel must have sufficient plastic ductility to redistribute stresses at the root of a notch to the surrounding material. Toughness may be measured using a variety of methods, but the steel industry standard is the Charpy V-Notch (CVN) method, as prescribed by ASTM A370. CVN testing is an added charge by the steel producer, and steel with CVN testing is not routinely ordered by steel service centers or steel fabricators for inventory. Therefore, steels with CVN testing are generally available only through mill order, which typically requires longer production lead times than service center or stock items.

e. Improved Through-thickness Properties. For certain high-restraint applications subject to the risk of lamellar tearing, steels with improved through-thickness properties may be specified. The most common method of improving through-thickness properties, to reduce the risk of lamellar tearing, is through the specification of low-sulfur or controlled sulfur-inclusion steels. By reducing the sulfur content, the number and size of manganese sulfide (MnS) inclusions is reduced. Typically, low-sulfur steels in plate form can be ordered to 0.005% sulfur, at a cost premium and with longer lead time. Most steel specifications permit maximum sulfur in amounts between 0.30% to 0.50%. Shapes are not routinely available with substantially reduced sulfur levels, and would be available only at substantial cost premium and considerable delay. However, a mill may be able to select heats of steel with particularly lower levels of sulfur for rolling specific sections. It is also possible to specify through-thickness tensile testing using reduction of area as the governing criteria, but this is rarely necessary.

f. Normalizing. Normalizing is defined in ASTM A6 / A6M as “a heat treating process in which a steel plate is reheated to a uniform temperature above the critical temperature and then cooled in air to below the transformation range.” In practice, steel is heated to approximately 900^{o}C to 930^{o}C (1650^{o}F to 1700^{o}F). The benefits include refined grain size and uniformity, improved ductility and improved toughness. Few building applications warrant the need for normalized steel. The specification of normalized steel is a mill order item only, an added expense with added time for delivery from the steel mill. Normalized steel is not routinely available from steel service centers or stocked by fabricators.

4. SELECTION OF STRUCTURAL STEELS FOR ENVIRONMENTAL EXPOSURE AND SERVICE APPLICATIONS.

a. High-seismic Applications. The AISC *Seismic Provisions*, Section 6.3, require steel in the Seismic Force Resisting System to have a minimum toughness of 27J at 21^{o}C (20 ft.-lb. at 70^{o}F), applicable to ASTM Group 4 and 5 shapes, Group 3 shapes with flanges 38 mm (1-1/2 in.) or thicker, and to plates in built-up members 38 mm (1-1/2 in.) or thicker. Studies indicate that a large percentage of domestically produced structural steel sections lighter or thinner than those mentioned in the previous paragraph will have a CVN toughness of at least 27J at 21^{o}C (20 ft.-lb. at 70^{o}F), and therefore it does not appear that CVN testing need be conducted to verify the toughness of all members. It is recommended that manufacturer’s accumulated data be used to verify that the steel routinely produced by that mill meets the indicated toughness levels. Specification of steel toughness levels, or the specification of A709 steels, is currently considered unnecessary for ordinary building-type applications.

b. Fatigue Applications. Toughness requirements should be considered for applications involving fatigue. As a guide, the toughness values specified in ASTM A709 / A709M, Table S1.1 and S1.2, summarized and adapted in Table 4-4, may be used for redundant fatigue applications. Modifications to this table are suggested for steels that have yield strengths 103 MPa (15 ksi) or more above the minimum specified yield strengths, for all but A36 steels. See the ASTM A709 / A709M specification for appropriate changes to the testing temperatures for these cases. For nonredundant fatigue applications, see ASTM A709 / A709M, Table S1.3 for guidance. The required CVN toughness and testing temperature may be specified directly in the specifications for the project, to be placed on the mill order. Alternatively, a given ASTM A709 / A709M steel and temperature zone may be specified.

Table 4-4. Toughness Guidelines for Structural Steel in Fatigue Applications, Redundant Applications.

Steel	Thickness	Application	Minimum Service Temperature		
			Zone 1 -18°C (0°F)	Zone 2 -34°C (-30°F)	Zone 3 -51°C (-60°F)
A36	to 100 mm (4 in.), incl.	bolted or welded	20J @ 21°C (15 ft-lbf @ 70°F)	20J @ 4°C (15 ft-lbf @ 40°F)	20J @ -12°C (15 ft-lbf @ 10°F)
A572, gr 50 A588	to 50 mm (2 in.), incl.	bolted or welded	20J @ 21°C (15 ft-lbf @ 70°F)	20J @ 4°C (15 ft-lbf @ 40°F)	20J @ -12°C (15 ft-lbf @ 10°F)
“	over 50 to 100 mm (2 in to 4 in.)	bolted	20J @ 21°C (15 ft-lbf @ 70°F)	20J @ 4°C (15 ft-lbf @ 40°F)	20J @ -12°C (15 ft-lbf @ 10°F)
“	over 50 to 100 mm (2 in to 4 in.)	welded	20J @ 21°C (20 ft-lbf @ 70°F)	20J @ 4°C (20 ft-lbf @ 40°F)	20J @ -12°C (20 ft-lbf @ 10°F)
A852	to 65 mm (2-1/2 in.), incl.	bolted or welded	27J @ 10°C (20 ft-lbf @ 50°F)	27J @ -7°C (20 ft-lbf @ 20°F)	27J @ -23°C (20 ft-lbf @ -10°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	bolted	27J @ 10°C (20 ft-lbf @ 50°F)	27J @ -7°C (20 ft-lbf @ 20°F)	27J @ -23°C (20 ft-lbf @ -10°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	welded	34J @ 10°C (25 ft-lbf @ 50°F)	34J @ -7°C (25 ft-lbf @ 20°F)	34J @ -23°C (25 ft-lbf @ -10°F)
A514	to 65 mm (2-1/2 in.), incl.	bolted or welded	34J @ -1°C (25 ft-lbf @ 30°F)	34J @ -18°C (25 ft-lbf @ 0°F)	34J @ -34°C (25 ft-lbf @ -30°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	bolted	34J @ -1°C (25 ft-lbf @ 30°F)	34J @ -18°C (25 ft-lbf @ 0°F)	34J @ -34°C (25 ft-lbf @ -30°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	welded	48J @ -1°C (35 ft-lbf @ 30°F)	48J @ -18°C (35 ft-lbf @ 0°F)	48J @ -34°C (35 ft-lbf @ -30°F)

c. Cold Weather Applications. Steel toughness requirements should be considered for major load-carrying components of structures exposed to extreme cold environments. When structural components in a low-temperature environment are not subject to significant impact loads or fatigue conditions, it is generally more cost effective to specify a type of steel with inherently good fracture toughness, and avoid a requirement for specific CVN toughness at a reference temperature. High-strength low alloy (HSLA) steels that are manufactured using fine grain practice have improved toughness at low temperature, compared to conventional carbon steels such as A36 steel. AISC-approved steels requiring production to fine-grain practice are A588, A709 (grades 50W, 70W, 100, 100W), A852, and A913 (grades 60, 65 and 70), although higher strength structural steels present additional welding difficulties and should not be specified unless necessary for weight savings. Fine-grain practice can optionally be specified using ASTM Supplemental Requirement S91 for A36, A572, A992, A709 (grades 36 and 50), and A913 (grade 50). It is not available for A529, A242, or A283 steels. Steels that require killing, which also improves toughness, include A992 and A709 (grades 100, 100W), but the higher strength grades should be avoided because of other welding difficulties. Nitrogen has a significant effect upon CVN transition temperatures, and limitations on nitrogen may be considered. A992 steels place a limit on nitrogen of 0.012%, unless nitrogen binders are added. A572, Type 4 steel has a limit on nitrogen of 0.015%.

d. High Stress / Strain / Restraint Applications. When welded joints are made to the side of a member, creating through-thickness shrinkage stresses and strains, consideration should be made for the risk of lamellar tearing. Lamellar tearing is a separation or tearing of the steel on planes parallel to the rolled surface of the member. There is no specific through-thickness at which lamellar tearing will or will not occur, nor specific values for weld size, stresses or strains that will induce tearing. Generally, lamellar tearing is avoided through using one or more of the following techniques: improved design or redesign of the joint, welding procedure controls, weld bead placement selection, sequencing, the use of preheat and/or postheat, the use of low-strength, high-ductility filler metals, “buttering,” and peening. However, steels with improved through-thickness properties may also be specified. The most common method of improving through-thickness properties, to reduce the risk of lamellar tearing, is through the specification of low-sulfur or controlled sulfur-inclusion steels. See 3.e.

5. AVAILABILITY OF STRUCTURAL STEELS. All AISC-approved structural steels are available from domestic steel mills, with the exception of A913. The AISC *Manual of Steel Construction*, Table 1-1, provides general information regarding availability of shapes, plates and bars in various steel specifications, grades and strengths. Table 1-4 provides similar information for round and rectangular sections, including availability as either steel service center stock or in mill order quantities only. Table 1-3 lists the producers of specific structural shapes, and Table 1-5 provides similar information for round and rectangular sections. This list is updated semi-annually in *Modern Steel Construction* magazine, published by AISC, in the January and July issues.

CHAPTER 5

DESIGN FOR WELDING

1. GENERAL.

a. Engineer's Responsibility. The Engineer is responsible for the analysis and design of the connection, including connections between elements in built-up members. Critical structural steel connections must be completely detailed and shown on the contract drawings. The Engineer may prescribe connection details, if desired or necessary, but generally it is best to allow the fabricator or erector to select the specific welding detail to be used for a particular joint. For instance, it may be adequate for the Engineer to specify a Complete Joint Penetration (CJP) groove weld, or specify a Partial Joint Penetration (PJP) groove weld and state the required throat. This may effectively be done through the use of AWS welding symbols, and when necessary for prequalified groove welds, the appropriate AWS designation. The fabricator and erector are typically in the best position to select which process, groove type (single, double, bevel, vee, J, U), and groove angle should be used based upon economics, availability of equipment and personnel, distortion control, and ease of welding operations. The Engineer must review and approve the final details selected by the contractor.

2. GOOD DESIGN PRACTICE.

a. Availability of Materials, Equipment and Personnel. In the selection of base metals, welding processes, filler metals, and joint designs, one should consider the availability of the structural steel, welding equipment, filler metals, personnel qualified to perform such welding, personnel qualified to inspect the welding, and NDT equipment and personnel necessary to perform NDT as required. Certain welded joint designs may require notch-tough filler materials, welding personnel qualified in out-of-position welding, welders qualified for specific processes, enclosures for field welding, or nondestructive testing. When the availability of any of the above is in question, alternative joint designs should be investigated.

b. Access. The following items should be considered to permit welding operations to be made with adequate quality:

(1) Welding personnel must have direct visual access to the root of the weld. All passes must be visually monitored by the welder during welding.

(2) Access should be adequate so that the welding electrode can be positioned at the proper angle for proper penetration and fusion. Generally, the electrode should be positioned so that the angle between the part and the electrode is not less than 30°. Smaller angles may cause a lack of fusion along the weld / base metal interface. Access should be checked at the design stage when welding in highly confined spaces or with closely spaced parts.

(3) Weld access holes, placed in beam and girder webs when splicing flanges or making beam-to-column moment connections, must be of adequate size to permit the weld to be placed by reaching through the access hole with the electrode. Minimum access hole sizes are specified in AWS *D1.1* Figure 5.2. Larger access holes may be warranted based upon the welding process and type of welding equipment used.

(4) Narrow root openings and narrow groove angles inhibit access to the joint root, contributing to lack of penetration at the root and lack of fusion along the joint sidewalls. Proper joint design, preferably using joints prequalified under AWS *D1.1* should be used.

c. Position. It is preferred to weld in the flat position when making groove welds, plug welds or slot welds, and in either the flat or horizontal positions when making fillet welds. Welding positions are defined in AWS *D1.1* in Figure 4.1 for groove welds and in Figure 4. 2 for fillet welds. To assist in interpreting the positions given, see AWS *D1.1* Figure 4.3 for groove welds, Figure 4.5 for fillet welds, and Figures 4.4 and 4.6 for tubular joints. Welding in other than the flat or horizontal positions increases welding time approximately four-fold, on average, increasing cost and construction time. Fewer welding personnel are qualified by test to perform welding out-of-position. Although personnel may be previously qualified by test to weld out-of-position, a welder may not have recently used the special techniques and procedures for welding in these positions, and therefore may have lost some of the skill necessary to perform quality out-of-position welding. In this case, close visual observation of the welder during the first few out-of-position passes is especially important, and requalification testing may be necessary. The quality of out-of-position welds is more difficult to maintain, and they typically do not have the smooth appearance of welds performed in the flat or horizontal positions. This makes visual inspection and some forms of NDT more difficult.

d. Joint Selection. For guidance in the selection of groove details that provide sufficient access, limited distortion, and cost-effectiveness, the prequalified groove weld details in AWS *D1.1* Figures 3.3 and 3.4 should be reviewed. The following items should be considered in selecting or evaluating joint selection:

(1) For butt joints, partial joint penetration (PJP) groove welds are more economical than complete joint penetration (CJP) groove welds. Provided CJP groove welds are not required by Code for the given application or for fatigue and seismic applications, PJP groove welds should be considered for tension- and shear-carrying joints when full strength of the connected members is not required, and for compression splices such as column splices. PJP groove welds are prepared to a required depth of chamfer, usually the required effective throat, or 3 mm (1/8 in.) deeper, depending upon groove angle, welding process and position.

(2) For most applications, by Code, CJP groove welds require the use of either backing bars, which may need to be removed in certain types of joints, or removal of a portion of the root pass area by backgouging followed by backwelding until the joint is complete. In addition, more welding is required to join the entire thickness of material, rather than just the amount of welding needed to carry the load.

(3) In butt joints, V-groove welds are preferred over bevel-groove welds. Bevel-groove welds are generally more difficult to weld, especially when the unbeveled face is vertical, and lack of fusion on the unbeveled face may result. V-groove welds, because they are balanced and usually have a downhand position on each groove face, are easier to weld. Access to the root is also easier to achieve because of the balance and the wider groove angle used.

(4) For tee joints, fillet welding is generally less expensive than groove welding, until the fillet size reaches approximately 16 to 20 mm (5/8 to 3/4 in.). Above this size, PJP groove welding, or a combination groove weld with reinforcing fillets, should be considered. There is added expense in joint preparation for groove welds that is not required with fillet welds, however, there may be offsetting cost savings with groove welds because of decreased weld volume, fewer passes, and therefore less labor and materials. Less distortion may also be incurred because of the reduced weld volume.

(5) Square groove welds have limited application for structural steel. They are better suited for thin materials. When square groove welds are used, the root opening must be closely controlled and the Welding Procedure Specification (WPS) closely developed and followed.

(6) For thick materials, generally starting at thicknesses of 50 mm (2 in.), J- and U-groove welds may be more economical than bevel- and V-groove welds. The wider root initially requires more weld metal, but the narrower groove angle reduces the total weld volume below that of bevel- and V-groove welds. There are also higher initial joint preparation costs to prepare a J- or U-groove joint, so even more weld metal must be saved to recover these costs. When angular distortion or shrinkage strains must be minimized, J- and U-groove joints should be considered. The reduced groove angle minimizes the differential in weld width from top to bottom of the joint.

(7) Root opening widths should be generous but not excessive. Wider root openings allow for complete penetration to the bottom of the joint preparation. However, very wide roots contribute to root pass cracking and root HAZ cracking from weld shrinkage. Narrow root openings contribute to lack of penetration, lack of fusion, and trapped slag at the root.

(8) Groove angles should be the minimum angle that will provide adequate access for penetration to the root, and adequate access to the groove faces for complete fusion. Excessively wide groove angles contribute to added angular distortion, increased risk of shrinkage cracking, increased risk of lamellar tearing in T-joints, and higher costs because of the additional material and labor used.

e. Prequalified Joint Details. The prequalified groove weld details in AWS *D1.1* Figure 3.3 for Partial Joint Penetration (PJP) groove welds, and Figure 3.4 for Complete Penetration Joint (CJP) groove welds, provide root opening, groove angle, root face, thickness limits, tolerances, and other information for the effective detailing of groove welds. Root openings and groove angles are considered adequate for the welding processes and positions noted, without causing excessive angular distortion. For PJP groove welds, the required depth of preparation is provided to achieve the desired effective throat. When the joint details as shown are used, qualification testing of the joint detail is not required to verify the suitability of the detail, provided other prequalification provisions of the Code are also met. See AWS *D1.1* Section 3 for these limits. The use of prequalified groove weld details does not guarantee that welding problems will not occur. The details may not always be the best detail, and other more efficient, cost-effective or easier-to-weld details may be used. However, when other groove details are used, qualification testing is required.

f. Qualified Joint Details. Groove weld details may be used other than those shown as prequalified in AWS *D1.1* Figures 3.3 and 3.4. Alternate details may be selected with reduced or wider root openings, reduced or wider groove angles, or other revised details. Generally, narrower root openings and groove angles increase the risk of incomplete penetration at the root and lack of fusion along the groove faces. These problems may be minimized through the use of suitable WPSs. Qualification testing, as prescribed in AWS *D1.1* Section 4, is required in such cases to verify the ability of the WPS to provide the penetration and quality necessary.

g. Distortion. Angular distortion can be minimized through the use of double-sided welding, the use of minimum groove angles, J- or U-groove welds, presetting of parts, and WPS selection. Double-sided welds balance weld shrinkage about the center of the part’s cross-section. When the part can be frequently rotated for welding on opposite sides, a balanced groove detail can be used. When one side will be welded in its entirety before proceeding to weld the opposite side, the first side groove depth should be approximately 35-40% of the total groove depth of both welds. The completed first side weld restrains the second side weld from shrinking as much as the unrestrained first-side weld. Minimum groove angles and J-and U-groove details reduce the difference in weld width between the root and the face of the weld, and therefore reduce the weld shrinkage.

3. DESIGN AND FABRICATION OF WELDED JOINTS.

a. Effective Weld Size / Throat. AWS *D1.1* Section 2, Part A provides the details for the calculation of effective weld size, also called effective throat, and effective weld length.

(1) Complete Joint Penetration (CJP) groove welds have an effective throat equal to the thickness of the thinner part joined.

(2) Partial Joint Penetration (PJP) groove welds must have their size specified in the design, and then be detailed to provide the throat required. AWS provides the required depth of preparation for PJP groove welds in *D1.1*, Figure 3.3. AISC provides similar information in Table J2.1.

(3) For flat and convex fillet welds, the effective size is specified in terms of weld leg, but the effective throat is the shortest distance from the root to a straight line drawn between the two weld toes. Should the fillet weld be concave, the measurement of leg size is ineffective, and the throat must be measured as the shortest distance from the root to the weld face.

b. Allowable Stresses / Design Strengths. Allowable weld stress, when using ASD, is provided in AWS *D1.1* Table 2.3, or in AISC Table J2.5 of the *ASD Specification*. Weld design strength (when using LRFD) is provided in AISC Table J2.5 of the *LRFD Specification*. Both AWS and AISC tables are similarly structured, with minor differences in certain sections. The following information is in terms of LRFD, without consideration of the resistance factor phi. If ASD is used, see the appropriate specification.

(1) For welds other than CJP groove welds loaded in transverse tension, the AWS *D1.1* Code permits the use of matching filler metal or a filler metal of lower strength. Overmatching is not permitted in AWS *D1.1*. AISC permits the use of undermatching for the same conditions, and also overmatching filler metal to the extent of one weld strength classification, nominally 70 MPa (10 ksi) more.

(2) For CJP groove welds that carry transverse tensile stress, the AWS *D1.1* Code requires the use of matching filler metal. Matching filler metal provides a weld with at least the strength of the base metal in such an application. See AWS *D1.1* Table 3.1 for matching filler metals. The strength of the weld is treated the same as the strength of the base metal, as the base metal will be the weaker of the two materials, with a phi of 0.9.

(2) Should the CJP groove weld be used in a T-joint or corner joint loaded in tension transverse to its axis, with the backing bar remaining in place, AISC *LRFD Specification* Table J2.5, Note [d] requires the use of filler metal with a designated CVN toughness of 27J @ +4^{o}C (20 ft.-lbf @ +40^{o}F). Alternatively, the weld must be designed as a PJP groove weld, similarly loaded.

(3) For CJP groove welds in transverse compression, the AWS *D1.1* Code requires the use of either matching filler metal or a filler metal one strength classification less, nominally 70 MPa (10 ksi) less. AISC places no limit on the undermatching strength. The strength of the weld is treated the same as the strength of the base metal, with a phi of 0.9.

(4) CJP groove welds in shear may carry 0.60 times the classification strength of the filler metal,

with a phi of 0.8.

(5) CJP groove welds and other welds carrying tension or compression parallel to the axis of the weld need not be designed for the tensile or compressive stress, only for any shear forces that may be transferred between the connected parts. As an example, girder web-to-flange welds need not be designed for the axial force from bending, only for the shear transferred between the web and flange.

(6) PJP groove welds in transverse tension are permitted to carry 0.60 times the classification strength of the filler metal, with a phi of 0.8. The stress on the base metal is also limited to the minimum specified yield strength of the base metal, with a phi of 0.90, using the effective size (throat) of the groove weld for the check of the base metal stress.

(7) PJP groove welds in compression are currently treated differently by AWS and AISC. Under AWS *D1.1*, PJP groove welds are categorized into joints designed to bear and joints not designed to bear. AISC, because it is based upon new construction, provides design values only for the joint designed to bear application. Under AISC, for joints designed to bear, the weld stress need not be checked, as the base metal will govern the strength of the joint, with a phi of 0.9.

(8) For joints not designed to bear, only AWS provides design values, based upon Allowable Stress Design (ASD). The weld stress may not exceed 0.50 times the classification strength of the filler metal, and the base metal stress may not exceed 0.60 times the minimum specified yield strength of the base metal, applied to the throat of the groove weld. LRFD values, considering the factor phi, are generally 1.5 times the ASD values.

(9) PJP groove welds in shear may be stressed to 0.60 times the classification strength of the filler metal, with a phi of 0.75.

(10) Fillet welds may be stressed to 0.45 times the classification strength of the filler metal, with a phi of 0.75. There is no need to check the shear stress in the base metal along the diagrammatic leg of the fillet weld. Research indicates that, because of penetration and HAZ hardening, the leg of the fillet weld is not a failure plane that needs checked.

(11) For transversely loaded fillets welds, AWS *D1.1* Section 2.14.4 and 2.14.5, and AISC *LRFD Specification* Appendix J2.4, permit a 50% increase in the allowable shear stress on the weld. For angles other than transverse, an increase is also permitted based upon an equation. For eccentrically loaded fillet weld groups, allowable shear stress increases are also permitted when using the instantaneous center of rotation approach for the analysis of the weld group. Design values for typical weld groups are provided in the AISC *Manual*.

(12) When fillet weld strength increases, as above, are used for loading other than parallel to the weld axis, AISC *LRFD Specification* Table J2.5, Note [h] requires the use of CVN toughness as above.

(13) When a fillet weld is loaded longitudinally along its axis, and is loaded from its end, as in a splice plate or brace member, there is a maximum effective length of 100 times the leg size before a reduction factor must be implemented. Longer fillet welds loaded in such a manner must be analyzed using a reduction coefficient Beta from AISC *LRFD Specification* equation J2-1. The maximum effective length is 180 times the leg size, which would apply when the weld is 300 times the leg size in length, with a reduction coefficient Beta of 0.6.

(14) Plug and slot welds may be stressed to 0.60 times the classification strength of the filler metal,

with a phi of 0.75. There is no need to check the stress in the base metal along the base of the plug or slot. Plug and slot welds may be designed only for shear forces along the base of the hole or slot, not for shear along the walls of the hole or slot.

(15) With shear stress in any type weld, the Code requires a check of the base metal in shear, limiting the base metal stress to 0.60 times the minimum specified yield strength of the base metal, with a phi of 0.75. This check is applied to the thickness of the material, not the weld/steel interface, to verify that the steel has the capacity to carry the load delivered to or from the weld. This is especially applicable to situations using fillet welds on opposite sides of thin beam and girder webs.

c. Minimum Weld Size. Minimum weld sizes are incorporated into both the AWS *D1.1* and AISC codes. AWS *D1.1* Table 5.8, provides minimum fillet weld sizes, and Table 3.4 provides minimum prequalified PJP groove weld sizes. The basis of these tables is the need to slow the cooling rate when welding on thicker materials. Small welds provide little heat input to the thick base metal, which acts as an efficient heat sink, and therefore the weld region cools very rapidly. The rapid cooling creates a hard, martensitic heat-affected zone (HAZ), with potentially high levels of trapped hydrogen, with a higher risk of cracking. Larger welds are made with higher welding heat input, therefore reducing the cooling rate, and reduce the risk of HAZ cracking to acceptable levels. AISC Table J2.3 provides minimum fillet weld sizes similar to AWS *D1.1* Table 5.8, but does not provide weld size reductions based upon the use of low hydrogen electrodes or preheat.

d. Maximum Fillet Weld Size. A maximum fillet weld size is established for lap joints where a fillet weld is placed along the edge of a part. The maximum fillet weld size that should be specified, when the part is 6 mm (1/4 in.) or more in thickness, is 2 mm (1/16 in.) less than the thickness of the part. This is to protect the edge of the part from melting under the arc, making it difficult to verify adequate leg size and throat. For lap joints where the part receiving the fillet weld along its edge is less than 6 mm (1/4 in.) in thickness, the specified fillet weld size may equal the thickness of the part. See AWS *D1.1* Section 2.4.5.

e. Available Design Aids. Design aids for welded connections, in the form of tables and software, are available. See Appendix B, Bibliography.

f. Weld Access Holes. Weld access holes provide access for welding equipment to reach the weld region, reducing the interference from the member itself. They also provide access for weld cleaning and inspection. Access holes also serve to separate weld shrinkage stresses when fully welded joints are made in both the member web and flange, as an example. Typically, weld access holes are provided in beam and girder webs when splicing flanges, or when making welded flange connections in beam-to-column joints, but may also be used in other joints where interferences exist. See AWS *D1.1* Section 5.17, and AISC *LRFD Specification* Section J1.6 for minimum access types, dimensions, and quality. When weld access holes are used in heavy sections or high-seismic applications, special provisions regarding surface quality and inspection apply.

g. Reentrant Corners. Reentrant corners are internal cuts in members. Typical reentrant corners in buildings are found at openings for piping and ductwork in beam webs. Reentrant corners must be smooth, with no notches, with a minimum radius of 25 mm (1 in.). Grinding of reentrant corners and tangency is not required. Beam copes and weld access holes are treated separately by the code. See AWS *D1.1* Section 5.16.

h. Heavy Section Joint Provisions. Under the AISC LRFD *Specification*, special material, welding and quality requirements apply for applications using ASTM Group 4 and 5 shapes, and for built-up sections using plates over 50 mm (2 in.) in thickness. AWS *D1.1* provisions apply for ASTM Group 4 and 5 shapes and for built-up sections with a web plate over 38 mm (1-1/2 in.) in thickness. Both codes apply these provisions only when the materials are used with welded tensile splices, but have also been applied to connections such as beam-to-column connections where the flanges are direct-welded for moment resistance. The special material requirements include a minimum CVN toughness taken from a specific, nonstandard location in the material. The special provisions listed do not apply when the joint carries only compression, such as column splices, or when bolted slices are used. Weld access holes must be preheated to 65^{o}C (150^{o}F) prior to thermal cutting, ground to bright metal, and inspected using either Penetrant Testing (PT) or Magnetic Particle Testing (MT). Optionally, weld access holes may be made by drilling and saw-cutting, but PT or MT of the cut surface is still required. For joint welding, minimum preheat and interpass temperature of 175^{o}C (350^{o}F) must be used, higher than that required by AWS *D1.1* Table 3.2. Weld tabs and backing bars must be removed after completion of the joint. AWS *D1.1* code provisions contain most, but not all, of these provisions. The AISC *ASD Specification* does not contain the latest joint details, and therefore AISC *LRFD Specification* provisions should be used. See AISC section A3.1c for materials requirements, J2.8 for preheat requirements, J1.6 for access hole requirements, and J1.5 for weld tab and backing bar removal requirements. See AISC LRFD Figure C-J1.2 for dimensional and fabrication requirements for weld access holes.

i. Backing Bars. Backing bars are used to close and support the root pass of groove welds when made from one side of the joint. Joint assembly tolerances are greater when backing bars are used, compared to joints without backing. Assembly tolerances without backing are typically within 3 mm (1/8 in.), difficult to achieve with structural steel sections in either the shop or field, but possible for some types of joints for shop fabrication. With backing, the assembly tolerances are typically enlarged to allow variations of 8 mm (5/16 in.). Welding is more easily performed with backing to support the root pass, eliminating concerns for melt-through and repair. In some joints, particularly in fatigue and seismic applications, it may be recommended or necessary to remove the backing bar after use. This adds cost to the operation, particularly when rewelding and / or finishing of the removed area is necessary.

(1) Steel backing is used almost universally in steel construction. Those applications that require subsequent backing removal are sometimes done with nonfusible backing materials such as copper, ceramic or flux. The use of backing materials other than steel is generally considered nonprequalified, requiring the testing of the WPS with these materials. Extreme caution should be used with copper backing, as the arc may strike the copper and melt copper into the weld, greatly increasing the risk of weld cracking.

(2) Welding personnel qualified to weld using backing are also qualified to weld without backing, provided the weld is backgouged and backwelded. If the joint is not backgouged and backwelded, then the welder must be qualified to weld without backing. If a welder is qualified without backing, then the welder may also weld with backing.

(3) The minimum backing thicknesses provided in AWS *D1.1* Section 5.10.3 are generally suitable to reduce the risk of melting thru the backing bar, but very high heat input procedures, particularly with Submerged Arc Welding (SAW), may require thicker backing.

(4) AWS *D1.1* Section 5.10, includes provisions for backing materials, thickness, splicing, and removal.

j. Weld Tabs. Weld tabs are also referred to as “extension bars”, “run-off tabs”, and similar terms in the industry. The purpose of a weld tab is to allow the weld to be started or stopped beyond the edge of the material being joined. Weld tabs are typically used in butt joint member splices, groove welded direct-welded flange joints in beam-to-column moment connections, and at the ends of built-up member welds such as girder web-to-flange welds. Weld tabs allow the welding of the full width of the joint, without starts and stops or build-out regions along the edges. The use of weld tabs places the inherent weld discontinuities made when starting or stopping a weld within the tab, and outside the major stress flow of the spliced material. Tabs also allow the welding arc to stabilize prior to welding the main material. For SAW, the tabs support the flux deposit at the edge of the workpiece.

(1) After welding is completed, the weld tabs may need to be removed. In some joints, particularly in fatigue and high-seismic applications, it may be recommended or necessary to remove the weld tab after use. Removal is required in most fatigue applications. In heavy section tensile splices, removal is required. In high seismic regions, removal is required at transverse groove welds in moment-resisting joints. For other applications, removal should be considered when splicing members over 25 mm (1 in.) in thickness when the members are subjected to high tensile stresses at the splice. This is because thicker members typically have less toughness than thinner members, and the low toughness may allow a crack or other discontinuity in the weld tab to propagate into the primary weld. For compression joints such as column splices, or for low-stress tensile splices, weld tabs in statically loaded structures should be allowed to remain in place.

(2) AWS *D1.1* Section 5.31, provides information on the use and removal requirements for weld tabs.

k. Welding Sequence and Distortion Control. Parts can be preset in a skewed position so that, when weld shrinkage occurs, the completed member will be approximately straight. WPSs that use large passes, rather than numerous small passes, generally cause less angular distortion. Distortion may also occur along the length of a member, resulting in unintended sweep, camber, or twist. This occurs because welding is not balanced about the center of gravity of the member cross-section. The use of intermittent welding, welding from the center of the member's length, and overwelding in some locations may also be used to reduce longitudinal distortion.

l. Lamellar Tearing. Lamellar tearing is a step-like crack in the base metal, generally parallel to the rolled surface, caused by weld shrinkage stresses applied to the steel in the through-thickness direction. The steel is somewhat weakened by the presence of very small, dispersed, planar-shaped, nonmetallic inclusions, generally sulfur-based, oriented parallel to the steel surface. These inclusions serve as initiation points for tearing. Large inclusions constitute laminations, which may be detectable using straight-beam ultrasonic testing prior to welding. The inclusions that initiate lamellar tearing are generally not reliably detected using any form of NDT.

(1) There is no specific through-thickness at which lamellar tearing will or will not occur, nor specific values for weld size, stresses or strains that will induce tearing. Generally, lamellar tearing is avoided by using one or more of the following techniques: improved design or redesign of the joint, welding procedure controls, weld bead placement selection, sequencing, the use of preheat and/or postheat, the use of low-strength, high-ductility filler metals, "buttering," and peening. AWS *D1.1* Commentary C2.1.3, provides guidance on these methods. Steels with improved through-thickness properties may also be specified. The most common method for improving through-thickness properties, to reduce the risk of lamellar tearing, is the specification of low-sulfur or controlled sulfur-inclusion steels.

(2) Should lamellar tears be detected, the stress type, application, and the implications of potential failure in service should be considered. Because the completed joint is more highly restrained than the original joint, repair of joints that have torn is difficult and expensive, with no assurance that a tear will not form beneath the repair weld. Repair may involve complete removal of the existing weld and

affected base metal. Reinforcement, if appropriate for the application, should be considered in lieu of repair or replacement.

m. Brittle Fracture. Brittle fracture is a failure that occurs in the steel or weld without appreciable deformation or energy absorption. Not all fractures are brittle, as the material may have undergone considerable straining and deformation prior to fracture. Sufficient ductility should be provided in joint design and detailing, and toughness in materials selection, so that brittle fracture will not occur. Many joint designs assume the ability to deform and redistribute stress throughout the connection. Standard design and detailing practices are typically adequate for building structures. Extreme loading conditions, cold temperature environments, high seismic risk, unusual materials, and fatigue applications may require more care in the selection and construction of connections and their details. Notches, whether inadvertent or inherent in the design, greatly increase the risk of brittle fracture. Care should be taken to avoid transversely loaded sharp notches and joint transitions, particularly in areas such as weld toes. Backing bars should be removed in some applications because the notch inherent at the root pass between backing bar and steel may initiate a crack in the weld, HAZ or base metal. Where it is assumed that plastic behavior will be required to provide ductility and energy absorption, such as seismically-loaded structures, sufficient length of base material should be provided in the assumed area of plastic yielding to allow this to occur, and notches that would serve as crack initiators should be avoided in this area. Notch-tough materials reduce the risk of brittle fracture.

4. DESIGN FOR CYCLICALLY LOADED STRUCTURES (FATIGUE).

a. General. The fatigue strength of a welded component is a combination of a stress range and a number of cycles (N) that causes failure of the component. The stress range is the total range between the maximum and minimum applied stresses. Stress range does not require stress reversal, only a variation in stress. The fatigue life of a component, also called the endurance limit, is the number of cycles to failure. The fatigue life of a welded joint is affected by the stress range at the location of crack initiation, and the fatigue strength of the detail, primarily a function of its geometry. In welded joints, fatigue life is generally not affected by applied stress level or the strength of the material.

(1) Traditional fatigue design is based upon high-cycle fatigue, generally in the range of 20,000 cycles to 100,000 cycles and up. However, low-cycle fatigue may also occur in cases of extreme stress and strain, such as seismic events or unanticipated out-of-plane bending from applied stresses or distortion. Applications that may experience low-cycle fatigue require design and detailing specific to the application that exceed the general fatigue design provisions of the codes.

(2) The S-N curves used for fatigue design provides an assumed relationship between fatigue life and stress range, and are commonly plotted on a logarithmic scale as a straight line. At the upper left end of the straight line, at the low endurance limit, the ultimate material strength is exceeded and failure occurs from static stress. At the lower right end of the curve, the high-endurance range, the stress ranges are generally too low to initiate crack propagation. The design S-N curves used to design structural members have been established approximately 25% below the mean failure values. Several design codes are now replacing the design S-N curves with the equations used to generate the plotted curves.

(3) The fatigue strength of different welded details varies according to the severity of the stress concentration effect. Those with similar fatigue life characteristics are grouped together into a Stress Category, identified as Classes A through F, with subcategories for special cases. There are several details that fall within each class. Each detail has a specific description that defines the geometry. The details and stress categories are classified by:

- form of the member (plate base metal, rolled section base metal, weld type),
- location of anticipated crack initiation (base metal, weld, weld toe),
- governing dimensions (attachment dimensions, radius of transition, weld length, etc.),
- fabrication requirements (ground flush, backing removed, etc.), and
- inspection requirements (ultrasonic or radiographic testing). The detail category should be evaluated carefully to verify that the actual detail realistically matches the standard detail.

(4) Careful design and fabrication can reduce the risk of failure by fatigue. Not all methods of fatigue life improvement are contained in the Codes, and not all methods are necessary. Smooth shapes and transitions are important, but radiused transitions are expensive and may not substantially improve fatigue life.

- Grinding groove welds flush in the direction of the applied stress may improve the Stress Category.
- Avoid reentrant, notch-like corners.
- Transitions between members of differing thicknesses or widths should be made with a slope of at least 2.5:1.
- Joints should be placed in low stress areas, when possible.
- Groove-welded butt joints have better fatigue life than lap or tee joints made with fillet welds.
- Parts should be aligned to minimize or eliminate eccentricity and minimize secondary bending stresses.
- Avoid attachments to members subject to fatigue loading.
- Attachment welds should be kept at least 12 mm (1/2 in.) from the edges of plates.
- Welds on the edges of flanges should be avoided. Fillet welds should be stopped about 12 mm (1/2 in.) short of the end of the attachment, provided this will not have any other detrimental effect on the structure.
- If a detail is highly sensitive to weld discontinuities, such as a transversely loaded CJP groove weld with reinforcement removed, appropriate quality, inspection, and NDT requirements should be specified.
- Fatigue life enhancement techniques such as those found in AWS *D1.1* Section 8, may be cost-effective in extending fatigue life.
- When grinding is appropriate, grinding should be in the direction of stress.
- Intermittent stitch welds should be avoided. Unauthorized attachments, often made by field or maintenance personnel or other trades, must be prohibited.
- A bolted assembly may be appropriate and more cost-effective in some applications.
- For critical details, provide for in-service inspection.

b. Fatigue Design Details. Fatigue details are identified as plain material, built-up members, groove welds, groove-welded attachments, fillet welds, fillet-welded attachments, stud welds, and plug and slot welds. Further divisions of these general categories are provided using general descriptions, and in some cases, by attachment length, radius, grinding requirements, NDT requirements, and member yield strength. Illustrative examples are typically provided by the codes to assist in the interpretation of these divisions.

(1) Stress Category A is limited to plain material, with no welding. Categories B, C, D and E follow the same line slope, with reduced permitted stress ranges for a given fatigue life demand. Category F behavior is sufficiently different to use a different slope. The endurance limit is also reached soonest, at the highest stress range, for Category A details, with progressively more cycles and lower stress ranges for the endurance limit in other categories.

(2) Various design codes may be used for fatigue design, and all are based upon the same principles and research data. Occasional revisions to these provisions and details are made by the various code organizations, so there may be minor differences between codes. Generally, AISC and AASHTO specifications are the most current and comprehensive, including bolted details. AWS *D1.1* provisions are limited to welded details. AASHTO and AWS currently use S-N curves, and AISC uses tabular values based upon the S-N curves. All three organizations are currently changing to equation-based design.

(3) AASHTO and AWS provide fatigue design curves for both redundant and nonredundant structures. The AWS nonredundant structure fatigue provisions are based upon bridge principles, where failure of the welded component would result in collapse of the structure, but special provisions for nonredundant structures are not required. The AASHTO code, however, requires the use of the AWS *D1.5*, Section 12, Fracture Control Plan for Nonredundant Structures. As a specification for building construction, AISC does not address nonredundant applications.

c. Allowable Stress Ranges. Stress ranges at the lower number of cycles, for the better fatigue categories, are often limited by the static stress applied. Because the number of cycles is usually established for the application, and often the type of detail needed to make the component or connection is established, the design must be established to keep the stress range below that permitted. Fatigue design begins with the sizing of the member and the connection for the maximum applied static load, then checked for the applied stress range. Adjustments are then made to increase the component or connection size as needed. Should the size become excessive, other improved details may be considered. This includes, for some groove details, grinding of the surface and NDT to improve the fatigue design category. Some joints may be changed from PJP groove or fillet welds to CJP groove welds. Another alternative is the use of fatigue life enhancement details to improve fatigue life. Fatigue life enhancement details are not to be used to increase allowable stress ranges.

d. Fatigue Life Enhancement. At the toe of every weld, with the exception of welds made using Tungsten Inert Gas (TIG) welding with no filler metal, a microscopic slag intrusion line is present. This line, for fatigue purposes, acts as a small crack. Fatigue life of welded joints, therefore, begins with an initial crack, and fatigue life is limited to crack propagation. With plain material, there is no pre-existing crack, so fatigue life is spent in both crack initiation and crack propagation. By applying fatigue life enhancement techniques, as described in AWS *D1.1* Section 8, fatigue life may be extended. The process of TIG dressing can be used to remelt the weld toe area to a limited depth, melting out and removing the microscopic slag intrusion line. Burr grinding of the weld toe, to a depth of approximately 1 mm (1/32 in.), may also be used to remove the slag line. Toe peening, in which localized mechanical compressive stresses are induced into the weld toe area, does not remove the slag line, but induces residual compressive stresses around the slag line to prevent the introduction of the tensile stresses necessary for crack propagation. Any of these enhancement processes typically double the fatigue life of the treated joint. Performing both toe grinding and hammer peening will provide additional benefits, achieving typically triple the fatigue life of the untreated weld toe. Caution should be used when extending fatigue life expectations, as other areas of the welded joint may now fail before the weld toe. Inspection of the weld should be performed prior to implementing fatigue life enhancement techniques, with any required inspection for surface discontinuities repeated following the work.

5. HIGH SEISMIC APPLICATIONS.

a. Latest Guidance. Recommendations for the design of welded connections in high seismic regions are undergoing substantial revision as of the date of this document. Users are advised to seek the latest guidance from FEMA and AISC documents.

b. Applicability. Improved materials and details should be used for building structures classified as Seismic Categories D, E and F. These applications include all buildings located in areas with 1 second spectral response accelerations (S_{D1}) of 0.20g or higher, or short period response accelerations (S_{DS}) of 0.50g, and buildings of Seismic Use Group III in areas with S_{D1} of 0.133g or higher, or S_{DS} of 0.33g or higher. Seismic Use Group III structures are essential facilities that are required for post-earthquake recovery and those containing substantial quantities of hazardous substances, including but not limited to: fire, rescue and police stations; hospitals; designated medical facilities providing emergency medical treatment; emergency operations centers; emergency shelters; emergency vehicle garages; designated communications towers; air traffic control towers; and water treatment facilities needed to provide water pressure for fire suppression. See TI 809-04, Table 4-1 for Seismic Use Groups, and Section 4.2 for Seismic Design Categories.

c. Materials Concerns and Specifications. Special compositional, materials toughness and other mechanical property requirements may be necessary for the steel and filer metal used in seismic applications:

(1) The AISC *Seismic Provisions*, Section 6.3, require steel in the Seismic Force Resisting System to have a minimum toughness of 27J at 21°C (20 ft.-lbf at 70°F), applicable to ASTM Group 4 and 5 shapes, Group 3 shapes with flanges 38 mm (1-1/2 in.) or thicker, and to plates in built-up members 38 mm (1-1/2 in.) or thicker.

(2) Studies indicate that a large percentage of domestically produced structural steel sections lighter or thinner than those mentioned in the previous paragraph will have a CVN toughness of at least 27J at 21°C (20 ft.-lbf at 70°F), and therefore it does not appear that CVN testing need be conducted to verify the toughness of all members. It is recommended that manufacturer’s accumulated data be used to verify that the steel routinely produced by that mill meets the indicated toughness levels. Specification of steel toughness levels, or the specification of A709 steels, is currently considered unnecessary for building-type applications.

(3) It is also recommended that structural steel shapes used in high seismic applications be specified as either ASTM A992 or A572, grade 50 manufactured to AISC Technical Bulletin #3. These specifications have provisions for a maximum ratio of F_y to F_u of 0.85, and a more controlled chemistry for weldability and properties.

(4) The AISC *Seismic Provisions*, section 7.3b, require filler metals in the Seismic Force Resisting System to have a minimum toughness of 27J at -29°C (20 ft.-lbf at -20°F). Additional requirements for toughness at service temperature, tested using welding procedures representative of the range of production WPSs, are also recommended in the latest FEMA Guidelines.

(5) There are concerns for the performance of rolled steel sections in the vicinity of the K-line, at the intersection of the web and the radius between web and flange. Studies have identified a reduced toughness in this region caused by cold-working during rotary straightening at the steel mill. Reduced toughness in these region may increase the risk of crack initiation from welding in the area, particularly stiffeners (continuity plates) and doubler plates. AISC Technical Advisory No. 1 should be followed, pending further study.

(6) Current studies indicate that through-thickness toughness properties or applied stress on the column face is not a limiting factor, and need not be specified or checked.

d. Joint Selection. Several types of details may be used to achieve satisfactory moment connection performance in high seismic applications. Enhanced quality, improved and reinforced details are recommended for conventional-type connections. See (e) below. For Reduced Beam Section (RBS) system connections, also called the “dogbone” system, current AISC guidelines should be followed. See Appendix D, Bibliography. Several limitations have been found in the cover-plated and ribbed details, and further investigation of the latest recommendations should be made prior to use.

e. Joint Detail Modifications and Enhancements. Current recommendations include the following modifications to the previous standard beam-to-column connection: (1) removal of bottom flange backing bar, backgouging of the root, and placement of a reinforcing fillet, (2) improved quality of the weld access hole, (3) removal and finishing of weld tabs, (4) control of profile and quality of the access hole, (5) use of partially or fully welded web connections. The exact requirements for access hole provisions and web welding depend upon the type of connection used and the design application, whether Special Moment resisting Frame (SMRF) or Ordinary Moment-Resisting Frame (OMRF).

f. Inspection Enhancements. Continuous inspection of all welding performed on CJP and PJP groove welds that are a part of the Seismic Force Resisting System is necessary. The Engineer may allow periodic inspections when appropriate. AISC *Seismic Provisions* require NDT for certain joints in high seismic applications, as follows: “All complete joint penetration and partial joint penetration groove welded joints that are subjected to net tensile forces as part of the Seismic Force Resisting Systems ... shall be tested using approved nondestructive testing methods conforming to AWS *D1.1*.” Such testing should include ultrasonic testing of welds in T-joints and butt joints over 8 mm (5/16 in.) in thickness. Radiographic testing may be used in some cases using butt joints. When using T-joints, with the thickness of the tee “flange” exceeding 40 mm (1-1/2 in.), ultrasonic testing should be performed after completion and cooling of the weld to check for lamellar tearing.

CHAPTER 6

STUD WELDING

1. GENERAL.

Stud welding for building applications is generally for shear connectors in composite beams, but may also include shear connector applications for composite columns and frames. Studs may be welded either directly to the structural steel or through metal decking. The purpose of most shear connectors is to integrally connect steel and concrete materials so that they act as a single unit in resisting load. Occasionally, threaded studs may be used for special connections where bolting is not practical, such as embedment plates or inaccessible connections. Stud welding is a fully automated process with controlled arc length and arc time, and is conducive to a suitable convenient load test, and therefore is treated separately by AWS *D1.1* for procedure qualification, personnel qualification, and inspection.

2. STUD WELDING PROCESS.

The arc stud welding process is used for structural studs, rather than the capacitor discharge stud welding process. A DCEN (straight) current is used to create an arc between the stud base and the steel. The stud welding gun draws the stud away from the steel, creating the arc, allows a brief period for the melting of the steel and stud base, then plunges the stud into the molten pool and terminates the current flow. The weld arc and molten pool is protected with the use of a flux tip on the base of the stud, plus the use of a ceramic ferrule to contain the molten pool. See AWS C5.4, *Recommended Practice for Stud Welding*, for complete information.

3. STUD BASE QUALIFICATION.

Stud bases are qualified by the manufacturer for application on bare steel in the flat position only. Qualification procedures for this application are provided in AWS *D1.1* Annex IX. For all other applications, including studs applied through metal decking, studs applied to curved surfaces, studs welded in vertical or overhead positions, or studs welded to steels not listed as Group I or II in AWS *D1.1* Table 3.1, the contractor must perform qualification testing. For the Type B studs used in composite construction, ten (10) specimens must pass a 90° bend test using representative material and application. Alternatively, a tension test method may be used. See AWS *D1.1* Section 7.6.

4. WELDING PERSONNEL QUALIFICATION.

The welding operator conducting the two pre-production tests at the start of the day or work shift is qualified for performing stud welding that day or shift. See AWS *D1.1* Section 7.7.4.

5. PRE-PRODUCTION TESTING.

After stud base qualification by the manufacturer, or qualification testing by the contractor for the applications listed, installation may begin. However, pre-production testing is required at the start of each day or shift to verify the setup of the equipment. This testing requires two studs to be welded, on the work if desired, visually inspected, then bent approximately 30^o. If the stud weld passes the visual and bend testing, then production welding may begin. For composite construction, the stud need not be bent back to the original position. See AWS *D1.1* Section 7.7.1. The pre-production test must be repeated whenever there are changes to the following items: voltage, current, time, or gun lift and plunge.

6. INSPECTION.

Following the application of studs and the removal of the ferrules, all stud welds are visually inspected for flash about the entire perimeter of the stud base. Those with missing flash may be repaired, or tested using a bend test applied approximately 15^o in the direction opposite the missing flash. Should the stud weld not fracture, the stud is accepted and may be left in place in the bent condition when used in composite construction. The inspector may 15^o bend test any stud, if desired, even if full flash is apparent. See AWS *D1.1* Section 7.8.

CHAPTER 7

WELDING TO EXISTING STRUCTURES

1. GENERAL.

When welding to reinforce existing structures, several areas require investigation and, in some cases, specific instructions. Other than load analysis of the structure to design the connections, several welding issues arise. These include weldability of the existing steel, the reduction of strength to existing members when being heated or welded, and the welding to existing weld deposits of unknown origin or made with FCAW-S electrodes. AWS *D1.1* Section 8, and its supporting Commentary, provides applicable code provisions.

2. DETERMINING WELDABILITY OF EXISTING STRUCTURAL STEELS.

a. Investigation. Investigation of weldability is generally warranted for buildings constructed prior to 1945, although structural steels were not manufactured specifically for welding properties until A373 and A36 came into use in the early 1960's. The weldability of steels between these periods is generally considered sufficiently weldable.

b. Carbon Equivalency.

(1) The most reliable method to establish chemical composition for determining carbon equivalent values is to remove samples from various members at selected no- or low-stress locations, then analyzed spectrographically for composition. Portable spectrographs may also be used, although only optical emission spectrography systems currently provide sufficient accuracy for measuring carbon content. The laboratory analysis report should list the quantities of each of the elements in the selected carbon equivalent equation, even if the percentage reported is zero.

(2) Other methods, although less reliable, include spark testing and weld sample tests. Spark testing applies a grinding wheel at approximately 5000 rpm to the steel, then observing and characterizing the color and nature of the sparks off the steel. Weld sample tests include welding small test plates to the steel, then destructively using a sledge hammer to break off the samples, if possible, and observing the nature of the fracture.

3. WELDING TO OLDER STRUCTURAL STEELS.

The poorer the weldability of steel, the greater the need for higher preheat and interpass temperatures, and the greater the importance of low-hydrogen welding. All welding to existing structures should be performed with low-hydrogen SMAW electrodes or with other wire-fed welding processes. Minimum preheat and interpass temperatures can be determined from AWS *D1.1* Annex XI, or from technical literature.

4. INTERMIXING WELD PROCESSES AND FILLER METALS.

a. FCAW-S Deposits. Self-shielded Flux-Cored Arc Welding (FCAW-S) weld deposits contain aluminum, nitrogen, carbon and other alloying elements. When weld processes that use consumables with significantly different metallurgical systems are mixed with FCAW-S deposits, there is the potential for reduced properties, particularly ductility and toughness. This is the result of the liberation of nitrogen and aluminum that were previously chemically combined as Al-N in the FCAW-S deposit. Other weld deposits, typically a carbon-manganese-silicon metallurgical system, do not contain the amount of aluminum necessary in order to preclude the formation of free nitrogen, which can embrittle the steel or weld deposit.

b. Investigation. When it is suspected that existing weld deposits that will receive subsequent welding were made using FCAW-S, further investigation of the weld deposit is warranted. An aluminum content in the range of 1% is indicative of FCAW-S. Low-admixture welding procedures, design assuming reduced mechanical properties, or requiring subsequent welding using appropriate FCAW-S should be considered.

c. Other Processes. Recent research indicates that this problem may not be limited to non-FCAW-S weld deposits on top of FCAW-S. Multiple weld processes in a single weld joint may also occur in new construction because of tack welding, root pass welding selection, or other reasons.

5. STRENGTH REDUCTION EFFECTS AND OTHER CONCERNS WHEN WELDING UNDER LOAD.

a. Elevated Temperature Effects. Elevated temperatures in steel reduce both the yield strength (F_y) and the modulus of elasticity (E). At approximately 300°C to 400°C (600°F to 800°F), F_y and E are reduced approximately 20%. Preheat temperatures at this level are rarely used, but localized temperatures near the weld region will exceed these temperatures for brief periods. As a general guide, steel during welding, within the weld region, will exceed these temperatures approximately 25 mm (1 in.) to the side of a weld, and a distance of approximately 100 mm (4 in.) trailing the weld puddle. Steel further from the weld region will remain at temperatures that will not significantly reduce the steel's properties.

b. Welding Direction and Sequence. When welding under load, consideration should be made for the temporarily reduced strength of localized areas of the steel. When welding parallel to the applied stress, the affected area is typically small compared to the area of the unaffected steel. When welding transverse to the load, additional caution is needed. It may be necessary to stagger welding operations, use shorter sections of weld and then allow cooling, or use lower heat input procedures.

6. HAZARDOUS MATERIALS.

When welding on steel having existing coatings, an investigation into the composition of the coating is warranted, unless all coatings in the vicinity of the welding are removed prior to welding. Zinc, used in numerous coating systems and galvanizing, produces noxious fumes. Some older structures may contain lead-based paints that must be removed using special hazardous materials precautions.

CHAPTER 8

QUALITY ASSURANCE AND INSPECTION

1. GENERAL.

The Engineer is responsible for establishing and specifying the requirements of the Quality Control and Quality Assurance programs for the project. These requirements should be a part of the contract documents. AWS *D1.1* requires inspection of welding, but requires only “Fabrication / Erection Inspection”, which is the designated responsibility of the Contractor. “Verification Inspection” is the prerogative of the Owner, under AWS *D1.1*. Therefore, any specific welding inspection operations to be performed by personnel other than the Contractor must be fully detailed and placed in the contract documents.

2. REVIEWING AND APPROVING WELDING PROCEDURES.

a. WPS Contents. Welding procedures are used to specify, for the welder and inspector, the welding parameters for the weld to be made. Weld procedures are written by the contractor responsible for the welding, and must be reviewed by the inspector. In some cases, the Engineer must approve the welding procedures. Welding Procedure Specifications (WPSs) are written based upon the steel to be welded, thickness of material to be joined, type of joint, type of weld, size of weld, and position of welding. Based upon the application, the WPS specifies the welding materials to be used (electrode, flux, shielding gas), electrode diameter, voltage, current (amperage) or wire feed speed, travel speed, shielding gas flow rate, minimum (and sometimes maximum) preheat and interpass temperatures, location and number of passes, and other pertinent information specific to the weld to be made. All WPSs, whether prequalified or qualified by test, must be in writing.

b. AWS Requirements. AWS *D1.1* Section 6.3.1 requires the use of and inspection of WPSs. The inspector should review the WPS for general conformity to the welding code and applicability to the joint to be welded. The WPS also provides information necessary for inspection duties. The Engineer is assigned the responsibility in AWS *D1.1* Section 4.1.1, to review and approve WPSs that are qualified. Prequalified WPSs need not be approved by the Engineer under *D1.1*. The purpose of the Engineer’s approval of the WPS is so that it can be verified that the qualification testing is representative of the actual welding conditions, such as for thick and highly restrained joints.

c. AISC Requirements. In the AISC *Seismic Provisions*, Section 7.3, the Engineer is made responsible for the review and approval of all WPSs, whether qualified or prequalified, for welds that are part of the Seismic Force Resisting System. This is primarily to ensure that WPSs are developed for the welds critical to building performance, and that filler metals with the required toughness have been selected by the contractor.

d. WPS Prequalification Limits. Prequalified WPSs need not be tested using the tests prescribed in AWS *D1.1* Section 4. The contractor may develop WPSs based upon manufacturer’s recommended operating parameters, verified by the contractor’s experience and testing as desired. To be prequalified, the welding process must be prequalified (SMAW, FCAW, GMAW except short-circuiting transfer, or SAW), the weld details must meet all the requirements of AWS *D1.1* Section 3, and welding parameters meet the provisions of AWS Table 3.7. This includes the use of the prequalified groove weld details in AWS Figures 3.3 and 3.4, minimum prequalified PJP groove weld size in AWS Table 3.4, and minimum fillet weld size in AWS Table 5.8. “Matching” filler metals must be used, per AWS Table 3.1, and minimum preheat and interpass temperatures must be provided per AWS Table 3.2.

e. WPS Qualification Requirements. When WPSs, joints, filler metal selection, or other details do not meet the prequalification requirements of AWS *D1.1* Section 3, the WPS to be used for the joint must be qualified by testing prescribed in AWS *D1.1* Section 4. Documentation of the WPS used and test results must be documented in the form of Procedure Qualification Records (PQRs). Qualified WPSs must be referenced to the applicable PQR. PQRs must be in writing, and made available for inspection by the inspector.

f. Guidance for Engineering Review of Procedures Submitted by Contractors. For review of WPSs, the contractor should submit all applicable manufacturer data sheets and operating recommendations for the filler material to be used. It may also be necessary to consult the AWS A5.XX filler metal specifications for information regarding the use and limitations of the filler metal.

(1) Generally, manufacturer’s operating recommendations provide a range of welding parameters such as voltage and current (amperage) or wire feed speed, and specify polarity, but do not provide specific travel speeds or adjustments necessary to achieve a particular weld size. The middle of the provided ranges are often good starting points, but contractors often tend to work near the high end of the ranges provided to maximize deposition rates and reduce welding time.

(2) Calculations such as heat input and deposition rates are helpful in determining if WPSs should produce a reasonable quality weld of the size specified. However, it is often difficult to verify FCAW procedures through calculation because of the variations between specific electrode types. Calculation should not be used to determine optimum operating characteristics for welding, as these final adjustments are made by experience. See references in Appendix B.

(3) Caution should be used when reviewing WPSs for thick materials and highly restrained joints. The 25 mm (1 in.) test plate thicknesses specified in AWS *D1.1* Section 4, do not adequately represent the heat sink capabilities of thicker sections (affecting cooling rates), nor is restraint developed in the welding of standard WPS test specimens. The use of thicker plates and NDT, and the use of restraint devices, should be specified as appropriate for critical welding. Alternately, other WPS testing methods may be used as appropriate.

(4) A checklist should be prepared to verify that all welded joints on the project have written WPSs. Critical joints should be reviewed to verify that the proper welding materials have been designated for the joint, particularly when CVN toughness is required.

(5) Approval of the WPS should be taken as review only, and that the responsibility for the suitability of the WPS, and the resultant weld quality and properties, remains with the contractor.

3. WELDING PERSONNEL QUALIFICATION.

a. Personnel Classification. Welding personnel are classified into three categories: welders, welding operators, and tack welders. Welders manipulate the electrode by hand, manipulating and controlling the arc, for manual or semi-automatic welding. Welding operators set up automatic welding equipment with wire-fed welding processes, such as mechanized SAW, to travel at selected speeds. Tack welders may only place tack welds to assemble pieces, with the finish welds to be performed by qualified welders or welding operators.

b. Qualification Testing. All welding personnel must demonstrate their skill by performing specific performance qualification tests prescribed by AWS *D1.1* Section 4, Part C. Welders are qualified by process - SMAW, FCAW, GMAW, SAW, GTAW, ESW, or EGW. FCAW-S (self-shielded) and FCAW-G (gas-shielded) are considered the same process for performance qualification testing. Welders are also qualified by position - Flat, Horizontal, Vertical and Overhead. These are designated on welding personnel qualification records as positions 1, 2, 3, and 4, respectively. Welding personnel qualified for more difficult positions, for example Vertical (3), are also qualified for Flat (1) and Horizontal (2) welding. However, Vertical (3) and Overhead (4) welding positions are considered separately. Additional position classifications apply for tubular construction, and are further identified in AWS *D1.1* Figures 4.4 and 4.6. Welding personnel are further classified by type of weld, testing using groove welds or fillet welds. Welding personnel qualified for groove welding in a given position and process are also qualified for fillet welding in the same position and process. Those who qualify using 9.5 mm (3/8 in.) thick plate or thicker are qualified for twice the test plate thickness. Welding personnel qualified using 25.4 mm (1 in.) thick plate are qualified for unlimited thicknesses of material. AWS *D1.1* Table 4.8 provides complete information regarding the cross-over of welding performance qualifications tests and the welding products, thicknesses and positions qualified.

c. Contractor Responsibilities. The contractor is responsible for the qualification of all welding personnel. The witnessing of performance testing is not required. All performance qualification tests must be fully documented in writing. Performance qualification expires six (6) months following testing, unless the person has used the process during that time period. Should a person not use the process within six months, the qualification period expires. There should be records documenting the use of various processes by the contractor. Welding position is not a factor in maintaining welding personnel qualification. Should the welder consistently produce poor quality welds, the welder’s qualification can be revoked, requiring retesting.

d. Qualification Testing by Others. Although standard practice is to require contractor-based qualification testing of welding personnel, it is acceptable, with the Engineer’s approval, for the contractor to rely upon qualification testing performed by others. Such testing may include independent testing laboratories, welding vocational schools, industry associations and unions, and the AWS Certified Welder program. The Engineer should review the basis and suitability of such programs prior to waiver of contractor-based qualification.

4. INSPECTOR QUALIFICATIONS

a. General Welding and Visual Inspectors. Visual welding inspection personnel should be qualified under AWS *D1.1* Section 6.1.4. The basis of qualification, if beyond these provisions, must be specified in the project documents. Acceptable qualification bases under *D1.1* are: (1) current or previous certification as an AWS Certified Welding Inspector (CWI) in accordance with the provisions of AWS QC1, *Standard for AWS Certification of Welding Inspectors*, or (2) current or previous qualification by the Canadian Welding Bureau (CWB) to the requirements of the Canadian Standard Association (CSA) Standard W178.2, *Certification of Welding Inspectors*, or (3) an engineer or technician who, by training or experience, or both, in metals fabrication, inspection and testing, is competent to perform inspection work. For the third case, the Engineer should establish minimum levels of training and experience, require a written resume detailing training and experience in welding inspection, and require a written and hands-on examination prior to approval of the inspector.

(1) The qualification of an previously certified inspector remains in effect indefinitely, even though the certification may have expired, provided the inspector remains active in the inspection of welded

steel fabrication, or unless there is a specific reason to question the inspector's ability.

(2) The American Welding Society offers certification to welding inspectors in the form of Certified Welding Inspectors, Certified Associate Welding Inspectors, and Certified Senior Welding Inspectors. ANSI/AWS QC1-96, *Standard for AWS Certification of Welding Inspectors*, governs the requirements and testing of such inspectors, including experience level. The CWI examination tests the inspector's knowledge of welding processes, welding procedures, welder qualification, destructive testing, nondestructive testing, terms, definitions, symbols, reports, records, safety and responsibilities. Although assumed to be competent to inspect welded construction, the AWS Certified Welding Inspector may not have the background or expertise in other areas of steel construction such as general fabrication and erection, bolted connections, steel bar joists, and metal decks, and additional education and training relative to these areas may be needed. It should also be verified that the AWS Certified Welding Inspector has tested, or is familiar with, the AWS *D1.1 Structural Welding Code*. It is permitted to take the AWS examinations using either the AWS *D1.1*, ASME *Boiler and Pressure Vessel Code*, or the API 1104 *Welding of Pipelines and Related Facilities* code, and welding inspection experience may be in any area of welding.

(3) AWS *D1.1* does not recognize the AWS Certified Associate Welding Inspector as qualified to perform the work solely based upon this certification. A CAWI has passed the same accreditation examination as the CWI, but has less experience, with two years minimum experience rather than five years, in the field of welding inspection. A CAWI could be acceptable under condition "c" as listed in AWS *D1.1* Section 6.1.4. The Senior Certified Welding Inspector is a new program offered by the AWS, and this recent certification option has not been included in the AWS *D1.1* code because of publication schedules. A SCWI should be considered the equivalent of a CWI.

(4) Although AWS *D1.1* allows inspector qualification without the CWI certification under AWS QC1 criteria, it is recommended that the welding inspection personnel for critical welding be AWS QC1 certified (or previously certified) by experience and written examination.

(5) All welding inspectors must have adequate visual acuity, documented by vision testing performed within the past three years. See AWS *D1.1* Section 6.1.4.4.

b. NDT Personnel Qualification. Certification of all levels of NDT personnel is the responsibility of the employer of the NDT technician. Nondestructive testing personnel should be qualified under the American Society for Nondestructive Testing, Inc., ANSI/ASNT CP-189, *ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel*, or ASNT *Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing.*

(1) Certification of NDT personnel should be based on demonstration of satisfactory qualification in accordance with Sections 6, 7 and 8 of ASNT SNT-TC-1A, as modified by the employer's written practice, or in accordance with Sections 4, 5 and 6 of ANSI/ASNT CP-189. Employers may rely upon outside training and testing for NDT personnel for certification, however, the employer should supplement such certification testing with a review of the technician's experience and skill levels. It is suggested that the certification of NDT personnel should be administered by an ASNT Certified Level III in the specific area on NDT. Personnel certifications must be maintained on file by the employer and a copy should be carried by the technician.

(2) AWS *D1.1* Section 6.14.6 requires that nondestructive testing be performed by NDT Level II technicians, or by Level I technicians only when working under the direct supervision of a Level II. Inspection by a Level III technician is not recognized, as the Level III may not perform actual testing

regularly enough to maintain the special skills required to set up or to conduct the tests. AWS *D1.5*-96 requires similar qualification, except in the case of Fracture Critical Members. Under Section 12.16.1.2, testing of Fracture Critical Members must be done by either a qualified Level II under the supervision of a qualified Level III, or by a Level III certified by ASNT, unless the Engineer accepts other forms of qualification.

(3) The following definitions, from ANSI / ASNT CP-189, apply to the various NDT Levels:

- NDT Level I - An NDT Level I individual shall have the skills to properly perform specific calibrations, specific NDT, and with prior written approval of the NDT Level III, perform specific interpretations and evaluations for acceptance or rejection and document the results. The NDT Level I shall be able to follow approved nondestructive testing procedures and shall receive the necessary guidance or supervision from a certified NDT Level II or NDT Level III individual.
- NDT Level II - An NDT Level II individual shall have the skills and knowledge to set up and calibrate equipment, to conduct tests, and to interpret, evaluate, and document results in accordance with procedures approved by an NDT Level III. The Level II shall be thoroughly familiar with the scope and limitations of the method to which certified and should be capable of directing the work of trainees and NDT Level I personnel. The NDT Level II shall be able to organize and report nondestructive test results.
- NDT Level III - An NDT Level III individual shall have the skills and knowledge to establish techniques; to interpret codes, standards, and specifications; designate the particular technique to be used; and verify the accuracy of procedures. The individual shall also have general familiarity with the other NDT methods. The NDT Level III shall be capable of conducting or directing the training and examining of NDT personnel in the methods for which the NDT Level III is qualified.

5. INSPECTION CATEGORIES AND TASKS.

a. General. The inspector assigned responsibility for the welding of the project should review and understand the applicable portions of the project specifications, the contract design drawings, and the shop or erection drawings for the project, as appropriate. The inspector should participate in a pre-project meeting with the contractor to discuss the quality control and quality assurance requirements for the project. A record should be kept of all welders, welding operators and tack welders, welding personnel qualifications, welding procedures, accepted parts, the status of all joints not accepted, NDT test reports, and other such information as may be required. The inspector's duties can be assigned or placed into four general categories, by time period: pre-project inspection for general welding operations, inspection prior to welding a particular joint, inspection during welding of the joint, and inspection of the completed joint.

b. Pre-project Inspection. A pre-project inspection should be conducted of the fabricator's and erector's facilities and operations to verify the adequacy of their welding operations. The scheduling of this inspection should be well before welding is scheduled to begin, allowing time for necessary corrections and improvements by the contractor before welding begins.

(1) Personnel. The inspector should verify that all applicable welder, welding operator and tack welder qualification records are available, current and complete, and that any required special supplemental qualification tests, such as mock-ups, have been passed. Requalification is required for any welder, welding operator or tack welder who has, for a period of six months, not used the process for which the person was qualified. Each person performing welding should have a unique identification

mark or die stamp to identify his or her welds. See AWS *D1.1* Section 4, Part C.

(2) Equipment. All welding equipment should be in proper operating condition, with functioning gauges necessary for following the WPS for the selected process. Periodic checks should be performed by the contractor to verify the accuracy of gauges and other operating components of welding machines. Welding leads should be inspected for worn or missing insulation, or inadequate connectors. Ammeters should be available for verifying the current (amperage) near the arc, rather than at the machine. Records of equipment inspections and calibrations should be maintained, but there is no specific requirements for such in AWS *D1.1*. Inspections at least annually are recommended. See AWS *D1.1* Sections 5.11 and 6.3.2.

(3) WPSs. The inspector should verify that all applicable welding Procedure Qualification Records (PQRs) and Welding Procedure Specifications (WPSs) are available, current and accurate. WPSs should be available at welding work stations and used by all welding personnel. PQRs should be referenced and available for review for any non-prequalified WPSs. Qualified WPSs must be approved by the Engineer, per AWS *D1.1* Section 4.1.1. For high seismic applications, all WPSs must be approved by the Engineer. See AISC *Seismic Provisions* Section 7.3a. The Engineer's approval should be verified.

(4) Materials Controls. Electrodes and fluxes should be stored in their original, manufacturer-sealed containers until ready for placement in storage ovens or use. The manufacturer's identification labels, including lot number, should remain on the packaging. The contractor should have an operating system to verify that all materials in inventory have proper certification papers on file. The contractor's quality control system should be used to confirm that the proper welding consumables are selected.

(5) Materials Storage. The contractor should have all necessary welding consumable drying and storage equipment. The proper operating temperatures should be verified on a regular basis as a part of the contractor's quality control program. Welding personnel should be familiar with the SMAW electrode and SAW flux storage and exposure limitations of AWS *D1.1*, with an ongoing system in place to confirm compliance. No materials other than electrodes or fluxes, as appropriate, may be placed in drying or storage ovens. See AWS *D1.1* Section 5.3 for storage requirements. In addition to AWS *D1.1* mandated storage requirements, research indicates that certain FCAW electrodes may warrant protected storage or limited atmospheric exposure times. Such controls and limitations should be based upon manufacturer's test data and recommendations.

c. Prior to Welding. Prior to the actual start of welding on the project, item c(1) below should be performed. All other inspection items should be performed prior to beginning the welding of each joint. It is not anticipated that the inspector physically perform these inspections at each individual joint, but will verify that the contractor's personnel understand and routinely perform these inspections as a part of their welding operations. This may be done through observation of welding operations and informal inquiries of welding personnel. The inspector may, when desired, perform any physical inspections prior to welding to verify the contractor personnel's work.

(1) Pre-project review. Prior to the beginning of actual welding on the project, it should be verified that all non-compliance revealed during pre-project inspection has been rectified.

(2) Base metal quality. Steel joints to be welded must be smooth, uniform, and free from significant surface discontinuities such as cracks or seams, and free of significant amounts of loose or thick scale, slag, rust, moisture, grease, or other harmful foreign materials. See AWS *D1.1* Section 5.15 for complete base metal preparation requirements.

(3) Fillet weld fitup. Fillet welded joints must be fitup with a maximum gap of 1.6 mm (1/16 in.), unless corrective measure are taken. For gaps exceeding 1.6 mm (1/16 in.), but not to exceed 5 mm (3/16 in.), the leg size of the weld must be increased by an amount equal to the gap. Gaps over 5 mm (3/16 in.) are permitted only for steels over 76 mm (3 in.) in thickness, when suitable backing is placed in the root of the joint, and the fillet leg size is increased. See AWS *D1.1* Section 5.22.1.

(4) Groove weld fitup. Prequalified groove welds must be assembled within the “as fit-up” tolerance specified for the joint in AWS *D1.1* Figures 3.3 and 3.4. For Partial Joint Penetration (PJP) groove welds, assembly tolerances are provided in AWS *D1.1* Section 5.22.2. For other groove dimension tolerances applicable to other groove welds, see AWS *D1.1* Section 5.22.4.1.

(5) Steel temperature. The temperature of the steel at the joint prior to the initiation of welding must not be below 0°C (32°F). When steel temperatures are below these minimum temperatures, it is necessary to heat the steel in the vicinity of the joint to at least 21°C (70°F). See AWS *D1.1* Table 3.2, Note 1. For prequalified steels listed in AWS *D1.1* Table 3.2, as Category C steels, the minimum steel temperature at the joint is 10°C (50°F). Steels of thicknesses requiring preheat, per AWS *D1.1* Table 3.2, require higher temperatures. After heating, the temperature of the steel should be measured a distance 75 mm (3 in.) away from the joint. For welding in extreme cold environments, it is advisable to heat the steel to higher temperatures and apply the heat over a wider area.

(6) Ambient temperature. Welding is not permitted when the ambient (air) temperature is below -18°C (0°F), or when welding personnel are exposed to inclement environmental conditions. Protective covering or enclosures, with heating as necessary, may be used to satisfy this requirement and provide adequate protection and warmth for the welders and welding equipment.

(7) Wind speed. Gas-shielded welding processes (FCAW-G, GMAW, GTAW, and EGW) may not be performed in winds exceeding 8 km per hour (5 mph), as wind above this speed blows away the necessary shielding gas and contributes to poor weld quality and poor mechanical properties. For self-shielded welding processes (SMAW, FCAW-S, SAW, and ESW), the maximum wind speed is not specified by AWS *D1.1*, but should be limited to a maximum of 30 to 40 km per hour (20 to 25 mph). See AWS *D1.1* Section 5.12 for welding environment provisions.

(8) WPS, including preheat. The inspector should verify compliance of the welding consumables selected (electrode, flux and shielding gas) with the project requirements and the WPS. The selected electrodes should be taken only from proper storage, and used only in the permitted positions and within the welding parameters specified by the manufacturer and in the WPS. It should be verified that the WPS is appropriate for the joint, within any specified limitations.

(9) Preheat. Preheat temperatures as specified in the WPS must be provided and checked for compliance with AWS *D1.1* Table 3.2 if prequalified. Higher preheat temperatures may be specified. It may also be necessary to verify that the preheat temperature does not exceed any maximum values specified in the WPS, sometimes required for quenched and tempered, TMCP, or other special steels, or when toughness requirements apply. Verification of preheat temperature should be taken 75 mm (3 in.) from the joint, provided the thickest material joined is 75 mm (3 in.) or less in thickness. If the steel is thicker, then the temperature verification is taken a distance equal to the material thickness. Temperatures may be checked with surface temperature thermometers, close-range focused infrared devices, or with temperature-indicating crayons.

(10) Tack welds. Tack welds must be made using appropriate WPSs, including preheat when required. Tack welds should be visually inspected prior to being welded over by the finish weld. Cracks in

tack welds are likely to propagate into the main weld. Slag that has not been removed will likely result in slag inclusions in the completed weld.

d. During Welding. Observation of welding techniques and performance for each welder should be done periodically during welding operations to verify that the applicable requirements of the WPS and the AWS *D1.1* Code are met. Each pass should be visually inspected by the welder for conformance to AWS *D1.1* Table 6.1 provisions for cracks, fusion and porosity prior to placement of subsequent passes. To avoid trapped slag, penetration and fusion discontinuities, each weld bead profile should be in substantial conformance with the requirements of Table 6.1.

(1) WPS compliance. The inspector should verify that the welding is performed following the appropriate Welding Procedure Specification (WPS). If desired, proper current (amperage) and voltage for the welding operation may be verified using a hand held calibrated amp and volt meter. Because of welding lead losses, measurement should as near the arc as practical. Welds not executed in conformance with the WPS may be considered rejectable, and should be referred to a knowledgeable welding consultant and the Engineer for review.

(2) Interpass temperatures. Interpass temperatures as specified in the WPS must be provided and checked with compliance with AWS *D1.1* Table 3.2 if a prequalified groove weld joint. Higher preheat temperatures may be specified. It may also be necessary to verify that the interpass temperature does not exceed any maximum values specified in the WPS, sometimes specified for quenched and tempered, TMCP, or other special steels, or when toughness requirements apply. Verification of interpass temperature should be taken 75 mm (3 in.) from the joint, provided the thickest material joined is 75 mm (3 in.) or less in thickness. Temperatures may be checked with surface temperature thermometers, close-range focused infrared devices, or with temperature-indicating crayons.

(3) Consumables control. Exposure of SMAW electrodes and SAW fluxes must meet the time limitations of AWS *D1.1* Section 5.3. See AWS *D1.1* Table 5.1 for SMAW electrode exposure limits. SAW fluxes may require drying, special handling, recycling, and removal of exposed flux from opened packages. Although not limited by AWS *D1.1*, research indicates that some FCAW electrodes may absorb moisture in the order of 50% of the “as-manufactured” moisture content. When extra-low hydrogen welding electrodes are required for critical welding applications, and FCAW wires removed from the manufacturer’s packaging will not be consumed within a few days, special storage conditions limiting exposure times, repackaging unused FCAW wire in closed moisture-resistant packing overnight, or the use of storage ovens, may be appropriate. AWS *D1.5 Bridge Welding Code*, Section 12 provisions for Fracture Critical Nonredundant Members should be considered for guidance in special cases.

(4) Cleaning. Completed weld passes must be cleaned of all slag prior to placement of the next pass. Removal of debris by brushing is required. Wire brushing of the completed weld is recommended, but not required. Slag that has not been removed will likely result in slag inclusions in the completed weld. See AWS *D1.1* Section 5.30.

e. After Welding. After completion of the weld, full compliance with the AWS *D1.1* provisions should be verified. If required or specified, NDT is to be performed. Upon completion of inspection of the weld, piece, or project, as appropriate, proper documentation of the acceptance of the welding should be prepared and submitted to the designated parties.

(1) Measurement. The work should be visually inspected for conformance with the Visual Inspection Acceptance Criteria prescribed in AWS *D1.1* Table 6.1. These provisions prohibit cracks and lack of fusion, and permit limited amounts of undercut, porosity, and weld size underrun. Weld profile

tolerances are provided in AWS *D1.1* Figure 5.4, and Section 5.24. Size and contour of welds should be measured with suitable gauges. Craters are accepted in certain circumstances. Other weld acceptance criteria that is verified visually include arc strikes (AWS *D1.1* Section 5.29), and weld cleaning (Section 5.30). Visual inspection may be aided by a strong light, magnifiers, or other devices that may be helpful.

(2) Tolerances. The tolerances for the completed member, including cross-section, depth, camber, sweep, straightness, flatness, flange warpage and tilt, stiffener fit, and bearing surface fit, are prescribed in AWS *D1.1* Section 5.23.

(3) Records. The Inspector should mark the welds, joints, or members, as appropriate, that have been inspected and accepted using a distinguishing mark or die stamp. Alternatively, records indicating the specific welds inspected by each person may be maintained. The accepted, rejected and repaired items should be documented in a written report, distributed to the designated recipients in a timely manner.

f. Nondestructive Testing Methods. AWS *D1.1* does not require NDT for statically-loaded building structures, but NDT is required by both AISC and AWS *D1.1* for certain fatigue detail categories for cyclically-loaded structures. AISC Seismic Provisions require NDT for certain joints in high seismic applications, as follows: “All complete joint penetration and partial joint penetration groove welded joints that are subjected to net tensile forces as part of the Seismic Force Resisting Systems ... shall be tested using approved nondestructive testing methods conforming to AWS *D1.1*.” Such testing should include ultrasonic testing of welds in T-joints and butt joints over 8 mm (5/16 in.) in thickness. Radiographic testing may be used in some cases using butt joints. When using T-joints, with the thickness of the tee “flange” exceeding 40 mm (1-1/2 in.), ultrasonic testing should be performed after completion and cooling to check for lamellar tearing.

(1) The specific types of NDT, and the applicable acceptance criteria, must be specified in the contract documents. NDT symbols should be used to specify locations and types of NDT. See AWS A2.4 Part C.

(2) The contractor is responsible for performing any required NDT, unless specifically designated to be performed by another party.

(3) Because of the risk of delayed hydrogen cracking, a delay period of 24 to 48 hours should be considered prior to performing NDT for final acceptance for higher strength steels. See AWS *D1.1* Table 6.1 (5). The AWS *D1.5 Bridge Welding Code* Section 12.16.4 requires a longer delay period for Fracture Critical Members, depending upon weld size and steel strength.

(4) Tables 8-1 and 8-2 provide general guidance for the selection of NDT method(s). For complete information, see Appendix D.

Table 8-1. Applicable Inspection Methods for Various Discontinuities and Joint Types

Inspection Method Application		VT	PT	MT	UT	RT
Discontinuity	Porosity	A[1]	A[1]	O[2]	O	A
	Slag Inclusions	U	U	O[2]	A	A
	Incomplete Fusion	U	U	U	A	O
	Inadequate Joint Penetration	U	U	U	A	A
	Undercut	A	O	O	O	A
	Overlap	O	A	A	O	U
	Cracks	A[1]	A[1]	A[2]	A	O
	Laminations	A[1,3]	A[1,3]	A[2,3]	A	U
Joints	Butt	A	A	A	A	A
	Corner	A	A	A	A	O
	T	A	A	A	A	O
	Lap	A	A	A	O	U

Notes:

A - Applicable
O - Marginal applicability, depending upon material thickness, discontinuity size, orientation, and location.
U - Generally not applicable.

[1] Surface only
[2] Surface and slightly subsurface only
[3] Weld preparation or edge of base metal

Table 8-2. Guidelines for Selecting Inspection Techniques

	VT	PT	MT	UT	RT
Equipment	Pocket magnifier, flashlight, weld gauges, scale, etc.	Fluorescent or visible penetration liquids and developers; ultraviolet light for fluorescent dyes	Wet or dry iron particles, or fluorescent; special power source; ultraviolet light for fluorescent particles	Ultrasonic units and probes; reference patterns	X-ray or gamma-ray; film processing and viewing equipment
Detection	Weld preparation, fit-up, cleanliness, roughness, spatter, undercut, overlap, weld contour and size	Discontinuities open to the surface only	Surface and near surface discontinuities: cracks; porosity; slag	Can locate all internal discontinuities located by other methods, as well as small discontinuities	Most internal discontinuities; limited by direction of discontinuity
Advantages	Easy to use; fast; inexpensive; usable at all stages of production	Detects small surface imperfections; easy application; inexpensive; low cost	Detects discontinuities not visible to the naked eye; useful for checking edges before welding; no size limitations	Extremely sensitive; complex weldments restrict usage	Provides permanent record of surface and internal discontinuities
Limitations	For surface conditions only; dependent on subjective opinion of inspector	Time-consuming; not permanent	Surface roughness may distort magnetic field; not permanent	Highly skilled interpreter required; not permanent	Usually not suitable for fillet weld or T-joint inspection; film exposure and processing critical; slow and expensive

Comments	**Most universally used inspection method**	**Indications may be misleading on poorly prepared or cleaned surfaces**	**Test from two perpendicular directions to detect any indications parallel to one set of magnetic lines**		**Radiation hazards**

6. WELD QUALITY.

a. Engineer's Responsibility for Acceptance Criteria. The Engineer is given the responsibility of determining and specifying the appropriate weld quality acceptance criteria. AWS *D1.1* quality criteria is a workmanship standard, based upon the quality readily achievable by a qualified welder. Non-destructive testing acceptance criteria is based upon achievable quality and the ability of the method to detect discontinuities of given size and location, with some consideration for the effect of surface and near-surface notches upon performance. The Engineer may use experience, analysis, or experimental evidence to establish alternate acceptance criteria. This criteria may be applied as the inspection criteria for the project, in lieu of AWS *D1.1* criteria, or may be used to establish when repair or replacement of a weld is required for a given discontinuity or situation. The first approach is valuable because it reduces the time and expense of inspection, and eliminates needless repairs, reducing the risk of creating additional discontinuities while performing repairs, and reduces the potential detrimental effects to the existing base metal. The second approach is also valuable, but does not reduce inspection expense. See AWS *D1.1* Section C6.8.

b. D1.1 Visual Acceptance Criteria. The following table provides the specification reference location for various forms of weld discontinuities:

Weld Discontinuity	**AWS D1.1 References**
Crack	**Table 6.1 (1)**
Fusion	**Table 6.1 (2)**
Weld Craters	**Table 6.1 (3)**
Weld Profile (convexity, concavity, overlap, reinforcement)	**Table 6.1 (4), 5.24**
Weld Size (underrun, lack of penetration, underfill)	**Table 6.1 (6), 6.5.1**
Undercut	**Table 6.1 (7)**
Porosity	**Table 6.1 (8)**
Arc Strike	**5.29**
Surface Slag	**5.30**
Spatter	**5.30.2**
Length	**6.5.1**
Location	**6.5.1**

c. NDT Acceptance Criteria. When penetrant testing (PT), and magnetic particle testing (MT) are specified, the acceptance criteria to be used is the same as that for visual inspection. For ultrasonic testing (UT), the visual inspection criteria is applicable, plus the requirements of AWS *D1.1* Section 6.13. For radiographic testing (RT), the visual inspection criteria is applicable, plus the requirements of AWS *D1.1* Section 6.12.

d. Alternate Acceptance Criteria. The Engineer may base alternate weld quality acceptance criteria on experience, experimental results, structural analysis, or fracture mechanics analysis considering material properties and behavior, service and fracture loads and strengths, and environmental factors. Sources of information to assist in the development of alternate acceptance criteria are provided in Appendix B, Bibliography.

7. REPAIRS TO BASE METAL AND WELDS.

a. Mill Defects. ASTM A6 Section 9, requires only visual inspection by the mill of the completed product for defects in workmanship. Subsurface inspection for laminations and other defects, such as straight-beam ultrasonic testing, would be performed only when specified in the mill order, at extra cost. The mill is permitted to perform removal and repairs to the surface using various means such as grinding and welding, to limits specified in ASTM A6 Section 9. During fabrication, should unacceptable internal discontinuities be discovered in the steel, the steel may be considered rejectable. The size or type of internal discontinuity considered rejectable is not defined by specification.

b. Laminations. When internal laminations in the steel are discovered during fabrication, AWS *D1.1* Section 5.15.1, provides procedures for the investigation and repair of the exposed laminations. All exposed laminations must be explored for depth. Shallow laminations need not be repaired, but longer and deeper laminations will need either removal by grinding or welding to close the lamination prior to welding the joint. Laminations at welded joints may serve as sources of porosity and as crack initiation points.

c. Weld Discontinuities. For welds with unacceptable convexity, excessive reinforcement, or overlap, the weld should have the excess weld metal removed. This is typically done by grinding, but may be done by gouging. For undersized welds, including craters, the weld should be filled to the required size. Some craters may be acceptable if outside the required effective length of weld. For excessive undercut, the undercut portion should be filled using an approved repair procedure. For cracks, lack of fusion, and excessive porosity, the unacceptable portion must be completely removed and replaced. Additional caution should be used when repairing cracks. The end of the crack should be located using PT or MT, then crack removal should begin approximately 50 mm (2 in.) from the end of the crack and work toward the center of the crack. Starting within the crack may cause the crack to grow during removal. See AWS *D1.1* Section 5.26.1. Should it be necessary to cut the materials apart, the Engineer must be notified.

d. Root Opening Corrections. Root openings that are too narrow must be increased in width to the required root opening. Narrow root openings contribute to trapped slag, poor penetration and lack of fusion near the root. Repairs for narrow root openings may be done by grinding, chipping, air carbon arc gouging, if refitting the parts is not feasible. Root openings that are too wide are significant in that they increase the weld volume, increasing distortion and increasing the risk of lamellar tearing in T-joints, as well as increasing cost. A root pass placed across a wide root opening may develop shrinkage cracks in the HAZ or in the throat of the weld. Repair of wide root openings entails facing the groove with weld metal until the required root opening is achieved. Such a repair does not reduce volume or cost, but controls distortion and through-thickness strains in T-joints. An alternative to repair of this type would be to use split-layer techniques for the root pass, and subsequently control bead placement to minimize shrinkage and distortion effects.

e. Mislocated Holes. When holes have been mislocated, it is best to either leave the hole unfilled or to place a bolt in the hole. It is difficult to fill a hole by welding. When the hole must be filled, generally when a new hole must be placed near or adjacent to the misplaced hole, a special repair procedure should be followed to elongate the hole, then weld using stringer passes. NDT may be necessary after welding, if required elsewhere on the project for groove welds. NDT is required for repair welds for holes in cyclically loaded members. See AWS *D1.1* Section 5.26.5.

CHAPTER 9

OTHER WELDING SPECIFICATIONS AND STANDARDS

1.TUBULAR STRUCTURES. For the welding of tubular members, also referred to as hollow structural sections, refer to ANSI/AWS *D1.1* tubular provisions and the AISC *Connections Manual for Hollow Structural Sections*. These documents apply to the specific requirements of tube-to-tube applications, but are also applicable to tube-to-plate applications.

2. SHEET STEEL WELDING. For welding steel materials less than 3.2 mm (1/8 in.) in thickness, refer to ANSI/AWS *D1.3 Structural Welding Code - Sheet Steel*, and the AISI *Specification for the Design of Cold-Formed Steel Structural Members* for general design provisions. Sheet steels equal to or greater than 3.2 mm (1/8 in.) thick, but less than or equal to 4.8 mm (3/16 in.) thick, may be welded under either AWS *D1.3* or AWS *D1.1*.

3. REINFORCING STEEL. For welding reinforcing steel, including mats, fabric, metal inserts and connections in reinforced concrete construction, refer to ANSI/AWS *D1.4 Structural Welding Code - Reinforcing Steel*. For reinforcing steel welded to structural steel, AWS *D1.4* must be met for the weld, but any applicable provisions, such as preheat requirements, based upon the structural steel must also be met.

4. STAINLESS STEEL. For welding of stainless steels, refer to ANSI/AWS *D1.6 Structural Welding Code - Stainless Steel*. This code includes welding of hot- and cold-rolled sheets and plate, shapes, tubular members, clad materials, castings and forgings of stainless steels. It is not applicable to pressure vessels or pressure piping with pressures exceeding 104 kPa (15 psig).

5. ALUMINUM. For the welding of structural aluminum alloys, refer to ANSI/AWS D1.2 *Structural Welding Code - Aluminum*.

6. BRIDGES. For the welding of highway bridges designed for vehicular traffic, refer to the ANSI/AASHTO/AWS *D1.5 Bridge Welding Code*, including the Fracture Control Plan for nonredundant bridge members, if applicable.

7. MATERIAL HANDLING EQUIPMENT. For the welding of material handling equipment, refer to ANSI/AWS D14.1 *Specification for Welding Industrial and Mill Cranes and Other Material Handling Equipment*. This specification applies to the welding of all principal structural weldments and all primary welds used in the manufacture of cranes for industrial, mill, powerhouse and nuclear facilities. It also applies to other overhead material handling machinery and equipment that supports and transports loads.

8. CAST STEEL. See Appendix B - Bibliography.

9. CAST IRON. See Appendix B - Bibliography.

10. WROUGHT IRON. See Appendix B - Bibliography.

11. OTHER GOVERNING SPECIFICATIONS

a. ASME. For the welding of pressure vessels, refer to ANSI/ASME BPVC, *Boiler and Pressure Vessel Code, Section 9, Welding and Brazing Qualifications.*

b. API. For the welding of offshore structures, refer to the API RP 2A series documents, *Planning, Designing and Constructing Fixed Offshore Platforms*. For the welding of pipelines, refer to API Standard 1104, *Welding of Pipelines and Related Facilities*. For the welding of storage tanks, refer to API 12D *Field Welded Tanks for Storage of Production Liquids*, or API 12F, *Shop Welded Tanks for Storage of Production Liquids*.

c. AWWA. For the welding of water tanks, refer to AWWA Manual M42, *Steel Water Storage Tanks* .

CHAPTER 10

SAFETY AND ENVIRONMENTAL CONSIDERATIONS

1. GENERAL.

The following provisions should not be considered all-inclusive, complete, or exclusive. Refer to applicable governing documents for complete information.

2. SAFETY.

a. Fire. Welding, thermal cutting, and arc gouging operations produce molten metal that may cause burns, fires, or explosion. The fuel gases used pose no hazard, provided they are handled and stored in a safe and proper manner. Oxygen for oxyfuel cutting is not flammable by itself, but will contribute to more intense fires if pure oxygen is available. SMAW electrode stubs are very hot and could cause a fire if carelessly thrown on wood or paper products. Poor quality or poorly maintained electrical connections can cause overheating or sparking and subsequent ignition. During operations, molten steel, sparks and spatter often travel a considerable distance, risking a fire in nearby flammable materials. The following safety guidelines should be considered:

- move the object to receive the work away from combustible materials
- move the combustible materials at least 15 m (50 ft.) from the welding or cutting operation
- provide suitable fire-resistant shielding around the work area or combustible material
- fire extinguishing equipment should be accessible to welding personnel
- trained fire watch personnel should be used if the operations are performed near combustible materials.

b. Confined Spaces. Work in confined spaces requires additional safety precautions. A confined space could be a tank, pit, etc. that does not allow for adequate ventilation for the removal of hazardous gases or fumes resulting from the work. Certain welding processes use gases such as argon, helium, carbon dioxide or nitrogen which will not support life. Deaths and severe injuries due to lack of oxygen have occurred where the concentration of these gases becomes too high, (i.e.,where the available oxygen is too low).The following additional safety guidelines should be considered:

- remove flammable or hazardous materials from the space,
- provide adequate ventilation air to the space,
- test the atmosphere in the space before and during the work,
- inspect all electrical cables and connections,
- test all fuel gas and shielding gas lines for leaks,
- cutting torches must not be lit or extinguished within the space,
- no compressed gas cylinders or welding power sources may be placed inside the space,
- electrical power must be disconnected and all gas valves closed when work is suspended for any substantial period of time,
- if only a small opening is available for entry, the welder must wear an approved safety harness equipped with a rope or lifeline, tied off and held by a worker stationed outside the space.

c. Eye Protection. The arc produced from welding or air carbon arc gouging may burn the eyes. Proper filters and cover plates must be worn to protect the eyes from sparks and the rays of the arc.

d. Burn protection. Arc burn may be more severe than sunburn. Molten metal, sparks, slag, and hot material can cause severe burns if precautionary measures are not used. Protect the skin against radiation and hot particles, electrodes, and metal. Suitable flame-resistant clothing must be worn as protection from sparks and arc rays.

e. Electrocution. The electrode, electrode reel (for wire-fed processes), and workpiece (or ground) are considered electrically “hot” when the welder is on. These parts must not be touched with bare skin or wet clothing. Dry, hole-free gloves are necessary. The work piece and welding equipment must be grounded.

f. Fumes and Gases.

(1) Many welding, cutting and allied processes produce fumes and gases that may be harmful. Fumes are solid particles that originate from welding consumables, the base metal and any coatings present on the base metal. In addition to shielding gases that may be used, gases are produced during the welding process or may be produced by the effects of process radiation on the surrounding environment. The amount and composition of these fumes and gases depend upon the composition of the filler metal and base material, welding process, current level, arc length and other factors.

(2) Most welding fumes from carbon steel and low alloy steel electrodes do not require any attention to limits for any specific compound or compounds. The compounds in the fume such as oxides and fluorides of aluminum, calcium, iron, magnesium, potassium, silicon (which is amorphous in welding fumes), sodium, and titantium, do not have individual effects, except that excessive iron may cause siderosis (iron deposits in the lungs). Their effects are submerged in the overall effects which may be expected from nuisance dusts.
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(3) Some specific fume components such as chromium, cobalt, copper, fluorides, manganese, and nickel are present in some electrodes, require special attention, and have special health hazards. When these are present at levels of concern, they are listed on the product label and in the MSDS. Their health hazards are discussed in the MSDS.

(4) Depending on material involved, fume effects range from irritation of eyes, skin and respiratory system to more severe complications and may occur immediately or at some later time. Fumes may also cause symptoms such as nausea, headache, and dizziness.

(5) The following safety guidelines should be considered, as a minimum:

- Keep the head out of the fumes.
- Do not breathe the fumes.
- Use enough ventilation or exhaust at the arc, or both, to keep fumes and gases from the breathing zone and general area.
- In some cases, natural air movement provides enough ventilation and fresh air.
- Where ventilation is questionable, use air sampling to determine the need for corrective measures.
- Use mechanical ventilation when necessary to improve air quality.
- If engineering controls are not feasible, use an approved respirator.
- Follow OSHA guidelines for permissible exposure limits (PELs) for various fumes.
- Follow the American Conference of Governmental Industrial Hygienists recommendations for threshold limit values (TLVs) for fumes and gases.

g. Further Guidance. See ANSI / AWS Z49.1 Safety in Welding, Cutting and Allied Processes, and the Bibliography in Appendix B for further general information. The Material Safety Data Sheet (MSDS) for each product used also provides essential information.

3. ENERGY CONSUMPTION.

Shop welding operations are almost always electrically powered. Field operations may be electrically powered or powered by generators. Some field welding equipment is directly engine driven. Power requirements depend more upon electrode diameter than welding process. SMAW, FCAW and GMAW welding equipment draws essentially the same current ranges, and SAW, ESW and EGW draws more current to provide the higher deposition rates achievable and desired. The total power consumption difference between processes for a given joint configuration is negligible. To save energy, the minimum weld size and minimum groove cross-sectional area adequate to carry the load should be specified.

APPENDIX A

REFERENCES

GOVERNMENT PUBLICATIONS

United States Army Corps of Engineers

TI 800-01, Design Criteria
TI 809-01, Load Assumptions for Buildings
TI 809-02, Structural Design Criteria for Buildings
TI 809-04, Seismic Design for Buildings
TI 809-05, Seismic Evaluation and Rehabilitation for Buildings
TI 809-07, Design of Cold-Formed Load Bearing Steel Systems and Masonry Veneer / Steel Stud Walls
TI 809-30, Metal Building Systems

MIL-HDBK-1002/1, Structural Engineering, General Requirements
MIL-HDBK-1002/3, Structural Engineering, Steel Structures
MIL-HDBK-1002/6, Aluminum Structures, Composite Structures, Structural Plastics, and Fiber-Reinforced Composites.

Department of the Army

TM 5-809-6, Structural Design Criteria for Structures Other Than Buildings *(to become TI 809-6)*

Federal Emergency Management Agency (FEMA)

FEMA 267, Interim Guidelines: Evaluation, Repair, Modification and Design of Steel Moment Frames, August 1995
FEMA 267B, Interim Guidelines Advisory No. 2
FEMA 273, NEHRP Guidelines for the Seismic Rehabilitation of Buildings, October 1997
FEMA 302, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, February 1998

NONGOVERNMENT PUBLICATIONS

American Institute of Steel Construction
One East Wacker Drive, Suite 3100
Chicago, IL 60601-2001
www.aisc.org

Metric Load and Resistance Factor Design Specification for Structural Steel Buildings, December 1, 1994
    (Supplement No. 1, January 30, 1998)
    (new specification to be issued in early 2000)
Load and Resistance Factor Design Specification for Structural Steel Buildings, December 1, 1993
    (Supplement No. 1, January 30, 1998)

(new specification to be issued in early 2000)
Specification for Structural Steel Buildings (Allowable Stress Design and Plastic Design), June 1, 1989
Seismic Provisions for Structural Steel Buildings, April 15, 1997
(Supplement No. 1, February 15, 1999)
Specification for Load and Resistance Factor Design of Single-Angle Members, December 1, 1993
Specification for the Design of Steel Hollow Structural Sections, April 15, 1997
Code of Standard Practice for Steel Buildings and Bridges, June 10, 1992
Metric Conversion of the 2nd Edition Manual of Steel Construction, Load and Resistance Factor Design, 2nd Edition, Volumes I and II, 1999
Manual of Steel Construction, Load and Resistance Factor Design, 2nd Edition, Volumes I and II, 1994
Manual of Steel Construction, Allowable Stress Design, 9th Edition, 1989
Manual of Steel Construction, ASD/LRFD, Volume II Connections, 1992
Hollow Structural Sections Connections Manual, 1997

American Society for Testing and Materials (ASTM)
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

Annual Book of Standards
- Volume 1.04, Steel - Structural, Reinforcing, Pressure Vessel, Railway
- Volume 3.03, Nondestructive Testing

American Welding Society
550 NW LeJeune Road
Miami, FL 33126
www.aws.org

ANSI/AWS D1.1-98, Structural Welding Code - Steel
ANSI/AWS D1.3-98, Structural Welding Code - Sheet Steel
ANSI/AWS D1.4-98, Structural Welding Code - Reinforcing Steel
ANSI/AASHTO/AWS D1.5-96, Bridge Welding Code
ANSI/AWS D1.6-98, Structural Welding Code - Stainless Steel
ANSI/AWS A2.4-98, Standard Symbols for Welding, Brazing, and Nondestructive Testing
ANSI/AWS A3.0-94, Standard Welding Terms and Definitions
ANSI/AWS A5.1-91, Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding
ANSI/AWS A5.5-96, Specification for Low–Alloy Steel Electrodes for Shielded Metal Arc Welding
ANSI/AWS A5.17/A5.17M-97, Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding
ANSI/AWS A5.18-93, Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding
ANSI/AWS A5.20-95, Specification for Carbon Steel Electrodes for Flux Cored Arc Welding
ANSI/AWS A5.23/A5.23M-97, Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding
ANSI/AWS A5.25/A5.25M-97, Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding
ANSI/AWS A5.26/A5.26M-97, Specification for Carbon and Low-Alloy Steel Electrodes for Electrogas Welding
ANSI/AWS A5.28-96, Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc

Welding
ANSI/AWS A5.29-98, Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding
ANSI/AWS A5.32/A5.32M-97, Specification for Welding Shielding Gases
ANSI/AWS Z49.1:1999, Safety in Welding, Cutting and Allied Processes

American Society for Nondestructive Testing, Inc.
PO Box 28518
Columbus, OH 43228-0518
www.asnt.org

ANSI/ASNT CP-189-1995, ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel
Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing, 1995

APPENDIX B

BIBLIOGRAPHY

Welding Cracks Investigation Report, Steel Special Moment Resisting Frames, Elmendorf Air Force Base Hospital, Anchorage, Alaska, December 1996

American Institute of Steel Construction
- Allowable Stress Design of Simple Shear Connections, 1990
- Engineering and Quality Criteria for Steel Structures, 4th Edition, 1997
- Engineering Journal, *Experimental Investigation of Dogbone Moment Connections* (Engelhart, et al), Vol 35, No 4, 4th Qtr 1998
- Engineering Journal, *Ultimate Strength Considerations for Seismic Design of the Reduced Beam Section (Internal Plastic Hinge)* (Iwankiw), Vol 34, No 1, 1st Qtr 1997
- Engineering and Quality Criteria for Steel Structures, 4th Edition, 1997
- Load and Resistance Factor Design of Simple Shear Connections, 1990

American Petroleum Institute
- API 12D, Field Welded Tanks for Storage of Production Liquids (1994)
- API 12F, Shop Welded Tanks for Storage of Production Liquids (1994)
- API RP 2A series documents, Planning, Designing and Constructing Fixed Offshore Platforms
- API Standard 1104, Welding of Pipelines and Related Facilities, 18th Ed. (1994)

American Society for Metals
- ASM Handbook, Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys, 1990
- ASM Handbook, Volume 6: Welding, Brazing and Soldering, 1993
- ASM Metals Handbook, 2nd Ed., 1998
- ASM Specialty Handbook: Carbon and Alloy Steels, 1996
- ASM Specialty Handbook: Cast Irons, 1996
- Steel Castings Handbook, 6th Ed., 1995
- Weld Integrity and Performance, 1997

American Society for Nondestructive Testing
- Nondestructive Testing Handbook
  - Volume 2: Liquid Penetrant Tests, 2nd Ed, 1982
  - Volume 3: Radiography and Radiation Testing, 2nd Ed, 1985
  - Volume 6: Magnetic Particle Testing, 2nd Ed, 1989
  - Volume 7: Ultrasonic Testing, 2nd Ed, 1991
  - Volume 8: Visual and Optical Testing, 2nd Ed, 1993

American Society of Mechanical Engineers
- ANSI/ASME BPVC, Boiler and Pressure Vessel Code, Section 9, Welding and Brazing Qualifications (1998)

American Water Works Association
- AWWA Manual M42 Steel Water Storage Tanks (1998)

American Welding Society

- Guide for Nondestructive Inspection of Welds, ANSI/AWS B1.10-86
- Guide for Visual Inspection of Welds, ANSI/AWS B1.11-88
- Guide for Welding Iron Castings, ANSI/AWS D11.2-89
- Oxygen Cutting Surface Roughness Gauge, AWS C4.1-G
- Recommended Practices for Air Carbon Arc Gouging and Cutting, ANSI/AWS C5.3-91
- Recommended Practices for Stud Welding, ANSI/AWS C5.4-93
- Specification for Underwater Welding, ANSI/AWS D3.6-93
- Specification for Welding Industrial and Mill Cranes and Other Material Handling Equipment, AWS D14.1-97
- Welding Handbook, 8th Edition
  - Volume 1, Welding Technology, 1987
  - Volume 2, Welding Processes, 1991
  - Volume 3, Materials and Applications, Part 1, 1996
  - Volume 4, Materials and Applications, Part 2, 1998
- Welding Inspection, 1980
- Welding Metallurgy, 4th Edition, Volume 1, Fundamentals, George E. Linnert, 1994
- Welding of Cast Iron, 1985

Federal Emergency Management Agency

- FEMA 288, Background Reports: Metallurgy, Fracture Mechanics, Welding, Moment Connections and Frame Systems Behavior, March 1997
- FEMA 303, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, February 1998

Alternate Weld Quality Acceptance Criteria

- British Standards Institution
  - BS PD-6493:1991, Guidance on methods for assessing the acceptability of flaws in structures
  - BS 7910: pending (1999), Guidance on methods for assessing the acceptability of flaws in structures

- Electric Power Research Institute
  - NP-5380, *Visual Weld Acceptance Criteria*

- International Institute of Welding
  - IIW / IIS-SST-1157-90, IIW Guidance on Assessment of the Fitness for Purpose of Welded Structures, Draft for Development, 1990

- Welding Research Council
  - WRC Bulletin 295, Fundamentals of Weld Discontinuities and their Significance (Lundin), 1984

Design Aids for Welded Connections

- American Institute of Steel Construction
  - AISC Manual of Steel Construction (ASD and LRFD versions)
  - Allowable Stress Design of Simple Shear Connections (1990)
  - CONXPRT (software)

Load and Resistance Design of Simple Shear Connections (1990)
    Module I - ASD Simple Shear Connections
    Module I - LRFD Simple Shear Connections
    Module II - ASD Moment Connections
Steel Detailing Software Packages with Connection Design
    CDS
    CompuSTEEL (Barasel Corp.)
    CVSpro8 (CadVantage, Inc.)
    DESCON (Omnitech Associates)
    DETAIL (MacroSoft)
    fabriCAD (Research Engineers, Inc.)
    SDS/2 (Design Data, Inc.)
    Steelcad (Steelcad International, Inc.)
    StruCad (AceCad Software, Inc.)
    StrucPro (Eagle Point)
Canadian Welding Bureau
    Weld_ IT (software)

Safety and Health

American Conference of Governmental Industrial Hygienists (ACGIH)
    Threshold Limit Values (TLV (R)) for Chemical Substances and Physical Agents in the Workroom Environment

American Welding Society, Fumes and Gases in the Welding Environment

National Fire Protection Association
    Standard for Fire Prevention in Use of Cutting and Welding Processes: NFPA 51B, National Fire Protection Association, 1994

Occupational Safety and Health Administration (OSHA)
    Code of Federal Regulations, Title 29, Labor, Chapter XV11, Parts 1901.1 to 1910.1450, Order No. 869-029-00222-5

Intermixed Weld Metal

The Effects of Intermixed Weld Metal on Mechanical Properties – Part 1, Quintana, M. A. and Johnson, M. Q., Welding Journal, March 1999

The Effects of Intermixed Weld Metal on Mechanical Properties – Part 2, Quintana, M. A. and Johnson, M. Q., Proceedings, AWS Annual Convention, Detroit, MI, 1998

The Effects of Intermixed Weld Metal on Mechanical Properties – Part 3, Quintana, M. A. and Johnson, M. Q., Proceedings, AWS Conference on Welded Construction in Seismic Areas, Maui, HI, 1998

Welding Procedures

Heat-Straightening Repairs of Damaged Steel Bridges – A Technical Guide and Manual of Practice, Report No. FHWA-IF-99-004, US Dept. of Transportation, Federal Highway Administration, October 1998

Lincoln Electric Company, The Procedure Handbook of Arc Welding, 13th Ed., 1994

Reviewing and Approving Welding Procedure Specifications, Miller, D. K., Proceedings, AISC National Steel Construction Conference, New Orleans, LA, April, 1998

What Every Engineer Should Know about Welding Procedures, Miller, D. K., Welding Journal, August 1999

Other References and Textbooks

Cast Publishing
- Metals Blue Book, Welding Filler Metals, 2nd Ed, 1998
- Metals Black Book, Ferrous Metals, 3rd Ed, 1998
- Metals Red Book, Nonferrous Metals, 2nd Ed, 1998

Fracture and Fatigue Control in Structures, 2nd Ed., Barsom, J. M. and Rolfe, S. T., Prentice-Hall, 1987

Lincoln Electric Co. / James F. Lincoln Arc Welding Foundation
- Design of Welded Structures, 1966
- Design of Weldments, 1976
- Metals & How to Weld Them, 1962
- The Procedure Handbook of Arc Welding, 13th Edition, 1994
- Tubular Steel Structures - Theory and Design, 1990

Modern Welding Technology, 4th Ed., Cary, H. B., Prentice-Hall, 1997

Weldability of Steels, Stout, R. D. and Doty, W. D., Welding Research Council, 1953

APPENDIX C

WELDING PROCESSES

1. SHIELDED METAL ARC WELDING (SMAW).

a. Process Principles. The Shielded Metal Arc Welding (SMAW) process is commonly known as “stick” welding, and is performed as “manual” welding. An electric arc is produced between the tip of the electrode and the base metal, melting both. The molten weld pool, and completed weld, is a mixture of base metal and electrode materials.

(1) The core of the electrode is steel. The coating is of various materials designed to provide arc stability, shield the molten weld puddle from atmospheric gases, flux the molten puddle of impurities, deoxidize the molten weld puddle, and cover the solidifying weld to improve bead profile. Some coatings contain metallic powders, adding specific alloys to the weld composition.

(2) SMAW may be operated using either DC (direct current) or AC (alternating current) polarity. Generally, DC is used for smaller diameter electrodes, typically those with a diameter of less than 4.8 mm (3/16 in.). To eliminate undesirable arc blow conditions, larger electrodes are typically operated using AC. Electrodes used on AC must be designed specifically to operate in this mode, where the current changes direction 120 times per second on 60 Hertz power. AC electrodes may also operate using either DCEN (DC Electrode Negative, DC-, also called “straight” polarity) or DCEP (DC Electrode Positive, DC+, also called “reverse” polarity), and in some cases, either DC polarity.

b. Filler Metal Designation, Specification and Certification. Filler metal specification AWS A5.1 provides the requirements for carbon steel covered electrodes used with SMAW. AWS A5.5 similarly covers the low-alloy steel electrodes for SMAW.

(1) Generally, when welding on structural steels with a minimum specified yield strength equal to or exceeding 485 MPa (50 ksi), SMAW electrodes should be of the low hydrogen type. See AWS *D1.1* Table 3.1 lists specific steels and grades where the use of low hydrogen electrodes is required for the prequalification of SMAW Welding Procedure Specifications (WPSs). Table 3.1 also provides the strength of electrode required for these steels to provide the “matching” strength for the base metal. Group I steels, including A36 steel, may be welded with non-low hydrogen electrodes. For Group II steels, including A572 grade 50, and higher strength groups, low hydrogen electrodes are required. For most structural steel fabrication today, low hydrogen electrodes are prescribed to offer additional assurance against hydrogen induced cracking.

(2) Low hydrogen electrodes have coatings of inorganic materials that are very low in hydrogen, and are designed to be extremely low in moisture. Water (H_2O) will break down into its components, hydrogen and oxygen, under the arc. This hydrogen can then enter into the weld deposit and may lead to unacceptable weld and heat affected zone cracking under certain conditions.

(3) The term “low hydrogen” was initially used to separate those SMAW electrodes capable of depositing weld metal with low levels of diffusible hydrogen from non-low hydrogen electrodes such as E6010 and E6012 that contain, by design, coating moisture levels of 2 to 4%. For prequalified WPSs, AWS *D1.1* Table 3.2 provides one series of minimum preheat and interpass temperatures for “non-low hydrogen electrodes”, and another series of values for SMAW with low hydrogen electrodes and all FCAW, SAW and GMAW. This implies a similarity in expected maximum levels of diffusible hydrogen.

When SMAW low hydrogen electrodes are used, the required levels of preheat are lower, offering economic and time-saving advantages to the contractor. AWS *D1.1* and the AWS A5 filler metal specifications do not currently define “low hydrogen.” International Institute of Welding (IIW) documents classify electrodes for diffusible hydrogen as follows: very low hydrogen (0-5 mL / 100 g deposited weld metal), low hydrogen (5-10), medium hydrogen (10-15), and high hydrogen (15-20), but these definitions are unrelated to AWS usage and specifications.

(4) SMAW electrodes are classified based on a four or five digit number that follows the letter E (for electrode). The electrode classification is imprinted on the coating near the end of the electrode, as well as on the electrode package. See Table C-1. In filler metal specification AWS A5.1, low hydrogen carbon steel SMAW electrodes are identified with the last “X” number in the designator EXXXX as a 5, 6 or 8. A5.1 SMAW low hydrogen electrode classifications include E7015, E7016, E7018, E7018M, E7028, and E7048. The E7015 electrodes operate using DCEP only. E7016 electrodes operate using either AC or DCEP. The E7018 electrodes operate using AC or DCEP, and include approximately 25% iron powder in their coatings to increase their deposition rate. An E7028 electrode contains approximately 50% iron powder in the coating, enabling it to deposit metal at even higher rates. However, as the nomenclature shows, the “2" would indicate that this electrode is suitable for flat position welding and, for fillet welds only, the horizontal position. E7018M electrodes may be used only with DCEP, and have been tested for absorbed moisture and diffusible hydrogen. E7048 electrodes are similar to E7018 electrodes in composition, and may be used in any position, AC or DCEP, except for vertical welding in the upward progression. E7048 electrodes are specifically designed for good welding in the vertical downward progression.

(5) In the AWS A5.5 low-alloy steel SMAW electrode specification, a similar format is used to identify SMAW electrodes. See Table C-2. The most significant difference in nomenclature from A5.1 is the inclusion of a suffix letter and number indicating the alloy content. As an example, an E8018-C3 nickel steel electrode, with suffix “-C3", indicates the electrode nominally contains 1% nickel. A “-C1" electrode nominally contains 2.5% nickel. Some electrodes carry the “-W” designation, indicating the presence of alloys capable of giving the weld atmospheric corrosion resistance for exposed weathering applications. Low hydrogen low-alloy SMAW electrodes are similarly identified with the last “X” number in the designator EXXXX-Y as a 5, 6 or 8.

(6) Optional supplemental designators may be used to indicate the maximum level of hydrogen that may be present in the test weld deposit. These designators are a part of the standard AWS classification system and consist of the letter H followed by a single or double digit. For example “E7018-H8" indicates that the deposit contains a maximum diffusible hydrogen content of 8 mL per 100 g of deposited weld metal. Most standard low hydrogen electrodes must deposit weld metal with a maximum of 16 mL per 100 g of diffusible hydrogen under test conditions. However, manufacturers may optionally list an H8 or H4 designation if their particular SMAW electrodes are capable of delivering these extra low levels of diffusible hydrogen.

(7) While “low-hydrogen” electrodes are required by AWS *D1.1* for welding on structural steels with minimum specified yield strength of 485 MPa (50 ksi) or greater, extra-low hydrogen levels should not be specified unless necessary. There is generally a cost premium associated with the lower diffusible hydrogen electrodes. Also, high notch toughness weld metal from electrodes with good operating characteristics may not be available with the lowest hydrogen designations, and some electrodes with very low diffusible hydrogen levels may have poor notch toughness.

(8) All low hydrogen electrodes listed in AWS A5.1 have minimum specified notch toughnesses of 27 J @ -20^{o}C (20 ft-lbf at 0°F) or better. See Table C-3 for specific data on these low hydrogen

electrodes. There are electrode classifications that have no required notch toughness (such as E6012, E6013, E6014, E7024), but these are not classified as low hydrogen electrodes. There is no direct correlation between the low hydrogen limits of various electrodes and notch toughness requirements.

(9) Low hydrogen, low-alloy SMAW electrodes, up through 550 MPa (80 ksi), as listed with operating limitations and uses in Table C-4. For electrodes exceeding 550 MPa (80 ksi), see AWS A5.5.

(10) Electrodes providing a given level of notch toughness are listed in Table C-5. For the notch toughness levels of higher strength electrodes, see AWS A5.5.

(11) Low hydrogen SMAW electrodes typically are supplied in hermetically sealed metal containers. When supplied in undamaged containers, they may be used without any preconditioning, or baking, before use. When SMAW electrodes are received in damaged containers or in non-hermetically sealed containers, AWS *D1.1* requires that the electrodes be baked prior to use, in the range of 260^{o}C to 430^{o}C (500 to 800°F), to remove any residual moisture picked up from exposure to the atmosphere. The electrode manufacturer's guidelines should be followed to ensure a baking procedure that eliminates retained moisture, and these recommendations may vary from AWS *D1.1* provisions.

(12) Once low hydrogen SMAW electrodes are removed from their hermetically sealed container, or from the baking oven, they should be placed in a holding oven, also called a "rod oven" or "storage oven", to avoid the pickup of moisture from the atmosphere. These heated ovens must maintain the electrodes at a minimum temperature of 120^{o}C (250°F). Once the electrode has been exposed to the atmosphere, it begins to pick up moisture. AWS *D1.1* Table 5.1 limits the exposure time of various electrode classifications. Higher strength electrodes, used to join high strength steels which are particularly susceptible to hydrogen assisted cracking, are limited to very short periods.

c. Advantages, Disadvantages and Limitations. Generally SMAW has a lower deposition rate and is less efficient, and is more costly than the other structural welding processes of FCAW, GMAW and SAW. SMAW is seldom used as the principal process for structural welding, but is commonly used for tack welding, fabrication of miscellaneous components, and repair welding.

(1) SMAW has the benefit of requiring relatively simple, inexpensive, portable, and easy to maintain welding equipment. Gas shielding is not required. Holding ovens for low hydrogen electrodes are required unless hermetically sealed containers are used to provide dry electrodes when needed. SMAW is capable of depositing high quality welds, and is relatively tolerant of welding technique, welding procedure variations, and wind. It can be used in areas with difficult access.

(2) Smaller prequalified weld bead sizes, maximum 8 mm (5/16 in.) in a single pass in the common horizontal position, requires more passes for large welds, with additional cleaning time required for slag removal. For long welds, because of the fixed length electrode, it may not be possible to complete the weld without stopping, removing the slag to allow restarting the weld, and using additional electrodes.

Table C-1. AWS A5.1 Classification System for Carbon Steel Electrodes for SMAW

E XX YY M - 1 HZ R

E	Electrode
XX	Minimum tensile strength in units of 1 ksi (7 MPa) 60 = 60 ksi (420 MPa) 70 = 70 ksi (480 MPa)
Y	Generally, welding positions permitted for use, but may be additionally limited by electrode diameter and class 1 = all positions (F, H, V, OH) 2 = F, H-fillets 4 = F, H, V-down, OH
Y	Type of covering 0 = high cellulose sodium (E6010) 0 = high iron oxide (E6020) 1 = high cellulose potassium 2 = high titania sodium 3 = high titania potassium 4 = iron powder, titania 5 = low hydrogen sodium 6 = low hydrogen potassium 7 = high iron oxide, iron powder 8 = low hydrogen potassium, iron powder (except E7018M) 9 = iron oxide titania potassium
M	If present, meets special Military specifications, and covering is low hydrogen, iron powder
-1	If present, indicates improved notch toughness (see AWS A5.1, Table 3) for E7016-1, average CVN of 27 J @ -46°C (20 ft-lbf @ -50°F) for E7018-1, average CVN of 27 J @ -46°C (20 ft-lbf @ -50°F) for E7024-1, average CVN of 27 J @ -18°C (20 ft-lbf @ -0°F)
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal (note: E7018M meets H4 requirements, but the H4 designation is not used)
R	If present, indicates electrode has lower moisture content and meets absorbed moisture test requirements (note: E7018M must meet more stringent requirements, but the R designation is not used)

Table C-2. AWS A5.5 Classification System for Low-Alloy Steel Electrodes for SMAW

E XX YY M - X# HZ R

E	Electrode
XX	Minimum tensile strength in units of 1 ksi (7 MPa) 70 = 70 ksi (480 MPa) 80 = 80 ksi (550 MPa) 90 = 90 ksi (620 MPa) 100 = 100 ksi (690 MPa) 110 = 110 ksi (760 MPa) 120 = 120 ksi (830 MPa)
Y	Generally, welding positions permitted for use, but may be additionally limited by electrode diameter and class 1 = all positions (F, H, V, OH) 2 = F, H-fillets
Y	Type of covering 0 = high cellulose sodium (except E7020) 0 = high iron oxide (E7020) 1 = high cellulose potassium 2 = high titania sodium 3 = high titania potassium 4 = iron powder, titania 5 = low hydrogen sodium 6 = low hydrogen potassium 7 = high iron oxide, iron powder 8 = low hydrogen potassium, iron powder (except EXX18M) 9 = iron oxide titania potassium
M	If present, meets special Military specifications, and covering is low hydrogen, iron powder
-	
X#	Alloy type A carbon-molybdenum steel B chromium-molybdenum steel C nickel steel D manganese-molybdenum steel G general low-alloy steel P for pipeline use W weathering steel
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal (note: EXX18M meets H4 requirements, but the H4 designation is not used)
R	If present, indicates electrode has lower moisture content and meets absorbed moisture test requirements

Table C-3. Low Hydrogen AWS A5.1 Carbon Steel Electrodes for SMAW [to 480 MPa (70 ksi)]

Electrode	Position	Current	CVN Toughness	Moisture Content Limit (as received)	Available Diffusible Hydrogen Limits
E7015	F, H, V, OH	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.6	H16, H8, H4
E7016	F, H, V, OH	AC, DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.6	H16, H8, H4
E7018	F, H, V, OH	AC, DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.6	H16, H8, H4
E7018M	F, H, V, OH	DCEP	68 J @ -29°C (50 ft-lbf @ -20°F)	0.1	4.0 [1]
E7028	F, H-fillets	AC, DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)	0.3	H16, H8, H4
E7048	F, H, V-down, OH	AC, DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.4	H16, H8, H4
E7016-1	F, H, V, OH	AC, DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)	0.6	H16, H8, H4
E7018-1	F, H, V, OH	AC, DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)	0.6	H16, H8, H4

[1] - no H designation used for E7018M

Table C-4. Low Hydrogen AWS A5.5 Low-Alloy Steel Electrodes for SMAW [to 550 MPa (80 ksi)]

Electrode	Position	Current	Moisture Content Limit (as received)	Available Diffusible Hydrogen Limits
E7015-X	F, H, V, OH	DCEP	0.4 [2]	H16, H8, H4
E7016-X	F, H, V, OH	AC, DCEP	0.4 [2]	H16, H8, H4
E7018-X	F, H, V, OH	AC, DCEP	0.4 [2]	H16, H8, H4
E8015-X [1]	F, H, V, OH	DCEP	0.2	H16, H8, H4
E8016-X [1]	F, H, V, OH	AC, DCEP	0.2	H16, H8, H4
E8018-X [1]	F, H, V, OH	AC, DCEP	0.2	H16, H8, H4

[1] - B3, B3L, B4L, B5, B6, B7, B7L, B8, B8L, and B9 series electrodes not prequalified under AWS *D1.1*

[2] - E70XX-XR and E70XX-X-HZR series Limit on Moisture Content (as received) = 0.3

Table C-5. Toughness Values for Low Hydrogen A5.5 Low Alloy Steel Electrodes [to 550 MPa (80 ksi)]

CVN Toughness	Electrodes
27 J @ -18°C (20 ft-lbf @ 0°F)	E7018-W1 E8018-W2
27 J @ -40°C (20 ft-lbf @ -40°F)	E8016-C3, E8018-C3, E8018-NM1
27 J @ -51°C (20 ft-lbf @ -60°F)	E7018-C3L E8016-C4, E8016-D3, E8018-C4, E8018-D1, E8018-D3
27 J @ -60°C (20 ft-lbf @ -75°F)	E8016-C1, E8018-C1
27 J @ -73°C (20 ft-lbf @ -100°F)	E7015-C1L, E7016-C1L, E7018-C2L E8016-C2, E8018-C2
27 J @ -100°C (20 ft-lbf @ -150°F)	E7015-C2L, E7016-C2L, E7018-C2L

2. FLUX CORED ARC WELDING (FCAW).

a. Process Principles. Flux cored arc welding (FCAW) is an arc welding process that uses a continuous tubular electrode fed from a coil or spool into a welding “gun”. The electrode core contains alloy additions, deoxidizers and flux materials. The heat of the arc causes the base metal, tubular electrode wire and core materials to melt. The flux materials bind impurities, rise to the top of the molten weld, and protect the cooling weld from atmospheric nitrogen or oxygen. Shielding of the exposed arc is provided either by the decomposition of the core in self-shielded electrodes, designated FCAW-S, or by an externally supplied gas or gas mixture, designated FCAW-G.

(1) With FCAW-G, carbon dioxide (CO_2) or a mixture of argon (Ar) of 75 to 90% and of CO_2 10 to 25% is used in addition to the gas provided by the flux core. The shielding gas selection may affect the mechanical properties (yield and tensile strength, elongation, and notch toughness) of the weld. Carbon dioxide, as a reactive gas, may cause some of the alloys in the electrode to become oxidized, and therefore less alloy is transferred to the weld deposit. When an inert gas such as argon is substituted for CO_2, alloy transfer typically increases. With more alloy in the weld deposit, higher yield and tensile strengths and reduced ductility is expected. The notch toughness of the weld deposit may increase or decrease, depending on the alloys affected.

(2) The power source is usually the constant voltage type, using either direct current electrode positive or electrode negative polarity. A separate wire feeder sends wire into the welding gun at a preset rate. The Welding Procedure Specification (WPS) provides the appropriate voltage, wire feed speed, electrode extension, and travel speed. For a given wire feed speed and electrode extension, a specific current (amperage) will be provided. As the wire feed speed is increased, the current is likewise increased. The WPS should, preferably, state the wire feed speed to be used because electrode extension, polarity and electrode diameter also affect current. Shorter electrical stickout results in higher current for a given wire feed speed. If current is used in the WPS, an inaccurate electrode extension may go undetected.

(3) FCAW is most commonly used as “semiautomatic”, wire fed but with the welding gun manipulated by the welder. It may also be used as automatic, but the intensity of arc rays from the high current arc, and the significant volume of smoke generated, make Submerged Arc Welding (SAW) more desirable for automatic welding.

b. Filler Metal Designation, Specification and Certification. FCAW electrodes are specified in AWS filler metal specifications AWS A5.20 and A5.29. AWS A5.20 is applicable to carbon steel electrodes, and AWS A5.29 is applicable to low alloy steel electrodes. The classification and identification system used for these two specifications is summarized in Tables C-6 and C-7.

(1) All FCAW electrodes are considered low hydrogen. Self-shielded FCAW electrodes are limited to 550 MPa (80 ksi) tensile strength of less, but higher strengths are available from gas-shielded FCAW electrodes. AWS A5.20 electrodes EXXT-2, -3, -10, -13, -14, and -GS electrodes are not permitted by AWS *D1.1* because they are limited to single pass welds. AWS A5.20 electrodes EXXT-3, EXXT-11, and EXXT-14 are for limited thickness applications only, and the manufacturer’s recommendations should be consulted.

(2) Tables C-8 and C-9 provide additional information regarding electrode limitations, usage and toughness properties for electrodes permitted by AWS *D1.1* for classification strengths of 550 MPa (80 ksi) and lower. For higher strength and other electrodes, the AWS A5.20 and A5.29 specifications should be consulted.

c. Advantages, Disadvantages and Limitations. The Flux Cored Arc Welding (FCAW) process offers several advantages over Shielded Metal Arc Welding (SMAW), but also has a few disadvantages and limitations

(1) The FCAW electrode is continuous, eliminating the numerous starts and stops necessary with SMAW on longer and larger welds.

(2) Increased deposition rates are possible with FCAW because the current can be higher than with SMAW. SMAW currents are limited by rod heating and coating breakdown concerns. With FCAW, the electrode is passed through a contact tip usually 20 to 25 mm (3/4 to 1 in.) from the end of the electrode, minimizing the buildup of heat from electrical resistance. This electrode extension distance, commonly called “stickout,” varies for each WPS, and may be considerably higher. Both factors provide FCAW an economic advantage over SMAW.

(3) The number of arc starts and stops, a potential source of weld discontinuities, is also reduced.

(4) The equipment required for FCAW is more expensive and complicated than SMAW, and more difficult to maintain. This increased cost is offset by the higher productivity levels achieved using FCAW compared to SMAW.

(5) FCAW electrode wires do not need heated holding ovens for ordinary applications, but caution should be used when FCAW wires are exposed to the elements for extended periods of time. For critical welds requiring very low hydrogen deposits, more restrictive storage requirements may be warranted.

(6) FCAW is capable of all-position welding when using small diameter electrodes. Large diameter electrodes, using higher electrical currents, are restricted to the flat and horizontal positions.

(7) There are several advantages to using FCAW-S (self-shielded) rather than FCAW-G (gas-shielded). The FCAW-S welding gun assembly does not require a gas nozzle, also called a gas cup, therefore access into smaller areas is possible, significant when welding in tight locations such as weld access holes in beam-to-column connections. The welder is also better able to see the arc and weld puddle because the gas cup is not present.

(8) A second advantage to FCAW-S over FCAW-G is its ability to make quality welds under field conditions involving wind. For FCAW-G, it is necessary to erect protective shielding from wind to maintain the shielding gas around the molten weld puddle. Such shielding may be expensive, time-consuming, require additional ventilation for the welder, and constitute a fire hazard. FCAW-S eliminates the handling of high pressure gas cylinders, theft of cylinders, protection of gas distribution hosing under field conditions, and the cost of the shielding gas. For shop fabrication, wind is less of a problem than under field conditions. However, drafts from doorways and windows, fans used to cool personnel and provide ventilation, and welding fume exhaust equipment can create unacceptable wind speeds that degrade weld quality.

(9) FCAW-G “operator appeal” is usually higher than with FCAW-S because of better arc control and less fume generation. FCAW-G is less sensitive to variations in electrode extension and arc voltage than FCAW-S. The range of suitable applications for a single size and classification of FCAW-G electrodes is generally broader than for FCAW-S electrodes.

(10) FCAW-S procedures must be closely controlled to ensure the required level of weld quality and mechanical properties. Because of the high deposition rates possible, travel speeds and technique

must be monitored to ensure that excessively large bead sizes are not produced. Large bead size, because of the high heat input and excessively slow cooling rates, may reduce notch toughness, reduce weld soundness, decrease heat affected zone toughness, and decrease the weld metal yield and tensile strengths.

Table C-6. AWS A5.20 Classification System for Carbon Steel Electrodes for FCAW

EXXT-XMJHZ

E	Electrode
X	Minimum Tensile Strength in units of 10 ksi (69 MPa) 6 = 60 ksi (420 MPa) 7 = 70 ksi (480 MPa)
X	Position of welding permitted 0 = flat and horizontal position only 1 = all positions
T	Tubular electrode
-	
X	Type of electrode, numbered 1-14, or letter G or GS
M	If used, electrode has been classified using 75-80% Ar, with balance CO_2
J	If used, electrode has toughness of 27 J @ -40°C (20 ft-lbf @ -40°F) If not used, electrode has toughness as listed in A5.20, Table 1
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal

Table C-7. AWS A5.29 Classification System for Low Alloy Steel Electrodes for FCAW

EXXTX-X#M

E	Electrode
X	Minimum Tensile Strength in units of 10 ksi (69 MPa) 6 = 60 ksi (420 MPa) 7 = 70 ksi (480 MPa) 8 = 80 ksi (550 MPa) 9 = 90 ksi (620 MPa) 10 = 100 ksi (690 MPa) 11 = 110 ksi (760 MPa) 12 = 120 ksi (830 MPa)
X	Position of welding permitted 0 = flat and horizontal position only 1 = all positions
T	Tubular electrode
X	Type of electrode, numbered 1, 4, 5, or 8 1 & 5 - gas-shielded 4 & 8 - self-shielded
-	
X#	Alloy type A carbon-molybdenum steel B chromium-molybdenum steel C nickel steel D manganese-molybdenum steel K other alloy steels W weathering steel
M	If used, electrode has been classified using 75-80% Ar, with balance CO_2

Table C-8. AWS A5.20 Carbon Steel Electrodes for FCAW [to 480 MPa (70 ksi), Multipass Only]

Electrode	Position	Testing Shielding Gas[d]	Current	CVN Toughness[c]
	F, H	CO		27 J @ -18°C
E70T-1M		75-80% Ar - CO_2	DCEP	C
E71T-1	F, H, V-up, OH	$_2$	DCEP	27 J @ -18°
	F, H, V-up, OH	75-80% Ar - CO		27 J @ -18°C
E70T-4		self	DCEP	
E70T-5	F, H	$_2$	DCEP	27 J @ -29°
	F, H	75-80% Ar - CO		27 J @ -29°C
E71T-5		CO_2	DCEP, DCEN	C
E71T-5M	F, H, V-up, OH	$_2$	DCEP, DCEN	27 J @ -29°
	F, H	self		27 J @ -29 C
E70T-7	F, H		DCEN	none specified
	F, H, V-up, OH	self		none specified
E70T-8		self	DCEN	°C
	F, H, V-up, OH	self		27 J @ -29 C
E70T-9	F, H	$_2$	DCEP	27 J @ -29°
	F, H	75-80% Ar - CO		27 J @ -29°C
E71T-9		CO_2	DCEP	C
E71T-9M	F, H, V-up, OH	$_2$	DCEP	27 J @ -29°
[b]	F, H	self		none specified
[b]	F, H, V-dn, OH	self		none specified
	F, H	CO		27 J @ -29°C
E71T-12		CO_2	DCEP	C
EX[a]0T-G		not specified	not specified	
EX[a]	F, H, V-up or V-dn,	not specified		not specified

Note - 27 J @ -18 C = 20 ft-lbf @ 0° °C = 20 ft-lbf @ -20 F

[a] - May be either 6 or 7, for 60 ksi or 70 ksi tensile strength.

[b] - electrodes with “J” at the end of the designator (e.g. E7XT-9J) have minimum CVN Toughness of 27 J @ -40°C (20 ft-lbf @ -20°

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

Table C-9. AWS A5.29 Low Alloy Steel Electrodes for FCAW [to 550 MPa (80 ksi), Multipass Only]

Electrode	Permitted Positions	Testing Shielding Gas[d]	Current	Minimum CVN Toughness
E61T8-K6	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E70T4-K2	F, H	self	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
E70T5-A1	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-K2	F, H	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-K6	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-Ni1	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-Ni2	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T1-A1	F, H	CO_2	DCEP	none specified
E81T1-A1	F, H, V, OH	CO_2	DCEP	none specified
E80T1-B1	F, H	CO_2	DCEP	none specified
E81T1-B1	F, H, V, OH	CO_2	DCEP	none specified
E81T1-B2	F, H, V, OH	CO_2	DCEP	none specified
E80T1-B2H	F, H, V, OH	CO_2	DCEP	none specified
E80T1-K2	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T1-Ni1	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E81T1-Ni1	F, H, V, OH	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T1-Ni2	F, H	CO_2	DCEP	27 J @ -40°C (20 ft-lbf @ -40°F)
E81T1-Ni2	F, H, V, OH	CO_2	DCEP	27 J @ -40°C (20 ft-lbf @ -40°F)
E80T1-W	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T5-B2	F, H	CO_2	DCEP	none specified
E80T5-B2L	F, H	CO_2	DCEP	none specified
E80T5-Ni1	F, H	CO_2	DCEP	27 J @ -51°C (20 ft-lbf @ -60°F)
E80T5-Ni2	F, H	CO_2	DCEP	27 J @ -60°C (20 ft-lbf @ -76°F)
E80T5-Ni3	F, H	CO_2	DCEP	27 J @ -73°C (20 ft-lbf @ -100°F)
E80T5-K1	F, H	CO_2	DCEP	27 J @ -40°C (20 ft-lbf @ -40°F)
E80T5-K2	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

3. GAS METAL ARC WELDING (GMAW).

a. Process Principles. The Gas Metal Arc Welding (GMAW) process, commonly referred to as “MIG” (Metal Inert Gas) welding, is very similar to gas-shielded flux cored arc welding (FCAW-G), and uses the same equipment. GMAW uses a solid or metal cored electrode, and subsequently leaves little, if any, slag. The shielding gas used for GMAW may be carbon dioxide (CO_2), or a mixture of argon (Ar) and either CO_2 or small levels of oxygen (O), or both. GMAW is commonly applied in one of four ways: spray arc transfer, globular transfer, pulsed arc transfer, and short arc transfer.

(1) Spray arc transfer uses high wire feed speeds and relatively high voltages. A fine spray of molten drops, all smaller in diameter than the electrode diameter, is ejected from the electrode toward the work. The arc in spray transfer is continuously maintained, resulting in high quality welds with good appearance. The shielding used for spray arc transfer is composed of at least 80% argon, with the balance made up of either carbon dioxide or oxygen. Typical mixtures are 90% argon with 10% CO_2, and 95% argon with 5% oxygen. Because of the intensity of the arc, puddle fluidity, and lack of slag to hold the molten metal in place, spray arc is limited to the flat and horizontal position.

(2) Globular transfer results when high concentrations of carbon dioxide are used. Carbon dioxide, as an active gas rather than inert gas, may be referred to as “MAG” (Metal Active Gas) welding. Because of the high concentration of CO_2, the arc ejects large globular pieces of molten steel from the end of the electrode, rather than a spray. This mode of transfer can result in deep penetration, but may have poor appearance with relatively high levels of spatter. It is also limited to the flat and horizontal positions. Because of the lower cost of CO_2 shielding gas, the lower level of heat generated, and increased welder comfort, globular transfer may be selected in place of spray transfer.

(3) Pulsed arc transfer uses a background current that is continuously applied to the electrode, plus a pulsing peak current applied at a rate proportional to the wire feed speed. Each pulse of current ejects a single droplet of metal from the electrode, usually between 100 and 400 times per second. The arc is maintained by the lower background current. Pulsed arc transfer can be used out-of-position, with better quality than short-circuiting mode. It is not as productive as spray transfer for welding in the flat and horizontal positions. Weld appearance and quality are generally good. Pulsed arc transfer GMAW equipment is somewhat more complex and costly than standard GMAW equipment.

(4) Short circuiting transfer, also called short arc, is suitable for welding only on thin gauge materials, and should not be used for structural steel. The small diameter electrode is fed at a moderate wire feed speed using relatively low voltage. The electrode contacts the workpiece, shorting the electrical circuit, extinguishing the arc, resulting in very high current flowing through the electrode, causing it to heat and melt. As the electrode melts, the arc is briefly reestablished. This cycle occurs up to 200 times per second, creating a characteristic buzzing sound. With structural steel, significant fusion problems such as cold lap may result. Short circuiting transfer provides a low deposition rate, but can be used out of position. While GMAW is considered prequalified by AWS *D1.1*, the short circuiting mode of transfer, abbreviated GMAW-S, is not. All GMAW-S welding procedures must be qualified by test.

b. Filler Metal Designation, Specification and Certification. GMAW electrodes are classified under AWS A5.18 for carbon steel electrodes, and AWS A5.28 for low alloy steel electrodes. The classification systems used for GMAW electrodes in AWS A5.18 and A5.28 are summarized in Tables C-10 and C-11.

(1) Classification testing is usually performed using specific welding procedures that use CO_2 shielding gas, therefore promoting globular transfer, but other gases, and therefore transfer modes, may be specified.

(2) Metal cored electrodes, previously classified as FCAW electrodes, are now listed in both A5.18 and A5.28. GMAW with metal cored electrodes is similar to FCAW, with a tubular electrode, but the core contains metallic powders (alloy) rather than flux materials. Metal cored electrodes require less current to obtain the same deposition rates, have better tolerance for mill scale and rust, and when used out-of-position, are less likely to cold lap. Metal cored electrodes typically provide higher deposition rates because higher currents may be used than with solid wire electrodes. Weld appearance is typically very good, and the weld is essentially free of slag. The consistency of mechanical properties is typically better with metal cored electrodes than with solid wire electrodes.

(3) Properties and usage for GMAW electrodes, up to 550 MPa (80 ksi), are summarized in Tables C-12 and C-13. For higher strength electrodes, see AWS A5.28.

c. Advantages, Disadvantages and Limitations. The Gas Metal Arc Welding (GMAW) process offers several advantages over Shielded Metal Arc Welding (SMAW), but also has some disadvantages and limitations.

(1) The GMAW electrode is continuous, eliminating the numerous starts and stops necessary with SMAW on longer and larger welds.

(2) Increased deposition rates are possible with GMAW because the current can be higher than with SMAW. SMAW currents are limited by rod heating and coating breakdown concerns. With GMAW, the electrode is passed through a contact tip usually 20 to 25 mm (3/4 to 1 in.) from the end of the electrode, minimizing the buildup of heat from electrical resistance. This electrode extension distance, commonly called “stickout,” varies for each WPS, and may be considerably higher. Both factors provide GMAW an economic advantage over SMAW.

(3) The number of arc starts and stops, a potential source of weld discontinuities, is also reduced.

(4) GMAW electrode wires do not need heated holding ovens. For critical welds requiring very low hydrogen deposits, GMAW electrode wires are available in the lowest diffusible hydrogen category, H2.

(5) GMAW “operator appeal” is usually high because of good arc control and little fume generation.

(6) Because no flux is involved, GMAW is intolerant of high levels of mill scale, rust, and other surface contaminants, and is limited to welding on relatively clean materials. Commonly, mill scale must be removed by blast cleaning or power wire brushing prior to welding.

(7) GMAW is also seriously affected by wind because of the removal of the shielding gas from around the weld puddle. For field work, it is often necessary to erect protective shielding from wind to maintain the shielding gas around the molten weld puddle. Such shielding may be expensive, time-consuming, require additional ventilation for the welder, and constitute a fire hazard. For shop fabrication, wind is less of a problem than under field conditions. However, drafts from doorways and windows, fans used to cool personnel and provide ventilation, and welding fume exhaust equipment can create unacceptable wind speeds that degrade weld quality.

(8) The equipment required for GMAW is more expensive and complicated than SMAW, and more difficult to maintain. This increased cost is offset by the higher productivity levels achieved using GMAW compared to SMAW.

Table C-10. AWS A5.18 Classification System for Carbon Steel Electrodes for GMAW

E XX C - X Y N HZ

E	
R	**If used, designates that electrode may also be used as filler rod**
XX	**Minimum Tensile Strength in units of 1 ksi (7 MPa)**
S or C	**S = Solid wire**
-	
X	**composite wire** **G = unspecified composition**
	Shielding gas used for classification testing **C = CO_2** **M = 75-80% Ar, balance CO_2**
N	**applications**
HZ	**H16 = maximum 16 mL / 100 g deposited weld metal** **H8 = maximum 8 mL / 100 g deposited weld metal** **H2 = maximum 2 mL / 100 g deposited weld metal**

Table C-11. AWS A5.28 Classification System for Low Alloy Steel Electrodes for GMAW

ER XX S - XXX HZ
E XX C - XXX HZ

E	Electrode
R	If used, designates that electrode may also be used as filler rod for GTAW
XX	Minimum Tensile Strength in units of 1 ksi (7 MPa) 70 = 70 ksi (480 MPa) 80 = 80 ksi (550 MPa) 90 = 90 ksi (620 MPa) 100 = 100 ksi (690 MPa) 110 = 110 ksi (760 MPa) 120 = 120 ksi (830 MPa)
S or C	S = Solid wire C = Composite (metal cored) wire
-	
XXX	Chemical composition of solid wire, or of weld deposit of composite wire A = carbon-molybdenum steel B = chromium-molybdenum steel Ni = nickel steel D = manganese-molybdenum steel 1 = other alloy steels G = not specified
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal H2 = maximum 2 mL / 100 g deposited weld metal

Table C-12. AWS A5.18 Carbon Steel Electrodes for GMAW [480 MPa (70 ksi) only]

Electrode	Testing Shielding Gas[d]	Polarity	CVN Toughness
ER70S-2	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
ER70S-3	CO_2	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
ER70S-4	CO_2	DCEP	not required
ER70S-5	CO_2	DCEP	not required
ER70S-6	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
ER70S-7	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
ER70S-G	as agreed		as agreed
E70C-3C	CO_2	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
E70C-3M	75-80% Ar, balance CO_2	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
E70C-6C	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E70C-6M	75-80% Ar, balance CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E70C-G(X)	as agreed		as agreed

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

Note - E70C-GS(X) electrode is limited to single pass applications, and is not prequalified.

Note - All above electrodes optionally available as H16, H8, and H4 for diffusible hydrogen requirements.

Table C-13. AWS A5.28 Low Alloy Steel Electrodes for GMAW [to 550 MPa (80 ksi), Multipass Only]

Electrode	Testing Shielding Gas[d]	Polarity	CVN Toughness
ER70S-A1	Ar / 1-5% O_2	DCEP	not required
ER70S-B2L	Ar / 1-5% O_2	DCEP	not required
E70C-B2L	Ar / 1-5% O_2	DCEP	not required
E70C-Ni2	Ar / 1-5% O_2	DCEP	27 J @ -62°C (20 ft-lbf @ -80°F)
ER80S-B2	Ar / 1-5% O_2	DCEP	not required
ER80S-Ni1	Ar / 1-5% O_2	DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)
ER80S-Ni2	Ar / 1-5% O_2	DCEP	27 J @ -62°C (20 ft-lbf @ -80°F)
ER80S-Ni3	Ar / 1-5% O_2	DCEP	27 J @ -73°C (20 ft-lbf @ -100°F)
ER80S-D2	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80C-B2	Ar / 1-5% O_2	DCEP	not required
E80C-Ni1	Ar / 1-5% O_2	DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)
E80C-Ni2	Ar / 1-5% O_2	DCEP	27 J @ -62°C (20 ft-lbf @ -80°F)
E80C-Ni3	Ar / 1-5% O_2	DCEP	27 J @ -73°C (20 ft-lbf @ -100°F)

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

Note - B3, B3L, B6, B8 and B9 classification electrodes are not prequalified
Note - All above electrodes optionally available as H16, H8, H4 and H2 for diffusible hydrogen requirements.

4. SUBMERGED ARC WELDING (SAW).

a. Process Principles. Submerged Arc Welding (SAW) uses a blanket of fusible granular material called flux to shield the arc and molten metal. The arc is struck between the workpiece and a bare wire or composite electrode, the tip of which is submerged in the flux. Since the arc is completely covered by flux, it is not visible and the weld is made without the flash, spatter, sparks and smoke common for the open-arc processes.

(1) The process is typically operated automatic, or fully mechanized, although semiautomatic operation is often used. The electrode is continuously fed from a coil or spool to the welding gun, which travels at a preset speed along the joint, preceded by a flux deposition system. In semiautomatic welding, the welder moves the gun, usually equipped with a flux-feeding device, along the joint by hand.

(2) Flux feed may be by gravity flow through a nozzle from a small hopper atop the welding gun, or it may be through a nozzle tube connected to an air-pressurized flux tank. Flux may also be applied in advance of the welding operation, ahead of the arc, from a hopper run along the joint. Many fully mechanized systems are equipped with vacuum devices to pick up the flux unfused after welding for reuse.

(3) During welding, the heat of the arc melts some of the flux along with the steel and the tip of the electrode. The tip of the electrode and the welding zone are always shielded by molten flux, surrounded by a layer of unfused flux. As the electrode progresses along the joint, the lighter molten flux rises above the molten metal in the form of a slag. The molten slag is a good conductor and provides an additional path for the current, thus generating additional heat. The weld metal, having a higher melting (freezing) point, solidifies while the slag above it is still molten. The slag then freezes over the newly solidified weld metal, continuing to protect the metal from contamination while it is very hot and reactive with atmospheric oxygen and nitrogen. Upon cooling and removal of any unmelted flux for reuse, the slag is removed from the weld.

(4) Several electrodes may be used in series or parallel, and multiple beads can be placed when using separate power supplies for each bead. Parallel electrode SAW uses two electrodes connected electrically in parallel to the same power supply. Both electrodes are fed by means of a single electrode feeder. For heat input calculation purposes, the total for the two electrodes is used. Multiple electrode SAW uses at least two separate power supplies and two separate wire drives to feed two electrodes independently. To minimize the potential interaction of magnetic fields between the two electrodes, typical SAW setups have the lead electrode operating on DC current while the trail electrode is operating AC.

(5) DC and AC welding machines of both conventional drooping voltage type or constant potential type can be used for SAW. With drooping voltage, a voltage sensitive relay adjusts the wire feed speed to maintain the desired arc voltage. With constant potential voltage, the arc length is self-adjusting, similar to the action in FCAW. Welding currents typically range from 500 to 1000 amperes.

(6) Flux must be stored so that it remains dry. Fluxes in open or damaged bags, or in flux hoppers, may become contaminated with moisture from the atmosphere, so exposure should be limited. The guidelines of the flux manufacturer, as well as AWS *D1.1* Section 5.3.3 regarding storage and usage of the flux must be followed. When not in use, flux hoppers should be covered or otherwise protected from the atmosphere.

(7) Because unmelted flux does not undergo chemical changes, it may be recovered for future use. Flux recovery systems range from vacuum recovery systems to sweeping with brooms and pans.

Flux contamination through contact with oil, moisture, dirt, scale of other contaminants may occur, therefore care is needed. Some loss of fine particulate matter may also occur with flux recovery, therefore blending reclaimed flux with new flux is required.

b. Filler Metal Designation, Specification and Certification. Submerged Arc Welding (SAW) filler materials, the electrodes and fluxes, are classified under AWS A5.17 for carbon steel electrodes and fluxes, and AWS A5.23 for low alloy steel electrodes and fluxes. Because SAW is dependent upon both components, flux and electrode, the classification system integrates both materials. After an electrode and flux combination is selected and a test plate welded, the flux-electrode classification may be established. Specimens are extracted from the weld deposit to obtain the mechanical properties of the flux-electrode combination, which must meet specific compositional and mechanical property requirements.

(1) The classification systems for SAW are summarized in Tables C-14 and C-15 for AWS A5.17 materials, and Table C-16 for AWS A5.23 materials. Low alloy steel SAW electrodes and fluxes classified under AWS A5.23 have a more complex classification system, because of the variety of alloys that may be involved, and because the composition of both the electrode and the resultant weld metal must be specified.

(2) Because the submerged arc welding process is frequently used for pressure vessel fabrication where assemblies are stress relieved, many submerged arc materials have been classified for the post weld heat treated, or stress relieved, condition. When this is done, a “P” is placed in the designation rather than an “A”. For structural work, which is seldom stress relieved, the “A” classification is commonly used. Flux-electrode combinations classified in the post weld stress relieved condition may not exhibit notch toughness when used in the as-welded condition, therefore investigation into weld metal properties is warranted whenever the weld will be used differently than the filler metal classification condition.

(3) Fluxes are manufactured using one of four basic processes, and are further classified as neutral, active or alloy fluxes, based upon their performance characteristics during welding.

(4) Fused fluxes are made by blending deoxidizing and alloying ingredients, as necessary, and then heating the mixture in a furnace until completely melted. A glass-like fused product is formed as the liquid is cooled to ambient temperature, and later ground to the sizes required for welding. Fused fluxes are nonhygroscopic, meaning they will not absorb water, but may be contaminated by moisture or other products that adhere to the outside of particles. Fused fluxes are not subject to chemical segregation during reuse because the complete composition is in each particle and cannot be separated. Fused fluxes may have less than desired amounts of deoxidizer and ferro-alloy ingredients because of losses that occur from the high temperatures during the manufacturing process. Fused flux performance can be impeded by loss of fines during recycling. Fused fluxes with the required chemical composition generally give the best low hydrogen welding performance.

(5) Bonded fluxes are made by combining all required chemical ingredients with a binder and baking the product at low temperature to form hard granules, then broken up and screened for size. Bonded fluxes contain chemically bonded moisture and can absorb moisture as well. Because the product is baked at low temperature, deoxidizer content or alloying elements that can be added as ferro-alloys or as elemental metals are not a problem as with fused fluxes. Bonded fluxes may segregate during use and reuse, and gases may be produced in the molten slag during welding. Bonded fluxes tend to break down during recycling and increase the percentage of fines.

(6) Agglomerated fluxes are similar to bonded fluxes in their method of manufacture, except that the binder is a ceramic material that requires baking at higher temperatures. This may limit deoxidizer or

ferro-alloy content due to high temperature losses. Agglomerated fluxes are generally considered

(7) Mechanically mixed fluxes can be a mixture of any flux type in any desired proportion, are subject to segregation, and will have the attributes of their components.

description and limitations of theses fluxes is provided in the Annexes to the AWS A5.17 and A5.23 filler metal specifications.

manganese and silicon content, is relatively unaffected by changes in welding procedure variables, primarily the voltage that determines arc length. For both active and alloy fluxes, the weld metal

(10) Active fluxes have small additions of manganese and silicon, or both, to help offset the effects of welding though mill scale and light coatings of rust. With active fluxes, a change in arc voltage will

are more resistant to porosity and cracking than welds made with neutral fluxes, active fluxes are often used in making single pass fillet welds. Active fluxes intended for single pass fillet welding should not be

combine with the same elements in the electrode to produce weld metal with unacceptable properties. The chemistry may build to unacceptable levels in larger multipass welds, therefore welding with active

with low levels of manganese and silicon. Where all mill scale and other contaminants are removed prior to welding, the surface contamination tolerance of active fluxes is not needed. Continued recycling of

(11) Alloy fluxes contain alloys intended to improve the strength or corrosion resistance of the weld metal, or both, and the composition of the weld metal is highly dependent upon the alloy content of the

mechanical properties of the weld. Alloy fluxes, properly used with carbon steel electrodes, provide a low-cost method of producing corrosion resistant weld metal for joining weathering steels. Unlike active

in the alloy content.

c. Advantages, Disadvantages and Limitations. Very high currents can be used in submerged arc

and deep penetration. The slag above the molten weld puddle acts as an insulating blanket, concentrating heat in the welding zone and preventing rapid escape of heat. Deep penetration allows the

High travel speeds reduce the total heat input into the joint, reducing distortion.

(1) SAW welds generally have good ductility and toughness, and a uniform bead appearance

reducing cleaning and surface preparation costs. The covered arc allows SAW to be operated without the need for extensive shielding to protect the operators from the high intensity arc created by the high

protection.

(2) The SAW process does not allow the operator to observe the molten weld puddle, forcing reliance on the appearance of the slag blanket to indicate the quality of the weld bead. When SAW is performed semi-automatically, the operator must acquire and practice a technique to produce good welds without reliance upon arc and weld bead appearance.

Table C-14. AWS A5.17 Classification System for Carbon Steel Electrodes and Fluxes for SAW
[US Customary Units]

FSXXX-ECXXX-HZ

	Flux (virgin flux if not followed by S)
S	
X	Minimum tensile strength in units of 10 ksi (70 MPa) 7 = 70 ksi (480 MPa)
X	A = tested as-welded P = tested after postweld heat treatment
	Temperature in F at or above the impact strength meets or exceeds 20 ft-lbf (27 J) Z = no impact strength test required 0 = tested at 0° C) 2 = tested at -20°F (-29° F (-40°C) 5 = tested at -50° C) 6 = tested at -60°F (-51° F (-62°C)
-	
	Electrode
C	specified in A5.17. ECG does not have a specified chemistry. Either type must be tested with a specific flux.
	Manganese (Mn) content, % weight L = low Mn (0.25 - 0.60) H = high Mn (varies by classification, 1.30 low to 2.20 high) G = chemistry not specified
	Number that makes up a part of the electrode classification system, indicating chemistry in A5.17, Table 1. Generally, indicates nominal carbon content in nominal carbon), 11,12, 13, 14, and 15.
X	
-	
HZ	H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H2 = maximum 2 mL / 100 g deposited weld metal

Table C-15. AWS A5.17 Classification System for Carbon Steel Electrodes and Fluxes for SAW
[SI (Metric) Units]

FSXXX-ECXXX-HZ

F	Flux (virgin flux if not followed by S)
S	If present, flux is from crushed slag or blend of crushed slag and virgin flux.
X	Minimum tensile strength in units of 10 MPa (1.45 ksi) 43 = 430 MPa (62 ksi) 48 = 480 MPa (70 ksi)
X	Test condition of plates A = tested as-welded P = tested after postweld heat treatment
X	Temperature in °C at or above the impact strength meets or exceeds 27 J (20 ft-lbf) Z = no impact requirements 0 = tested at 0°C (32°F) 2 = tested at -20°C (-4°F) 3 = tested at -30°C (-22°F) 4 = tested at -40°C (-40°F) 5 = tested at -50°C (-58°F) 6 = tested at -60°C (-76°F)
-	
E	Electrode
C	If present, electrode is Composite electrode. Electrode EC1 meets a chemistry specified in A5.17. ECG does not have a specified chemistry. Either type must be tested with a specific flux.
X	Manganese (Mn) content, % weight L = low Mn (0.25 - 0.60) M = medium Mn (varies by classification, 0.80 low to 1.50 high) H = high Mn (varies by classification, 1.30 low to 2.20 high) G = chemistry not specified
X	Number that makes up a part of the electrode classification system, indicating chemistry in A5.17, Table 1. Generally, indicates nominal carbon content in hundredths of a percent. Listed classification numbers: 8 (indicating 0.08% nominal carbon), 11,12, 13, 14, and 15.
X	K indicates that the electrode was made from silicon-killed steel.
-	

HZ	**Optional supplemental diffusible hydrogen designator** **H16 = maximum 16 mL / 100 g deposited weld metal** **H8 = maximum 8 mL / 100 g deposited weld metal** **H4 = maximum 4 mL / 100 g deposited weld metal** **H2 = maximum 2 mL / 100 g deposited weld metal**

Table C-16. AWS A5.23 Classification System for Low Alloy Steel Electrodes and Fluxes for SAW
[US Customary Units]

F	Flux
	Minimum tensile strength in units of 10 ksi (70 MPa) 7 = 70 ksi (480 MPa) 9 = 90 ksi (620 MPa) 10 = 100 ksi (690 MPa)
	Test condition of plates A = tested as-welded
X	Temperature in ° Z = no impact strength test required F (-18°C) 2 = tested at -20° C) 4 = tested at -40°F (-40° F (-46°C) 6 = tested at -60° C) 8 = tested at -80°F (-62° F (-73°C) 15 = tested at -150° C)
-	
E	
C	If present, electrode is Composite electrode with composition per AWS A5.23
X	Chemical composition of electrode (Table 1) or weld metal (Table 2) M = carbon steel, medium Mn solid electrode (EM12K) A = carbon-molybdenum weld metal[1] Ni = nickel M = military W = weathering
XX	Number (and letter, if needed) that makes up a part of the electrode classification
N	Indicates that the electrode is intended for the core belt region of nuclear reactor
-	
X	above

N	**Indicates that the weld metal is intended for the core belt region of nuclear reactor vessels, with limited chemistry for phosphorous, vanadium, and copper.**
HZ	**Optional supplemental diffusible hydrogen designator** **H16 = maximum 16 mL / 100 g deposited weld metal** **H8 = maximum 8 mL / 100 g deposited weld metal** **H4 = maximum 4 mL / 100 g deposited weld metal**

[1] **- B3, B4, B5, B6, B6H, B8 are not prequalified in AWS** *D1.1*

5.

a. Process Principles. Gas Tungsten Arc Welding (GTAW), also frequently called TIG (Tungsten Inert Gas) welding, is done using the heat of an arc between a non-consumable tungsten electrode and

external shielding gas or gas mixture. Direct current electrode negative (DCEN) (straight) polarity is used to produce a deep, narrow penetration when welding thicker materials. Direct current electrode positive

metals. Alternating current (AC) is generally used for welding aluminum and magnesium alloys. A high frequency oscillator is usually incorporated into GTAW power supplies to initiate the arc. This reduces

tungsten to the base metal. The process may be performed manually, but may also be used as automatic. The tungsten electrode in the welding “torch” gets very hot under high duty cycles, therefore

deposition rate through the use a continuous filler metal, supplied with current from a separate power source, to preheat the wire using resistance heating.

welding torch are classified in AWS A5.12, *Specification for Tungsten and Tungsten Alloy Electrodes for*
. The filler metal used, if any, is rod classified for GMAW in AWS A5.18 or A5.28, with a designation ER at the beginning. Tungsten electrodes are summarized in Table C-17.

spatter, with excellent arc control that is very beneficial for root passes. It can be used on material thicknesses that range from thin sheet metals up to maximum of about 10 mm (3/8 in.). However,

welding processes. Gas shielding is also critical, and wind speeds over 8 km per hour (5 mph) cause quality and mechanical property degradation. GTAW, as an unfluxed welding process, also requires very

Table C-17. AWS A5.12 Classification System for Tungsten Electrodes for GTAW

EWX-X

E	Electrode
W	Tungsten
X-X	Letter (and optionally -number) describing type of tungsten electrode P = pure tungsten Ce = tungsten-cesium alloy La = tungsten-lanthanum alloy Th = tungsten-thorium alloy Zr = tungsten-zirconium alloy G = general, not specified

a. Process Principles. Electroslag Welding (ESW) is used for welding thick sections, typically 50 mm to 500 mm (2 to 20 in.) in thickness, for short to moderate lengths. The plates to be joined are positioned

40 mm (3/4 to 1-1/2 in.), depending on welding equipment and material thickness, with no edge preparation generally required. Water-cooled copper shoes are placed on each side of the joint, forming

used. Shielding of the arc and weld pool is provided by the addition of flux into the joint as welding progresses. To start the weld, an arc is struck in a sump at the bottom of the joint, underneath a deposit

The arc is extinguished by the slag, but the fed electrode wire and adjacent base metal melts from the heat generated by the high electrical resistance of the slag. The weld proceeds as more electrode is fed

weld termination. Both the starting sump and finishing run-off tab are removed after completion of welding.

specified in AWS A5.25, *Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for*
. Electrode wires may be either solid or composite. The classification system is summarized in Table C-18.

deposition rates, in the range of 20 kg (40 lb.) per hour, offering considerable cost and time savings for vertical welding of thick steels. Time and expense is also saved in the avoidance of joint preparation,

distortion upon completion.

(1) ESW, if interrupted during welding, can leave major discontinuities in the joint that are difficult

may cause low toughness properties, as well as make ultrasonic testing more difficult.

(2) ESW can be used for joints over 12 mm (1/2 in.) thick, but generally does not become the most

including the number of joints to be welded. ESW is not prequalified under AWS *D1.1*
qualification testing following AWS *D1.1*
vertical require special setups and procedures, although ESW has been performed at angles to 45 degrees.

Table C-18. AWS A5.25 Classification System for Electrodes and Fluxes for ESW

FESXX-XXX

FES	Flux for Electroslag Welding
X	Minimum tensile strength in units of 10 ksi (70 MPa) 6 = 60 ksi (420 MPa) 7 = 70 ksi (480 MPa)
X	Temperature in °F at or above the impact strength meets or exceeds 15 ft-lbf (20 J) Z = no impact strength test required 0 = tested at 0°F (-18°C) 2 = tested at -20°F (-29°C)
-	
XXX	Electrode classification used (EM5K-EW, for example), see AWS A5.25

7.

a. Process Principles. Electrogas Welding (EGW) is very similar to Electroslag Welding (ESW), and is used for welding thick sections, typically 50 mm to 500 mm (2 to 20 in.) in thickness, for short to

opening gap at the joint is generally set to approximately 22 mm (7/8 in.), depending on welding equipment and material thickness, with no edge preparation generally required. Water-cooled copper

current electrode negative (DCEN) currents of 500 to 700 amperes are commonly used. The electrode is either a solid wire, composite (cored) wire, or a flux cored wire designed for EGW. For solid wires,
or an argon-CO_2 mix.
When flux cored wires are used, the shielding gas may or may not be necessary, depending upon the

weld pool and allows the welding arc to stabilize before reaching the actual joint. The arc is maintained, and the fed electrode wire and adjacent base metal melts from the heat generated by the arc. The weld

Both the starting sump and finishing run-off tab are removed after completion of welding.

b. Filler Metal Designation, Specification and Certification. Filler materials, electrodes and fluxes
Specification for Carbon and Low-Alloy Steel Electrodes and Electrogas Welding
classification system is summarized in Table C-19.

c. Advantages, Disadvantages and Limitations. Electrogas Welding (EGW) provides very high

vertical welding of thick steels. Time and expense is also saved in the avoidance of joint preparation, preheating and interpass temperature control, and interpass cleaning. The joint is also free from angular

(1) EGW, if interrupted during welding, can leave major discontinuities in the joint that are difficult to access and repair. The large grain size from the substantial heat input, and subsequent slow cooling,

disadvantage, compared to ESW, of requiring protection of the joint from wind over 8 km per hour (5 mph).

economical choice until a thickness of around 50 mm (2 in.) is welded, depending upon several factors including the number of joints to be welded. EGW is not prequalified under AWS , therefore qualification testing following AWS Section 4 is required. Angles beyond 10 to 15 degrees from vertical may require special setups and procedures.

Table C-19. AWS A5.26 Classification System for Electrodes for EGW

EGXXX-XXX

EG	Electrogas Welding
X	Minimum tensile strength in units of 10 ksi (70 MPa) 6 = 60 ksi (420 MPa) 7 = 70 ksi (480 MPa) 8 = 80 ksi (550 MPa)
X	Temperature in ^{o}F at or above the impact strength meets or exceeds 20 ft-lbf (27 J) Z = no impact strength test required 0 = tested at 0^{o}F (-18^{o}C) 2 = tested at -20^{o}F (-29^{o}C)
X	S = solid wire T = tubular wire
-	
XXX	Electrode classification used, see AWS A5.26

APPENDIX D

1. VISUAL TESTING (VT).

a. Method Description. Visual inspection, as a form of nondestructive testing, is the visual observation

the first nondestructive testing method applied, and if the inspected item fails to meet visual criteria, more extensive nondestructive testing should not be conducted until the visual criteria is satisfied.

and other enhancements. Such instruments tend to distort the perception of the inspector. When surface discontinuities such as cracks are suspected, the use of magnifying devices to further investigate the

(2) Visual inspection includes the measurement of the work, which may include the smoothness of thermally cut edges, and the measurement of root openings, groove angles, weld size, convexity and

such as weld gauges are required.

b. Advantages and Disadvantages.

arc strikes, excessive convexity, overlap, toe cracks, undersized welds, undercut, seams and laminations at exposed edges. Not all listed discontinuities are structurally significant, but they may provide indication

(2) Visual inspection cannot reveal subsurface discontinuities such as cracks, incomplete fusion, slag inclusions, incomplete penetration, buried laminations or lamellar tearing. See Table D-1.

surrounding heat-affected zone (HAZ).

(4) The cost of visual inspection is usually less, per unit length of weld, that the other methods of

rather than simple verification measurements and recording of unsatisfactory workmanship.

Table D-1. Visual Inspection

	Most Applicable	Applicable	Least Applicable
Discontinuity	Microcracks Shrinkage Cavity Undercut Excessive Reinforcement Excessive Convexity Excessive Penetration Misalignment Burn-Through Underfilled Groove Irregular Bead Root Concavity Poor Restart Miscellaneous Surface Discontinuities (Spatter, etc.)	Crater Cracks Group Discontinuous Cracks Branching Cracks Surface Pore Crater Pipe Incomplete Penetration Overlap	Longitudinal Cracks Transverse Cracks Radiating Cracks Uniform Porosity Linear Porosity Elongated Cavity “Worm Hole” Incomplete Fusion (Sidewall or Interpass) Incomplete Fusion (Root)
Joint Geometry	Lap, < 6 mm (< 0.2 in.)	Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

2. PENETRANT TESTING (PT).

a. Method Description. Penetrant testing, also called dye penetrant or liquid penetrant testing, is the use of a liquid penetrating dye to detect discontinuities at the surface of a weld or base metal. The penetrant is applied to the surface, allowed to remain on the surface for a specified dwell time to penetrate cracks, pores, or other surface-breaking discontinuities, and then is carefully removed. A developer is then applied to the surface, which draws the penetrant out of the discontinuities. This leaves a visible contrasting indication in the developer, which is then removed for closer visual examination of the area providing indications. One method of penetrant testing uses a visible dye, usually red, which contrasts with the developer, usually white. The second method uses a flourescent dye, visible under ultraviolet light. Flourescent methods are usually more sensitive, but require a darkened area for testing.

b. Advantages and Disadvantages.

(1) Penetrant testing is relatively economical compared to ultrasonic testing, and especially economical when compared to radiographic testing.

(2) Testing materials are small, portable, and inexpensive, with no specialized equipment required unless an ultraviolet light is used.

(3) A relatively short period of training is necessary for technicians who will be performing PT.

(4) PT can be performed relatively quickly, depending upon the penetrant used and the required dwell time.

(4) A disadvantage with some penetrants and developers is the safe handling and disposal of used liquids and cleaning rags.

(5) Cleaning after inspection to remove residual penetrant and developer prior to weld repairs or the application of coating systems can sometime be difficult and time-consuming.

(6) Rough surface conditions, and irregular profile conditions such as undercut and overlap, can sometimes provide false indications of weld toe cracks when cleaning is not thoroughly performed. Weld spatter can also make surface removal of the penetrant more difficult.

(7) PT cannot be performed when the surface remains hot, unless special high-temperature PT materials are used, so waiting time is sometimes necessary with PT that would not be required with magnetic particle testing.

(8) Existing coatings should be removed prior to PT because the coating may bridge narrow cracks, preventing the entry of the penetrant.

(9) PT is especially effective with small surface-breaking cracks, such as toe cracks, and also surface-breaking piping porosity, crater cracks, laminations along exposed edges and joint preparations, and other surface discontinuities.

(10 PT is ineffective for any discontinuity below the surface, such as buried cracks, slag inclusions, lack of fusion, or incomplete penetration. See Table D-2.

Table D-2. Penetrant Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity	Radiating Cracks Surface Pore\ Crater Pipe Overlap Miscellaneous Surface Discontinuities (Spatter, etc.)	Longitudinal Cracks Transverse Cracks Crater Cracks Group Discontinuous Cracks Branching Cracks Uniform Porosity Linear Porosity Shinkage Cavity Incomplete Fusion (Sidewall or Interpass) Incomplete Fusion (Root) Incomplete Penetration Undercut Burn-Through	Microcracks Elongated Cavity “Worm Hole”
Joint Geometry		Lap, < 6 mm (< 0.2 in.) Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

3. MAGNETIC PARTICLE TESTING (MT).

a. Method Description. Magnetic particle testing uses the relationship between electricity and magnetism to induce magnetic fields in the steel. Magnetic particles, commonly in the form of iron powder colored for better visibility, are dusted onto the magnetized surface. Cracks and other discontinuities on or near the surface disturb the lines of magnetic force, essentially acting as poles of a magnet, attracting the magnetic particles. After the area has been magnetized, the particles are applied, then removed with gentle dusting or application of air. Particles attracted to discontinuities remain on the surface at the discontinuity, attracted to the magnetic poles. The MT technician then evaluates the location and nature of the indicating particles. Tight lines are indicative of surface cracks or other discontinuities. Subsurface cracks and slag inclusions would show a broader indication. A permanent record of detected discontinuities can be made with the use of transparent adhesive tape or photography.

(1) The magnetic fields can be induced using either prods, which directly magnetize the steel through direct contact with the steel and the induction of current flow in the steel, or with a yoke, which does not transfer electrical current but provides magnetic flux between the two elements of the yoke.

(2) MT equipment may be operated either DC (rectified AC) or AC. DC provides higher magnetization levels which allows for inspection for discontinuities somewhat below the surface. Inspection with AC is generally limited to surface-breaking and very near-surface discontinuities, and is considered more effective for surface discontinuities because the particles are more mobile.

b. Advantages and Disadvantages.

(1) MT is relatively fast and economical.

(2) The equipment is relatively inexpensive, compared with ultrasonic or radiographic equipment.

(3) A source of electric power is necessary.

(4) Inspection costs are generally equal to or slightly more than PT, but considerably less than UT or RT.

(5) More training is necessary for MT, compared to PT, but substantially less than that required for UT or RT.

(6) MT can be performed effectively while the joint is still warm from welding or postheating.

(7) After inspection, removal of magnetic particles is quick and thorough, not delaying repairs or affecting coating application.

(8) Existing coatings may reduce the effectiveness of MT.

(9)The depth of inspectability depends upon the equipment, selection of current, and the type of particles used. Although opinions vary as to the maximum depth that can be effectively inspected using MT, 8 mm (5/16 in.) is generally considered the deepest discontinuity that can be detected under good conditions.

(10) MT is effective for detecting surface-breaking discontinuities such as cracks and laminations. It is also effective for cracks, laminations, incomplete fusion, slag inclusions, and incomplete penetration

if slightly below the surface. Rounded discontinuities such as porosity do not disturb the magnetic flux lines sufficiently to be effectively detected. See Table D-3.

Table D-3. Magnetic Particle Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity		Longitudinal Cracks Transverse Cracks Radiating Cracks Crater Cracks Group Discontinuous Cracks Branching Cracks Surface Pore Shrinkage Cavity Crater Pipe Incomplete Fusion (Sidewall or Interpass) Incomplete Fusion (Root) Incomplete Penetration Undercut Overlap	Microcracks Uniform Porosity Linear Porosity Elongated Cavity “Worm Hole” Burn-Through Miscellaneous Surface Discontinuities (Spatter, etc.)
Joint Geometry	Lap, < 6 mm (< 0.2 in.)	Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

4. ULTRASONIC TESTING (UT).

a. Method Description. Ultrasonic testing requires specialized equipment to produce and receive precise ultrasonic waves induced into the steel using piezoelectric materials. The unit sends electric pulses into the piezoelectric crystal, which converts electrical energy into vibration energy. The vibration is transmitted into the steel from the transducer using a liquid couplant. The vibration is introduced into the steel at a known angle, depending upon the design of the transducer, with a known frequency and waveform. The speed of travel of the vibration in steel is also known. The vibration pulse travels through the steel until it strikes a discontinuity, or the opposite face of the steel, either of which reflects energy back to the transducer unit or another receiving transducer. Using a system of calibration and measurements, the location, relative size and nature of the discontinuity, if any, can be determined by close evaluation of the reflected signals. Small reflections are generally ignored, unless located in specific regions such as along edges. Locations of discontinuities can be determined using the display screen scale and simple geometry.

(1) AWS *D1.1* Section 6, Part F provides the UT inspection procedures, including calibration, scanning methods, scanning faces, and transducer angles, and weld acceptance criteria, including reflected signal strength, discontinuity lengths and locations for weld discontinuities. Report forms, generally hand written, are prepared by the UT technician, recording weld discontinuities and other material discontinuities that exceed the acceptance criteria specified.

(2) More expensive and sophisticated UT equipment can be operated in digital mode, recording and printing display screen images with input data. Very sophisticated automated UT equipment can record the transducer location and the corresponding reflections, then use computer software systems to produce representative two-dimensional images, from various directions, of the inspected area and discontinuities. Such equipment is rarely used in normal construction inspection applications, but is available and sometimes used for very complex and critical inspections.

(3) Even with conventional equipment, more complex inspection methods can be used to locate, evaluate and size weld discontinuities. These techniques include tip diffraction and time-of-flight techniques, and can be incorporated into project inspection through the use of AWS *D1.1* Annex K provisions. Annex K requires the use of written UT procedures specific to the application, with experienced and qualified UT technicians tested in the use of the procedures, and also provides for alternate acceptance criteria in lieu of the tables found in Section 6, Part F of AWS *D1.1*. Such provisions are necessary when using miniature transducers, alternate frequencies, or scanning angles other than those prescribed.

b. Advantages and Disadvantages.

(1) Ultrasonic testing is a highly sensitive method of NDT, and is capable of detecting discontinuity in welds and base metal in a wide variety of joint applications and thicknesses.

(2) AWS *D1.1* provisions are applicable for thickness ranges from 8 mm (5/16 in.) to 200 mm (8 in.) Both thinner and thicker materials may be examined and evaluated using UT, but Annex K must be used for technique and acceptance.

(3) Although capable of locating discontinuities and measuring discontinuity length, it is less capable of directly sizing discontinuities or determining discontinuity height without the use of advanced techniques.

(4) A primary disadvantage of ultrasonic testing is that it is highly dependent upon the skill of the UT technician.

(6) The cost of the equipment is considerably more that MT, but also much less than RT. The cost of more sophisticated UT units capable of computer-generated imaging approaches, and sometimes exceeds, the cost of RT equipment.

(7) UT indications are difficult to interpret in certain geometric applications. It is ineffective for fillet welds unless very large, and then only for the root area for fillet welds above approximately 18 mm (3/4 in.). When backing bars remain in place, it is difficult to distinguish between the backing bar interface and cracks, slag lines, or lack of penetration or fusion at the root. With partial joint penetration groove welds, it is difficult to distinguish between the unfused root face and discontinuities near the root. In welded beam-to-column moment connections, the interference of the web with inspection of the bottom flange makes direct evaluation of the area beneath the weld access hole difficult. Second-leg inspections, not as accurate or as reliable as first-leg inspections, are necessary to evaluate the entire depth of many welds unless the weld face is ground flush. Discontinuities located just below the weld or material surface are also difficult to detect.

(8) UT is best suited for planar discontinuities such as cracks and lack of fusion, discontinuities which are generally most detrimental to joint performance when oriented transverse to the direction of loading. These discontinuities tend to be irregular with rough surfaces, and therefore reflect signals even when not exactly perpendicular to the direction of the pulse. Laminations and lamellar tears are also easily detected. Smooth surfaces, such as unfused root faces, would redirect a signal and provide a weak response unless oriented perpendicular to the pulse. Rounded and cylindrical discontinuities such as porosity disperse the signal, also providing a weak response, but such rounded discontinuities are rarely detrimental to joint performance. Slag inclusions are irregular and provide easily identifiable responses. See Table D-4.

(9) The cost of ultrasonic testing is considerably more than PT or MT, and considerably less than RT. However, UT is the best method for detection of the most serious weld discontinuties in a wide variety of thicknesses and joints. The time, and therefore cost, of UT inspection can vary greatly, depending upon the quality of the weld to be inspected. A good quality weld will provide few responses, requiring little evaluation time. A difficult configuration, or a poor quality weld, will require numerous time-consuming evaluations and recording of test data.

Table D-4. Ultrasonic Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity	Longitudinal Cracks Incomplete Fusion (Sidewall or Interpass)	Transverse Cracks Radiating Cracks Elongated Cavity Solid Inclusion Slag or Flux Inclusion Oxide Inclusion Metallic Inclusion Incomplete Fusion (Root) Incomplete Penetration Burn-Through Irregular Bead Poor Restart	Microcracks Crater Cracks Group Discontinuous Cracks Branching Cracks Uniform Porosity Linear Porosity “Worm Hole” Surface Pore Shrinkage Cavity Crater Pipe Undercut Excessive Reinforcement Excessive Convexity Excessive Penetration Overlap Misalignment Underfilled Groove Root Concavity
Joint Geometry		Lap, < 6 mm (< 0.2 in.) Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

5. RADIOGRAPHIC TESTING (RT).

a. Method Description. Radiographic Testing (RT) uses a radioactive source and, typically, a film imaging process similar to X-ray film. The film provides a permanent record of the inspection. When a weld is exposed to penetrating radiation, some radiation is absorbed, some scattered, and some transmitted through the weld onto the film. Image Quality Indicators (IQIs) are used to verify the quality and sensitivity of the image. Most conventional RT techniques involve exposures that record a permanent image on film, although other image recording methods are also used. Real-time radiography uses a fluoroscope to receive radiation, then presents an on-screen image for evaluation. The two types of radiation sources commonly used in weld inspection are x-ray machines and radioactive isotopes.

(1) X-rays are produced by portable units capable of radiographing relatively thin objects. A large 2000 kV X-ray unit is capable of penetrating approximately 200 mm (8 in.) of steel, a 400 kV unit to 75 mm (3 in.), and a 200 kV unit to 25 mm (1 in.) of steel.

(2) Radioisotopes are used to emit gamma radiation. The three most common RT isotopes are cobalt 60, cesium 137, and iridium 192. Cobalt 60 can effectively penetrate up to approximately 230 mm (9 in.) of steel, cesium 137 to 100 mm (4 in.), and iridium 192 to 75 mm (3 in.) of steel.

b. Advantages and Disadvantages.

(1) RT can detect subsurface porosity, slag, voids, cracks, irregularities, and lack of fusion. See Table D-5.

(2) Accessibility to both sides of the weld is required.

(3) RT is limited to butt joint applications by AWS *D1.1*. Because of the constantly changing thickness for the exposure, RT is not effective when testing fillet welds or groove welds in tee or corner joints.

(4) To be detected, an imperfection must be oriented roughly parallel to the radiation beam. As a consequence, RT may miss laminations and cracks parallel to the film surface. Because they are usually volumetric in cross-section, discontinuities such as porosity or slag are readily detected.

(5) The limitations on RT sensitivity are such that discontinuities smaller than about 1½ percent of the metal thickness may not be detected.

(6) The radiographic images provide a permanent record for future review, and aid in characterizing and locating discontinuities for repair.

(7) RT is generally unaffected by grain structure, particularly helpful with ESW and EGW welds.

(8) RT is a potential radiation hazard to personnel, and strict safety regulations must be monitored and enforced.

(9) The cost of radiographic equipment, facilities, safety programs, and related licensing is higher than any other NDT process.

(10) There is usually a significant waiting time between the testing process and the availability of results.

Table D-5. Radiographic Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity	Longitudinal Cracks Transverse Cracks Radiating Cracks Crater Cracks Group Discontinuous Cracks Branching Cracks Uniform Porosity Linear Porosity Elongated Cavity “Worm Hole” Solid Inclusion Slag or Flux Inclusion Oxide Inclusion Metallic Inclusion Incomplete Fusion (Root) Incomplete Penetration	Surface Pore Shrinkage Cavity Crater Pipe Incomplete Fusion (Sidewall or Interpass) Undercut Excessive Reinforcement Excessive Convexity Excessive Penetration Burn-Through Underfilled Groove Root Concavity Miscellaneous Surface Discontinuities (Spatter, etc.)	Microcracks Overlap
Joint Geometry	Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, < 6 mm (< 0.2 in.) Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) Single-V Groove	

6. OTHER METHODS.

Because of severe limitations in applicability, the use of eddy current, acoustic emission, or other methods not mentioned above is discouraged.

TI 809-26
1 March 2000

US Army Corps
of Engineers®

Technical Instructions

Welding - Design Procedures And Inspections

Headquarters
US Army Corps of Engineers
Engineering and Construction Division
Directorate of Military Programs
Washington, DC 20314-1000

CEMP-E **TI 809-26**
1 March 2000

TECHNICAL INSTRUCTIONS

WELDING - DESIGN PROCEDURES AND INSPECTIONS

Record of Changes (changes indicated \1\.../1/)
No. Date Location

This Technical Instruction supersedes TM 5-805-7, Welding Design, Procedures and Inspection dated 20 May 1985

CEMP-E **TI 809-26**
1 March 2000

FOREWORD

These technical instructions (TI) provide design and construction criteria and apply to all U.S. Army Corps of Engineers (USACE) commands having military construction responsibilities. TI will be used for all Army projects and for projects executed for other military services or work for other customers where appropriate.

TI are living documents and will be periodically reviewed, updated, and made available to users as part of the HQUSACE responsibility for technical criteria and policy for new military construction. CEMP-ET is responsible for administration of the TI system; technical content of TI is the responsibility of the HQUSACE element of the discipline involved. Recommended changes to TI, with rationale for the changes, should be sent to HQUSACE, ATTN: CEMP-ET, 20 Massachusetts Ave., NW, Washington, DC 20314-1000.

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FOR THE COMMANDER:

DWIGHT A. BERANEK, P.E.
Chief, Engineering and Construction Division

Directorate of Military Programs

WELDING - DESIGN PROCEDURES AND INSPECTIONS

Table of Contents

Page

CHAPTER 1. GENERAL

CHAPTER 2. APPLICABLE DESIGN SPECIFICATIONS

CHAPTER 3. WELDING PROCESSES AND MATERIALS

CHAPTER 4. STRUCTURAL STEELS

CHAPTER 5. DESIGN FOR WELDING

CHAPTER 6. STUD WELDING

CHAPTER 7. WELDING TO EXISTING STRUCTURES

CHAPTER 8. QUALITY ASSURANCE AND INSPECTION

CHAPTER 9. OTHER WELDING SPECIFICATIONS AND STANDARDS

CHAPTER 10. SAFETY & ENVIRONMENTAL CONSIDERATIONS

APPENDIX C. WELDING PROCESSES

APPENDIX D. NONDESTRUCTIVE TESTING METHODS

CHAPTER 1

GENERAL

1. PURPOSE AND SCOPE. This document provides criteria and guidance for the design and specification of welded structural components and systems in accordance with current technology, standards and materials. This includes information on design approaches, use of technical manuals, guidance on the application of codes and industry standards, and the design and specification of welded details, inspection and quality. The scope of this document is welding for general building construction for military applications, and does not include underwater, piping, or cryogenic applications, bridges, sheet steels, or the welding of materials other than structural steel. A building is defined as any structure, fully or partially enclosed, used or intended for sheltering persons or property.

2. APPLICABILITY. These instructions are applicable to all USACE elements having military construction responsibilities.

3. REFERENCES. Appendix A contains a list of references pertaining to this document.

4. BIBLIOGRAPHY. A bibliography of publications that provides additional information and background data is in Appendix B.

CHAPTER 2

APPLICABLE DESIGN SPECIFICATIONS

1. GENERAL.

a. Specification Cycles. Building design and welding design are governed by a variety of specifications and standards, as listed. Because of the varying focus of each standard or specification, and the varying dates of adoption and publication, the standards and specifications are in a constant cycle of revision.

b. Specification Conflicts. Conflicts may arise between codes as new research and methods are adopted in one code before another. There are also specific exceptions one code may take with another, as the AISC *Specification* does with AWS *D1.1*, listing those exceptions in AISC *Specification* section J1.2.

c. New Materials. New steels and welding materials, adopted by the industry, may not be listed in the codes for periods of several years because of the adoption and printing cycles. Within AWS standards, the filler metal specifications are being revised for metrication. The AWS *D1.1* code is also being fully metricated for the year 2000, with independent dimensional units and values. Those values established as of the date of this document have been adopted. Others may change with the publication of the *D1.1*-2000 *Structural Welding Code - Steel*.

d. Preferred Design Methodology. The American Institute of Steel Construction provides two methodologies for the design of steel-framed buildings. The first method is Allowable Stress Design (ASD), which provides adequate strength based upon service load conditions. All loads are assumed to have the same variability. The second method, Load and Resistance Factor Design (LRFD), is a more modern probabilistic approach also known as limit states design. LRFD uses load factors and load combinations applied to service loads, and resistance (strength reduction) factors applied to the nominal resistance of the component to achieve a design strength. Both methods are in current practice. The use of the LRFD method is preferred over the use of the ASD method, but is not required.

e. Standards Evaluation. Users of this document should evaluate the various standards listed, and new standards that may be published, for suitable application. It may be necessary to take exceptions to various code provisions, or to expand the code provisions through the use of the project specifications, to resolve conflicting issues and to permit new materials.

2. USACE AND OTHER MILITARY DOCUMENTS.

a. TI 809-01 Load Assumptions for Buildings. This document provides minimum snow and wind loads plus frost penetration data to be used in the design and construction of buildings and other structures. Except as designated within the document, all loadings are based upon ASCE 7-95, *Minimum Design Loads for Buildings and Other Structures*. Buildings are categorized according to occupancy.

b. TI 809-02 Structural Design Criteria for Buildings. General structural design guidance for buildings, and for building systems constructed of concrete, masonry, steel and wood is presented in this TI document. The design requirements provided herein, or cited by reference, are based on national building codes, industry standards, and technical manuals developed by the Army, Navy, and Air Force.

Instructions necessary to provide serviceable buildings and to assure load path integrity and continuity is included. Requirements unique to Army, Navy, and Air Force facilities are indicated. Supplemental information to help engineers interpret and apply code provisions, and meet serviceability and strength performance objectives is also included in the TI.

c. TI 809-04 Seismic Design for Buildings. This document provides qualified designers with the criteria and guidance for the performance-based seismic analysis and design of new military buildings, and the non-structural systems and components in those buildings. Chapter 7 includes discussion of structural steel framing systems, but does not provide specific details for welded connections in those systems.

d. TI 809-05 Seismic Evaluation and Rehabilitation for Buildings. This document is intended to provide qualified designers with the necessary criteria and guidance for the performance-based seismic analysis and design of new military buildings, and the nonstructural systems and components in the buildings. The primary basis for this document is the 1997 edition of the NEHRP Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 302). This document provides guidance in the interpretation and implementation of the FEMA 302 provisions for the Life Safety performance objective for all buildings, and it provides criteria for the design and analysis of buildings with enhanced performance objectives.

e. TI 809-07 Design of Cold-Formed Load Bearing Steel Systems and Masonry Veneer / Steel Stud Walls. This document provides design guidance on the use of cold-formed steel systems for both load-bearing and nonload-bearing applications. Cold-formed steel members are generally of a thickness that welding is governed by AWS *D1.3 Structural Welding Code - Sheet Steel*, rather than AWS *D1.1 Structural Welding Code - Steel*, and therefore are not covered by TI 809-26.

f. TI 809-30 Metal Building Systems. This document provides guidance on the use of Metal Building Systems, defined as a complete integrated set of mutually dependent components and assemblies that form a building, including primary and secondary framing, covering and accessories. These types of structures were previously referred to as pre-engineered buildings. Paragraph 5.i addresses welding for manufacturers not AISC certified in Category MB.

g. TM 5-809-6 Structural Design Criteria for Structures Other Than Buildings. This document will become TI 809-03. Revise as needed.

3. AISC SPECIFICATIONS AND STANDARDS.

a. Metric Load and Resistance Design Specification for Structural Steel Buildings. The Metric LRFD *Specification* contains provisions regarding welding design and application. Section J contains design provisions, and Section M contains limited supplemental information regarding quality and inspection. The Metric LRFD *Specification*, published in 1994, is based upon AWS *D1.1*-92, and takes exception to certain provisions of that edition. This metric specification is a dimensional conversion of the December 1, 1993 customary units edition. The principles and concepts of these two specifications (metric and customary) are identical, only the units differ. It is anticipated that a new LRFD *Specification*, containing both SI and US Customary Units within one document, will be published by AISC in early 2000.

b. Load and Resistance Factor Design Specification for Structural Steel Buildings. The LRFD *Specification* contains provisions regarding welding design and application. Section J contains design provisions, and Section M contains limited supplemental information regarding quality and inspection.

The LRFD *Specification*, published in 1993, is based upon AWS *D1.1*-92, and takes exception to certain provisions of that edition. It is anticipated that a new LRFD *Specification*, containing both SI and US Customary Units within one document, will be published by AISC in early 2000.

c. Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design. The ASD *Specification* contains provisions regarding welding design and application. Section J contains design provisions, and Section M contains limited supplemental information regarding quality and inspection. The ASD *Specification*, published in 1989, is based upon the use of AWS *D1.1*-88, and takes exception to certain provisions of AWS *D1.1*. Publication of an updated or new ASD *Specification* is not being planned by AISC.

d. Seismic Provisions for Structural Steel Buildings. This AISC document addresses the design and construction of structural steel and composite steel / reinforced concrete building systems in seismic regions. It is applicable for use in either LRFD or ASD. The provisions are for the members and connections that comprise the Seismic Force Resisting System (SFRS) in buildings that are classified as Seismic Design Category D or higher in FEMA 302, NEHRP *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. These structures include all buildings with an S_{DS} >= 0.50g (S_{D1} >= 0.20g), and Seismic Use Group III when S_{DS} >= 0.33g (S_{D1} >= 0.133g). See TI 809-04, Chapter 4. The *Seismic Provisions* document cites AWS *D1.1*-96 as the reference welding standard. Part I, Section 7.3 is applicable to welded joints, containing provisions regarding Welding Procedure Specification approvals, filler metal toughness requirements, and special concerns for discontinuities in SFRS members.

e. Code of Standard Practice. The AISC *Code of Standard Practice* defines practices adopted as commonly accepted standards of the structural steel fabricating industry. In the absence of other contract documents, the trade practices of the document govern the fabrication and erection of structural steel. Within the document, Materials are discussed in Section 5, Fabrication in Section 6, Erection in Section 7, and Quality Control in Section 8.

f. Manual of Steel Construction, LRFD, Metric Conversion. The AISC *Manual of Steel Construction* contains informational tables and design aids, as well as the AISC Specifications themselves. The *Manual* contains welding design aids in Volume II - Connections. Chapter 8 includes prequalified joint details, AWS welding symbols, tables for eccentrically loaded fillet welds, design examples, and general information regarding welding. Design examples are contained within Chapter 9 for Simple Shear and PR Moment Connections, Chapter 10 for Fully Restrained (FR) Moment Connections, and Chapter 11 for Connections for Tension and Compression. One is cautioned that the welded prequalified joint tables are based upon AWS *D1.1*-92, and have been substantially revised in subsequent editions of AWS *D1.1*.

g. Manual of Steel Construction, LRFD. The AISC *Manual of Steel Construction* contains informational tables and design aids, as well as the AISC Specifications themselves. When using LRFD, the *Manual of Steel Construction, 2nd Edition*, is applicable, and is in two volumes. The *Manual* contains welding design aids in Volume II - Connections. Chapter 8 includes prequalified joint details, AWS welding symbols, tables for eccentrically loaded fillet welds, design examples, and general information regarding welding. Design examples are contained within Chapter 9 for Simple Shear and PR Moment Connections, Chapter 10 for Fully Restrained (FR) Moment Connections, and Chapter 11 for Connections for Tension and Compression. One is cautioned that the welded prequalified joint tables are based upon AWS *D1.1*-92, and have been substantially revised in subsequent editions of AWS *D1.1*.

h. Manual of Steel Construction, ASD. The AISC *Manual of Steel Construction* contains informational tables and design aids, as well as the AISC Specifications themselves. The 9th Edition of the *Manual* contains welding design aids in Part 4 - Connections, including prequalified joint details, AWS welding symbols, tables for eccentrically loaded fillet welds, and design examples. One is cautioned that the welded prequalified joint tables are based upon AWS *D1.1*-88, and have been substantially revised in subsequent editions of AWS *D1.1*. The 9th Edition ASD *Manual* is supplemented by a separate book, Volume II - *Connections*. Chapter 2 contains general information regarding welding, Chapter 3 contains design examples for Simple Shear Connections, Chapter 4 contains Moment Connections, and Chapter 6 contains Column Connections.

4. AWS SPECIFICATIONS AND STANDARDS.

a. *D1.1* Structural Welding Code - Steel. ANSI/AWS *D1.1* contains the requirements for fabricating and erecting welded steel structures. The *D1.1* Code is limited to carbon and low-alloy steels, of minimum specified yield strength not greater than 690 MPa (100 ksi), 3.2 mm (1/8 in.) in thickness or greater. It is not applicable to pressure vessel or pressure piping applications. *D1.1* contains eight sections: (1) General Requirements, (2) Design of Welded Connections, (3) Prequalification, (4) Qualification, (5) Fabrication, (6) Inspection, (7) Stud Welding, and (8) Strengthening and Repair. It also contains both mandatory and nonmandatory annexes, plus commentary. It is updated biannually, in even years.

b. *D1.3* Structural Welding Code - Sheet Steel. ANSI/AWS *D1.3* covers arc welding of sheet and strip steels, including cold-formed members that are equal to or less than 4.8 mm (3/16 in.) in nominal thickness. Arc spot, arc seam, and arc plug welds are included in the Code. The *D1.3* Code is applicable when welding sheet steels to other sheet steels, or when welding to other thicker structural members. With the latter application, the use of AWS *D1.1* is also required for the structural steel. The *D1.3* Code contents are similar to AWS *D1.1*, except Sections 7 and 8 are not included.

c. *D1.4* Structural Welding Code - Reinforcing Steel. ANSI/AWS *D1.4* covers the welding of reinforcing steel, as used in concrete construction. Welding of reinforcing steel to reinforcing steel, and reinforcing steel to other carbon and low-alloy steels, is covered. With the latter application, the use of AWS *D1.1* is also required for the structural steel. *D1.4* follows a different organizational structure than AWS *D1.1* and *D1.3*, and includes the following sections: (1) General Provisions, (2) Allowable Stresses, (3) Structural Details, (4) Workmanship, (5) Technique, (6) Qualification, and (7) Inspection, plus annexes.

d. A2.4 Standard Symbols for Welding, Brazing and Nondestructive Testing. ANSI/AWS A2.4 contains standards for the application of welding symbols on structural design and detail drawings, as well as examples of their use. Part A of the document covers Welding Symbols, Part B covers Brazing Symbols, and Part C covers Nondestructive Examination Symbols. The symbols and use specified in this document supersedes symbols that may be shown in other AWS and industry documents, as they may be incorrect or outdated in the other documents.

e. A5-series Filler Metal Related Specifications. ANSI/AWS A5-series documents establish the requirements for electrodes, fluxes, and shielding gases, as applicable, for given general types of electrodes and given welding processes. The requirements include, as applicable, chemical composition of the electrode, moisture content, usability, markings, packaging, storage, certifications, and the as-tested mechanical properties (strength, ductility, and toughness) and soundness of weld metal. An Appendix or Annex is provided to explain the provisions and provide additional information. The A5-

series specifications applicable to structural steel are listed in Appendix A - References, of TI 809-26.

5. FEDERAL EMERGENCY MANAGEMENT AGENCY.

a. FEMA 267 and 267B Steel Moment Frame Structures - Interim Guidelines. The *Interim Guidelines*, published in 1995, are applicable to steel moment-resisting frame structures incorporating fully restrained connections in which the girder flanges are welded to the columns, and are subject to significant inelastic demands from strong earthquake ground motion. Guideline recommendations are provided based upon research conducted under the SAC Joint Venture, Phase 1 project. The Guidelines include information regarding the pre-earthquake evaluation and inspection of existing buildings, post-earthquake evaluation and inspection of existing buildings, repairing damaged buildings, retrofitting existing damaged and undamaged buildings, and designing, constructing and inspecting new buildings.
FEMA 267A was published as an additional advisory to FEMA 267, based upon information available as of August 1996. A second advisory, FEMA 267B, was published in mid-1999, replacing FEMA 267A.

b. FEMA 267 Replacement. A series of five new documents are planned for publication in early 2000, based upon the results of the SAC Joint Venture Phase 2 project. These will supersede FEMA 267 and issued advisories. The documents will be as follows: (1) *Seismic Design Criteria for New Moment-Resisting Steel Frame Construction*, (2) *Post-Earthquake Evaluation and Repair Criteria for Welded Moment-Resisting Steel Frame Construction*, (3) *Seismic Evaluation and Upgrade Criteria for Existing Steel Moment-Resisting Frame Construction*, and (4) *Quality Assurance Guidelines for Moment-Resisting Steel Frame Construction*, and (5) *Recommended Specifications for Moment-Resisting Steel Frame Buildings*.

c. FEMA 273 NEHRP Guidelines for the Seismic Rehabilitation of Buildings. FEMA 273 provides guidelines for the seismic rehabilitation of buildings constructed of steel or cast iron, concrete, masonry, wood and light metal, including foundations and architectural, mechanical and electrical components. The document is oriented toward structural analysis procedures, with limited information regarding specific details for welding or inspection.

d. FEMA 302 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. FEMA 302 provides minimum design criteria for the design and construction of structures to resist earthquake motions. Included are provisions for foundations, steel structures, concrete structures, composite structures, masonry structures, seismic isolation, related building components, and nonbuilding structures such as racks, towers, piers and wharves, tanks and vessels, stacks and chimneys, electrical distribution structures, and several other structures. Not included in the provisions are certain classes of one-and two-family residential structures, agricultural structures, and structures in areas of low seismicity.

CHAPTER 3

WELDING PROCESSES AND MATERIALS

1. WELDING AND RELATED PROCESSES.

a. General - Welding. The proper selection of welding processes, materials, and procedures is vital to achieving the strength and quality necessary for adequate performance in the structure. The contract documents, prepared by the Engineer, should specify any special requirements for materials, inspection, or testing beyond that required by the codes and standards.

b. General - Heating and Thermal Cutting. The application of heat, whether for straightening, cutting, or welding, may have a significant effect upon the mechanical properties of the steel, weld, and heat-affected zones. Should any limitations in the use of heat be needed beyond those specified in the codes, the contract documents prepared by the Engineer should so state.

c. General - Weld Heat-Affected Zone. The heat-affected zone (HAZ) is the portion of steel immediately adjacent to the weld that has been metallurgically modified by the heat of the welding. The microstructure has been changed, and the mechanical properties typically have been degraded with reduced ductility and toughness, but with increased strength. Also, hydrogen from the welding operation will have migrated into the hot HAZ, then subsequently been trapped within the metallurgical structure, embrittling the steel. The hydrogen will eventually migrate out the HAZ, at rates dependent upon initial hydrogen levels, thickness and temperature. The HAZ is typically about 3 mm (1/8 in.) thick for common size welds, primarily depending upon welding heat input.

d. Project Specifications. In most cases, it is adequate to simply require compliance with the codes. The contractor may be allowed the full choice of welding processes and materials. The use of “matching” prequalified filler metals is encouraged. When SMAW is performed, the use of low-hydrogen electrodes is encouraged. Recently, the use of specified toughness levels for filler metals in specific seismic building applications has been added to standard practice. For further guidance in the use and selection of welding processes and materials, see Appendix C.

2. APPLICATION OF HEAT FOR WELDING.

a. Cooling Rate Control. Preheat is used primarily to slow the cooling rate of the heat-affected zone (HAZ). Because preheating slows the cooling rate, the steel remains at an elevated temperature longer, increasing the rate and time of hydrogen diffusion and reducing the risk of hydrogen-assisted cracking. Preheat also aids in the removal of surface moisture and organic compounds, if present, from the surface to be welded, reducing porosity and other discontinuities. Preheating may also reduce residual stresses and improve the toughness of the completed joint.

(1) High Cooling Rates. A high cooling rate may cause a hard, martensitic HAZ microstructure with a higher risk of cracking during cooling. The HAZ will also contain higher levels of hydrogen, also embrittling the steel and increasing the risk of cracking.

(2) Low Cooling Rates. Conversely, a very low cooling rate can detrimentally affect toughness because of grain growth. When preheat above approximately 300°C (550°F) is used, weld metal properties may be degraded as well. If the steel is manufactured using heat treatment processes, such as

quenched and tempered steels, too high a preheat may affect steel properties by retempering the steel. For quenched and tempered steels, preheat and interpass temperatures above 230°C (450°F) should be avoided.

b. Preheat for Prequalified Applications. The basic values for minimum preheat temperatures for prequalified structural steels are provided in AWS *D1.1* Table 3.2. A summary of this table is provided as Table 3-1, with suggestions in Table 3-2 for non-prequalified steels. With any non-prequalified steel, a competent welding advisor should be consulted. When steels of different categories are joined, use the higher preheat required for their respective thicknesses.

(1) Category A is applicable when non-low hydrogen SMAW electrodes are used. This is permitted as prequalified only for AWS Group I steels, but is not recommended practice. See Appendix C, Paragraph 1b. Because of the higher diffusible hydrogen present when non-low hydrogen electrodes are used, higher preheats are required to allow additional time for hydrogen to escape from the heat-affected zone. When low-hydrogen SMAW electrodes are used, the preheat can be reduced because of the reduced hydrogen levels present.

(2) Category D is applicable to A913 steel, a thermo-mechanically controlled processed (TMCP) steel that has low carbon and alloy levels. Weldability tests have been conducted to document that the steel may be welded without preheat, provided the steel temperature is above 0°C (32°F), and an electrode classified as H8 (tested under ANSI/AWS A4.3 for 8 mL or less of diffusible hydrogen per 100 g of deposited weld metal) or lower is used.

(3) Users are cautioned that the use of these minimum preheat tables may not be sufficient to avoid cracking in all cases. Increased preheat temperatures may be necessary in situations involving higher restraint, higher hydrogen levels, lower welding heat input, or with steel compositions at the upper end of their respective specification. Conversely, preheats lower than those tabulated may be adequate for conditions of low restraint, low hydrogen levels, higher welding heat input, and steel compositions low in carbon and other alloys. Additional guidance for these situations may be found in AWS *D1.1* Annex XI, *Guideline on Alternative Methods for Determining Preheat*. The Guide considers hydrogen level, steel composition, and restraint and allows for calculation of the estimated preheat necessary to avoid cold cracking. When higher preheats are calculated, it is advisable to use these values, provided maximum preheat levels are not exceeded. When lower preheat values are calculated, the AWS *D1.1* Code requires the WPS to be qualified using the lower preheat value. Such testing may not always adequately replicate restraint conditions, so caution is advised.

(4) Although not required for building applications under AWS *D1.1*, consideration for higher preheat and interpass temperature requirements may be made for critical applications where fracture would result in a catastrophic collapse. For these conditions, AWS *D1.5 Bridge Welding Code* Tables 12.3, 12.4 and 12.5 provide recommended values. Seismic applications with routine building structures is not considered appropriate for requiring higher levels of preheat and interpass temperatures, and AWS *D1.1* Table 3.2 should suffice.

Table 3-1. Minimum Preheat and Interpass Temperatures for AISC-Approved Structural Steels Prequalified under AWS D1.1

Category	Structural Steel	Material Thickness of Thickest Part at Point of Welding	Minimum Preheat and Interpass Temperature
A *When using SMAW with other than low-hydrogen electrodes*	**Shapes and Plates** A36 A529, grade 42 A709, grade 36 **Round and Rectangular Sections** A53, grade B (round) A500, grades A and B (round) A500, grades A and B (rectangular) A501 (round)	3 to 19 mm (incl.) (1/8 to 3/4 in.) over 19 to 38.1 mm (incl.) (3/4 to 1-1/2 in.) over 38.1 to 63.5 mm (incl.) (1-1/2 to 2-1/2 in.) over 63.5 mm (2-1/2 in.)	0°C (32°F)[1] 66°C (150°F) 107°C (225°F) 150°C (300°F)
B *When using SMAW with low-hydrogen electrodes, or FCAW, GMAW or SAW*	**Shapes and Plates** A36 A529, grade 42 A709, grades 36, 50 & 50W A572, grades 42 and 50 A588, 100 mm (4 in.) thick and under A913, grade 50 A992, grade 50 (shapes only) **Round and Rectangular Sections** A53, grade B (round) A500, grades A and B (round) A500, grades A and B (rectangular) A501 (round) A618, grades Ib, II, & III (round)	3 to 19 mm (incl.) (1/8 to 3/4 in.) over 19 to 38.1 mm (incl.) (3/4 to 1-1/2 in.) over 38.1 to 63.5 mm (incl.) (1-1/2 to 2-1/2 in.) over 63.5 mm (2-1/2 in.)	0°C (32°F)[1] 10°C (50°F) 66°C (150°F) 107°C (225°F)

Category	Structural Steel	Material Thickness of Thickest Part at Point of Welding	Minimum Preheat and Interpass Temperature
C *When using SMAW with low-hydrogen electrodes, or FCAW, GMAW or SAW*	**Shapes and Plates** **A572, grades 60 and 65** **A709, grade 70W[2]** **A852, grades 70[2]** **A913, grades 60 and 65**	**3 to 19 mm (incl.) (1/8 to 3/4 in.)**	**10°C (50°F)**
		over 19 to 38.1 mm (incl.) (3/4 to 1-1/2 in.)	**66°C (150°F)**
		over 38.1 to 63.5 mm (incl.) (1-1/2 to 2-1/2 in.)	**107°C (225°F)**
		over 63.5 mm (2-1/2 in.)	**150°C (300°F)**
D *When using SMAW with low-hydrogen electrodes, or FCAW, GMAW or SAW, with electrodes of class H8 or lower*	**Shapes and Plates** **A913, Grades 50, 60, and 65**	**all thicknesses**	**0°C (32°F)[1]**

[1] - If the steel is below 0°C (32°F), the steel, in the vicinity of welding, must be raised to and maintained at a minimum temperature of 21°C (70°F) prior to and during welding.

[2] - Maximum preheat and interpass temperature of 200°C (400°F) for thicknesses up to 40 mm (1-1/2 inches) inclusive, and 230°C (450°F) for thickness greater than 40 mm (1-1/2 inches).

**Table 3-2. Suggested Minimum Preheat and Interpass Temperatures for AISC-Approved Structural Steels Not Prequalified under AWS D1.1.
(Seek advice of competent welding consultant prior to use of this Table.)**

Category	Structural Steel	Minimum Preheat and Interpass Temperature
NPQ-A	Shapes and Plates A529, grade 46 A283 (plates) Round and Rectangular Sections A500, grade C (round)	same as Table 3-1, Category A
NPQ-B	Shapes and Plates A242, all grades A529, grades 50 and 55 A588, over 4" thick Round and Rectangular Sections A500, grade C (rectangular) A618, grades Ib, II, and III (round) A847	same as Table 3-1, Category B

c. Preheat for Non-prequalified Applications. Preheat requirements for non-prequalified steels and applications may be determined using rational engineering judgement considering material composition, restraint, hydrogen levels, and experience. Table 3-2 provides suggested values for common structural steels not currently listed in AWS *D1.1*. Other steels should be evaluated by a competent welding consultant. The use of AWS *D1.1* Annex XI is suggested, with suitable qualification testing to be performed to verify the analytical results.

d. Preheat for Sheet Steel to Structural Steel. When the structural steel element is of a grade or thickness requiring preheat under the provisions of AWS *D1.1*, preheat must be provided to the structural steel element. The sheet steel itself need not be preheated.

e. Interpass Temperature. Interpass temperature is the temperature maintained during welding, until completion of the weld joint. Minimum and maximum interpass temperatures are typically the same as the minimum and maximum preheat temperatures, but may vary in specific WPSs.

(1) Thicker materials may absorb enough heat from the weld region that it is necessary to reapply heat to the weld region prior to resuming welding of the joint.

(2) With maximum interpass temperature considerations, it may be necessary to pause welding operations to allow the steel to cool to below the maximum interpass temperature before resuming welding. Accelerated cooling using water should not be permitted, but the use of forced air is acceptable. Cooling time may be necessary for larger multi-pass welds on thinner materials or smaller members.

(3) When necessary to shut down welding operations on a joint prior to joint completion, it should be verified that adequate welding has been completed to sustain any currently applied or anticipated loadings until completion of the joint. The joint may be allowed to cool below the prescribed interpass temperature, but must be reheated to the required preheat / interpass temperature before resumption of welding of the joint.

f. Postheat (PWHT). Postheating is the continued application of heat following completion of the weld joint. It is not required by specification, but may be used in some cases when conditions of high restraint, poor weldability steels, and poor hydrogen control exist. In most cases, when proper attention is applied to preheat and interpass temperatures, and adequate control of hydrogen levels is maintained, postheating is not necessary to avoid cold cracking. Under the difficult conditions mentioned, it may be adequate to slow cooling rates through the use of insulating blankets applied immediately after completion of welding. The PWHT described in AWS *D1.1* Section 5.8, is for the purpose of stress relief, not cracking control.

3. APPLICATION OF HEAT FOR STRAIGHTENING AND CAMBERING.

a. Principle. Heat applied from a heating torch may be used to straighten curved or distorted members, and also to camber or curve members when desired. The method is commonly called “flame shrinking”, because the heat is applied to the part of the member that needs to become shorter.

b. Cambering Procedure. Cambering a beam with positive camber requires heat to be applied to the bottom flange of the beam. It is recommended to first apply a V-heat to the web, starting with a point near the top, to soften the web and minimize web crippling that may occur if only the flange is heated.

c. Maximum Temperatures. The temperature to which the steel may be heated as a part of the straightening or cambering process is limited to 650^{o}C (1200^{o}F) for most structural steels, and to 590^{o}C (1100^{o}F) for quenched and tempered steels. See AWS *D1.1* Section 5.26.2. For TMCP steels, the manufacturer’s recommendations for maximum temperatures should be followed. It is recommended that accelerated cooling using water mist not be used until the temperature of the steel has dropped below approximately 300^{o}C (600^{o}F).

4. THERMAL CUTTING. Thermal cutting is used in steel fabrication to cut material to size and to perform edge preparation for groove welding. Thermal cutting is generally grouped into two categories - oxyfuel gas cutting, also commonly called flame cutting or burning, and plasma arc cutting.

a. Oxyfuel Cutting. With oxyfuel gas cutting (OFC), the steel is heated with a torch to its ignition temperature, then exposed to a stream of oxygen from the same torch. The oxygen causes rapid oxidation, or “burning” to occur, which itself creates additional heat to allow the process to continue. The force of the oxygen stream blows away the molten steel, leaving a cut edge. The fuel gas used in oxyfuel cutting may be natural gas, propane, acetylene, propylene, MPS, or other proprietary fuel gases.

b. Plasma Arc Cutting. Plasma arc cutting (PAC) is sometimes used in shop fabrication, and is generally limited to steels 25 mm (1 in.) thick or less. Similar to oxyfuel cutting, the steel is heated to the point of melting, only this function is performed using an electric arc. The molten steel is then removed by the high velocity stream of plasma (ionized gas) created by the arc itself, within the cutting torch. Gases used for PAC include nitrogen, argon, air, oxygen, and mixtures of nitrogen/oxygen and argon/hydrogen. With plasma arc cutting, the area of steel heated by the process is less, resulting in less steel metallurgically affected by the heat of cutting, as well as less distortion. PAC generates considerable fume and noise, and therefore a water table and water shroud is typically used to minimize these undesirable environmental effects.

c. Edge Quality. The quality of thermally cut edges is governed by AWS *D1.1* Section 5.15.4. Limits are placed on surface roughness, as measured using ANSI/ASME B46.1, *Surface Texture (Surface Roughness, Waviness and Lay)*. A plastic sample, AWS C4.1-G, *Oxygen Cutting Surface Roughness Gauge*, is typically used for visual comparison in lieu of physical measurement of surface roughness. Limitations are also placed on the depth and sharpness of gouges and notches. AISC, in Section M2.2, takes a minor exception to AWS *D1.1* quality criteria.

5. AIR CARBON ARC GOUGING. Air carbon arc gouging (ACAG) is commonly used to perform edge preparation for groove joints (especially J- and U-grooves), to remove unacceptable discontinuities from weld deposits, and to remove temporary attachments such as backing bars or lifting lugs. It may also be used to remove entire welds when structural repairs or modifications are necessary.

a. Process. The process appears similar to SMAW, with an electrode holder and a single electrode, and is usually performed manually, however, the electrode is a carbon electrode covered with a copper sheath. The electrode creates a controlled arc, melting the steel, which is quickly followed by the focused application of compressed air from the electrode holder. The air provides continued rapid oxidation, as well as removes the molten steel from the area. For complete information, see ANSI/AWS C5.3, *Recommended Practices for Air Carbon Arc Gouging and Cutting*.

b. Surface Finishing. Following ACAG, the joint should be thoroughly cleaned by wire brushing. Grinding of surfaces prior to welding is not required. If not welded, light grinding of the ACAG surface is suggested.

CHAPTER 4

STRUCTURAL STEELS

1. AISC AND AWS LISTED STRUCTURAL STEELS.

a. AISC Approved Steels. For building-type structures, the AISC lists approved steels in Section A3.1 of the *Specification for Structural Steel Buildings*. Additional steels are listed in the AISC *Seismic Provisions for Structural Steel Buildings* because of a more recent publication date. New structural steel specifications have been developed and approved since publication, such as ASTM A992, and should also be considered for application in structures. Structural steels currently accepted by AISC in the LRFD *Specification*, or pending acceptance as noted, are as follows:

Shapes and Plates
- A36
- A242
- A283[1]
- A514
- A529
- A572
- A588
- A709
- A852
- A913[2]
- A992[4] (wide flange shapes only)

Rounds and Rectangular Sections
- A53
- A500
- A501
- A618
- A847[3]

Sheet and Strip
- A570
- A606
- A607

[1] - added in AISC *Seismic Provisions* (1997)
[2] -added in AISC LRFD Supplement (1998)
[3] - added in AISC *Hollow Structural Sections* (1997)
[4] - approved for next specification

b. AWS Prequalified Steels. AWS *D1.1* lists prequalified steels in Table 3.1, and other approved steels in Annex M. Prequalified steels have been determined to be generally weldable when using the AWS *D1.1* Code. For some steel specifications, only certain strength levels or grades are considered prequalified. This situation may be because certain grades have compositional levels outside the range considered readily weldable, because certain strength levels are less weldable, or because certain steels or grades recently came into production and inadequate information was known about their weldability at the time of printing.

c. AWS Approved Steels. The steels listed in Annex M are approved for use, but Welding Procedure Specifications (WPSs) must be qualified prior to use in welding these steels. These steels are generally quenched and tempered steels, which are sensitive to temperature changes from welding operations that may affect their strength, ductility, and toughness. They are also generally more sensitive to diffusible hydrogen and are at higher risk of hydrogen-assisted HAZ cracking.

d. Matching Filler Metals for Prequalified Steels. Table 4-1 provides a summary of structural steels that are both approved by AISC and listed by AWS as prequalified. For joint designs requiring “matching” filler metal, the “matching” filler metal for the given welding process is provided.

Table 4-1. AISC-Approved Structural Steels Prequalified under AWS D1.1 Table 3.1

AWS Group	Structural Steel	Prequalified “Matching” Filler Metal
I	**Shapes and Plates** A36 A529, grade 42 A709, grade 36 **Round and Rectangular Sections** A53, grade B (round) A500, grades A and B (round) A500, grades A and B (rectangular) A501 (round)	**SMAW** A5.1: E60XX, E70XX A5.5: E70XX-X[1] **FCAW** A5.20: E6XT-X, E6XT-XM E7XT-X, E7XT-XM (Except -2, -2M, -3, -10, -13, -14, -GS) A5.29: E6XTX-X[1], E6XTX-X[1]M E7XTX-X[1], E7XTX-X[1]M **GMAW** A5.18: ER70S-X, E70C-XC, E70C-XM (Except -GS(X)) A5.28: ER70S-X[1]XX, E70C-X[1]XX **SAW** A5.17: F6XX-EXXX, F6XX-ECXXX F7XX-EXXX, F7XX-ECXXX A5.23: F7XX-EXXX-X[1], F7XX-ECXXX[1]

II	Shapes and Plates A572, grades 42 and 50 A588, 100 mm (4 in.) thick and under A709, grades 50 and 50W A913, grade 50 Round and Rectangular Sections A618, grades Ib, II, and III (round)	SMAW A5.1: E70XX, low hydrogen A5.5: E70XX-X[1], low hydrogen FCAW A5.20: E7XT-X, E7XT-XM (Except -2, -2M, -3, -10, -13, -14, -GS) A5.29: E7XTX-X[1], E7XTX-X[1]M GMAW A5.18: ER70S-X, E70C-XC, E70C-XM (Except -GS(X)) A5.28: ER70S-X[1]XX, E70C-X[1]XX SAW A5.17: F7XX-EXXX, F7XX-ECXXX A5.23: F7XX-EXXX-X[1], F7XX-ECXXX[1]
III	Shapes and Plates A572, grades 60 and 65 A913, grades 60 and 65	SMAW A5.5: E80XX-X[1], low hydrogen FCAW A5.29: E8XTX-X[1], E8XTX-X[1]M GMAW A5.28: ER80S-X[1]XX, E80C-X[1]XX SAW A5.23: F8XX-EXXX-X[1], F8XX-ECXXX[1]

IV	Shapes and Plates A709, grade 70W A852, grade 70	SMAW A5.5: E90XX-X[1], low hydrogen E9018M FCAW A5.29: E9XTX-X[1], E9XT-X[1]M GMAW A5.28: ER90S-X[1]XX, E90C-X[1]XX SAW A5.23: F9XX-EXXX-X[1], F9XX-ECXXX[1]

[1] - except alloy groups B3, B3L, B4, B4L, B5, B5L, B6, B6L, B7, B7L, B8, B8L, B9

e. Matching Filler Metals for Non-prequalified Steels. Table 4-2 provides “matching” filler metal information for structural steels approved by AISC, but not listed as prequalified by AWS *D1.1*. Quenched and tempered steels are not listed in this table. With the exception of A992, the advice of a competent welding consultant should be used prior to welding these steels. A992 steel is a new steel specification which is essentially a more restricted A572, grade 50 steel.

Table 4-2. AISC-Approved Structural Steels Not Prequalified under AWS D1.1 Table 3.1

Group	Structural Steel	Suggested "Matching" Filler Metal (Not Prequalified)
NPQ-I	Shapes and Plates A529, grade 46 A283, grade D (plates) Round and Rectangular Sections A500, grade C (round)	same as Table 4-1, Category I
NPQ-II	Shapes and Plates A242, all grades A529, grades 50 and 55 A588, over 100 mm (4 in.) A992, (W shapes only) Round and Rectangular Sections A500, grade C (rectangular) A618, grades Ib, II, and III (round) A847	same as Table 4-1, Category II

f. Unlisted Steels.

(1) Steels not listed as approved by AISC must be evaluated for structural properties such as yield strength, tensile strength, ductility and toughness. AISC design specifications assume adequate strength and ductility. For seismic applications, an assumed minimum level of toughness is assumed inherent with the steels listed in AISC *Seismic Provisions*. Other steels may warrant CVN testing or other mill documentation of typical toughness properties.

(2) Steels not listed as prequalified by AWS *D1.1* must be evaluated for their weldability. Weldability may be evaluated using methods such as carbon equivalency, the performance of WPS qualification testing, or physical testing such as the Tekken test, Lehigh Restraint Cracking Test, or the Varestraint Test. The Tekken and Lehigh methods simulate restraint that may be present in the actual joint. See Appendix B, Weldability of Steels, Stout and Doty, for further information on these tests.

2. WELDABILITY OF STRUCTURAL STEELS.

a. Chemical Composition. The chemical composition of the steel affects weldability and other mechanical properties. Several elements are purposefully added in the production of structural steel, but other undesirable elements may be present in the scrap materials used to make the steel. Carbon and other elements that increase hardenability increase the risk of “cold” cracking, and therefore higher preheat and interpass temperatures, better hydrogen control, and sometimes postheat are necessary to avoid cold cracking.

(1) Carbon (C) is the most common element for increasing the strength of steel, but high levels of carbon reduce weldability. Carbon increases the hardenability of the steel, increasing the formation of undesirable martensite with rapid HAZ cooling. Higher preheats and higher heat input welding procedures may be needed when welding a steel with relatively high carbon contents. Typical steel specifications limit carbon below 0.27%, but some steel specifications have much lower limits.

(2) Manganese (Mn) is an alloying element that increases strength and hardenability, but to a lesser extent than carbon. One of the principal benefits of manganese is that it combines with undesirable sulphur to form manganese sulfide (MnS), reducing the detrimental effects of sulfur. With high levels of sulfur, however, numerous large MnS inclusions may be present, flattened by the rolling operation, increasing the risk of lamellar tearing when high through-thickness weld shrinkage strains are created. Manganese limits are typically in the order of 1.40% or lower. A steel such as A36 does not place limits on Mn content for shapes up to 634 kg/m (426 lb./ft.), or for plates and bars up to 20 mm (3/4 in.), inclusive.

(3) Phosphorous (P) is an alloying element that increases the strength and brittleness of steel. Larger quantities of phosphorous reduce ductility and toughness. Phosphorous tends to segregate in steel, therefore creating weaker areas. Phosphorous is typically limited to 0.04% to minimize the risk of weld and HAZ cracking.

(4) Sulfur (S) reduces ductility, particularly in the transverse direction, thereby increasing the risk of lamellar tearing, and also reduces toughness and weldability. Higher sulfur levels will form iron sulfide (FeS) along the grain boundaries, increasing the risk of hot cracking. Manganese is used to form MnS to reduce this tendency. A minimum Mn:S ratio of 5:1 to 10:1 is recommended. Typical steel specifications limit sulfur to 0.05%.

(5) Silicon (Si) is a deoxidizer used to improve the soundness of the steel, and is commonly used to “kill” steel. It increases both strength and hardness. Silicon of up to 0.40% is considered acceptable for most steels.

(6) Copper (Cu) is added to improve the corrosion resistance of the steel, such as in weathering steels. Most steels contain some copper, whether specified or not. When specified to achieve atmospheric corrosion resistance, a minimum copper content of 0.20% is required. Generally, copper up to 1.50% does not reduce weldability, but copper over 0.50% may affect mechanical properties in heat-treated steels.

(7) Nickel (Ni) is an alloying element used to improve toughness and ductility, while still increasing strength and hardenability. It has relatively little detrimental effect upon weldability. Where nickel is reported as a part of steel composition, it is generally limited to a maximum value between 0.25% and 0.50%.

(8) Vanadium (V) is an alloying element used for increasing strength and hardenability. Weldability may be reduced by vanadium. When vanadium is reported as a part of steel composition, vanadium is generally limited to a maximum value between 0.06% and 0.15%.

(9) Molybdenum (Mo) is an alloying element which greatly increases hardenability and helps maintain strength and minimize creep at higher temperature. When molybdenum is reported as a part of steel composition, it is generally limited to a maximum value between 0.07% and 0.10%.

(10) So-called “tramp” elements such as tin (Sn), lead (Pb), and zinc (Zn), may be present in steel from the scrap material melted for steel-making. They have a low melting point, and may adversely affect weldability and cause “hot” cracking. Other low-melting point elements that create a risk of hot cracking include sulfur, phosphorous, and copper. When welding with high levels of these elements, it may be necessary to use low heat input welding procedures to minimize dilution effects.

b. Carbon Equivalency. The weldability of a steel can be estimated from its composition, using a calculation system termed the carbon equivalent (CE). The most significant element affecting weldability is carbon. The effects of other elements can be estimated by equating them to an additional amount of carbon. The total alloy content has the same effect on weldability as an equivalent amount of carbon. There are numerous carbon equivalent equations available and in use.

(1) The following equation is used in AWS *D1.1* Annex XI.

$$CE = C + Mn/6 + Cr/5 + Mo/5 + V/5 + Ni/15 + Cu/15 + Si/6$$

Where C = carbon content (%)
Mn = manganese content (%)
Cr = chromium content (%)
Mo = molybdenum content (%)
V = vanadium content (%)
Ni = nickel content (%)
Cu = copper content (%)
Si = silicon content (%)

A carbon equivalent of less than 0.48 generally assures good weldability.

(2) Another common carbon equivalent equation is:

$$CE = C + Mn/6 + Cr/10 + Ni/20 + Cu/40 - V/10 - Mo/50.$$

If the CE from this equation is below 0.40, the material is considered readily weldable, and AWS *D1.1* Table 3.2 guidance for the given steel strength should be adequate. For values between 0.40 and 0.55, the use of preheat and low-hydrogen electrodes is generally necessary, regardless of thickness. Carbon equivalent values above 0.55 indicate a high risk that cracks may develop unless special precautions are implemented.

(3) The Dearden and O’Neill equation, applicable for steels with C greater than 0.12%, is similar:

$$CE = C + Cr/5 + Mo/5 + V/5 + Mn/6 + Ni/15 + Cu/15$$

A CE of 0.35% or lower is considered a steel with good weldability

(4) For steels with C between 0.07% and 0.22%, the Ito and Bessyo equation may be used. The Ito-Bessyo equation is also termed the composition-characterizing parameter, P_{cm}.

$$CE = C + 5B + V/10 + Mo/15 + Mn/20 + Cu/20 + Cr/20 + Si/30 + Ni/60$$

Where B = boron content (%)

A CE of 0.35% or lower is considered a steel with good weldability.

(5) The Yurioka equation may also used to calculate CE for steel with C between 0.02% and 0.26%, as follows:

$$CE = C + A(C) * \{5B + Si/24 + Mn/6 + Cu/15 + Ni/20 + Cr/5 + Mo/5 + Nb/5 + V/5\}$$

Where Nb = niobium content (%)
$A(C) = 0.75 + 0.25 * \tanh [20 (C- 0.12)]$

Table 4-3. Chemical Requirements for Sample Structural Steels (heat analysis, %, maximum, unless range is provided)

(Refer to ASTM specifications for complete information, including applicable thickness ranges, grades, types, combinations of elements, etc.)

Steel Composition	A36 (shapes)	A572 grade 50 (shapes) Type 1	A572 grade 50 (shapes) Type 2	A992	A588, grade B	A852
C	0.26	0.23	0.23	0.23	0.20	0.19
Mn	---	1.35	1.35	0.50-1.50	0.75-1.35	0.80-1.35
P	0.04	0.04	0.04	0.035	0.04	0.035
S	0.05	0.05	0.05	0.045	0.05	0.04
Si	0.40	0.40	0.40	0.40	0.15-0.50	0.20-0.65
Cu	#	#	#	0.60	0.20-0.40	0.20-0.40
V	---		0.01-0.15	0.11	0.01-0.10	0.02-0.10
Co	---	0.005-0.05	---	0.05	---	---
Ni	---	---	---	0.45	0.50	0.50
Cr	---	---	---	0.35	0.40-0.70	0.40-0.70
Mo	---	---	---	0.15	---	---

Shapes composition limits are listed for sections up to 634 kg/m (426 plf).
 # minimum 0.20% when specified

3. PROPERTY ENHANCEMENTS FOR STRUCTURAL STEELS.

a. Yield to Ultimate Strength Ratio. AISC design equations assume some margin in structural steel from the point of yielding to the point of fracture to allow for the redistribution of stress. Some structural steels have been produced with F_y:F_u ratios as high as 0.95, considerably higher than that considered by

AISC in developing design methodologies.

(1) ASTM A572, grade 50, manufactured to the supplemental requirements of AISC Technical Bulletin #3, provides a requirement for a maximum F_y:F_u ratio of 0.85. This same value is a requirement for ASTM A992 steels. Although not considered critical in low-seismic applications, this requirement is advisable for members in the lateral load resisting systems in high-seismic applications.

(2) Structural steels providing this maximum F_y:F_u ratio are readily available from mill sources. Such a requirement can be met by special mill order requirements, the specification of A572, grade 50 meeting AISC Technical Bulletin #3, the specification of A992 shapes, or through the review of mill test reports of existing steels in inventory that are traceable to the mill heat number. There is currently no premium in steel mill cost to specify such properties, but some minor delays may be encountered in purchasing until the inventory of such materials is predominant.

b. Killed Steel. Killed steel has been processed to remove or bind the oxygen that saturates the molten steel prior to solidification. ASTM A6 / A6M defines killed steel as “steel deoxidized, either by addition of strong deoxidizing agents or by vacuum treatment, to reduce the oxygen content to such a level that no reaction occurs between carbon and oxygen during solidification.” Semi-killed steel is incompletely deoxidized, and may also be specified.

(1) The benefit of killing is to reduce the number of gas pockets present in the steel, which can adversely affect the mechanical properties of the steel, including ductility and toughness, as well as reduce the number of oxide-type inclusions in the steel.

(2) Most mills provide some form of deoxidation, in the form of semi-killed steel, as a part of routine production practices. AISC does not require killed steel for any specific applications.

(3) Most commonly, killing is done using additions of silicon, but may also be done with aluminum or manganese. Killed steels often have silicon levels in the range of 0.10% to 0.30%, but may be higher.

(4) Project requirements for killed steel should be considered when using wide-flange sections in Groups 4 or 5, and plates when over 50 mm (2 inches) in thickness, in tension applications, which have special AISC requirements for toughness in AISC *Specification* section A3.1c. ASTM A992 requires the steel to be killed.

(5) Specifying killed or semi-killed steel may carry a slight cost premium, except in the case of A992 steel. Because killed steel is typically a cost-premium mill order item, the inventory of killed structural steels available at steel service centers and in steel fabricating plants is less than that of regular steels. Mill orders typically require longer production lead times than service center or stock items.

c. Fine Grain Practice. Fine grain practice is the method of achieving Fine Austenitic Grain Size, defined by ASTM A6 / A6M as grain size number 5 or higher, measured using test methods prescribed by ASTM E112. Aluminum is typically used to achieve fine grain practice, which binds oxygen and nitrogen. When aluminum content is above 0.20%, by heat analysis, the steel is considered fine-grained, without the need for testing.

(1) Fine grain practice is beneficial in improving ductility and toughness. Consideration of requirements for fine grain practice should be made when using wide-flange sections in Groups 4 or 5, and plates when over 50 mm (2 inches) in thickness, in tension applications, which have special AISC

requirements for toughness in AISC *Specification* section A3.1c. When specifying steel to fine grain practice, ASTM Supplementary Requirement S91 should be consulted for the specific steel grade.

(2) Because fine grain practice is typically a cost-premium mill order item, the inventory of structural steels available at steel service centers and in steel fabricating plants manufactured to fine grain practice is less than that of regular structural steel. Mill orders typically require longer production lead times than service center or stock items.

d. Toughness. Steel toughness, also commonly referred to as “notch toughness”, is the resistance to brittle crack initiation and propagation. For this resistance, the steel must have sufficient plastic ductility to redistribute stresses at the root of a notch to the surrounding material. Toughness may be measured using a variety of methods, but the steel industry standard is the Charpy V-Notch (CVN) method, as prescribed by ASTM A370. CVN testing is an added charge by the steel producer, and steel with CVN testing is not routinely ordered by steel service centers or steel fabricators for inventory. Therefore, steels with CVN testing are generally available only through mill order, which typically requires longer production lead times than service center or stock items.

e. Improved Through-thickness Properties. For certain high-restraint applications subject to the risk of lamellar tearing, steels with improved through-thickness properties may be specified. The most common method of improving through-thickness properties, to reduce the risk of lamellar tearing, is through the specification of low-sulfur or controlled sulfur-inclusion steels. By reducing the sulfur content, the number and size of manganese sulfide (MnS) inclusions is reduced. Typically, low-sulfur steels in plate form can be ordered to 0.005% sulfur, at a cost premium and with longer lead time. Most steel specifications permit maximum sulfur in amounts between 0.30% to 0.50%. Shapes are not routinely available with substantially reduced sulfur levels, and would be available only at substantial cost premium and considerable delay. However, a mill may be able to select heats of steel with particularly lower levels of sulfur for rolling specific sections. It is also possible to specify through-thickness tensile testing using reduction of area as the governing criteria, but this is rarely necessary.

f. Normalizing. Normalizing is defined in ASTM A6 / A6M as “a heat treating process in which a steel plate is reheated to a uniform temperature above the critical temperature and then cooled in air to below the transformation range.” In practice, steel is heated to approximately 900^{o}C to 930^{o}C (1650^{o}F to 1700^{o}F). The benefits include refined grain size and uniformity, improved ductility and improved toughness. Few building applications warrant the need for normalized steel. The specification of normalized steel is a mill order item only, an added expense with added time for delivery from the steel mill. Normalized steel is not routinely available from steel service centers or stocked by fabricators.

4. SELECTION OF STRUCTURAL STEELS FOR ENVIRONMENTAL EXPOSURE AND SERVICE APPLICATIONS.

a. High-seismic Applications. The AISC *Seismic Provisions*, Section 6.3, require steel in the Seismic Force Resisting System to have a minimum toughness of 27J at 21^{o}C (20 ft.-lb. at 70^{o}F), applicable to ASTM Group 4 and 5 shapes, Group 3 shapes with flanges 38 mm (1-1/2 in.) or thicker, and to plates in built-up members 38 mm (1-1/2 in.) or thicker. Studies indicate that a large percentage of domestically produced structural steel sections lighter or thinner than those mentioned in the previous paragraph will have a CVN toughness of at least 27J at 21^{o}C (20 ft.-lb. at 70^{o}F), and therefore it does not appear that CVN testing need be conducted to verify the toughness of all members. It is recommended that manufacturer’s accumulated data be used to verify that the steel routinely produced by that mill meets the indicated toughness levels. Specification of steel toughness levels, or the specification of A709 steels, is currently considered unnecessary for ordinary building-type applications.

b. Fatigue Applications. Toughness requirements should be considered for applications involving fatigue. As a guide, the toughness values specified in ASTM A709 / A709M, Table S1.1 and S1.2, summarized and adapted in Table 4-4, may be used for redundant fatigue applications. Modifications to this table are suggested for steels that have yield strengths 103 MPa (15 ksi) or more above the minimum specified yield strengths, for all but A36 steels. See the ASTM A709 / A709M specification for appropriate changes to the testing temperatures for these cases. For nonredundant fatigue applications, see ASTM A709 / A709M, Table S1.3 for guidance. The required CVN toughness and testing temperature may be specified directly in the specifications for the project, to be placed on the mill order. Alternatively, a given ASTM A709 / A709M steel and temperature zone may be specified.

Table 4-4. Toughness Guidelines for Structural Steel in Fatigue Applications, Redundant Applications.

Steel	Thickness	Application	Minimum Service Temperature		
			Zone 1 -18°C (0°F)	Zone 2 -34°C (-30°F)	Zone 3 -51°C (-60°F)
A36	to 100 mm (4 in.), incl.	bolted or welded	20J @ 21°C (15 ft-lbf @ 70°F)	20J @ 4°C (15 ft-lbf @ 40°F)	20J @ -12°C (15 ft-lbf @ 10°F)
A572, gr 50 A588	to 50 mm (2 in.), incl.	bolted or welded	20J @ 21°C (15 ft-lbf @ 70°F)	20J @ 4°C (15 ft-lbf @ 40°F)	20J @ -12°C (15 ft-lbf @ 10°F)
“	over 50 to 100 mm (2 in to 4 in.)	bolted	20J @ 21°C (15 ft-lbf @ 70°F)	20J @ 4°C (15 ft-lbf @ 40°F)	20J @ -12°C (15 ft-lbf @ 10°F)
“	over 50 to 100 mm (2 in to 4 in.)	welded	20J @ 21°C (20 ft-lbf @ 70°F)	20J @ 4°C (20 ft-lbf @ 40°F)	20J @ -12°C (20 ft-lbf @ 10°F)
A852	to 65 mm (2-1/2 in.), incl.	bolted or welded	27J @ 10°C (20 ft-lbf @ 50°F)	27J @ -7°C (20 ft-lbf @ 20°F)	27J @ -23°C (20 ft-lbf @ -10°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	bolted	27J @ 10°C (20 ft-lbf @ 50°F)	27J @ -7°C (20 ft-lbf @ 20°F)	27J @ -23°C (20 ft-lbf @ -10°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	welded	34J @ 10°C (25 ft-lbf @ 50°F)	34J @ -7°C (25 ft-lbf @ 20°F)	34J @ -23°C (25 ft-lbf @ -10°F)
A514	to 65 mm (2-1/2 in.), incl.	bolted or welded	34J @ -1°C (25 ft-lbf @ 30°F)	34J @ -18°C (25 ft-lbf @ 0°F)	34J @ -34°C (25 ft-lbf @ -30°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	bolted	34J @ -1°C (25 ft-lbf @ 30°F)	34J @ -18°C (25 ft-lbf @ 0°F)	34J @ -34°C (25 ft-lbf @ -30°F)
“	over 65 mm to 100 mm (2-1/2 in to 4 in.)	welded	48J @ -1°C (35 ft-lbf @ 30°F)	48J @ -18°C (35 ft-lbf @ 0°F)	48J @ -34°C (35 ft-lbf @ -30°F)

c. Cold Weather Applications. Steel toughness requirements should be considered for major load-carrying components of structures exposed to extreme cold environments. When structural components in a low-temperature environment are not subject to significant impact loads or fatigue conditions, it is generally more cost effective to specify a type of steel with inherently good fracture toughness, and avoid a requirement for specific CVN toughness at a reference temperature. High-strength low alloy (HSLA) steels that are manufactured using fine grain practice have improved toughness at low temperature, compared to conventional carbon steels such as A36 steel. AISC-approved steels requiring production to fine-grain practice are A588, A709 (grades 50W, 70W, 100, 100W), A852, and A913 (grades 60, 65 and 70), although higher strength structural steels present additional welding difficulties and should not be specified unless necessary for weight savings. Fine-grain practice can optionally be specified using ASTM Supplemental Requirement S91 for A36, A572, A992, A709 (grades 36 and 50), and A913 (grade 50). It is not available for A529, A242, or A283 steels. Steels that require killing, which also improves toughness, include A992 and A709 (grades 100, 100W), but the higher strength grades should be avoided because of other welding difficulties. Nitrogen has a significant effect upon CVN transition temperatures, and limitations on nitrogen may be considered. A992 steels place a limit on nitrogen of 0.012%, unless nitrogen binders are added. A572, Type 4 steel has a limit on nitrogen of 0.015%.

d. High Stress / Strain / Restraint Applications. When welded joints are made to the side of a member, creating through-thickness shrinkage stresses and strains, consideration should be made for the risk of lamellar tearing. Lamellar tearing is a separation or tearing of the steel on planes parallel to the rolled surface of the member. There is no specific through-thickness at which lamellar tearing will or will not occur, nor specific values for weld size, stresses or strains that will induce tearing. Generally, lamellar tearing is avoided through using one or more of the following techniques: improved design or redesign of the joint, welding procedure controls, weld bead placement selection, sequencing, the use of preheat and/or postheat, the use of low-strength, high-ductility filler metals, “buttering,” and peening. However, steels with improved through-thickness properties may also be specified. The most common method of improving through-thickness properties, to reduce the risk of lamellar tearing, is through the specification of low-sulfur or controlled sulfur-inclusion steels. See 3.e.

5. AVAILABILITY OF STRUCTURAL STEELS. All AISC-approved structural steels are available from domestic steel mills, with the exception of A913. The AISC *Manual of Steel Construction*, Table 1-1, provides general information regarding availability of shapes, plates and bars in various steel specifications, grades and strengths. Table 1-4 provides similar information for round and rectangular sections, including availability as either steel service center stock or in mill order quantities only. Table 1-3 lists the producers of specific structural shapes, and Table 1-5 provides similar information for round and rectangular sections. This list is updated semi-annually in *Modern Steel Construction* magazine, published by AISC, in the January and July issues.

CHAPTER 5

DESIGN FOR WELDING

1. GENERAL.

a. Engineer’s Responsibility. The Engineer is responsible for the analysis and design of the connection, including connections between elements in built-up members. Critical structural steel connections must be completely detailed and shown on the contract drawings. The Engineer may prescribe connection details, if desired or necessary, but generally it is best to allow the fabricator or erector to select the specific welding detail to be used for a particular joint. For instance, it may be adequate for the Engineer to specify a Complete Joint Penetration (CJP) groove weld, or specify a Partial Joint Penetration (PJP) groove weld and state the required throat. This may effectively be done through the use of AWS welding symbols, and when necessary for prequalified groove welds, the appropriate AWS designation. The fabricator and erector are typically in the best position to select which process, groove type (single, double, bevel, vee, J, U), and groove angle should be used based upon economics, availability of equipment and personnel, distortion control, and ease of welding operations. The Engineer must review and approve the final details selected by the contractor.

2. GOOD DESIGN PRACTICE.

a. Availability of Materials, Equipment and Personnel. In the selection of base metals, welding processes, filler metals, and joint designs, one should consider the availability of the structural steel, welding equipment, filler metals, personnel qualified to perform such welding, personnel qualified to inspect the welding, and NDT equipment and personnel necessary to perform NDT as required. Certain welded joint designs may require notch-tough filler materials, welding personnel qualified in out-of-position welding, welders qualified for specific processes, enclosures for field welding, or nondestructive testing. When the availability of any of the above is in question, alternative joint designs should be investigated.

b. Access. The following items should be considered to permit welding operations to be made with adequate quality:

(1) Welding personnel must have direct visual access to the root of the weld. All passes must be visually monitored by the welder during welding.

(2) Access should be adequate so that the welding electrode can be positioned at the proper angle for proper penetration and fusion. Generally, the electrode should be positioned so that the angle between the part and the electrode is not less than 30°. Smaller angles may cause a lack of fusion along the weld / base metal interface. Access should be checked at the design stage when welding in highly confined spaces or with closely spaced parts.

(3) Weld access holes, placed in beam and girder webs when splicing flanges or making beam-to-column moment connections, must be of adequate size to permit the weld to be placed by reaching through the access hole with the electrode. Minimum access hole sizes are specified in AWS *D1.1* Figure 5.2. Larger access holes may be warranted based upon the welding process and type of welding equipment used.

(4) Narrow root openings and narrow groove angles inhibit access to the joint root, contributing to lack of penetration at the root and lack of fusion along the joint sidewalls. Proper joint design, preferably using joints prequalified under AWS *D1.1* should be used.

c. Position. It is preferred to weld in the flat position when making groove welds, plug welds or slot welds, and in either the flat or horizontal positions when making fillet welds. Welding positions are defined in AWS *D1.1* in Figure 4.1 for groove welds and in Figure 4. 2 for fillet welds. To assist in interpreting the positions given, see AWS *D1.1* Figure 4.3 for groove welds, Figure 4.5 for fillet welds, and Figures 4.4 and 4.6 for tubular joints. Welding in other than the flat or horizontal positions increases welding time approximately four-fold, on average, increasing cost and construction time. Fewer welding personnel are qualified by test to perform welding out-of-position. Although personnel may be previously qualified by test to weld out-of-position, a welder may not have recently used the special techniques and procedures for welding in these positions, and therefore may have lost some of the skill necessary to perform quality out-of-position welding. In this case, close visual observation of the welder during the first few out-of-position passes is especially important, and requalification testing may be necessary. The quality of out-of-position welds is more difficult to maintain, and they typically do not have the smooth appearance of welds performed in the flat or horizontal positions. This makes visual inspection and some forms of NDT more difficult.

d. Joint Selection. For guidance in the selection of groove details that provide sufficient access, limited distortion, and cost-effectiveness, the prequalified groove weld details in AWS *D1.1* Figures 3.3 and 3.4 should be reviewed. The following items should be considered in selecting or evaluating joint selection:

(1) For butt joints, partial joint penetration (PJP) groove welds are more economical than complete joint penetration (CJP) groove welds. Provided CJP groove welds are not required by Code for the given application or for fatigue and seismic applications, PJP groove welds should be considered for tension- and shear-carrying joints when full strength of the connected members is not required, and for compression splices such as column splices. PJP groove welds are prepared to a required depth of chamfer, usually the required effective throat, or 3 mm (1/8 in.) deeper, depending upon groove angle, welding process and position.

(2) For most applications, by Code, CJP groove welds require the use of either backing bars, which may need to be removed in certain types of joints, or removal of a portion of the root pass area by backgouging followed by backwelding until the joint is complete. In addition, more welding is required to join the entire thickness of material, rather than just the amount of welding needed to carry the load.

(3) In butt joints, V-groove welds are preferred over bevel-groove welds. Bevel-groove welds are generally more difficult to weld, especially when the unbeveled face is vertical, and lack of fusion on the unbeveled face may result. V-groove welds, because they are balanced and usually have a downhand position on each groove face, are easier to weld. Access to the root is also easier to achieve because of the balance and the wider groove angle used.

(4) For tee joints, fillet welding is generally less expensive than groove welding, until the fillet size reaches approximately 16 to 20 mm (5/8 to 3/4 in.). Above this size, PJP groove welding, or a combination groove weld with reinforcing fillets, should be considered. There is added expense in joint preparation for groove welds that is not required with fillet welds, however, there may be offsetting cost savings with groove welds because of decreased weld volume, fewer passes, and therefore less labor and materials. Less distortion may also be incurred because of the reduced weld volume.

(5) Square groove welds have limited application for structural steel. They are better suited for thin materials. When square groove welds are used, the root opening must be closely controlled and the Welding Procedure Specification (WPS) closely developed and followed.

(6) For thick materials, generally starting at thicknesses of 50 mm (2 in.), J- and U-groove welds may be more economical than bevel- and V-groove welds. The wider root initially requires more weld metal, but the narrower groove angle reduces the total weld volume below that of bevel- and V-groove welds. There are also higher initial joint preparation costs to prepare a J- or U-groove joint, so even more weld metal must be saved to recover these costs. When angular distortion or shrinkage strains must be minimized, J- and U-groove joints should be considered. The reduced groove angle minimizes the differential in weld width from top to bottom of the joint.

(7) Root opening widths should be generous but not excessive. Wider root openings allow for complete penetration to the bottom of the joint preparation. However, very wide roots contribute to root pass cracking and root HAZ cracking from weld shrinkage. Narrow root openings contribute to lack of penetration, lack of fusion, and trapped slag at the root.

(8) Groove angles should be the minimum angle that will provide adequate access for penetration to the root, and adequate access to the groove faces for complete fusion. Excessively wide groove angles contribute to added angular distortion, increased risk of shrinkage cracking, increased risk of lamellar tearing in T-joints, and higher costs because of the additional material and labor used.

e. Prequalified Joint Details. The prequalified groove weld details in AWS *D1.1* Figure 3.3 for Partial Joint Penetration (PJP) groove welds, and Figure 3.4 for Complete Penetration Joint (CJP) groove welds, provide root opening, groove angle, root face, thickness limits, tolerances, and other information for the effective detailing of groove welds. Root openings and groove angles are considered adequate for the welding processes and positions noted, without causing excessive angular distortion. For PJP groove welds, the required depth of preparation is provided to achieve the desired effective throat. When the joint details as shown are used, qualification testing of the joint detail is not required to verify the suitability of the detail, provided other prequalification provisions of the Code are also met. See AWS *D1.1* Section 3 for these limits. The use of prequalified groove weld details does not guarantee that welding problems will not occur. The details may not always be the best detail, and other more efficient, cost-effective or easier-to-weld details may be used. However, when other groove details are used, qualification testing is required.

f. Qualified Joint Details. Groove weld details may be used other than those shown as prequalified in AWS *D1.1* Figures 3.3 and 3.4. Alternate details may be selected with reduced or wider root openings, reduced or wider groove angles, or other revised details. Generally, narrower root openings and groove angles increase the risk of incomplete penetration at the root and lack of fusion along the groove faces. These problems may be minimized through the use of suitable WPSs. Qualification testing, as prescribed in AWS *D1.1* Section 4, is required in such cases to verify the ability of the WPS to provide the penetration and quality necessary.

g. Distortion. Angular distortion can be minimized through the use of double-sided welding, the use of minimum groove angles, J- or U-groove welds, presetting of parts, and WPS selection. Double-sided welds balance weld shrinkage about the center of the part's cross-section. When the part can be frequently rotated for welding on opposite sides, a balanced groove detail can be used. When one side will be welded in its entirety before proceeding to weld the opposite side, the first side groove depth should be approximately 35-40% of the total groove depth of both welds. The completed first side weld restrains the second side weld from shrinking as much as the unrestrained first-side weld. Minimum groove angles and J-and U-groove details reduce the difference in weld width between the root and the face of the weld, and therefore reduce the weld shrinkage.

3. DESIGN AND FABRICATION OF WELDED JOINTS.

a. Effective Weld Size / Throat. AWS *D1.1* Section 2, Part A provides the details for the calculation of effective weld size, also called effective throat, and effective weld length.

(1) Complete Joint Penetration (CJP) groove welds have an effective throat equal to the thickness of the thinner part joined.

(2) Partial Joint Penetration (PJP) groove welds must have their size specified in the design, and then be detailed to provide the throat required. AWS provides the required depth of preparation for PJP groove welds in *D1.1*, Figure 3.3. AISC provides similar information in Table J2.1.

(3) For flat and convex fillet welds, the effective size is specified in terms of weld leg, but the effective throat is the shortest distance from the root to a straight line drawn between the two weld toes. Should the fillet weld be concave, the measurement of leg size is ineffective, and the throat must be measured as the shortest distance from the root to the weld face.

b. Allowable Stresses / Design Strengths. Allowable weld stress, when using ASD, is provided in AWS *D1.1* Table 2.3, or in AISC Table J2.5 of the *ASD Specification*. Weld design strength (when using LRFD) is provided in AISC Table J2.5 of the *LRFD Specification*. Both AWS and AISC tables are similarly structured, with minor differences in certain sections. The following information is in terms of LRFD, without consideration of the resistance factor phi. If ASD is used, see the appropriate specification.

(1) For welds other than CJP groove welds loaded in transverse tension, the AWS *D1.1* Code permits the use of matching filler metal or a filler metal of lower strength. Overmatching is not permitted in AWS *D1.1*. AISC permits the use of undermatching for the same conditions, and also overmatching filler metal to the extent of one weld strength classification, nominally 70 MPa (10 ksi) more.

(2) For CJP groove welds that carry transverse tensile stress, the AWS *D1.1* Code requires the use of matching filler metal. Matching filler metal provides a weld with at least the strength of the base metal in such an application. See AWS *D1.1* Table 3.1 for matching filler metals. The strength of the weld is treated the same as the strength of the base metal, as the base metal will be the weaker of the two materials, with a phi of 0.9.

(2) Should the CJP groove weld be used in a T-joint or corner joint loaded in tension transverse to its axis, with the backing bar remaining in place, AISC *LRFD Specification* Table J2.5, Note [d] requires the use of filler metal with a designated CVN toughness of 27J @ +4^{o}C (20 ft.-lbf @ +40^{o}F). Alternatively, the weld must be designed as a PJP groove weld, similarly loaded.

(3) For CJP groove welds in transverse compression, the AWS *D1.1* Code requires the use of either matching filler metal or a filler metal one strength classification less, nominally 70 MPa (10 ksi) less. AISC places no limit on the undermatching strength. The strength of the weld is treated the same as the strength of the base metal, with a phi of 0.9.

(4) CJP groove welds in shear may carry 0.60 times the classification strength of the filler metal,

with a phi of 0.8.

(5) CJP groove welds and other welds carrying tension or compression parallel to the axis of the weld need not be designed for the tensile or compressive stress, only for any shear forces that may be transferred between the connected parts. As an example, girder web-to-flange welds need not be designed for the axial force from bending, only for the shear transferred between the web and flange.

(6) PJP groove welds in transverse tension are permitted to carry 0.60 times the classification strength of the filler metal, with a phi of 0.8. The stress on the base metal is also limited to the minimum specified yield strength of the base metal, with a phi of 0.90, using the effective size (throat) of the groove weld for the check of the base metal stress.

(7) PJP groove welds in compression are currently treated differently by AWS and AISC. Under AWS *D1.1*, PJP groove welds are categorized into joints designed to bear and joints not designed to bear. AISC, because it is based upon new construction, provides design values only for the joint designed to bear application. Under AISC, for joints designed to bear, the weld stress need not be checked, as the base metal will govern the strength of the joint, with a phi of 0.9.

(8) For joints not designed to bear, only AWS provides design values, based upon Allowable Stress Design (ASD). The weld stress may not exceed 0.50 times the classification strength of the filler metal, and the base metal stress may not exceed 0.60 times the minimum specified yield strength of the base metal, applied to the throat of the groove weld. LRFD values, considering the factor phi, are generally 1.5 times the ASD values.

(9) PJP groove welds in shear may be stressed to 0.60 times the classification strength of the filler metal, with a phi of 0.75.

(10) Fillet welds may be stressed to 0.45 times the classification strength of the filler metal, with a phi of 0.75. There is no need to check the shear stress in the base metal along the diagrammatic leg of the fillet weld. Research indicates that, because of penetration and HAZ hardening, the leg of the fillet weld is not a failure plane that needs checked.

(11) For transversely loaded fillets welds, AWS *D1.1* Section 2.14.4 and 2.14.5, and AISC *LRFD Specification* Appendix J2.4, permit a 50% increase in the allowable shear stress on the weld. For angles other than transverse, an increase is also permitted based upon an equation. For eccentrically loaded fillet weld groups, allowable shear stress increases are also permitted when using the instantaneous center of rotation approach for the analysis of the weld group. Design values for typical weld groups are provided in the AISC *Manual*.

(12) When fillet weld strength increases, as above, are used for loading other than parallel to the weld axis, AISC *LRFD Specification* Table J2.5, Note [h] requires the use of CVN toughness as above.

(13) When a fillet weld is loaded longitudinally along its axis, and is loaded from its end, as in a splice plate or brace member, there is a maximum effective length of 100 times the leg size before a reduction factor must be implemented. Longer fillet welds loaded in such a manner must be analyzed using a reduction coefficient Beta from AISC *LRFD Specification* equation J2-1. The maximum effective length is 180 times the leg size, which would apply when the weld is 300 times the leg size in length, with a reduction coefficient Beta of 0.6.

(14) Plug and slot welds may be stressed to 0.60 times the classification strength of the filler metal,

with a phi of 0.75. There is no need to check the stress in the base metal along the base of the plug or slot. Plug and slot welds may be designed only for shear forces along the base of the hole or slot, not for shear along the walls of the hole or slot.

(15) With shear stress in any type weld, the Code requires a check of the base metal in shear, limiting the base metal stress to 0.60 times the minimum specified yield strength of the base metal, with a phi of 0.75. This check is applied to the thickness of the material, not the weld/steel interface, to verify that the steel has the capacity to carry the load delivered to or from the weld. This is especially applicable to situations using fillet welds on opposite sides of thin beam and girder webs.

c. Minimum Weld Size. Minimum weld sizes are incorporated into both the AWS *D1.1* and AISC codes. AWS *D1.1* Table 5.8, provides minimum fillet weld sizes, and Table 3.4 provides minimum prequalified PJP groove weld sizes. The basis of these tables is the need to slow the cooling rate when welding on thicker materials. Small welds provide little heat input to the thick base metal, which acts as an efficient heat sink, and therefore the weld region cools very rapidly. The rapid cooling creates a hard, martensitic heat-affected zone (HAZ), with potentially high levels of trapped hydrogen, with a higher risk of cracking. Larger welds are made with higher welding heat input, therefore reducing the cooling rate, and reduce the risk of HAZ cracking to acceptable levels. AISC Table J2.3 provides minimum fillet weld sizes similar to AWS *D1.1* Table 5.8, but does not provide weld size reductions based upon the use of low hydrogen electrodes or preheat.

d. Maximum Fillet Weld Size. A maximum fillet weld size is established for lap joints where a fillet weld is placed along the edge of a part. The maximum fillet weld size that should be specified, when the part is 6 mm (1/4 in.) or more in thickness, is 2 mm (1/16 in.) less than the thickness of the part. This is to protect the edge of the part from melting under the arc, making it difficult to verify adequate leg size and throat. For lap joints where the part receiving the fillet weld along its edge is less than 6 mm (1/4 in.) in thickness, the specified fillet weld size may equal the thickness of the part. See AWS *D1.1* Section 2.4.5.

e. Available Design Aids. Design aids for welded connections, in the form of tables and software, are available. See Appendix B, Bibliography.

f. Weld Access Holes. Weld access holes provide access for welding equipment to reach the weld region, reducing the interference from the member itself. They also provide access for weld cleaning and inspection. Access holes also serve to separate weld shrinkage stresses when fully welded joints are made in both the member web and flange, as an example. Typically, weld access holes are provided in beam and girder webs when splicing flanges, or when making welded flange connections in beam-to-column joints, but may also be used in other joints where interferences exist. See AWS *D1.1* Section 5.17, and AISC *LRFD Specification* Section J1.6 for minimum access types, dimensions, and quality. When weld access holes are used in heavy sections or high-seismic applications, special provisions regarding surface quality and inspection apply.

g. Reentrant Corners. Reentrant corners are internal cuts in members. Typical reentrant corners in buildings are found at openings for piping and ductwork in beam webs. Reentrant corners must be smooth, with no notches, with a minimum radius of 25 mm (1 in.). Grinding of reentrant corners and tangency is not required. Beam copes and weld access holes are treated separately by the code. See AWS *D1.1* Section 5.16.

h. Heavy Section Joint Provisions. Under the AISC LRFD *Specification*, special material, welding and quality requirements apply for applications using ASTM Group 4 and 5 shapes, and for built-up sections using plates over 50 mm (2 in.) in thickness. AWS *D1.1* provisions apply for ASTM Group 4 and 5 shapes and for built-up sections with a web plate over 38 mm (1-1/2 in.) in thickness. Both codes apply these provisions only when the materials are used with welded tensile splices, but have also been applied to connections such as beam-to-column connections where the flanges are direct-welded for moment resistance. The special material requirements include a minimum CVN toughness taken from a specific, nonstandard location in the material. The special provisions listed do not apply when the joint carries only compression, such as column splices, or when bolted slices are used. Weld access holes must be preheated to 65°C (150°F) prior to thermal cutting, ground to bright metal, and inspected using either Penetrant Testing (PT) or Magnetic Particle Testing (MT). Optionally, weld access holes may be made by drilling and saw-cutting, but PT or MT of the cut surface is still required. For joint welding, minimum preheat and interpass temperature of 175°C (350°F) must be used, higher than that required by AWS *D1.1* Table 3.2. Weld tabs and backing bars must be removed after completion of the joint. AWS *D1.1* code provisions contain most, but not all, of these provisions. The AISC *ASD Specification* does not contain the latest joint details, and therefore AISC *LRFD Specification* provisions should be used. See AISC section A3.1c for materials requirements, J2.8 for preheat requirements, J1.6 for access hole requirements, and J1.5 for weld tab and backing bar removal requirements. See AISC LRFD Figure C-J1.2 for dimensional and fabrication requirements for weld access holes.

i. Backing Bars. Backing bars are used to close and support the root pass of groove welds when made from one side of the joint. Joint assembly tolerances are greater when backing bars are used, compared to joints without backing. Assembly tolerances without backing are typically within 3 mm (1/8 in.), difficult to achieve with structural steel sections in either the shop or field, but possible for some types of joints for shop fabrication. With backing, the assembly tolerances are typically enlarged to allow variations of 8 mm (5/16 in.). Welding is more easily performed with backing to support the root pass, eliminating concerns for melt-through and repair. In some joints, particularly in fatigue and seismic applications, it may be recommended or necessary to remove the backing bar after use. This adds cost to the operation, particularly when rewelding and / or finishing of the removed area is necessary.

(1) Steel backing is used almost universally in steel construction. Those applications that require subsequent backing removal are sometimes done with nonfusible backing materials such as copper, ceramic or flux. The use of backing materials other than steel is generally considered nonprequalified, requiring the testing of the WPS with these materials. Extreme caution should be used with copper backing, as the arc may strike the copper and melt copper into the weld, greatly increasing the risk of weld cracking.

(2) Welding personnel qualified to weld using backing are also qualified to weld without backing, provided the weld is backgouged and backwelded. If the joint is not backgouged and backwelded, then the welder must be qualified to weld without backing. If a welder is qualified without backing, then the welder may also weld with backing.

(3) The minimum backing thicknesses provided in AWS *D1.1* Section 5.10.3 are generally suitable to reduce the risk of melting thru the backing bar, but very high heat input procedures, particularly with Submerged Arc Welding (SAW), may require thicker backing.

(4) AWS *D1.1* Section 5.10, includes provisions for backing materials, thickness, splicing, and removal.

j. Weld Tabs. Weld tabs are also referred to as “extension bars”, “run-off tabs”, and similar terms in the industry. The purpose of a weld tab is to allow the weld to be started or stopped beyond the edge of the material being joined. Weld tabs are typically used in butt joint member splices, groove welded direct-welded flange joints in beam-to-column moment connections, and at the ends of built-up member welds such as girder web-to-flange welds. Weld tabs allow the welding of the full width of the joint, without starts and stops or build-out regions along the edges. The use of weld tabs places the inherent weld discontinuities made when starting or stopping a weld within the tab, and outside the major stress flow of the spliced material. Tabs also allow the welding arc to stabilize prior to welding the main material. For SAW, the tabs support the flux deposit at the edge of the workpiece.

(1) After welding is completed, the weld tabs may need to be removed. In some joints, particularly in fatigue and high-seismic applications, it may be recommended or necessary to remove the weld tab after use. Removal is required in most fatigue applications. In heavy section tensile splices, removal is required. In high seismic regions, removal is required at transverse groove welds in moment-resisting joints. For other applications, removal should be considered when splicing members over 25 mm (1 in.) in thickness when the members are subjected to high tensile stresses at the splice. This is because thicker members typically have less toughness than thinner members, and the low toughness may allow a crack or other discontinuity in the weld tab to propagate into the primary weld. For compression joints such as column splices, or for low-stress tensile splices, weld tabs in statically loaded structures should be allowed to remain in place.

(2) AWS *D1.1* Section 5.31, provides information on the use and removal requirements for weld tabs.

k. Welding Sequence and Distortion Control. Parts can be preset in a skewed position so that, when weld shrinkage occurs, the completed member will be approximately straight. WPSs that use large passes, rather than numerous small passes, generally cause less angular distortion. Distortion may also occur along the length of a member, resulting in unintended sweep, camber, or twist. This occurs because welding is not balanced about the center of gravity of the member cross-section. The use of intermittent welding, welding from the center of the member’s length, and overwelding in some locations may also be used to reduce longitudinal distortion.

l. Lamellar Tearing. Lamellar tearing is a step-like crack in the base metal, generally parallel to the rolled surface, caused by weld shrinkage stresses applied to the steel in the through-thickness direction. The steel is somewhat weakened by the presence of very small, dispersed, planar-shaped, nonmetallic inclusions, generally sulfur-based, oriented parallel to the steel surface. These inclusions serve as initiation points for tearing. Large inclusions constitute laminations, which may be detectable using straight-beam ultrasonic testing prior to welding. The inclusions that initiate lamellar tearing are generally not reliably detected using any form of NDT.

(1) There is no specific through-thickness at which lamellar tearing will or will not occur, nor specific values for weld size, stresses or strains that will induce tearing. Generally, lamellar tearing is avoided by using one or more of the following techniques: improved design or redesign of the joint, welding procedure controls, weld bead placement selection, sequencing, the use of preheat and/or postheat, the use of low-strength, high-ductility filler metals, “buttering,” and peening. AWS *D1.1* Commentary C2.1.3, provides guidance on these methods. Steels with improved through-thickness properties may also be specified. The most common method for improving through-thickness properties, to reduce the risk of lamellar tearing, is the specification of low-sulfur or controlled sulfur-inclusion steels.

(2) Should lamellar tears be detected, the stress type, application, and the implications of potential failure in service should be considered. Because the completed joint is more highly restrained than the original joint, repair of joints that have torn is difficult and expensive, with no assurance that a tear will not form beneath the repair weld. Repair may involve complete removal of the existing weld and

affected base metal. Reinforcement, if appropriate for the application, should be considered in lieu of repair or replacement.

m. Brittle Fracture. Brittle fracture is a failure that occurs in the steel or weld without appreciable deformation or energy absorption. Not all fractures are brittle, as the material may have undergone considerable straining and deformation prior to fracture. Sufficient ductility should be provided in joint design and detailing, and toughness in materials selection, so that brittle fracture will not occur. Many joint designs assume the ability to deform and redistribute stress throughout the connection. Standard design and detailing practices are typically adequate for building structures. Extreme loading conditions, cold temperature environments, high seismic risk, unusual materials, and fatigue applications may require more care in the selection and construction of connections and their details. Notches, whether inadvertent or inherent in the design, greatly increase the risk of brittle fracture. Care should be taken to avoid transversely loaded sharp notches and joint transitions, particularly in areas such as weld toes. Backing bars should be removed in some applications because the notch inherent at the root pass between backing bar and steel may initiate a crack in the weld, HAZ or base metal. Where it is assumed that plastic behavior will be required to provide ductility and energy absorption, such as seismically-loaded structures, sufficient length of base material should be provided in the assumed area of plastic yielding to allow this to occur, and notches that would serve as crack initiators should be avoided in this area. Notch-tough materials reduce the risk of brittle fracture.

4. DESIGN FOR CYCLICALLY LOADED STRUCTURES (FATIGUE).

a. General. The fatigue strength of a welded component is a combination of a stress range and a number of cycles (N) that causes failure of the component. The stress range is the total range between the maximum and minimum applied stresses. Stress range does not require stress reversal, only a variation in stress. The fatigue life of a component, also called the endurance limit, is the number of cycles to failure. The fatigue life of a welded joint is affected by the stress range at the location of crack initiation, and the fatigue strength of the detail, primarily a function of its geometry. In welded joints, fatigue life is generally not affected by applied stress level or the strength of the material.

(1) Traditional fatigue design is based upon high-cycle fatigue, generally in the range of 20,000 cycles to 100,000 cycles and up. However, low-cycle fatigue may also occur in cases of extreme stress and strain, such as seismic events or unanticipated out-of-plane bending from applied stresses or distortion. Applications that may experience low-cycle fatigue require design and detailing specific to the application that exceed the general fatigue design provisions of the codes.

(2) The S-N curves used for fatigue design provides an assumed relationship between fatigue life and stress range, and are commonly plotted on a logarithmic scale as a straight line. At the upper left end of the straight line, at the low endurance limit, the ultimate material strength is exceeded and failure occurs from static stress. At the lower right end of the curve, the high-endurance range, the stress ranges are generally too low to initiate crack propagation. The design S-N curves used to design structural members have been established approximately 25% below the mean failure values. Several design codes are now replacing the design S-N curves with the equations used to generate the plotted curves.

(3) The fatigue strength of different welded details varies according to the severity of the stress concentration effect. Those with similar fatigue life characteristics are grouped together into a Stress Category, identified as Classes A through F, with subcategories for special cases. There are several details that fall within each class. Each detail has a specific description that defines the geometry. The details and stress categories are classified by:

- form of the member (plate base metal, rolled section base metal, weld type),
- location of anticipated crack initiation (base metal, weld, weld toe),
- governing dimensions (attachment dimensions, radius of transition, weld length, etc.),
- fabrication requirements (ground flush, backing removed, etc.), and
- inspection requirements (ultrasonic or radiographic testing). The detail category should be evaluated carefully to verify that the actual detail realistically matches the standard detail.

(4) Careful design and fabrication can reduce the risk of failure by fatigue. Not all methods of fatigue life improvement are contained in the Codes, and not all methods are necessary. Smooth shapes and transitions are important, but radiused transitions are expensive and may not substantially improve fatigue life.

- Grinding groove welds flush in the direction of the applied stress may improve the Stress Category.
- Avoid reentrant, notch-like corners.
- Transitions between members of differing thicknesses or widths should be made with a slope of at least 2.5:1.
- Joints should be placed in low stress areas, when possible.
- Groove-welded butt joints have better fatigue life than lap or tee joints made with fillet welds.
- Parts should be aligned to minimize or eliminate eccentricity and minimize secondary bending stresses.
- Avoid attachments to members subject to fatigue loading.
- Attachment welds should be kept at least 12 mm (1/2 in.) from the edges of plates.
- Welds on the edges of flanges should be avoided. Fillet welds should be stopped about 12 mm (1/2 in.) short of the end of the attachment, provided this will not have any other detrimental effect on the structure.
- If a detail is highly sensitive to weld discontinuities, such as a transversely loaded CJP groove weld with reinforcement removed, appropriate quality, inspection, and NDT requirements should be specified.
- Fatigue life enhancement techniques such as those found in AWS *D1.1* Section 8, may be cost-effective in extending fatigue life.
- When grinding is appropriate, grinding should be in the direction of stress.
- Intermittent stitch welds should be avoided. Unauthorized attachments, often made by field or maintenance personnel or other trades, must be prohibited.
- A bolted assembly may be appropriate and more cost-effective in some applications.
- For critical details, provide for in-service inspection.

b. Fatigue Design Details. Fatigue details are identified as plain material, built-up members, groove welds, groove-welded attachments, fillet welds, fillet-welded attachments, stud welds, and plug and slot welds. Further divisions of these general categories are provided using general descriptions, and in some cases, by attachment length, radius, grinding requirements, NDT requirements, and member yield strength. Illustrative examples are typically provided by the codes to assist in the interpretation of these divisions.

(1) Stress Category A is limited to plain material, with no welding. Categories B, C, D and E follow the same line slope, with reduced permitted stress ranges for a given fatigue life demand. Category F behavior is sufficiently different to use a different slope. The endurance limit is also reached soonest, at the highest stress range, for Category A details, with progressively more cycles and lower stress ranges for the endurance limit in other categories.

(2) Various design codes may be used for fatigue design, and all are based upon the same principles and research data. Occasional revisions to these provisions and details are made by the various code organizations, so there may be minor differences between codes. Generally, AISC and AASHTO specifications are the most current and comprehensive, including bolted details. AWS *D1.1* provisions are limited to welded details. AASHTO and AWS currently use S-N curves, and AISC uses tabular values based upon the S-N curves. All three organizations are currently changing to equation-based design.

(3) AASHTO and AWS provide fatigue design curves for both redundant and nonredundant structures. The AWS nonredundant structure fatigue provisions are based upon bridge principles, where failure of the welded component would result in collapse of the structure, but special provisions for nonredundant structures are not required. The AASHTO code, however, requires the use of the AWS *D1.5*, Section 12, Fracture Control Plan for Nonredundant Structures. As a specification for building construction, AISC does not address nonredundant applications.

c. Allowable Stress Ranges. Stress ranges at the lower number of cycles, for the better fatigue categories, are often limited by the static stress applied. Because the number of cycles is usually established for the application, and often the type of detail needed to make the component or connection is established, the design must be established to keep the stress range below that permitted. Fatigue design begins with the sizing of the member and the connection for the maximum applied static load, then checked for the applied stress range. Adjustments are then made to increase the component or connection size as needed. Should the size become excessive, other improved details may be considered. This includes, for some groove details, grinding of the surface and NDT to improve the fatigue design category. Some joints may be changed from PJP groove or fillet welds to CJP groove welds. Another alternative is the use of fatigue life enhancement details to improve fatigue life. Fatigue life enhancement details are not to be used to increase allowable stress ranges.

d. Fatigue Life Enhancement. At the toe of every weld, with the exception of welds made using Tungsten Inert Gas (TIG) welding with no filler metal, a microscopic slag intrusion line is present. This line, for fatigue purposes, acts as a small crack. Fatigue life of welded joints, therefore, begins with an initial crack, and fatigue life is limited to crack propagation. With plain material, there is no pre-existing crack, so fatigue life is spent in both crack initiation and crack propagation. By applying fatigue life enhancement techniques, as described in AWS *D1.1* Section 8, fatigue life may be extended. The process of TIG dressing can be used to remelt the weld toe area to a limited depth, melting out and removing the microscopic slag intrusion line. Burr grinding of the weld toe, to a depth of approximately 1 mm (1/32 in.), may also be used to remove the slag line. Toe peening, in which localized mechanical compressive stresses are induced into the weld toe area, does not remove the slag line, but induces residual compressive stresses around the slag line to prevent the introduction of the tensile stresses necessary for crack propagation. Any of these enhancement processes typically double the fatigue life of the treated joint. Performing both toe grinding and hammer peening will provide additional benefits, achieving typically triple the fatigue life of the untreated weld toe. Caution should be used when extending fatigue life expectations, as other areas of the welded joint may now fail before the weld toe. Inspection of the weld should be performed prior to implementing fatigue life enhancement techniques, with any required inspection for surface discontinuities repeated following the work.

5. HIGH SEISMIC APPLICATIONS.

a. Latest Guidance. Recommendations for the design of welded connections in high seismic regions are undergoing substantial revision as of the date of this document. Users are advised to seek the latest guidance from FEMA and AISC documents.

b. Applicability. Improved materials and details should be used for building structures classified as Seismic Categories D, E and F. These applications include all buildings located in areas with 1 second spectral response accelerations (S_{D1}) of 0.20g or higher, or short period response accelerations (S_{DS}) of 0.50g, and buildings of Seismic Use Group III in areas with S_{D1} of 0.133g or higher, or S_{DS} of 0.33g or higher. Seismic Use Group III structures are essential facilities that are required for post-earthquake recovery and those containing substantial quantities of hazardous substances, including but not limited to: fire, rescue and police stations; hospitals; designated medical facilities providing emergency medical treatment; emergency operations centers; emergency shelters; emergency vehicle garages; designated communications towers; air traffic control towers; and water treatment facilities needed to provide water pressure for fire suppression. See TI 809-04, Table 4-1 for Seismic Use Groups, and Section 4.2 for Seismic Design Categories.

c. Materials Concerns and Specifications. Special compositional, materials toughness and other mechanical property requirements may be necessary for the steel and filer metal used in seismic applications:

(1) The AISC *Seismic Provisions*, Section 6.3, require steel in the Seismic Force Resisting System to have a minimum toughness of 27J at 21^{o}C (20 ft.-lbf at 70^{o}F), applicable to ASTM Group 4 and 5 shapes, Group 3 shapes with flanges 38 mm (1-1/2 in.) or thicker, and to plates in built-up members 38 mm (1-1/2 in.) or thicker.

(2) Studies indicate that a large percentage of domestically produced structural steel sections lighter or thinner than those mentioned in the previous paragraph will have a CVN toughness of at least 27J at 21^{o}C (20 ft.-lbf at 70^{o}F), and therefore it does not appear that CVN testing need be conducted to verify the toughness of all members. It is recommended that manufacturer's accumulated data be used to verify that the steel routinely produced by that mill meets the indicated toughness levels. Specification of steel toughness levels, or the specification of A709 steels, is currently considered unnecessary for building-type applications.

(3) It is also recommended that structural steel shapes used in high seismic applications be specified as either ASTM A992 or A572, grade 50 manufactured to AISC Technical Bulletin #3. These specifications have provisions for a maximum ratio of F_y to F_u of 0.85, and a more controlled chemistry for weldability and properties.

(4) The AISC *Seismic Provisions*, section 7.3b, require filler metals in the Seismic Force Resisting System to have a minimum toughness of 27J at -29^{o}C (20 ft.-lbf at -20^{o}F). Additional requirements for toughness at service temperature, tested using welding procedures representative of the range of production WPSs, are also recommended in the latest FEMA Guidelines.

(5) There are concerns for the performance of rolled steel sections in the vicinity of the K-line, at the intersection of the web and the radius between web and flange. Studies have identified a reduced toughness in this region caused by cold-working during rotary straightening at the steel mill. Reduced toughness in these region may increase the risk of crack initiation from welding in the area, particularly stiffeners (continuity plates) and doubler plates. AISC Technical Advisory No. 1 should be followed, pending further study.

(6) Current studies indicate that through-thickness toughness properties or applied stress on the column face is not a limiting factor, and need not be specified or checked.

d. Joint Selection. Several types of details may be used to achieve satisfactory moment connection performance in high seismic applications. Enhanced quality, improved and reinforced details are recommended for conventional-type connections. See (e) below. For Reduced Beam Section (RBS) system connections, also called the “dogbone” system, current AISC guidelines should be followed. See Appendix D, Bibliography. Several limitations have been found in the cover-plated and ribbed details, and further investigation of the latest recommendations should be made prior to use.

e. Joint Detail Modifications and Enhancements. Current recommendations include the following modifications to the previous standard beam-to-column connection: (1) removal of bottom flange backing bar, backgouging of the root, and placement of a reinforcing fillet, (2) improved quality of the weld access hole, (3) removal and finishing of weld tabs, (4) control of profile and quality of the access hole, (5) use of partially or fully welded web connections. The exact requirements for access hole provisions and web welding depend upon the type of connection used and the design application, whether Special Moment resisting Frame (SMRF) or Ordinary Moment-Resisting Frame (OMRF).

f. Inspection Enhancements. Continuous inspection of all welding performed on CJP and PJP groove welds that are a part of the Seismic Force Resisting System is necessary. The Engineer may allow periodic inspections when appropriate. AISC *Seismic Provisions* require NDT for certain joints in high seismic applications, as follows: “All complete joint penetration and partial joint penetration groove welded joints that are subjected to net tensile forces as part of the Seismic Force Resisting Systems ... shall be tested using approved nondestructive testing methods conforming to AWS *D1.1*.” Such testing should include ultrasonic testing of welds in T-joints and butt joints over 8 mm (5/16 in.) in thickness. Radiographic testing may be used in some cases using butt joints. When using T-joints, with the thickness of the tee “flange” exceeding 40 mm (1-1/2 in.), ultrasonic testing should be performed after completion and cooling of the weld to check for lamellar tearing.

CHAPTER 6

STUD WELDING

1. GENERAL.

Stud welding for building applications is generally for shear connectors in composite beams, but may also include shear connector applications for composite columns and frames. Studs may be welded either directly to the structural steel or through metal decking. The purpose of most shear connectors is to integrally connect steel and concrete materials so that they act as a single unit in resisting load. Occasionally, threaded studs may be used for special connections where bolting is not practical, such as embedment plates or inaccessible connections. Stud welding is a fully automated process with controlled arc length and arc time, and is conducive to a suitable convenient load test, and therefore is treated separately by AWS *D1.1* for procedure qualification, personnel qualification, and inspection.

2. STUD WELDING PROCESS.

The arc stud welding process is used for structural studs, rather than the capacitor discharge stud welding process. A DCEN (straight) current is used to create an arc between the stud base and the steel. The stud welding gun draws the stud away from the steel, creating the arc, allows a brief period for the melting of the steel and stud base, then plunges the stud into the molten pool and terminates the current flow. The weld arc and molten pool is protected with the use of a flux tip on the base of the stud, plus the use of a ceramic ferrule to contain the molten pool. See AWS C5.4, *Recommended Practice for Stud Welding*, for complete information.

3. STUD BASE QUALIFICATION.

Stud bases are qualified by the manufacturer for application on bare steel in the flat position only. Qualification procedures for this application are provided in AWS *D1.1* Annex IX. For all other applications, including studs applied through metal decking, studs applied to curved surfaces, studs welded in vertical or overhead positions, or studs welded to steels not listed as Group I or II in AWS *D1.1* Table 3.1, the contractor must perform qualification testing. For the Type B studs used in composite construction, ten (10) specimens must pass a 90^o bend test using representative material and application. Alternatively, a tension test method may be used. See AWS *D1.1* Section 7.6.

4. WELDING PERSONNEL QUALIFICATION.

The welding operator conducting the two pre-production tests at the start of the day or work shift is qualified for performing stud welding that day or shift. See AWS *D1.1* Section 7.7.4.

5. PRE-PRODUCTION TESTING.

After stud base qualification by the manufacturer, or qualification testing by the contractor for the applications listed, installation may begin. However, pre-production testing is required at the start of each day or shift to verify the setup of the equipment. This testing requires two studs to be welded, on the work if desired, visually inspected, then bent approximately 30°. If the stud weld passes the visual and bend testing, then production welding may begin. For composite construction, the stud need not be bent back to the original position. See AWS *D1.1* Section 7.7.1. The pre-production test must be repeated whenever there are changes to the following items: voltage, current, time, or gun lift and plunge.

6. INSPECTION.

Following the application of studs and the removal of the ferrules, all stud welds are visually inspected for flash about the entire perimeter of the stud base. Those with missing flash may be repaired, or tested using a bend test applied approximately 15° in the direction opposite the missing flash. Should the stud weld not fracture, the stud is accepted and may be left in place in the bent condition when used in composite construction. The inspector may 15° bend test any stud, if desired, even if full flash is apparent. See AWS *D1.1* Section 7.8.

CHAPTER 7

WELDING TO EXISTING STRUCTURES

1. GENERAL.

When welding to reinforce existing structures, several areas require investigation and, in some cases, specific instructions. Other than load analysis of the structure to design the connections, several welding issues arise. These include weldability of the existing steel, the reduction of strength to existing members when being heated or welded, and the welding to existing weld deposits of unknown origin or made with FCAW-S electrodes. AWS *D1.1* Section 8, and its supporting Commentary, provides applicable code provisions.

2. DETERMINING WELDABILITY OF EXISTING STRUCTURAL STEELS.

a. Investigation. Investigation of weldability is generally warranted for buildings constructed prior to 1945, although structural steels were not manufactured specifically for welding properties until A373 and A36 came into use in the early 1960's. The weldability of steels between these periods is generally considered sufficiently weldable.

b. Carbon Equivalency.

(1) The most reliable method to establish chemical composition for determining carbon equivalent values is to remove samples from various members at selected no- or low-stress locations, then analyzed spectrographically for composition. Portable spectrographs may also be used, although only optical emission spectrography systems currently provide sufficient accuracy for measuring carbon content. The laboratory analysis report should list the quantities of each of the elements in the selected carbon equivalent equation, even if the percentage reported is zero.

(2) Other methods, although less reliable, include spark testing and weld sample tests. Spark testing applies a grinding wheel at approximately 5000 rpm to the steel, then observing and characterizing the color and nature of the sparks off the steel. Weld sample tests include welding small test plates to the steel, then destructively using a sledge hammer to break off the samples, if possible, and observing the nature of the fracture.

3. WELDING TO OLDER STRUCTURAL STEELS.

The poorer the weldability of steel, the greater the need for higher preheat and interpass temperatures, and the greater the importance of low-hydrogen welding. All welding to existing structures should be performed with low-hydrogen SMAW electrodes or with other wire-fed welding processes. Minimum preheat and interpass temperatures can be determined from AWS *D1.1* Annex XI, or from technical literature.

4. INTERMIXING WELD PROCESSES AND FILLER METALS.

a. FCAW-S Deposits. Self-shielded Flux-Cored Arc Welding (FCAW-S) weld deposits contain aluminum, nitrogen, carbon and other alloying elements. When weld processes that use consumables with significantly different metallurgical systems are mixed with FCAW-S deposits, there is the potential for reduced properties, particularly ductility and toughness. This is the result of the liberation of nitrogen and aluminum that were previously chemically combined as Al-N in the FCAW-S deposit. Other weld deposits, typically a carbon-manganese-silicon metallurgical system, do not contain the amount of aluminum necessary in order to preclude the formation of free nitrogen, which can embrittle the steel or weld deposit.

b. Investigation. When it is suspected that existing weld deposits that will receive subsequent welding were made using FCAW-S, further investigation of the weld deposit is warranted. An aluminum content in the range of 1% is indicative of FCAW-S. Low-admixture welding procedures, design assuming reduced mechanical properties, or requiring subsequent welding using appropriate FCAW-S should be considered.

c. Other Processes. Recent research indicates that this problem may not be limited to non-FCAW-S weld deposits on top of FCAW-S. Multiple weld processes in a single weld joint may also occur in new construction because of tack welding, root pass welding selection, or other reasons.

5. STRENGTH REDUCTION EFFECTS AND OTHER CONCERNS WHEN WELDING UNDER LOAD.

a. Elevated Temperature Effects. Elevated temperatures in steel reduce both the yield strength (F_y) and the modulus of elasticity (E). At approximately 300°C to 400°C (600°F to 800°F), F_y and E are reduced approximately 20%. Preheat temperatures at this level are rarely used, but localized temperatures near the weld region will exceed these temperatures for brief periods. As a general guide, steel during welding, within the weld region, will exceed these temperatures approximately 25 mm (1 in.) to the side of a weld, and a distance of approximately 100 mm (4 in.) trailing the weld puddle. Steel further from the weld region will remain at temperatures that will not significantly reduce the steel's properties.

b. Welding Direction and Sequence. When welding under load, consideration should be made for the temporarily reduced strength of localized areas of the steel. When welding parallel to the applied stress, the affected area is typically small compared to the area of the unaffected steel. When welding transverse to the load, additional caution is needed. It may be necessary to stagger welding operations, use shorter sections of weld and then allow cooling, or use lower heat input procedures.

6. HAZARDOUS MATERIALS.

When welding on steel having existing coatings, an investigation into the composition of the coating is warranted, unless all coatings in the vicinity of the welding are removed prior to welding. Zinc, used in numerous coating systems and galvanizing, produces noxious fumes. Some older structures may contain lead-based paints that must be removed using special hazardous materials precautions.

CHAPTER 8

QUALITY ASSURANCE AND INSPECTION

1. GENERAL.

The Engineer is responsible for establishing and specifying the requirements of the Quality Control and Quality Assurance programs for the project. These requirements should be a part of the contract documents. AWS *D1.1* requires inspection of welding, but requires only “Fabrication / Erection Inspection”, which is the designated responsibility of the Contractor. “Verification Inspection” is the prerogative of the Owner, under AWS *D1.1*. Therefore, any specific welding inspection operations to be performed by personnel other than the Contractor must be fully detailed and placed in the contract documents.

2. REVIEWING AND APPROVING WELDING PROCEDURES.

a. WPS Contents. Welding procedures are used to specify, for the welder and inspector, the welding parameters for the weld to be made. Weld procedures are written by the contractor responsible for the welding, and must be reviewed by the inspector. In some cases, the Engineer must approve the welding procedures. Welding Procedure Specifications (WPSs) are written based upon the steel to be welded, thickness of material to be joined, type of joint, type of weld, size of weld, and position of welding. Based upon the application, the WPS specifies the welding materials to be used (electrode, flux, shielding gas), electrode diameter, voltage, current (amperage) or wire feed speed, travel speed, shielding gas flow rate, minimum (and sometimes maximum) preheat and interpass temperatures, location and number of passes, and other pertinent information specific to the weld to be made. All WPSs, whether prequalified or qualified by test, must be in writing.

b. AWS Requirements. AWS *D1.1* Section 6.3.1 requires the use of and inspection of WPSs. The inspector should review the WPS for general conformity to the welding code and applicability to the joint to be welded. The WPS also provides information necessary for inspection duties. The Engineer is assigned the responsibility in AWS *D1.1* Section 4.1.1, to review and approve WPSs that are qualified. Prequalified WPSs need not be approved by the Engineer under *D1.1*. The purpose of the Engineer’s approval of the WPS is so that it can be verified that the qualification testing is representative of the actual welding conditions, such as for thick and highly restrained joints.

c. AISC Requirements. In the AISC *Seismic Provisions*, Section 7.3, the Engineer is made responsible for the review and approval of all WPSs, whether qualified or prequalified, for welds that are part of the Seismic Force Resisting System. This is primarily to ensure that WPSs are developed for the welds critical to building performance, and that filler metals with the required toughness have been selected by the contractor.

d. WPS Prequalification Limits. Prequalified WPSs need not be tested using the tests prescribed in AWS *D1.1* Section 4. The contractor may develop WPSs based upon manufacturer’s recommended operating parameters, verified by the contractor’s experience and testing as desired. To be prequalified, the welding process must be prequalified (SMAW, FCAW, GMAW except short-circuiting transfer, or SAW), the weld details must meet all the requirements of AWS *D1.1* Section 3, and welding parameters meet the provisions of AWS Table 3.7. This includes the use of the prequalified groove weld details in AWS Figures 3.3 and 3.4, minimum prequalified PJP groove weld size in AWS Table 3.4, and minimum fillet weld size in AWS Table 5.8. “Matching” filler metals must be used, per AWS Table 3.1, and minimum preheat and interpass temperatures must be provided per AWS Table 3.2.

e. WPS Qualification Requirements. When WPSs, joints, filler metal selection, or other details do not meet the prequalification requirements of AWS *D1.1* Section 3, the WPS to be used for the joint must be qualified by testing prescribed in AWS *D1.1* Section 4. Documentation of the WPS used and test results must be documented in the form of Procedure Qualification Records (PQRs). Qualified WPSs must be referenced to the applicable PQR. PQRs must be in writing, and made available for inspection by the inspector.

f. Guidance for Engineering Review of Procedures Submitted by Contractors. For review of WPSs, the contractor should submit all applicable manufacturer data sheets and operating recommendations for the filler material to be used. It may also be necessary to consult the AWS A5.XX filler metal specifications for information regarding the use and limitations of the filler metal.

(1) Generally, manufacturer’s operating recommendations provide a range of welding parameters such as voltage and current (amperage) or wire feed speed, and specify polarity, but do not provide specific travel speeds or adjustments necessary to achieve a particular weld size. The middle of the provided ranges are often good starting points, but contractors often tend to work near the high end of the ranges provided to maximize deposition rates and reduce welding time.

(2) Calculations such as heat input and deposition rates are helpful in determining if WPSs should produce a reasonable quality weld of the size specified. However, it is often difficult to verify FCAW procedures through calculation because of the variations between specific electrode types. Calculation should not be used to determine optimum operating characteristics for welding, as these final adjustments are made by experience. See references in Appendix B.

(3) Caution should be used when reviewing WPSs for thick materials and highly restrained joints. The 25 mm (1 in.) test plate thicknesses specified in AWS *D1.1* Section 4, do not adequately represent the heat sink capabilities of thicker sections (affecting cooling rates), nor is restraint developed in the welding of standard WPS test specimens. The use of thicker plates and NDT, and the use of restraint devices, should be specified as appropriate for critical welding. Alternately, other WPS testing methods may be used as appropriate.

(4) A checklist should be prepared to verify that all welded joints on the project have written WPSs. Critical joints should be reviewed to verify that the proper welding materials have been designated for the joint, particularly when CVN toughness is required.

(5) Approval of the WPS should be taken as review only, and that the responsibility for the suitability of the WPS, and the resultant weld quality and properties, remains with the contractor.

3. WELDING PERSONNEL QUALIFICATION.

a. Personnel Classification. Welding personnel are classified into three categories: welders, welding operators, and tack welders. Welders manipulate the electrode by hand, manipulating and controlling the arc, for manual or semi-automatic welding. Welding operators set up automatic welding equipment with wire-fed welding processes, such as mechanized SAW, to travel at selected speeds. Tack welders may only place tack welds to assemble pieces, with the finish welds to be performed by qualified welders or welding operators.

b. Qualification Testing. All welding personnel must demonstrate their skill by performing specific performance qualification tests prescribed by AWS *D1.1* Section 4, Part C. Welders are qualified by process - SMAW, FCAW, GMAW, SAW, GTAW, ESW, or EGW. FCAW-S (self-shielded) and FCAW-G (gas-shielded) are considered the same process for performance qualification testing. Welders are also qualified by position - Flat, Horizontal, Vertical and Overhead. These are designated on welding personnel qualification records as positions 1, 2, 3, and 4, respectively. Welding personnel qualified for more difficult positions, for example Vertical (3), are also qualified for Flat (1) and Horizontal (2) welding. However, Vertical (3) and Overhead (4) welding positions are considered separately. Additional position classifications apply for tubular construction, and are further identified in AWS *D1.1* Figures 4.4 and 4.6. Welding personnel are further classified by type of weld, testing using groove welds or fillet welds. Welding personnel qualified for groove welding in a given position and process are also qualified for fillet welding in the same position and process. Those who qualify using 9.5 mm (3/8 in.) thick plate or thicker are qualified for twice the test plate thickness. Welding personnel qualified using 25.4 mm (1 in.) thick plate are qualified for unlimited thicknesses of material. AWS *D1.1* Table 4.8 provides complete information regarding the cross-over of welding performance qualifications tests and the welding products, thicknesses and positions qualified.

c. Contractor Responsibilities. The contractor is responsible for the qualification of all welding personnel. The witnessing of performance testing is not required. All performance qualification tests must be fully documented in writing. Performance qualification expires six (6) months following testing, unless the person has used the process during that time period. Should a person not use the process within six months, the qualification period expires. There should be records documenting the use of various processes by the contractor. Welding position is not a factor in maintaining welding personnel qualification. Should the welder consistently produce poor quality welds, the welder's qualification can be revoked, requiring retesting.

d. Qualification Testing by Others. Although standard practice is to require contractor-based qualification testing of welding personnel, it is acceptable, with the Engineer's approval, for the contractor to rely upon qualification testing performed by others. Such testing may include independent testing laboratories, welding vocational schools, industry associations and unions, and the AWS Certified Welder program. The Engineer should review the basis and suitability of such programs prior to waiver of contractor-based qualification.

4. INSPECTOR QUALIFICATIONS

a. General Welding and Visual Inspectors. Visual welding inspection personnel should be qualified under AWS *D1.1* Section 6.1.4. The basis of qualification, if beyond these provisions, must be specified in the project documents. Acceptable qualification bases under *D1.1* are: (1) current or previous certification as an AWS Certified Welding Inspector (CWI) in accordance with the provisions of AWS QC1, *Standard for AWS Certification of Welding Inspectors*, or (2) current or previous qualification by the Canadian Welding Bureau (CWB) to the requirements of the Canadian Standard Association (CSA) Standard W178.2, *Certification of Welding Inspectors*, or (3) an engineer or technician who, by training or experience, or both, in metals fabrication, inspection and testing, is competent to perform inspection work. For the third case, the Engineer should establish minimum levels of training and experience, require a written resume detailing training and experience in welding inspection, and require a written and hands-on examination prior to approval of the inspector.

(1) The qualification of an previously certified inspector remains in effect indefinitely, even though the certification may have expired, provided the inspector remains active in the inspection of welded

steel fabrication, or unless there is a specific reason to question the inspector's ability.

(2) The American Welding Society offers certification to welding inspectors in the form of Certified Welding Inspectors, Certified Associate Welding Inspectors, and Certified Senior Welding Inspectors. ANSI/AWS QC1-96, *Standard for AWS Certification of Welding Inspectors*, governs the requirements and testing of such inspectors, including experience level. The CWI examination tests the inspector’s knowledge of welding processes, welding procedures, welder qualification, destructive testing, nondestructive testing, terms, definitions, symbols, reports, records, safety and responsibilities. Although assumed to be competent to inspect welded construction, the AWS Certified Welding Inspector may not have the background or expertise in other areas of steel construction such as general fabrication and erection, bolted connections, steel bar joists, and metal decks, and additional education and training relative to these areas may be needed. It should also be verified that the AWS Certified Welding Inspector has tested, or is familiar with, the AWS *D1.1 Structural Welding Code*. It is permitted to take the AWS examinations using either the AWS *D1.1*, ASME *Boiler and Pressure Vessel Code*, or the API 1104 *Welding of Pipelines and Related Facilities* code, and welding inspection experience may be in any area of welding.

(3) AWS *D1.1* does not recognize the AWS Certified Associate Welding Inspector as qualified to perform the work solely based upon this certification. A CAWI has passed the same accreditation examination as the CWI, but has less experience, with two years minimum experience rather than five years, in the field of welding inspection. A CAWI could be acceptable under condition “c” as listed in AWS *D1.1* Section 6.1.4. The Senior Certified Welding Inspector is a new program offered by the AWS, and this recent certification option has not been included in the AWS *D1.1* code because of publication schedules. A SCWI should be considered the equivalent of a CWI.

(4) Although AWS *D1.1* allows inspector qualification without the CWI certification under AWS QC1 criteria, it is recommended that the welding inspection personnel for critical welding be AWS QC1 certified (or previously certified) by experience and written examination.

(5) All welding inspectors must have adequate visual acuity, documented by vision testing performed within the past three years. See AWS *D1.1* Section 6.1.4.4.

b. NDT Personnel Qualification. Certification of all levels of NDT personnel is the responsibility of the employer of the NDT technician. Nondestructive testing personnel should be qualified under the American Society for Nondestructive Testing, Inc., ANSI/ASNT CP-189, *ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel*, or ASNT *Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing.*

(1) Certification of NDT personnel should be based on demonstration of satisfactory qualification in accordance with Sections 6, 7 and 8 of ASNT SNT-TC-1A, as modified by the employer's written practice, or in accordance with Sections 4, 5 and 6 of ANSI/ASNT CP-189. Employers may rely upon outside training and testing for NDT personnel for certification, however, the employer should supplement such certification testing with a review of the technician’s experience and skill levels. It is suggested that the certification of NDT personnel should be administered by an ASNT Certified Level III in the specific area on NDT. Personnel certifications must be maintained on file by the employer and a copy should be carried by the technician.

(2) AWS *D1.1* Section 6.14.6 requires that nondestructive testing be performed by NDT Level II technicians, or by Level I technicians only when working under the direct supervision of a Level II. Inspection by a Level III technician is not recognized, as the Level III may not perform actual testing

regularly enough to maintain the special skills required to set up or to conduct the tests. AWS *D1.5*-96 requires similar qualification, except in the case of Fracture Critical Members. Under Section 12.16.1.2, testing of Fracture Critical Members must be done by either a qualified Level II under the supervision of a qualified Level III, or by a Level III certified by ASNT, unless the Engineer accepts other forms of qualification.

(3) The following definitions, from ANSI / ASNT CP-189, apply to the various NDT Levels:

- NDT Level I - An NDT Level I individual shall have the skills to properly perform specific calibrations, specific NDT, and with prior written approval of the NDT Level III, perform specific interpretations and evaluations for acceptance or rejection and document the results. The NDT Level I shall be able to follow approved nondestructive testing procedures and shall receive the necessary guidance or supervision from a certified NDT Level II or NDT Level III individual.
- NDT Level II - An NDT Level II individual shall have the skills and knowledge to set up and calibrate equipment, to conduct tests, and to interpret, evaluate, and document results in accordance with procedures approved by an NDT Level III. The Level II shall be thoroughly familiar with the scope and limitations of the method to which certified and should be capable of directing the work of trainees and NDT Level I personnel. The NDT Level II shall be able to organize and report nondestructive test results.
- NDT Level III - An NDT Level III individual shall have the skills and knowledge to establish techniques; to interpret codes, standards, and specifications; designate the particular technique to be used; and verify the accuracy of procedures. The individual shall also have general familiarity with the other NDT methods. The NDT Level III shall be capable of conducting or directing the training and examining of NDT personnel in the methods for which the NDT Level III is qualified.

5. INSPECTION CATEGORIES AND TASKS.

a. General. The inspector assigned responsibility for the welding of the project should review and understand the applicable portions of the project specifications, the contract design drawings, and the shop or erection drawings for the project, as appropriate. The inspector should participate in a pre-project meeting with the contractor to discuss the quality control and quality assurance requirements for the project. A record should be kept of all welders, welding operators and tack welders, welding personnel qualifications, welding procedures, accepted parts, the status of all joints not accepted, NDT test reports, and other such information as may be required. The inspector's duties can be assigned or placed into four general categories, by time period: pre-project inspection for general welding operations, inspection prior to welding a particular joint, inspection during welding of the joint, and inspection of the completed joint.

b. Pre-project Inspection. A pre-project inspection should be conducted of the fabricator's and erector's facilities and operations to verify the adequacy of their welding operations. The scheduling of this inspection should be well before welding is scheduled to begin, allowing time for necessary corrections and improvements by the contractor before welding begins.

(1) Personnel. The inspector should verify that all applicable welder, welding operator and tack welder qualification records are available, current and complete, and that any required special supplemental qualification tests, such as mock-ups, have been passed. Requalification is required for any welder, welding operator or tack welder who has, for a period of six months, not used the process for which the person was qualified. Each person performing welding should have a unique identification

mark or die stamp to identify his or her welds. See AWS *D1.1* Section 4, Part C.

(2) Equipment. All welding equipment should be in proper operating condition, with functioning gauges necessary for following the WPS for the selected process. Periodic checks should be performed by the contractor to verify the accuracy of gauges and other operating components of welding machines. Welding leads should be inspected for worn or missing insulation, or inadequate connectors. Ammeters should be available for verifying the current (amperage) near the arc, rather than at the machine. Records of equipment inspections and calibrations should be maintained, but there is no specific requirements for such in AWS *D1.1*. Inspections at least annually are recommended. See AWS *D1.1* Sections 5.11 and 6.3.2.

(3) WPSs. The inspector should verify that all applicable welding Procedure Qualification Records (PQRs) and Welding Procedure Specifications (WPSs) are available, current and accurate. WPSs should be available at welding work stations and used by all welding personnel. PQRs should be referenced and available for review for any non-prequalified WPSs. Qualified WPSs must be approved by the Engineer, per AWS *D1.1* Section 4.1.1. For high seismic applications, all WPSs must be approved by the Engineer. See AISC *Seismic Provisions* Section 7.3a. The Engineer's approval should be verified.

(4) Materials Controls. Electrodes and fluxes should be stored in their original, manufacturer-sealed containers until ready for placement in storage ovens or use. The manufacturer's identification labels, including lot number, should remain on the packaging. The contractor should have an operating system to verify that all materials in inventory have proper certification papers on file. The contractor's quality control system should be used to confirm that the proper welding consumables are selected.

(5) Materials Storage. The contractor should have all necessary welding consumable drying and storage equipment. The proper operating temperatures should be verified on a regular basis as a part of the contractor's quality control program. Welding personnel should be familiar with the SMAW electrode and SAW flux storage and exposure limitations of AWS *D1.1*, with an ongoing system in place to confirm compliance. No materials other than electrodes or fluxes, as appropriate, may be placed in drying or storage ovens. See AWS *D1.1* Section 5.3 for storage requirements. In addition to AWS *D1.1* mandated storage requirements, research indicates that certain FCAW electrodes may warrant protected storage or limited atmospheric exposure times. Such controls and limitations should be based upon manufacturer's test data and recommendations.

c. Prior to Welding. Prior to the actual start of welding on the project, item c(1) below should be performed. All other inspection items should be performed prior to beginning the welding of each joint. It is not anticipated that the inspector physically perform these inspections at each individual joint, but will verify that the contractor's personnel understand and routinely perform these inspections as a part of their welding operations. This may be done through observation of welding operations and informal inquiries of welding personnel. The inspector may, when desired, perform any physical inspections prior to welding to verify the contractor personnel's work.

(1) Pre-project review. Prior to the beginning of actual welding on the project, it should be verified that all non-compliance revealed during pre-project inspection has been rectified.

(2) Base metal quality. Steel joints to be welded must be smooth, uniform, and free from significant surface discontinuities such as cracks or seams, and free of significant amounts of loose or thick scale, slag, rust, moisture, grease, or other harmful foreign materials. See AWS *D1.1* Section 5.15 for complete base metal preparation requirements.

(3) Fillet weld fitup. Fillet welded joints must be fitup with a maximum gap of 1.6 mm (1/16 in.), unless corrective measure are taken. For gaps exceeding 1.6 mm (1/16 in.), but not to exceed 5 mm (3/16 in.), the leg size of the weld must be increased by an amount equal to the gap. Gaps over 5 mm (3/16 in.) are permitted only for steels over 76 mm (3 in.) in thickness, when suitable backing is placed in the root of the joint, and the fillet leg size is increased. See AWS *D1.1* Section 5.22.1.

(4) Groove weld fitup. Prequalified groove welds must be assembled within the “as fit-up” tolerance specified for the joint in AWS *D1.1* Figures 3.3 and 3.4. For Partial Joint Penetration (PJP) groove welds, assembly tolerances are provided in AWS *D1.1* Section 5.22.2. For other groove dimension tolerances applicable to other groove welds, see AWS *D1.1* Section 5.22.4.1.

(5) Steel temperature. The temperature of the steel at the joint prior to the initiation of welding must not be below 0^oC (32^oF). When steel temperatures are below these minimum temperatures, it is necessary to heat the steel in the vicinity of the joint to at least 21^oC (70^oF). See AWS *D1.1* Table 3.2, Note 1. For prequalified steels listed in AWS *D1.1* Table 3.2, as Category C steels, the minimum steel temperature at the joint is 10^oC (50^oF). Steels of thicknesses requiring preheat, per AWS *D1.1* Table 3.2, require higher temperatures. After heating, the temperature of the steel should be measured a distance 75 mm (3 in.) away from the joint. For welding in extreme cold environments, it is advisable to heat the steel to higher temperatures and apply the heat over a wider area.

(6) Ambient temperature. Welding is not permitted when the ambient (air) temperature is below -18^oC (0^oF), or when welding personnel are exposed to inclement environmental conditions. Protective covering or enclosures, with heating as necessary, may be used to satisfy this requirement and provide adequate protection and warmth for the welders and welding equipment.

(7) Wind speed. Gas-shielded welding processes (FCAW-G, GMAW, GTAW, and EGW) may not be performed in winds exceeding 8 km per hour (5 mph), as wind above this speed blows away the necessary shielding gas and contributes to poor weld quality and poor mechanical properties. For self-shielded welding processes (SMAW, FCAW-S, SAW, and ESW), the maximum wind speed is not specified by AWS *D1.1*, but should be limited to a maximum of 30 to 40 km per hour (20 to 25 mph). See AWS *D1.1* Section 5.12 for welding environment provisions.

(8) WPS, including preheat. The inspector should verify compliance of the welding consumables selected (electrode, flux and shielding gas) with the project requirements and the WPS. The selected electrodes should be taken only from proper storage, and used only in the permitted positions and within the welding parameters specified by the manufacturer and in the WPS. It should be verified that the WPS is appropriate for the joint, within any specified limitations.

(9) Preheat. Preheat temperatures as specified in the WPS must be provided and checked for compliance with AWS *D1.1* Table 3.2 if prequalified. Higher preheat temperatures may be specified. It may also be necessary to verify that the preheat temperature does not exceed any maximum values specified in the WPS, sometimes required for quenched and tempered, TMCP, or other special steels, or when toughness requirements apply. Verification of preheat temperature should be taken 75 mm (3 in.) from the joint, provided the thickest material joined is 75 mm (3 in.) or less in thickness. If the steel is thicker, then the temperature verification is taken a distance equal to the material thickness. Temperatures may be checked with surface temperature thermometers, close-range focused infrared devices, or with temperature-indicating crayons.

(10) Tack welds. Tack welds must be made using appropriate WPSs, including preheat when required. Tack welds should be visually inspected prior to being welded over by the finish weld. Cracks in

tack welds are likely to propagate into the main weld. Slag that has not been removed will likely result in slag inclusions in the completed weld.

d. During Welding. Observation of welding techniques and performance for each welder should be done periodically during welding operations to verify that the applicable requirements of the WPS and the AWS *D1.1* Code are met. Each pass should be visually inspected by the welder for conformance to AWS *D1.1* Table 6.1 provisions for cracks, fusion and porosity prior to placement of subsequent passes. To avoid trapped slag, penetration and fusion discontinuities, each weld bead profile should be in substantial conformance with the requirements of Table 6.1.

(1) WPS compliance. The inspector should verify that the welding is performed following the appropriate Welding Procedure Specification (WPS). If desired, proper current (amperage) and voltage for the welding operation may be verified using a hand held calibrated amp and volt meter. Because of welding lead losses, measurement should as near the arc as practical. Welds not executed in conformance with the WPS may be considered rejectable, and should be referred to a knowledgeable welding consultant and the Engineer for review.

(2) Interpass temperatures. Interpass temperatures as specified in the WPS must be provided and checked with compliance with AWS *D1.1* Table 3.2 if a prequalified groove weld joint. Higher preheat temperatures may be specified. It may also be necessary to verify that the interpass temperature does not exceed any maximum values specified in the WPS, sometimes specified for quenched and tempered, TMCP, or other special steels, or when toughness requirements apply. Verification of interpass temperature should be taken 75 mm (3 in.) from the joint, provided the thickest material joined is 75 mm (3 in.) or less in thickness. Temperatures may be checked with surface temperature thermometers, close-range focused infrared devices, or with temperature-indicating crayons.

(3) Consumables control. Exposure of SMAW electrodes and SAW fluxes must meet the time limitations of AWS *D1.1* Section 5.3. See AWS *D1.1* Table 5.1 for SMAW electrode exposure limits. SAW fluxes may require drying, special handling, recycling, and removal of exposed flux from opened packages. Although not limited by AWS *D1.1*, research indicates that some FCAW electrodes may absorb moisture in the order of 50% of the “as-manufactured” moisture content. When extra-low hydrogen welding electrodes are required for critical welding applications, and FCAW wires removed from the manufacturer’s packaging will not be consumed within a few days, special storage conditions limiting exposure times, repackaging unused FCAW wire in closed moisture-resistant packing overnight, or the use of storage ovens, may be appropriate. AWS *D1.5 Bridge Welding Code*, Section 12 provisions for Fracture Critical Nonredundant Members should be considered for guidance in special cases.

(4) Cleaning. Completed weld passes must be cleaned of all slag prior to placement of the next pass. Removal of debris by brushing is required. Wire brushing of the completed weld is recommended, but not required. Slag that has not been removed will likely result in slag inclusions in the completed weld. See AWS *D1.1* Section 5.30.

e. After Welding. After completion of the weld, full compliance with the AWS *D1.1* provisions should be verified. If required or specified, NDT is to be performed. Upon completion of inspection of the weld, piece, or project, as appropriate, proper documentation of the acceptance of the welding should be prepared and submitted to the designated parties.

(1) Measurement. The work should be visually inspected for conformance with the Visual Inspection Acceptance Criteria prescribed in AWS *D1.1* Table 6.1. These provisions prohibit cracks and lack of fusion, and permit limited amounts of undercut, porosity, and weld size underrun. Weld profile

tolerances are provided in AWS *D1.1* Figure 5.4, and Section 5.24. Size and contour of welds should be measured with suitable gauges. Craters are accepted in certain circumstances. Other weld acceptance criteria that is verified visually include arc strikes (AWS *D1.1* Section 5.29), and weld cleaning (Section 5.30). Visual inspection may be aided by a strong light, magnifiers, or other devices that may be helpful.

(2) Tolerances. The tolerances for the completed member, including cross-section, depth, camber, sweep, straightness, flatness, flange warpage and tilt, stiffener fit, and bearing surface fit, are prescribed in AWS *D1.1* Section 5.23.

(3) Records. The Inspector should mark the welds, joints, or members, as appropriate, that have been inspected and accepted using a distinguishing mark or die stamp. Alternatively, records indicating the specific welds inspected by each person may be maintained. The accepted, rejected and repaired items should be documented in a written report, distributed to the designated recipients in a timely manner.

f. Nondestructive Testing Methods. AWS *D1.1* does not require NDT for statically-loaded building structures, but NDT is required by both AISC and AWS *D1.1* for certain fatigue detail categories for cyclically-loaded structures. AISC Seismic Provisions require NDT for certain joints in high seismic applications, as follows: “All complete joint penetration and partial joint penetration groove welded joints that are subjected to net tensile forces as part of the Seismic Force Resisting Systems ... shall be tested using approved nondestructive testing methods conforming to AWS *D1.1*.” Such testing should include ultrasonic testing of welds in T-joints and butt joints over 8 mm (5/16 in.) in thickness. Radiographic testing may be used in some cases using butt joints. When using T-joints, with the thickness of the tee “flange” exceeding 40 mm (1-1/2 in.), ultrasonic testing should be performed after completion and cooling to check for lamellar tearing.

(1) The specific types of NDT, and the applicable acceptance criteria, must be specified in the contract documents. NDT symbols should be used to specify locations and types of NDT. See AWS A2.4 Part C.

(2) The contractor is responsible for performing any required NDT, unless specifically designated to be performed by another party.

(3) Because of the risk of delayed hydrogen cracking, a delay period of 24 to 48 hours should be considered prior to performing NDT for final acceptance for higher strength steels. See AWS *D1.1* Table 6.1 (5). The AWS *D1.5 Bridge Welding Code* Section 12.16.4 requires a longer delay period for Fracture Critical Members, depending upon weld size and steel strength.

(4) Tables 8-1 and 8-2 provide general guidance for the selection of NDT method(s). For complete information, see Appendix D.

Table 8-1. Applicable Inspection Methods for Various Discontinuities and Joint Types

Application	Inspection Method	VT	PT	MT	UT	RT
Discontinuity	Porosity	A[1]	A[1]	O[2]	O	A
	Slag Inclusions	U	U	O[2]	A	A
	Incomplete Fusion	U	U	U	A	O
	Inadequate Joint Penetration	U	U	U	A	A
	Undercut	A	O	O	O	A
	Overlap	O	A	A	O	U
	Cracks	A[1]	A[1]	A[2]	A	O
	Laminations	A[1,3]	A[1,3]	A[2,3]	A	U
Joints	Butt	A	A	A	A	A
	Corner	A	A	A	A	O
	T	A	A	A	A	O
	Lap	A	A	A	O	U

Notes:

A - Applicable
O - Marginal applicability, depending upon material thickness, discontinuity size, orientation, and location.
U - Generally not applicable.

[1] Surface only
[2] Surface and slightly subsurface only
[3] Weld preparation or edge of base metal

Table 8-2. Guidelines for Selecting Inspection Techniques

	VT	PT	MT	UT	RT
Equipment	Pocket magnifier, flashlight, weld gauges, scale, etc.	Fluorescent or visible penetration liquids and developers; ultraviolet light for fluorescent dyes	Wet or dry iron particles, or fluorescent; special power source; ultraviolet light for fluorescent particles	Ultrasonic units and probes; reference patterns	X-ray or gamma-ray; film processing and viewing equipment
Detection	Weld preparation, fit-up, cleanliness, roughness, spatter, undercut, overlap, weld contour and size	Discontinuities open to the surface only	Surface and near surface discontinuities: cracks; porosity; slag	Can locate all internal discontinuities located by other methods, as well as small discontinuities	Most internal discontinuities; limited by direction of discontinuity
Advantages	Easy to use; fast; inexpensive; usable at all stages of production	Detects small surface imperfections; easy application; inexpensive; low cost	Detects discontinuities not visible to the naked eye; useful for checking edges before welding; no size limitations	Extremely sensitive; complex weldments restrict usage	Provides permanent record of surface and internal discontinuities
Limitations	For surface conditions only; dependent on subjective opinion of inspector	Time-consuming; not permanent	Surface roughness may distort magnetic field; not permanent	Highly skilled interpreter required; not permanent	Usually not suitable for fillet weld or T-joint inspection; film exposure and processing critical; slow and expensive

Comments	Most universally used inspection method	Indications may be misleading on poorly prepared or cleaned surfaces	Test from two perpendicular directions to detect any indications parallel to one set of magnetic lines		Radiation hazards

6. WELD QUALITY.

a. Engineer’s Responsibility for Acceptance Criteria. The Engineer is given the responsibility of determining and specifying the appropriate weld quality acceptance criteria. AWS *D1.1* quality criteria is a workmanship standard, based upon the quality readily achievable by a qualified welder. Non-destructive testing acceptance criteria is based upon achievable quality and the ability of the method to detect discontinuities of given size and location, with some consideration for the effect of surface and near-surface notches upon performance. The Engineer may use experience, analysis, or experimental evidence to establish alternate acceptance criteria. This criteria may be applied as the inspection criteria for the project, in lieu of AWS *D1.1* criteria, or may be used to establish when repair or replacement of a weld is required for a given discontinuity or situation. The first approach is valuable because it reduces the time and expense of inspection, and eliminates needless repairs, reducing the risk of creating additional discontinuities while performing repairs, and reduces the potential detrimental effects to the existing base metal. The second approach is also valuable, but does not reduce inspection expense. See AWS *D1.1* Section C6.8.

b. D1.1 Visual Acceptance Criteria. The following table provides the specification reference location for various forms of weld discontinuities:

Weld Discontinuity	**AWS D1.1 References**
Crack	**Table 6.1 (1)**
Fusion	**Table 6.1 (2)**
Weld Craters	**Table 6.1 (3)**
Weld Profile (convexity, concavity, overlap, reinforcement)	**Table 6.1 (4), 5.24**
Weld Size (underrun, lack of penetration, underfill)	**Table 6.1 (6), 6.5.1**
Undercut	**Table 6.1 (7)**
Porosity	**Table 6.1 (8)**
Arc Strike	**5.29**
Surface Slag	**5.30**
Spatter	**5.30.2**
Length	**6.5.1**
Location	**6.5.1**

c. NDT Acceptance Criteria. When penetrant testing (PT), and magnetic particle testing (MT) are specified, the acceptance criteria to be used is the same as that for visual inspection. For ultrasonic testing (UT), the visual inspection criteria is applicable, plus the requirements of AWS *D1.1* Section 6.13. For radiographic testing (RT), the visual inspection criteria is applicable, plus the requirements of AWS *D1.1* Section 6.12.

d. Alternate Acceptance Criteria. The Engineer may base alternate weld quality acceptance criteria on experience, experimental results, structural analysis, or fracture mechanics analysis considering material properties and behavior, service and fracture loads and strengths, and environmental factors. Sources of information to assist in the development of alternate acceptance criteria are provided in Appendix B, Bibliography.

7. REPAIRS TO BASE METAL AND WELDS.

a. Mill Defects. ASTM A6 Section 9, requires only visual inspection by the mill of the completed product for defects in workmanship. Subsurface inspection for laminations and other defects, such as straight-beam ultrasonic testing, would be performed only when specified in the mill order, at extra cost. The mill is permitted to perform removal and repairs to the surface using various means such as grinding and welding, to limits specified in ASTM A6 Section 9. During fabrication, should unacceptable internal discontinuities be discovered in the steel, the steel may be considered rejectable. The size or type of internal discontinuity considered rejectable is not defined by specification.

b. Laminations. When internal laminations in the steel are discovered during fabrication, AWS *D1.1* Section 5.15.1, provides procedures for the investigation and repair of the exposed laminations. All exposed laminations must be explored for depth. Shallow laminations need not be repaired, but longer and deeper laminations will need either removal by grinding or welding to close the lamination prior to welding the joint. Laminations at welded joints may serve as sources of porosity and as crack initiation points.

c. Weld Discontinuities. For welds with unacceptable convexity, excessive reinforcement, or overlap, the weld should have the excess weld metal removed. This is typically done by grinding, but may be done by gouging. For undersized welds, including craters, the weld should be filled to the required size. Some craters may be acceptable if outside the required effective length of weld. For excessive undercut, the undercut portion should be filled using an approved repair procedure. For cracks, lack of fusion, and excessive porosity, the unacceptable portion must be completely removed and replaced. Additional caution should be used when repairing cracks. The end of the crack should be located using PT or MT, then crack removal should begin approximately 50 mm (2 in.) from the end of the crack and work toward the center of the crack. Starting within the crack may cause the crack to grow during removal. See AWS *D1.1* Section 5.26.1. Should it be necessary to cut the materials apart, the Engineer must be notified.

d. Root Opening Corrections. Root openings that are too narrow must be increased in width to the required root opening. Narrow root openings contribute to trapped slag, poor penetration and lack of fusion near the root. Repairs for narrow root openings may be done by grinding, chipping, air carbon arc gouging, if refitting the parts is not feasible. Root openings that are too wide are significant in that they increase the weld volume, increasing distortion and increasing the risk of lamellar tearing in T-joints, as well as increasing cost. A root pass placed across a wide root opening may develop shrinkage cracks in the HAZ or in the throat of the weld. Repair of wide root openings entails facing the groove with weld metal until the required root opening is achieved. Such a repair does not reduce volume or cost, but controls distortion and through-thickness strains in T-joints. An alternative to repair of this type would be to use split-layer techniques for the root pass, and subsequently control bead placement to minimize shrinkage and distortion effects.

e. Mislocated Holes. When holes have been mislocated, it is best to either leave the hole unfilled or to place a bolt in the hole. It is difficult to fill a hole by welding. When the hole must be filled, generally when a new hole must be placed near or adjacent to the misplaced hole, a special repair procedure should be followed to elongate the hole, then weld using stringer passes. NDT may be necessary after welding, if required elsewhere on the project for groove welds. NDT is required for repair welds for holes in cyclically loaded members. See AWS *D1.1* Section 5.26.5.

CHAPTER 9

OTHER WELDING SPECIFICATIONS AND STANDARDS

1.TUBULAR STRUCTURES. For the welding of tubular members, also referred to as hollow structural sections, refer to ANSI/AWS *D1.1* tubular provisions and the AISC *Connections Manual for Hollow Structural Sections*. These documents apply to the specific requirements of tube-to-tube applications, but are also applicable to tube-to-plate applications.

2. SHEET STEEL WELDING. For welding steel materials less than 3.2 mm (1/8 in.) in thickness, refer to ANSI/AWS *D1.3 Structural Welding Code - Sheet Steel*, and the AISI *Specification for the Design of Cold-Formed Steel Structural Members* for general design provisions. Sheet steels equal to or greater than 3.2 mm (1/8 in.) thick, but less than or equal to 4.8 mm (3/16 in.) thick, may be welded under either AWS *D1.3* or AWS *D1.1*.

3. REINFORCING STEEL. For welding reinforcing steel, including mats, fabric, metal inserts and connections in reinforced concrete construction, refer to ANSI/AWS *D1.4 Structural Welding Code - Reinforcing Steel*. For reinforcing steel welded to structural steel, AWS *D1.4* must be met for the weld, but any applicable provisions, such as preheat requirements, based upon the structural steel must also be met.

4. STAINLESS STEEL. For welding of stainless steels, refer to ANSI/AWS *D1.6 Structural Welding Code - Stainless Steel*. This code includes welding of hot- and cold-rolled sheets and plate, shapes, tubular members, clad materials, castings and forgings of stainless steels. It is not applicable to pressure vessels or pressure piping with pressures exceeding 104 kPa (15 psig).

5. ALUMINUM. For the welding of structural aluminum alloys, refer to ANSI/AWS D1.2 *Structural Welding Code - Aluminum*.

6. BRIDGES. For the welding of highway bridges designed for vehicular traffic, refer to the ANSI/AASHTO/AWS *D1.5 Bridge Welding Code*, including the Fracture Control Plan for nonredundant bridge members, if applicable.

7. MATERIAL HANDLING EQUIPMENT. For the welding of material handling equipment, refer to ANSI/AWS D14.1 *Specification for Welding Industrial and Mill Cranes and Other Material Handling Equipment*. This specification applies to the welding of all principal structural weldments and all primary welds used in the manufacture of cranes for industrial, mill, powerhouse and nuclear facilities. It also applies to other overhead material handling machinery and equipment that supports and transports loads.

8. CAST STEEL. See Appendix B - Bibliography.

9. CAST IRON. See Appendix B - Bibliography.

10. WROUGHT IRON. See Appendix B - Bibliography.

11. OTHER GOVERNING SPECIFICATIONS

a. ASME. For the welding of pressure vessels, refer to ANSI/ASME BPVC, *Boiler and Pressure Vessel Code, Section 9, Welding and Brazing Qualifications.*

b. API. For the welding of offshore structures, refer to the API RP 2A series documents, *Planning, Designing and Constructing Fixed Offshore Platforms*. For the welding of pipelines, refer to API Standard 1104, *Welding of Pipelines and Related Facilities*. For the welding of storage tanks, refer to API 12D *Field Welded Tanks for Storage of Production Liquids*, or API 12F, *Shop Welded Tanks for Storage of Production Liquids*.

c. AWWA. For the welding of water tanks, refer to AWWA Manual M42, *Steel Water Storage Tanks* .

CHAPTER 10

SAFETY AND ENVIRONMENTAL CONSIDERATIONS

1. GENERAL.

The following provisions should not be considered all-inclusive, complete, or exclusive. Refer to applicable governing documents for complete information.

2. SAFETY.

a. Fire. Welding, thermal cutting, and arc gouging operations produce molten metal that may cause burns, fires, or explosion. The fuel gases used pose no hazard, provided they are handled and stored in a safe and proper manner. Oxygen for oxyfuel cutting is not flammable by itself, but will contribute to more intense fires if pure oxygen is available. SMAW electrode stubs are very hot and could cause a fire if carelessly thrown on wood or paper products. Poor quality or poorly maintained electrical connections can cause overheating or sparking and subsequent ignition. During operations, molten steel, sparks and spatter often travel a considerable distance, risking a fire in nearby flammable materials. The following safety guidelines should be considered:

- move the object to receive the work away from combustible materials
- move the combustible materials at least 15 m (50 ft.) from the welding or cutting operation
- provide suitable fire-resistant shielding around the work area or combustible material
- fire extinguishing equipment should be accessible to welding personnel
- trained fire watch personnel should be used if the operations are performed near combustible materials.

b. Confined Spaces. Work in confined spaces requires additional safety precautions. A confined space could be a tank, pit, etc. that does not allow for adequate ventilation for the removal of hazardous gases or fumes resulting from the work. Certain welding processes use gases such as argon, helium, carbon dioxide or nitrogen which will not support life. Deaths and severe injuries due to lack of oxygen have occurred where the concentration of these gases becomes too high, (i.e.,where the available oxygen is too low).The following additional safety guidelines should be considered:

- remove flammable or hazardous materials from the space,
- provide adequate ventilation air to the space,
- test the atmosphere in the space before and during the work,
- inspect all electrical cables and connections,
- test all fuel gas and shielding gas lines for leaks,
- cutting torches must not be lit or extinguished within the space,
- no compressed gas cylinders or welding power sources may be placed inside the space,
- electrical power must be disconnected and all gas valves closed when work is suspended for any substantial period of time,
- if only a small opening is available for entry, the welder must wear an approved safety harness equipped with a rope or lifeline, tied off and held by a worker stationed outside the space.

c. Eye Protection. The arc produced from welding or air carbon arc gouging may burn the eyes. Proper filters and cover plates must be worn to protect the eyes from sparks and the rays of the arc.

d. Burn protection. Arc burn may be more severe than sunburn. Molten metal, sparks, slag, and hot material can cause severe burns if precautionary measures are not used. Protect the skin against radiation and hot particles, electrodes, and metal. Suitable flame-resistant clothing must be worn as protection from sparks and arc rays.

e. Electrocution. The electrode, electrode reel (for wire-fed processes), and workpiece (or ground) are considered electrically “hot” when the welder is on. These parts must not be touched with bare skin or wet clothing. Dry, hole-free gloves are necessary. The work piece and welding equipment must be grounded.

f. Fumes and Gases.

(1) Many welding, cutting and allied processes produce fumes and gases that may be harmful. Fumes are solid particles that originate from welding consumables, the base metal and any coatings present on the base metal. In addition to shielding gases that may be used, gases are produced during the welding process or may be produced by the effects of process radiation on the surrounding environment. The amount and composition of these fumes and gases depend upon the composition of the filler metal and base material, welding process, current level, arc length and other factors.

(2) Most welding fumes from carbon steel and low alloy steel electrodes do not require any attention to limits for any specific compound or compounds. The compounds in the fume such as oxides and fluorides of aluminum, calcium, iron, magnesium, potassium, silicon (which is amorphous in welding fumes), sodium, and titantium, do not have individual effects, except that excessive iron may cause siderosis (iron deposits in the lungs). Their effects are submerged in the overall effects which may be expected from nuisance dusts.
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(3) Some specific fume components such as chromium, cobalt, copper, fluorides, manganese, and nickel are present in some electrodes, require special attention, and have special health hazards. When these are present at levels of concern, they are listed on the product label and in the MSDS. Their health hazards are discussed in the MSDS.

(4) Depending on material involved, fume effects range from irritation of eyes, skin and respiratory system to more severe complications and may occur immediately or at some later time. Fumes may also cause symptoms such as nausea, headache, and dizziness.

(5) The following safety guidelines should be considered, as a minimum:

- Keep the head out of the fumes.
- Do not breathe the fumes.
- Use enough ventilation or exhaust at the arc, or both, to keep fumes and gases from the breathing zone and general area.
- In some cases, natural air movement provides enough ventilation and fresh air.
- Where ventilation is questionable, use air sampling to determine the need for corrective measures.
- Use mechanical ventilation when necessary to improve air quality.
- If engineering controls are not feasible, use an approved respirator.
- Follow OSHA guidelines for permissible exposure limits (PELs) for various fumes.
- Follow the American Conference of Governmental Industrial Hygienists recommendations for threshold limit values (TLVs) for fumes and gases.

g. Further Guidance. See ANSI / AWS Z49.1 Safety in Welding, Cutting and Allied Processes, and the Bibliography in Appendix B for further general information. The Material Safety Data Sheet (MSDS) for each product used also provides essential information.

3. ENERGY CONSUMPTION.

Shop welding operations are almost always electrically powered. Field operations may be electrically powered or powered by generators. Some field welding equipment is directly engine driven. Power requirements depend more upon electrode diameter than welding process. SMAW, FCAW and GMAW welding equipment draws essentially the same current ranges, and SAW, ESW and EGW draws more current to provide the higher deposition rates achievable and desired. The total power consumption difference between processes for a given joint configuration is negligible. To save energy, the minimum weld size and minimum groove cross-sectional area adequate to carry the load should be specified.

APPENDIX A

REFERENCES

GOVERNMENT PUBLICATIONS

United States Army Corps of Engineers

TI 800-01, Design Criteria
TI 809-01, Load Assumptions for Buildings
TI 809-02, Structural Design Criteria for Buildings
TI 809-04, Seismic Design for Buildings
TI 809-05, Seismic Evaluation and Rehabilitation for Buildings
TI 809-07, Design of Cold-Formed Load Bearing Steel Systems and Masonry Veneer / Steel Stud Walls
TI 809-30, Metal Building Systems

MIL-HDBK-1002/1, Structural Engineering, General Requirements
MIL-HDBK-1002/3, Structural Engineering, Steel Structures
MIL-HDBK-1002/6, Aluminum Structures, Composite Structures, Structural Plastics, and Fiber-Reinforced Composites.

Department of the Army

TM 5-809-6, Structural Design Criteria for Structures Other Than Buildings *(to become TI 809-6)*

Federal Emergency Management Agency (FEMA)

FEMA 267, Interim Guidelines: Evaluation, Repair, Modification and Design of Steel Moment Frames, August 1995
FEMA 267B, Interim Guidelines Advisory No. 2
FEMA 273, NEHRP Guidelines for the Seismic Rehabilitation of Buildings, October 1997
FEMA 302, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, February 1998

NONGOVERNMENT PUBLICATIONS

American Institute of Steel Construction
One East Wacker Drive, Suite 3100
Chicago, IL 60601-2001
www.aisc.org

Metric Load and Resistance Factor Design Specification for Structural Steel Buildings, December 1, 1994
  (Supplement No. 1, January 30, 1998)
  (new specification to be issued in early 2000)
Load and Resistance Factor Design Specification for Structural Steel Buildings, December 1, 1993
  (Supplement No. 1, January 30, 1998)

(new specification to be issued in early 2000)
Specification for Structural Steel Buildings (Allowable Stress Design and Plastic Design), June 1, 1989
Seismic Provisions for Structural Steel Buildings, April 15, 1997
(Supplement No. 1, February 15, 1999)
Specification for Load and Resistance Factor Design of Single-Angle Members, December 1, 1993
Specification for the Design of Steel Hollow Structural Sections, April 15, 1997
Code of Standard Practice for Steel Buildings and Bridges, June 10, 1992
Metric Conversion of the 2nd Edition Manual of Steel Construction, Load and Resistance Factor Design, 2nd Edition, Volumes I and II, 1999
Manual of Steel Construction, Load and Resistance Factor Design, 2nd Edition, Volumes I and II, 1994
Manual of Steel Construction, Allowable Stress Design, 9th Edition, 1989
Manual of Steel Construction, ASD/LRFD, Volume II Connections, 1992
Hollow Structural Sections Connections Manual, 1997

American Society for Testing and Materials (ASTM)
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

Annual Book of Standards
Volume 1.04, Steel - Structural, Reinforcing, Pressure Vessel, Railway
Volume 3.03, Nondestructive Testing

American Welding Society
550 NW LeJeune Road
Miami, FL 33126
www.aws.org

ANSI/AWS D1.1-98, Structural Welding Code - Steel
ANSI/AWS D1.3-98, Structural Welding Code - Sheet Steel
ANSI/AWS D1.4-98, Structural Welding Code - Reinforcing Steel
ANSI/AASHTO/AWS D1.5-96, Bridge Welding Code
ANSI/AWS D1.6-98, Structural Welding Code - Stainless Steel
ANSI/AWS A2.4-98, Standard Symbols for Welding, Brazing, and Nondestructive Testing
ANSI/AWS A3.0-94, Standard Welding Terms and Definitions
ANSI/AWS A5.1-91, Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding
ANSI/AWS A5.5-96, Specification for Low–Alloy Steel Electrodes for Shielded Metal Arc Welding
ANSI/AWS A5.17/A5.17M-97, Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding
ANSI/AWS A5.18-93, Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding
ANSI/AWS A5.20-95, Specification for Carbon Steel Electrodes for Flux Cored Arc Welding
ANSI/AWS A5.23/A5.23M-97, Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding
ANSI/AWS A5.25/A5.25M-97, Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding
ANSI/AWS A5.26/A5.26M-97, Specification for Carbon and Low-Alloy Steel Electrodes for Electrogas Welding
ANSI/AWS A5.28-96, Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc

Welding
ANSI/AWS A5.29-98, Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding
ANSI/AWS A5.32/A5.32M-97, Specification for Welding Shielding Gases
ANSI/AWS Z49.1:1999, Safety in Welding, Cutting and Allied Processes

American Society for Nondestructive Testing, Inc.
PO Box 28518
Columbus, OH 43228-0518
www.asnt.org

ANSI/ASNT CP-189-1995, ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel
Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing, 1995

APPENDIX B

BIBLIOGRAPHY

Welding Cracks Investigation Report, Steel Special Moment Resisting Frames, Elmendorf Air Force Base Hospital, Anchorage, Alaska, December 1996

American Institute of Steel Construction
- Allowable Stress Design of Simple Shear Connections, 1990
- Engineering and Quality Criteria for Steel Structures, 4th Edition, 1997
- Engineering Journal, *Experimental Investigation of Dogbone Moment Connections* (Engelhart, et al), Vol 35, No 4, 4th Qtr 1998
- Engineering Journal, *Ultimate Strength Considerations for Seismic Design of the Reduced Beam Section (Internal Plastic Hinge)* (Iwankiw), Vol 34, No 1, 1st Qtr 1997
- Engineering and Quality Criteria for Steel Structures, 4th Edition, 1997
- Load and Resistance Factor Design of Simple Shear Connections, 1990

American Petroleum Institute
- API 12D, Field Welded Tanks for Storage of Production Liquids (1994)
- API 12F, Shop Welded Tanks for Storage of Production Liquids (1994)
- API RP 2A series documents, Planning, Designing and Constructing Fixed Offshore Platforms
- API Standard 1104, Welding of Pipelines and Related Facilities, 18th Ed. (1994)

American Society for Metals
- ASM Handbook, Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys, 1990
- ASM Handbook, Volume 6: Welding, Brazing and Soldering, 1993
- ASM Metals Handbook, 2nd Ed., 1998
- ASM Specialty Handbook: Carbon and Alloy Steels, 1996
- ASM Specialty Handbook: Cast Irons, 1996
- Steel Castings Handbook, 6th Ed., 1995
- Weld Integrity and Performance, 1997

American Society for Nondestructive Testing
- Nondestructive Testing Handbook
  - Volume 2: Liquid Penetrant Tests, 2nd Ed, 1982
  - Volume 3: Radiography and Radiation Testing, 2nd Ed, 1985
  - Volume 6: Magnetic Particle Testing, 2nd Ed, 1989
  - Volume 7: Ultrasonic Testing, 2nd Ed, 1991
  - Volume 8: Visual and Optical Testing, 2nd Ed, 1993

American Society of Mechanical Engineers
- ANSI/ASME BPVC, Boiler and Pressure Vessel Code, Section 9, Welding and Brazing Qualifications (1998)

American Water Works Association
- AWWA Manual M42 Steel Water Storage Tanks (1998)

American Welding Society

- Guide for Nondestructive Inspection of Welds, ANSI/AWS B1.10-86
- Guide for Visual Inspection of Welds, ANSI/AWS B1.11-88
- Guide for Welding Iron Castings, ANSI/AWS D11.2-89
- Oxygen Cutting Surface Roughness Gauge, AWS C4.1-G
- Recommended Practices for Air Carbon Arc Gouging and Cutting, ANSI/AWS C5.3-91
- Recommended Practices for Stud Welding, ANSI/AWS C5.4-93
- Specification for Underwater Welding, ANSI/AWS D3.6-93
- Specification for Welding Industrial and Mill Cranes and Other Material Handling Equipment, AWS D14.1-97
- Welding Handbook, 8th Edition
  - Volume 1, Welding Technology, 1987
  - Volume 2, Welding Processes, 1991
  - Volume 3, Materials and Applications, Part 1, 1996
  - Volume 4, Materials and Applications, Part 2, 1998
- Welding Inspection, 1980
- Welding Metallurgy, 4th Edition, Volume 1, Fundamentals, George E. Linnert, 1994
- Welding of Cast Iron, 1985

Federal Emergency Management Agency

- FEMA 288, Background Reports: Metallurgy, Fracture Mechanics, Welding, Moment Connections and Frame Systems Behavior, March 1997
- FEMA 303, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, February 1998

Alternate Weld Quality Acceptance Criteria

- British Standards Institution
  - BS PD-6493:1991, Guidance on methods for assessing the acceptability of flaws in structures
  - BS 7910: pending (1999), Guidance on methods for assessing the acceptability of flaws in structures

- Electric Power Research Institute
  - NP-5380, *Visual Weld Acceptance Criteria*

- International Institute of Welding
  - IIW / IIS-SST-1157-90, IIW Guidance on Assessment of the Fitness for Purpose of Welded Structures, Draft for Development, 1990

- Welding Research Council
  - WRC Bulletin 295, Fundamentals of Weld Discontinuities and their Significance (Lundin), 1984

Design Aids for Welded Connections

- American Institute of Steel Construction
  - AISC Manual of Steel Construction (ASD and LRFD versions)
  - Allowable Stress Design of Simple Shear Connections (1990)
  - CONXPRT (software)

- Load and Resistance Design of Simple Shear Connections (1990)
    - Module I - ASD Simple Shear Connections
    - Module I - LRFD Simple Shear Connections
    - Module II - ASD Moment Connections
- Steel Detailing Software Packages with Connection Design
    - CDS
    - CompuSTEEL (Barasel Corp.)
    - CVSpro8 (CadVantage, Inc.)
    - DESCON (Omnitech Associates)
    - DETAIL (MacroSoft)
    - fabriCAD (Research Engineers, Inc.)
    - SDS/2 (Design Data, Inc.)
    - Steelcad (Steelcad International, Inc.)
    - StruCad (AceCad Software, Inc.)
    - StrucPro (Eagle Point)
- Canadian Welding Bureau
    - Weld_ IT (software)

Safety and Health

American Conference of Governmental Industrial Hygienists (ACGIH)
Threshold Limit Values (TLV (R)) for Chemical Substances and Physical Agents in the Workroom Environment

American Welding Society, Fumes and Gases in the Welding Environment

National Fire Protection Association
Standard for Fire Prevention in Use of Cutting and Welding Processes: NFPA 51B, National Fire Protection Association, 1994

Occupational Safety and Health Administration (OSHA)
Code of Federal Regulations, Title 29, Labor, Chapter XV11, Parts 1901.1 to 1910.1450, Order No. 869-029-00222-5

Intermixed Weld Metal

The Effects of Intermixed Weld Metal on Mechanical Properties – Part 1, Quintana, M. A. and Johnson, M. Q., Welding Journal, March 1999

The Effects of Intermixed Weld Metal on Mechanical Properties – Part 2, Quintana, M. A. and Johnson, M. Q., Proceedings, AWS Annual Convention, Detroit, MI, 1998

The Effects of Intermixed Weld Metal on Mechanical Properties – Part 3, Quintana, M. A. and Johnson, M. Q., Proceedings, AWS Conference on Welded Construction in Seismic Areas, Maui, HI, 1998

Welding Procedures

Heat-Straightening Repairs of Damaged Steel Bridges – A Technical Guide and Manual of Practice, Report No. FHWA-IF-99-004, US Dept. of Transportation, Federal Highway Administration, October 1998

Lincoln Electric Company, The Procedure Handbook of Arc Welding, 13th Ed., 1994

Reviewing and Approving Welding Procedure Specifications, Miller, D. K., Proceedings, AISC National Steel Construction Conference, New Orleans, LA, April, 1998

What Every Engineer Should Know about Welding Procedures, Miller, D. K., Welding Journal, August 1999

Other References and Textbooks

Cast Publishing
  Metals Blue Book, Welding Filler Metals, 2nd Ed, 1998
  Metals Black Book, Ferrous Metals, 3rd Ed, 1998
  Metals Red Book, Nonferrous Metals, 2nd Ed, 1998

Fracture and Fatigue Control in Structures, 2nd Ed., Barsom, J. M. and Rolfe, S. T., Prentice-Hall, 1987

Lincoln Electric Co. / James F. Lincoln Arc Welding Foundation
  Design of Welded Structures, 1966
  Design of Weldments, 1976
  Metals & How to Weld Them, 1962
  The Procedure Handbook of Arc Welding, 13th Edition, 1994
  Tubular Steel Structures - Theory and Design, 1990

Modern Welding Technology, 4th Ed., Cary, H. B., Prentice-Hall, 1997

Weldability of Steels, Stout, R. D. and Doty, W. D., Welding Research Council, 1953

APPENDIX C

WELDING PROCESSES

1. SHIELDED METAL ARC WELDING (SMAW).

a. Process Principles. The Shielded Metal Arc Welding (SMAW) process is commonly known as "stick" welding, and is performed as "manual" welding. An electric arc is produced between the tip of the electrode and the base metal, melting both. The molten weld pool, and completed weld, is a mixture of base metal and electrode materials.

(1) The core of the electrode is steel. The coating is of various materials designed to provide arc stability, shield the molten weld puddle from atmospheric gases, flux the molten puddle of impurities, deoxidize the molten weld puddle, and cover the solidifying weld to improve bead profile. Some coatings contain metallic powders, adding specific alloys to the weld composition.

(2) SMAW may be operated using either DC (direct current) or AC (alternating current) polarity. Generally, DC is used for smaller diameter electrodes, typically those with a diameter of less than 4.8 mm (3/16 in.). To eliminate undesirable arc blow conditions, larger electrodes are typically operated using AC. Electrodes used on AC must be designed specifically to operate in this mode, where the current changes direction 120 times per second on 60 Hertz power. AC electrodes may also operate using either DCEN (DC Electrode Negative, DC-, also called "straight" polarity) or DCEP (DC Electrode Positive, DC+, also called "reverse" polarity), and in some cases, either DC polarity.

b. Filler Metal Designation, Specification and Certification. Filler metal specification AWS A5.1 provides the requirements for carbon steel covered electrodes used with SMAW. AWS A5.5 similarly covers the low-alloy steel electrodes for SMAW.

(1) Generally, when welding on structural steels with a minimum specified yield strength equal to or exceeding 485 MPa (50 ksi), SMAW electrodes should be of the low hydrogen type. See AWS *D1.1* Table 3.1 lists specific steels and grades where the use of low hydrogen electrodes is required for the prequalification of SMAW Welding Procedure Specifications (WPSs). Table 3.1 also provides the strength of electrode required for these steels to provide the "matching" strength for the base metal. Group I steels, including A36 steel, may be welded with non-low hydrogen electrodes. For Group II steels, including A572 grade 50, and higher strength groups, low hydrogen electrodes are required. For most structural steel fabrication today, low hydrogen electrodes are prescribed to offer additional assurance against hydrogen induced cracking.

(2) Low hydrogen electrodes have coatings of inorganic materials that are very low in hydrogen, and are designed to be extremely low in moisture. Water (H_2O) will break down into its components, hydrogen and oxygen, under the arc. This hydrogen can then enter into the weld deposit and may lead to unacceptable weld and heat affected zone cracking under certain conditions.

(3) The term "low hydrogen" was initially used to separate those SMAW electrodes capable of depositing weld metal with low levels of diffusible hydrogen from non-low hydrogen electrodes such as E6010 and E6012 that contain, by design, coating moisture levels of 2 to 4%. For prequalified WPSs, AWS *D1.1* Table 3.2 provides one series of minimum preheat and interpass temperatures for "non-low hydrogen electrodes", and another series of values for SMAW with low hydrogen electrodes and all FCAW, SAW and GMAW. This implies a similarity in expected maximum levels of diffusible hydrogen.

When SMAW low hydrogen electrodes are used, the required levels of preheat are lower, offering economic and time-saving advantages to the contractor. AWS *D1.1* and the AWS A5 filler metal specifications do not currently define “low hydrogen.” International Institute of Welding (IIW) documents classify electrodes for diffusible hydrogen as follows: very low hydrogen (0-5 mL / 100 g deposited weld metal), low hydrogen (5-10), medium hydrogen (10-15), and high hydrogen (15-20), but these definitions are unrelated to AWS usage and specifications.

(4) SMAW electrodes are classified based on a four or five digit number that follows the letter E (for electrode). The electrode classification is imprinted on the coating near the end of the electrode, as well as on the electrode package. See Table C-1. In filler metal specification AWS A5.1, low hydrogen carbon steel SMAW electrodes are identified with the last “X” number in the designator EXXXX as a 5, 6 or 8. A5.1 SMAW low hydrogen electrode classifications include E7015, E7016, E7018, E7018M, E7028, and E7048. The E7015 electrodes operate using DCEP only. E7016 electrodes operate using either AC or DCEP. The E7018 electrodes operate using AC or DCEP, and include approximately 25% iron powder in their coatings to increase their deposition rate. An E7028 electrode contains approximately 50% iron powder in the coating, enabling it to deposit metal at even higher rates. However, as the nomenclature shows, the “2" would indicate that this electrode is suitable for flat position welding and, for fillet welds only, the horizontal position. E7018M electrodes may be used only with DCEP, and have been tested for absorbed moisture and diffusible hydrogen. E7048 electrodes are similar to E7018 electrodes in composition, and may be used in any position, AC or DCEP, except for vertical welding in the upward progression. E7048 electrodes are specifically designed for good welding in the vertical downward progression.

(5) In the AWS A5.5 low-alloy steel SMAW electrode specification, a similar format is used to identify SMAW electrodes. See Table C-2. The most significant difference in nomenclature from A5.1 is the inclusion of a suffix letter and number indicating the alloy content. As an example, an E8018-C3 nickel steel electrode, with suffix “-C3", indicates the electrode nominally contains 1% nickel. A “-C1" electrode nominally contains 2.5% nickel. Some electrodes carry the “-W” designation, indicating the presence of alloys capable of giving the weld atmospheric corrosion resistance for exposed weathering applications. Low hydrogen low-alloy SMAW electrodes are similarly identified with the last “X” number in the designator EXXXX-Y as a 5, 6 or 8.

(6) Optional supplemental designators may be used to indicate the maximum level of hydrogen that may be present in the test weld deposit. These designators are a part of the standard AWS classification system and consist of the letter H followed by a single or double digit. For example “E7018-H8" indicates that the deposit contains a maximum diffusible hydrogen content of 8 mL per 100 g of deposited weld metal. Most standard low hydrogen electrodes must deposit weld metal with a maximum of 16 mL per 100 g of diffusible hydrogen under test conditions. However, manufacturers may optionally list an H8 or H4 designation if their particular SMAW electrodes are capable of delivering these extra low levels of diffusible hydrogen.

(7) While “low-hydrogen” electrodes are required by AWS *D1.1* for welding on structural steels with minimum specified yield strength of 485 MPa (50 ksi) or greater, extra-low hydrogen levels should not be specified unless necessary. There is generally a cost premium associated with the lower diffusible hydrogen electrodes. Also, high notch toughness weld metal from electrodes with good operating characteristics may not be available with the lowest hydrogen designations, and some electrodes with very low diffusible hydrogen levels may have poor notch toughness.

(8) All low hydrogen electrodes listed in AWS A5.1 have minimum specified notch toughnesses of 27 J @ -20^{o}C (20 ft-lbf at 0°F) or better. See Table C-3 for specific data on these low hydrogen

electrodes. There are electrode classifications that have no required notch toughness (such as E6012, E6013, E6014, E7024), but these are not classified as low hydrogen electrodes. There is no direct correlation between the low hydrogen limits of various electrodes and notch toughness requirements.

(9) Low hydrogen, low-alloy SMAW electrodes, up through 550 MPa (80 ksi), as listed with operating limitations and uses in Table C-4. For electrodes exceeding 550 MPa (80 ksi), see AWS A5.5.

(10) Electrodes providing a given level of notch toughness are listed in Table C-5. For the notch toughness levels of higher strength electrodes, see AWS A5.5.

(11) Low hydrogen SMAW electrodes typically are supplied in hermetically sealed metal containers. When supplied in undamaged containers, they may be used without any preconditioning, or baking, before use. When SMAW electrodes are received in damaged containers or in non-hermetically sealed containers, AWS *D1.1* requires that the electrodes be baked prior to use, in the range of 260°C to 430°C (500 to 800°F), to remove any residual moisture picked up from exposure to the atmosphere. The electrode manufacturer's guidelines should be followed to ensure a baking procedure that eliminates retained moisture, and these recommendations may vary from AWS *D1.1* provisions.

(12) Once low hydrogen SMAW electrodes are removed from their hermetically sealed container, or from the baking oven, they should be placed in a holding oven, also called a "rod oven" or "storage oven", to avoid the pickup of moisture from the atmosphere. These heated ovens must maintain the electrodes at a minimum temperature of 120°C (250°F). Once the electrode has been exposed to the atmosphere, it begins to pick up moisture. AWS *D1.1* Table 5.1 limits the exposure time of various electrode classifications. Higher strength electrodes, used to join high strength steels which are particularly susceptible to hydrogen assisted cracking, are limited to very short periods.

c. Advantages, Disadvantages and Limitations. Generally SMAW has a lower deposition rate and is less efficient, and is more costly than the other structural welding processes of FCAW, GMAW and SAW. SMAW is seldom used as the principal process for structural welding, but is commonly used for tack welding, fabrication of miscellaneous components, and repair welding.

(1) SMAW has the benefit of requiring relatively simple, inexpensive, portable, and easy to maintain welding equipment. Gas shielding is not required. Holding ovens for low hydrogen electrodes are required unless hermetically sealed containers are used to provide dry electrodes when needed. SMAW is capable of depositing high quality welds, and is relatively tolerant of welding technique, welding procedure variations, and wind. It can be used in areas with difficult access.

(2) Smaller prequalified weld bead sizes, maximum 8 mm (5/16 in.) in a single pass in the common horizontal position, requires more passes for large welds, with additional cleaning time required for slag removal. For long welds, because of the fixed length electrode, it may not be possible to complete the weld without stopping, removing the slag to allow restarting the weld, and using additional electrodes.

Table C-1. AWS A5.1 Classification System for Carbon Steel Electrodes for SMAW

E XX YY M - 1 HZ R

E	Electrode
XX	Minimum tensile strength in units of 1 ksi (7 MPa) 60 = 60 ksi (420 MPa) 70 = 70 ksi (480 MPa)
Y	Generally, welding positions permitted for use, but may be additionally limited by electrode diameter and class 1 = all positions (F, H, V, OH) 2 = F, H-fillets 4 = F, H, V-down, OH
Y	Type of covering 0 = high cellulose sodium (E6010) 0 = high iron oxide (E6020) 1 = high cellulose potassium 2 = high titania sodium 3 = high titania potassium 4 = iron powder, titania 5 = low hydrogen sodium 6 = low hydrogen potassium 7 = high iron oxide, iron powder 8 = low hydrogen potassium, iron powder (except E7018M) 9 = iron oxide titania potassium
M	If present, meets special Military specifications, and covering is low hydrogen, iron powder
-1	If present, indicates improved notch toughness (see AWS A5.1, Table 3) for E7016-1, average CVN of 27 J @ -46°C (20 ft-lbf @ -50°F) for E7018-1, average CVN of 27 J @ -46°C (20 ft-lbf @ -50°F) for E7024-1, average CVN of 27 J @ -18°C (20 ft-lbf @ -0°F)
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal (note: E7018M meets H4 requirements, but the H4 designation is not used)
R	If present, indicates electrode has lower moisture content and meets absorbed moisture test requirements (note: E7018M must meet more stringent requirements, but the R designation is not used)

Table C-2. AWS A5.5 Classification System for Low-Alloy Steel Electrodes for SMAW

E XX YY M - X# HZ R

E	Electrode
XX	Minimum tensile strength in units of 1 ksi (7 MPa) 70 = 70 ksi (480 MPa) 80 = 80 ksi (550 MPa) 90 = 90 ksi (620 MPa) 100 = 100 ksi (690 MPa) 110 = 110 ksi (760 MPa) 120 = 120 ksi (830 MPa)
Y	Generally, welding positions permitted for use, but may be additionally limited by electrode diameter and class 1 = all positions (F, H, V, OH) 2 = F, H-fillets
Y	Type of covering 0 = high cellulose sodium (except E7020) 0 = high iron oxide (E7020) 1 = high cellulose potassium 2 = high titania sodium 3 = high titania potassium 4 = iron powder, titania 5 = low hydrogen sodium 6 = low hydrogen potassium 7 = high iron oxide, iron powder 8 = low hydrogen potassium, iron powder (except EXX18M) 9 = iron oxide titania potassium
M	If present, meets special Military specifications, and covering is low hydrogen, iron powder
-	
X#	Alloy type A carbon-molybdenum steel B chromium-molybdenum steel C nickel steel D manganese-molybdenum steel G general low-alloy steel P for pipeline use W weathering steel
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal (note: EXX18M meets H4 requirements, but the H4 designation is not used)
R	If present, indicates electrode has lower moisture content and meets absorbed moisture test requirements

Table C-3. Low Hydrogen AWS A5.1 Carbon Steel Electrodes for SMAW [to 480 MPa (70 ksi)]

Electrode	Position	Current	CVN Toughness	Moisture Content Limit (as received)	Available Diffusible Hydrogen Limits
E7015	F, H, V, OH	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.6	H16, H8, H4
E7016	F, H, V, OH	AC, DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.6	H16, H8, H4
E7018	F, H, V, OH	AC, DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.6	H16, H8, H4
E7018M	F, H, V, OH	DCEP	68 J @ -29°C (50 ft-lbf @ -20°F)	0.1	4.0 [1]
E7028	F, H-fillets	AC, DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)	0.3	H16, H8, H4
E7048	F, H, V-down, OH	AC, DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)	0.4	H16, H8, H4
E7016-1	F, H, V, OH	AC, DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)	0.6	H16, H8, H4
E7018-1	F, H, V, OH	AC, DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)	0.6	H16, H8, H4

[1] - no H designation used for E7018M

Table C-4. Low Hydrogen AWS A5.5 Low-Alloy Steel Electrodes for SMAW [to 550 MPa (80 ksi)]

Electrode	Position	Current	Moisture Content Limit (as received)	Available Diffusible Hydrogen Limits
E7015-X	F, H, V, OH	DCEP	0.4 [2]	H16, H8, H4
E7016-X	F, H, V, OH	AC, DCEP	0.4 [2]	H16, H8, H4
E7018-X	F, H, V, OH	AC, DCEP	0.4 [2]	H16, H8, H4
E8015-X [1]	F, H, V, OH	DCEP	0.2	H16, H8, H4
E8016-X [1]	F, H, V, OH	AC, DCEP	0.2	H16, H8, H4
E8018-X [1]	F, H, V, OH	AC, DCEP	0.2	H16, H8, H4

[1] - B3, B3L, B4L, B5, B6, B7, B7L, B8, B8L, and B9 series electrodes not prequalified under AWS *D1.1*

[2] - E70XX-XR and E70XX-X-HZR series Limit on Moisture Content (as received) = 0.3

Table C-5. Toughness Values for Low Hydrogen A5.5 Low Alloy Steel Electrodes [to 550 MPa (80 ksi)]

CVN Toughness	Electrodes
27 J @ -18°C (20 ft-lbf @ 0°F)	E7018-W1 E8018-W2
27 J @ -40°C (20 ft-lbf @ -40°F)	E8016-C3, E8018-C3, E8018-NM1
27 J @ -51°C (20 ft-lbf @ -60°F)	E7018-C3L E8016-C4, E8016-D3, E8018-C4, E8018-D1, E8018-D3
27 J @ -60°C (20 ft-lbf @ -75°F)	E8016-C1, E8018-C1
27 J @ -73°C (20 ft-lbf @ -100°F)	E7015-C1L, E7016-C1L, E7018-C2L E8016-C2, E8018-C2
27 J @ -100°C (20 ft-lbf @ -150°F)	E7015-C2L, E7016-C2L, E7018-C2L

2. FLUX CORED ARC WELDING (FCAW).

a. Process Principles. Flux cored arc welding (FCAW) is an arc welding process that uses a continuous tubular electrode fed from a coil or spool into a welding “gun”. The electrode core contains alloy additions, deoxidizers and flux materials. The heat of the arc causes the base metal, tubular electrode wire and core materials to melt. The flux materials bind impurities, rise to the top of the molten weld, and protect the cooling weld from atmospheric nitrogen or oxygen. Shielding of the exposed arc is provided either by the decomposition of the core in self-shielded electrodes, designated FCAW-S, or by an externally supplied gas or gas mixture, designated FCAW-G.

(1) With FCAW-G, carbon dioxide (CO_2) or a mixture of argon (Ar) of 75 to 90% and of CO_2 10 to 25% is used in addition to the gas provided by the flux core. The shielding gas selection may affect the mechanical properties (yield and tensile strength, elongation, and notch toughness) of the weld. Carbon dioxide, as a reactive gas, may cause some of the alloys in the electrode to become oxidized, and therefore less alloy is transferred to the weld deposit. When an inert gas such as argon is substituted for CO_2, alloy transfer typically increases. With more alloy in the weld deposit, higher yield and tensile strengths and reduced ductility is expected. The notch toughness of the weld deposit may increase or decrease, depending on the alloys affected.

(2) The power source is usually the constant voltage type, using either direct current electrode positive or electrode negative polarity. A separate wire feeder sends wire into the welding gun at a preset rate. The Welding Procedure Specification (WPS) provides the appropriate voltage, wire feed speed, electrode extension, and travel speed. For a given wire feed speed and electrode extension, a specific current (amperage) will be provided. As the wire feed speed is increased, the current is likewise increased. The WPS should, preferably, state the wire feed speed to be used because electrode extension, polarity and electrode diameter also affect current. Shorter electrical stickout results in higher current for a given wire feed speed. If current is used in the WPS, an inaccurate electrode extension may go undetected.

(3) FCAW is most commonly used as “semiautomatic”, wire fed but with the welding gun manipulated by the welder. It may also be used as automatic, but the intensity of arc rays from the high current arc, and the significant volume of smoke generated, make Submerged Arc Welding (SAW) more desirable for automatic welding.

b. Filler Metal Designation, Specification and Certification. FCAW electrodes are specified in AWS filler metal specifications AWS A5.20 and A5.29. AWS A5.20 is applicable to carbon steel electrodes, and AWS A5.29 is applicable to low alloy steel electrodes. The classification and identification system used for these two specifications is summarized in Tables C-6 and C-7.

(1) All FCAW electrodes are considered low hydrogen. Self-shielded FCAW electrodes are limited to 550 MPa (80 ksi) tensile strength of less, but higher strengths are available from gas-shielded FCAW electrodes. AWS A5.20 electrodes EXXT-2, -3, -10, -13, -14, and -GS electrodes are not permitted by AWS *D1.1* because they are limited to single pass welds. AWS A5.20 electrodes EXXT-3, EXXT-11, and EXXT-14 are for limited thickness applications only, and the manufacturer’s recommendations should be consulted.

(2) Tables C-8 and C-9 provide additional information regarding electrode limitations, usage and toughness properties for electrodes permitted by AWS *D1.1* for classification strengths of 550 MPa (80 ksi) and lower. For higher strength and other electrodes, the AWS A5.20 and A5.29 specifications should be consulted.

c. Advantages, Disadvantages and Limitations. The Flux Cored Arc Welding (FCAW) process offers several advantages over Shielded Metal Arc Welding (SMAW), but also has a few disadvantages and limitations

(1) The FCAW electrode is continuous, eliminating the numerous starts and stops necessary with SMAW on longer and larger welds.

(2) Increased deposition rates are possible with FCAW because the current can be higher than with SMAW. SMAW currents are limited by rod heating and coating breakdown concerns. With FCAW, the electrode is passed through a contact tip usually 20 to 25 mm (3/4 to 1 in.) from the end of the electrode, minimizing the buildup of heat from electrical resistance. This electrode extension distance, commonly called "stickout," varies for each WPS, and may be considerably higher. Both factors provide FCAW an economic advantage over SMAW.

(3) The number of arc starts and stops, a potential source of weld discontinuities, is also reduced.

(4) The equipment required for FCAW is more expensive and complicated than SMAW, and more difficult to maintain. This increased cost is offset by the higher productivity levels achieved using FCAW compared to SMAW.

(5) FCAW electrode wires do not need heated holding ovens for ordinary applications, but caution should be used when FCAW wires are exposed to the elements for extended periods of time. For critical welds requiring very low hydrogen deposits, more restrictive storage requirements may be warranted.

(6) FCAW is capable of all-position welding when using small diameter electrodes. Large diameter electrodes, using higher electrical currents, are restricted to the flat and horizontal positions.

(7) There are several advantages to using FCAW-S (self-shielded) rather than FCAW-G (gas-shielded). The FCAW-S welding gun assembly does not require a gas nozzle, also called a gas cup, therefore access into smaller areas is possible, significant when welding in tight locations such as weld access holes in beam-to-column connections. The welder is also better able to see the arc and weld puddle because the gas cup is not present.

(8) A second advantage to FCAW-S over FCAW-G is its ability to make quality welds under field conditions involving wind. For FCAW-G, it is necessary to erect protective shielding from wind to maintain the shielding gas around the molten weld puddle. Such shielding may be expensive, time-consuming, require additional ventilation for the welder, and constitute a fire hazard. FCAW-S eliminates the handling of high pressure gas cylinders, theft of cylinders, protection of gas distribution hosing under field conditions, and the cost of the shielding gas. For shop fabrication, wind is less of a problem than under field conditions. However, drafts from doorways and windows, fans used to cool personnel and provide ventilation, and welding fume exhaust equipment can create unacceptable wind speeds that degrade weld quality.

(9) FCAW-G "operator appeal" is usually higher than with FCAW-S because of better arc control and less fume generation. FCAW-G is less sensitive to variations in electrode extension and arc voltage than FCAW-S. The range of suitable applications for a single size and classification of FCAW-G electrodes is generally broader than for FCAW-S electrodes.

(10) FCAW-S procedures must be closely controlled to ensure the required level of weld quality and mechanical properties. Because of the high deposition rates possible, travel speeds and technique

must be monitored to ensure that excessively large bead sizes are not produced. Large bead size, because of the high heat input and excessively slow cooling rates, may reduce notch toughness, reduce weld soundness, decrease heat affected zone toughness, and decrease the weld metal yield and tensile strengths.

Table C-6. AWS A5.20 Classification System for Carbon Steel Electrodes for FCAW

EXXT-XMJHZ

E	Electrode
X	Minimum Tensile Strength in units of 10 ksi (69 MPa) 6 = 60 ksi (420 MPa) 7 = 70 ksi (480 MPa)
X	Position of welding permitted 0 = flat and horizontal position only 1 = all positions
T	Tubular electrode
-	
X	Type of electrode, numbered 1-14, or letter G or GS
M	If used, electrode has been classified using 75-80% Ar, with balance CO_2
J	If used, electrode has toughness of 27 J @ -40°C (20 ft-lbf @ -40°F) If not used, electrode has toughness as listed in A5.20, Table 1
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal

Table C-7. AWS A5.29 Classification System for Low Alloy Steel Electrodes for FCAW

EXXTX-X#M

E	Electrode
X	Minimum Tensile Strength in units of 10 ksi (69 MPa) 6 = 60 ksi (420 MPa) 7 = 70 ksi (480 MPa) 8 = 80 ksi (550 MPa) 9 = 90 ksi (620 MPa) 10 = 100 ksi (690 MPa) 11 = 110 ksi (760 MPa) 12 = 120 ksi (830 MPa)
X	Position of welding permitted 0 = flat and horizontal position only 1 = all positions
T	Tubular electrode
X	Type of electrode, numbered 1, 4, 5, or 8 1 & 5 - gas-shielded 4 & 8 - self-shielded
-	
X#	Alloy type A carbon-molybdenum steel B chromium-molybdenum steel C nickel steel D manganese-molybdenum steel K other alloy steels W weathering steel
M	If used, electrode has been classified using 75-80% Ar, with balance CO_2

Table C-8. AWS A5.20 Carbon Steel Electrodes for FCAW
[to 480 MPa (70 ksi), Multipass Only]

Electrode	Position	Testing Shielding Gas[d]	Current	CVN Toughness[c]
	F, H	CO		27 J @ -18°C
E70T-1M		75-80% Ar - CO$_2$	DCEP	C
E71T-1	F, H, V-up, OH	$_2$	DCEP	27 J @ -18°
	F, H, V-up, OH	75-80% Ar - CO		27 J @ -18°C
E70T-4		self	DCEP	
E70T-5	F, H	$_2$	DCEP	27 J @ -29°
	F, H	75-80% Ar - CO		27 J @ -29°C
E71T-5		CO$_2$	DCEP, DCEN	C
E71T-5M	F, H, V-up, OH	$_2$	DCEP, DCEN	27 J @ -29°
	F, H	self		27 J @ -29 C
E70T-7	F, H		DCEN	none specified
	F, H, V-up, OH	self		none specified
E70T-8		self	DCEN	°C
	F, H, V-up, OH	self		27 J @ -29 C
E70T-9	F, H	$_2$	DCEP	27 J @ -29°
	F, H	75-80% Ar - CO		27 J @ -29°C
E71T-9		CO$_2$	DCEP	C
E71T-9M	F, H, V-up, OH	$_2$	DCEP	27 J @ -29°
[b]	F, H	self		none specified
[b]	F, H, V-dn, OH	self		none specified
	F, H	CO		27 J @ -29°C
E71T-12		CO$_2$	DCEP	C
EX[a]0T-G		not specified	not specified	
EX[a]	F, H, V-up or V-dn,	not specified		not specified

Note - 27 J @ -18 C = 20 ft-lbf @ 0° °C = 20 ft-lbf @ -20 F

[a] - May be either 6 or 7, for 60 ksi or 70 ksi tensile strength.

[b] - electrodes with “J” at the end of the designator (e.g. E7XT-9J) have minimum CVN Toughness of 27 J @ -40°C (20 ft-lbf @ -20°

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

Table C-9. AWS A5.29 Low Alloy Steel Electrodes for FCAW [to 550 MPa (80 ksi), Multipass Only]

Electrode	Permitted Positions	Testing Shielding Gas[d]	Current	Minimum CVN Toughness
E61T8-K6	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E70T4-K2	F, H	self	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
E70T5-A1	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-K2	F, H	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-K6	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-Ni1	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E71T8-Ni2	F, H, V, OH	self	DCEN	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T1-A1	F, H	CO_2	DCEP	none specified
E81T1-A1	F, H, V, OH	CO_2	DCEP	none specified
E80T1-B1	F, H	CO_2	DCEP	none specified
E81T1-B1	F, H, V, OH	CO_2	DCEP	none specified
E81T1-B2	F, H, V, OH	CO_2	DCEP	none specified
E80T1-B2H	F, H, V, OH	CO_2	DCEP	none specified
E80T1-K2	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T1-Ni1	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E81T1-Ni1	F, H, V, OH	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T1-Ni2	F, H	CO_2	DCEP	27 J @ -40°C (20 ft-lbf @ -40°F)
E81T1-Ni2	F, H, V, OH	CO_2	DCEP	27 J @ -40°C (20 ft-lbf @ -40°F)
E80T1-W	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80T5-B2	F, H	CO_2	DCEP	none specified
E80T5-B2L	F, H	CO_2	DCEP	none specified
E80T5-Ni1	F, H	CO_2	DCEP	27 J @ -51°C (20 ft-lbf @ -60°F)
E80T5-Ni2	F, H	CO_2	DCEP	27 J @ -60°C (20 ft-lbf @ -76°F)
E80T5-Ni3	F, H	CO_2	DCEP	27 J @ -73°C (20 ft-lbf @ -100°F)
E80T5-K1	F, H	CO_2	DCEP	27 J @ -40°C (20 ft-lbf @ -40°F)
E80T5-K2	F, H	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

3. GAS METAL ARC WELDING (GMAW).

a. Process Principles. The Gas Metal Arc Welding (GMAW) process, commonly referred to as "MIG" (Metal Inert Gas) welding, is very similar to gas-shielded flux cored arc welding (FCAW-G), and uses the same equipment. GMAW uses a solid or metal cored electrode, and subsequently leaves little, if any, slag. The shielding gas used for GMAW may be carbon dioxide (CO_2), or a mixture of argon (Ar) and either CO_2 or small levels of oxygen (O), or both. GMAW is commonly applied in one of four ways: spray arc transfer, globular transfer, pulsed arc transfer, and short arc transfer.

(1) Spray arc transfer uses high wire feed speeds and relatively high voltages. A fine spray of molten drops, all smaller in diameter than the electrode diameter, is ejected from the electrode toward the work. The arc in spray transfer is continuously maintained, resulting in high quality welds with good appearance. The shielding used for spray arc transfer is composed of at least 80% argon, with the balance made up of either carbon dioxide or oxygen. Typical mixtures are 90% argon with 10% CO_2, and 95% argon with 5% oxygen. Because of the intensity of the arc, puddle fluidity, and lack of slag to hold the molten metal in place, spray arc is limited to the flat and horizontal position.

(2) Globular transfer results when high concentrations of carbon dioxide are used. Carbon dioxide, as an active gas rather than inert gas, may be referred to as "MAG" (Metal Active Gas) welding. Because of the high concentration of CO_2, the arc ejects large globular pieces of molten steel from the end of the electrode, rather than a spray. This mode of transfer can result in deep penetration, but may have poor appearance with relatively high levels of spatter. It is also limited to the flat and horizontal positions. Because of the lower cost of CO_2 shielding gas, the lower level of heat generated, and increased welder comfort, globular transfer may be selected in place of spray transfer.

(3) Pulsed arc transfer uses a background current that is continuously applied to the electrode, plus a pulsing peak current applied at a rate proportional to the wire feed speed. Each pulse of current ejects a single droplet of metal from the electrode, usually between 100 and 400 times per second. The arc is maintained by the lower background current. Pulsed arc transfer can be used out-of-position, with better quality than short-circuiting mode. It is not as productive as spray transfer for welding in the flat and horizontal positions. Weld appearance and quality are generally good. Pulsed arc transfer GMAW equipment is somewhat more complex and costly than standard GMAW equipment.

(4) Short circuiting transfer, also called short arc, is suitable for welding only on thin gauge materials, and should not be used for structural steel. The small diameter electrode is fed at a moderate wire feed speed using relatively low voltage. The electrode contacts the workpiece, shorting the electrical circuit, extinguishing the arc, resulting in very high current flowing through the electrode, causing it to heat and melt. As the electrode melts, the arc is briefly reestablished. This cycle occurs up to 200 times per second, creating a characteristic buzzing sound. With structural steel, significant fusion problems such as cold lap may result. Short circuiting transfer provides a low deposition rate, but can be used out of position. While GMAW is considered prequalified by AWS *D1.1*, the short circuiting mode of transfer, abbreviated GMAW-S, is not. All GMAW-S welding procedures must be qualified by test.

b. Filler Metal Designation, Specification and Certification. GMAW electrodes are classified under AWS A5.18 for carbon steel electrodes, and AWS A5.28 for low alloy steel electrodes. The classification systems used for GMAW electrodes in AWS A5.18 and A5.28 are summarized in Tables C-10 and C-11.

(1) Classification testing is usually performed using specific welding procedures that use CO_2 shielding gas, therefore promoting globular transfer, but other gases, and therefore transfer modes, may be specified.

(2) Metal cored electrodes, previously classified as FCAW electrodes, are now listed in both A5.18 and A5.28. GMAW with metal cored electrodes is similar to FCAW, with a tubular electrode, but the core contains metallic powders (alloy) rather than flux materials. Metal cored electrodes require less current to obtain the same deposition rates, have better tolerance for mill scale and rust, and when used out-of-position, are less likely to cold lap. Metal cored electrodes typically provide higher deposition rates because higher currents may be used than with solid wire electrodes. Weld appearance is typically very good, and the weld is essentially free of slag. The consistency of mechanical properties is typically better with metal cored electrodes than with solid wire electrodes.

(3) Properties and usage for GMAW electrodes, up to 550 MPa (80 ksi), are summarized in Tables C-12 and C-13. For higher strength electrodes, see AWS A5.28.

c. Advantages, Disadvantages and Limitations. The Gas Metal Arc Welding (GMAW) process offers several advantages over Shielded Metal Arc Welding (SMAW), but also has some disadvantages and limitations.

(1) The GMAW electrode is continuous, eliminating the numerous starts and stops necessary with SMAW on longer and larger welds.

(2) Increased deposition rates are possible with GMAW because the current can be higher than with SMAW. SMAW currents are limited by rod heating and coating breakdown concerns. With GMAW, the electrode is passed through a contact tip usually 20 to 25 mm (3/4 to 1 in.) from the end of the electrode, minimizing the buildup of heat from electrical resistance. This electrode extension distance, commonly called “stickout,” varies for each WPS, and may be considerably higher. Both factors provide GMAW an economic advantage over SMAW.

(3) The number of arc starts and stops, a potential source of weld discontinuities, is also reduced.

(4) GMAW electrode wires do not need heated holding ovens. For critical welds requiring very low hydrogen deposits, GMAW electrode wires are available in the lowest diffusible hydrogen category, H2.

(5) GMAW “operator appeal” is usually high because of good arc control and little fume generation.

(6) Because no flux is involved, GMAW is intolerant of high levels of mill scale, rust, and other surface contaminants, and is limited to welding on relatively clean materials. Commonly, mill scale must be removed by blast cleaning or power wire brushing prior to welding.

(7) GMAW is also seriously affected by wind because of the removal of the shielding gas from around the weld puddle. For field work, it is often necessary to erect protective shielding from wind to maintain the shielding gas around the molten weld puddle. Such shielding may be expensive, time-consuming, require additional ventilation for the welder, and constitute a fire hazard. For shop fabrication, wind is less of a problem than under field conditions. However, drafts from doorways and windows, fans used to cool personnel and provide ventilation, and welding fume exhaust equipment can create unacceptable wind speeds that degrade weld quality.

(8) The equipment required for GMAW is more expensive and complicated than SMAW, and more difficult to maintain. This increased cost is offset by the higher productivity levels achieved using GMAW compared to SMAW.

Table C-10. AWS A5.18 Classification System for Carbon Steel Electrodes for GMAW

E XX C - X Y N HZ

E	
R	If used, designates that electrode may also be used as filler rod
XX	Minimum Tensile Strength in units of 1 ksi (7 MPa)
S or C	S = Solid wire
-	
X	composite wire G = unspecified composition
	Shielding gas used for classification testing C = CO_2 M = 75-80% Ar, balance CO_2
N	applications
HZ	H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H2 = maximum 2 mL / 100 g deposited weld metal

Table C-11. AWS A5.28 Classification System for Low Alloy Steel Electrodes for GMAW

ER XX S - XXX HZ
E XX C - XXX HZ

E	Electrode
R	If used, designates that electrode may also be used as filler rod for GTAW
XX	Minimum Tensile Strength in units of 1 ksi (7 MPa) 70 = 70 ksi (480 MPa) 80 = 80 ksi (550 MPa) 90 = 90 ksi (620 MPa) 100 = 100 ksi (690 MPa) 110 = 110 ksi (760 MPa) 120 = 120 ksi (830 MPa)
S or C	S = Solid wire C = Composite (metal cored) wire
-	
XXX	Chemical composition of solid wire, or of weld deposit of composite wire A = carbon-molybdenum steel B = chromium-molybdenum steel Ni = nickel steel D = manganese-molybdenum steel 1 = other alloy steels G = not specified
HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal H2 = maximum 2 mL / 100 g deposited weld metal

Table C-12. AWS A5.18 Carbon Steel Electrodes for GMAW [480 MPa (70 ksi) only]

Electrode	Testing Shielding Gas[d]	Polarity	CVN Toughness
ER70S-2	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
ER70S-3	CO_2	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
ER70S-4	CO_2	DCEP	not required
ER70S-5	CO_2	DCEP	not required
ER70S-6	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
ER70S-7	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
ER70S-G	as agreed		as agreed
E70C-3C	CO_2	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
E70C-3M	75-80% Ar, balance CO_2	DCEP	27 J @ -18°C (20 ft-lbf @ 0°F)
E70C-6C	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E70C-6M	75-80% Ar, balance CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E70C-G(X)	as agreed		as agreed

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

Note - E70C-GS(X) electrode is limited to single pass applications, and is not prequalified.

Note - All above electrodes optionally available as H16, H8, and H4 for diffusible hydrogen requirements.

Table C-13. AWS A5.28 Low Alloy Steel Electrodes for GMAW [to 550 MPa (80 ksi), Multipass Only]

Electrode	Testing Shielding Gas[d]	Polarity	CVN Toughness
ER70S-A1	Ar / 1-5% O_2	DCEP	not required
ER70S-B2L	Ar / 1-5% O_2	DCEP	not required
E70C-B2L	Ar / 1-5% O_2	DCEP	not required
E70C-Ni2	Ar / 1-5% O_2	DCEP	27 J @ -62°C (20 ft-lbf @ -80°F)
ER80S-B2	Ar / 1-5% O_2	DCEP	not required
ER80S-Ni1	Ar / 1-5% O_2	DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)
ER80S-Ni2	Ar / 1-5% O_2	DCEP	27 J @ -62°C (20 ft-lbf @ -80°F)
ER80S-Ni3	Ar / 1-5% O_2	DCEP	27 J @ -73°C (20 ft-lbf @ -100°F)
ER80S-D2	CO_2	DCEP	27 J @ -29°C (20 ft-lbf @ -20°F)
E80C-B2	Ar / 1-5% O_2	DCEP	not required
E80C-Ni1	Ar / 1-5% O_2	DCEP	27 J @ -46°C (20 ft-lbf @ -50°F)
E80C-Ni2	Ar / 1-5% O_2	DCEP	27 J @ -62°C (20 ft-lbf @ -80°F)
E80C-Ni3	Ar / 1-5% O_2	DCEP	27 J @ -73°C (20 ft-lbf @ -100°F)

[d] - Electrodes classified using the shielding gas listed shall not be used with any other shielding gas mixture without first consulting the manufacturer.

Note - B3, B3L, B6, B8 and B9 classification electrodes are not prequalified
Note - All above electrodes optionally available as H16, H8, H4 and H2 for diffusible hydrogen requirements.

4. SUBMERGED ARC WELDING (SAW).

a. Process Principles. Submerged Arc Welding (SAW) uses a blanket of fusible granular material called flux to shield the arc and molten metal. The arc is struck between the workpiece and a bare wire or composite electrode, the tip of which is submerged in the flux. Since the arc is completely covered by flux, it is not visible and the weld is made without the flash, spatter, sparks and smoke common for the open-arc processes.

(1) The process is typically operated automatic, or fully mechanized, although semiautomatic operation is often used. The electrode is continuously fed from a coil or spool to the welding gun, which travels at a preset speed along the joint, preceded by a flux deposition system. In semiautomatic welding, the welder moves the gun, usually equipped with a flux-feeding device, along the joint by hand.

(2) Flux feed may be by gravity flow through a nozzle from a small hopper atop the welding gun, or it may be through a nozzle tube connected to an air-pressurized flux tank. Flux may also be applied in advance of the welding operation, ahead of the arc, from a hopper run along the joint. Many fully mechanized systems are equipped with vacuum devices to pick up the flux unfused after welding for reuse.

(3) During welding, the heat of the arc melts some of the flux along with the steel and the tip of the electrode. The tip of the electrode and the welding zone are always shielded by molten flux, surrounded by a layer of unfused flux. As the electrode progresses along the joint, the lighter molten flux rises above the molten metal in the form of a slag. The molten slag is a good conductor and provides an additional path for the current, thus generating additional heat. The weld metal, having a higher melting (freezing) point, solidifies while the slag above it is still molten. The slag then freezes over the newly solidified weld metal, continuing to protect the metal from contamination while it is very hot and reactive with atmospheric oxygen and nitrogen. Upon cooling and removal of any unmelted flux for reuse, the slag is removed from the weld.

(4) Several electrodes may be used in series or parallel, and multiple beads can be placed when using separate power supplies for each bead. Parallel electrode SAW uses two electrodes connected electrically in parallel to the same power supply. Both electrodes are fed by means of a single electrode feeder. For heat input calculation purposes, the total for the two electrodes is used. Multiple electrode SAW uses at least two separate power supplies and two separate wire drives to feed two electrodes independently. To minimize the potential interaction of magnetic fields between the two electrodes, typical SAW setups have the lead electrode operating on DC current while the trail electrode is operating AC.

(5) DC and AC welding machines of both conventional drooping voltage type or constant potential type can be used for SAW. With drooping voltage, a voltage sensitive relay adjusts the wire feed speed to maintain the desired arc voltage. With constant potential voltage, the arc length is self-adjusting, similar to the action in FCAW. Welding currents typically range from 500 to 1000 amperes.

(6) Flux must be stored so that it remains dry. Fluxes in open or damaged bags, or in flux hoppers, may become contaminated with moisture from the atmosphere, so exposure should be limited. The guidelines of the flux manufacturer, as well as AWS *D1.1* Section 5.3.3 regarding storage and usage of the flux must be followed. When not in use, flux hoppers should be covered or otherwise protected from the atmosphere.

(7) Because unmelted flux does not undergo chemical changes, it may be recovered for future use. Flux recovery systems range from vacuum recovery systems to sweeping with brooms and pans.

Flux contamination through contact with oil, moisture, dirt, scale of other contaminants may occur, therefore care is needed. Some loss of fine particulate matter may also occur with flux recovery, therefore blending reclaimed flux with new flux is required.

b. Filler Metal Designation, Specification and Certification. Submerged Arc Welding (SAW) filler materials, the electrodes and fluxes, are classified under AWS A5.17 for carbon steel electrodes and fluxes, and AWS A5.23 for low alloy steel electrodes and fluxes. Because SAW is dependent upon both components, flux and electrode, the classification system integrates both materials. After an electrode and flux combination is selected and a test plate welded, the flux-electrode classification may be established. Specimens are extracted from the weld deposit to obtain the mechanical properties of the flux-electrode combination, which must meet specific compositional and mechanical property requirements.

(1) The classification systems for SAW are summarized in Tables C-14 and C-15 for AWS A5.17 materials, and Table C-16 for AWS A5.23 materials. Low alloy steel SAW electrodes and fluxes classified under AWS A5.23 have a more complex classification system, because of the variety of alloys that may be involved, and because the composition of both the electrode and the resultant weld metal must be specified.

(2) Because the submerged arc welding process is frequently used for pressure vessel fabrication where assemblies are stress relieved, many submerged arc materials have been classified for the post weld heat treated, or stress relieved, condition. When this is done, a “P” is placed in the designation rather than an “A”. For structural work, which is seldom stress relieved, the “A” classification is commonly used. Flux-electrode combinations classified in the post weld stress relieved condition may not exhibit notch toughness when used in the as-welded condition, therefore investigation into weld metal properties is warranted whenever the weld will be used differently than the filler metal classification condition.

(3) Fluxes are manufactured using one of four basic processes, and are further classified as neutral, active or alloy fluxes, based upon their performance characteristics during welding.

(4) Fused fluxes are made by blending deoxidizing and alloying ingredients, as necessary, and then heating the mixture in a furnace until completely melted. A glass-like fused product is formed as the liquid is cooled to ambient temperature, and later ground to the sizes required for welding. Fused fluxes are nonhygroscopic, meaning they will not absorb water, but may be contaminated by moisture or other products that adhere to the outside of particles. Fused fluxes are not subject to chemical segregation during reuse because the complete composition is in each particle and cannot be separated. Fused fluxes may have less than desired amounts of deoxidizer and ferro-alloy ingredients because of losses that occur from the high temperatures during the manufacturing process. Fused flux performance can be impeded by loss of fines during recycling. Fused fluxes with the required chemical composition generally give the best low hydrogen welding performance.

(5) Bonded fluxes are made by combining all required chemical ingredients with a binder and baking the product at low temperature to form hard granules, then broken up and screened for size. Bonded fluxes contain chemically bonded moisture and can absorb moisture as well. Because the product is baked at low temperature, deoxidizer content or alloying elements that can be added as ferro-alloys or as elemental metals are not a problem as with fused fluxes. Bonded fluxes may segregate during use and reuse, and gases may be produced in the molten slag during welding. Bonded fluxes tend to break down during recycling and increase the percentage of fines.

(6) Agglomerated fluxes are similar to bonded fluxes in their method of manufacture, except that the binder is a ceramic material that requires baking at higher temperatures. This may limit deoxidizer or

ferro-alloy content due to high temperature losses. Agglomerated fluxes are generally considered

(7) Mechanically mixed fluxes can be a mixture of any flux type in any desired proportion, are subject to segregation, and will have the attributes of their components.

description and limitations of theses fluxes is provided in the Annexes to the AWS A5.17 and A5.23 filler metal specifications.

manganese and silicon content, is relatively unaffected by changes in welding procedure variables, primarily the voltage that determines arc length. For both active and alloy fluxes, the weld metal

(10) Active fluxes have small additions of manganese and silicon, or both, to help offset the effects of welding though mill scale and light coatings of rust. With active fluxes, a change in arc voltage will

are more resistant to porosity and cracking than welds made with neutral fluxes, active fluxes are often used in making single pass fillet welds. Active fluxes intended for single pass fillet welding should not be

combine with the same elements in the electrode to produce weld metal with unacceptable properties. The chemistry may build to unacceptable levels in larger multipass welds, therefore welding with active

with low levels of manganese and silicon. Where all mill scale and other contaminants are removed prior to welding, the surface contamination tolerance of active fluxes is not needed. Continued recycling of

(11) Alloy fluxes contain alloys intended to improve the strength or corrosion resistance of the weld metal, or both, and the composition of the weld metal is highly dependent upon the alloy content of the

mechanical properties of the weld. Alloy fluxes, properly used with carbon steel electrodes, provide a low-cost method of producing corrosion resistant weld metal for joining weathering steels. Unlike active

in the alloy content.

c. Advantages, Disadvantages and Limitations. Very high currents can be used in submerged arc

and deep penetration. The slag above the molten weld puddle acts as an insulating blanket, concentrating heat in the welding zone and preventing rapid escape of heat. Deep penetration allows the

High travel speeds reduce the total heat input into the joint, reducing distortion.

(1) SAW welds generally have good ductility and toughness, and a uniform bead appearance

reducing cleaning and surface preparation costs. The covered arc allows SAW to be operated without the need for extensive shielding to protect the operators from the high intensity arc created by the high

protection.

(2) The SAW process does not allow the operator to observe the molten weld puddle, forcing reliance on the appearance of the slag blanket to indicate the quality of the weld bead. When SAW is performed semi-automatically, the operator must acquire and practice a technique to produce good welds without reliance upon arc and weld bead appearance.

Table C-14. AWS A5.17 Classification System for Carbon Steel Electrodes and Fluxes for SAW
[US Customary Units]

FSXXX-ECXXX-HZ

	Flux (virgin flux if not followed by S)
S	
X	Minimum tensile strength in units of 10 ksi (70 MPa) 7 = 70 ksi (480 MPa)
X	A = tested as-welded P = tested after postweld heat treatment
	Temperature in F at or above the impact strength meets or exceeds 20 ft-lbf (27 J) Z = no impact strength test required 0 = tested at 0° C) 2 = tested at -20°F (-29° F (-40°C) 5 = tested at -50° C) 6 = tested at -60°F (-51° F (-62°C)
-	
	Electrode
C	specified in A5.17. ECG does not have a specified chemistry. Either type must be tested with a specific flux.
	Manganese (Mn) content, % weight L = low Mn (0.25 - 0.60) H = high Mn (varies by classification, 1.30 low to 2.20 high) G = chemistry not specified
	Number that makes up a part of the electrode classification system, indicating chemistry in A5.17, Table 1. Generally, indicates nominal carbon content in nominal carbon), 11,12, 13, 14, and 15.
X	
-	
HZ	H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H2 = maximum 2 mL / 100 g deposited weld metal

Table C-15. AWS A5.17 Classification System for Carbon Steel Electrodes and Fluxes for SAW
[SI (Metric) Units]

FSXXX-ECXXX-HZ

F	Flux (virgin flux if not followed by S)
S	If present, flux is from crushed slag or blend of crushed slag and virgin flux.
X	Minimum tensile strength in units of 10 MPa (1.45 ksi) 43 = 430 MPa (62 ksi) 48 = 480 MPa (70 ksi)
X	Test condition of plates A = tested as-welded P = tested after postweld heat treatment
X	Temperature in °C at or above the impact strength meets or exceeds 27 J (20 ft-lbf) Z = no impact requirements 0 = tested at 0°C (32°F) 2 = tested at -20°C (-4°F) 3 = tested at -30°C (-22°F) 4 = tested at -40°C (-40°F) 5 = tested at -50°C (-58°F) 6 = tested at -60°C (-76°F)
-	
E	Electrode
C	If present, electrode is Composite electrode. Electrode EC1 meets a chemistry specified in A5.17. ECG does not have a specified chemistry. Either type must be tested with a specific flux.
X	Manganese (Mn) content, % weight L = low Mn (0.25 - 0.60) M = medium Mn (varies by classification, 0.80 low to 1.50 high) H = high Mn (varies by classification, 1.30 low to 2.20 high) G = chemistry not specified
X	Number that makes up a part of the electrode classification system, indicating chemistry in A5.17, Table 1. Generally, indicates nominal carbon content in hundredths of a percent. Listed classification numbers: 8 (indicating 0.08% nominal carbon), 11,12, 13, 14, and 15.
X	K indicates that the electrode was made from silicon-killed steel.
-	

HZ	Optional supplemental diffusible hydrogen designator H16 = maximum 16 mL / 100 g deposited weld metal H8 = maximum 8 mL / 100 g deposited weld metal H4 = maximum 4 mL / 100 g deposited weld metal H2 = maximum 2 mL / 100 g deposited weld metal

Table C-16. AWS A5.23 Classification System for Low Alloy Steel Electrodes and Fluxes for SAW
[US Customary Units]

F	Flux
	Minimum tensile strength in units of 10 ksi (70 MPa) 7 = 70 ksi (480 MPa) 9 = 90 ksi (620 MPa) 10 = 100 ksi (690 MPa)
	Test condition of plates A = tested as-welded
X	Temperature in ° Z = no impact strength test required F (-18°C) 2 = tested at -20° C) 4 = tested at -40°F (-40° F (-46°C) 6 = tested at -60° C) 8 = tested at -80°F (-62° F (-73°C) 15 = tested at -150° C)
-	
E	
C	If present, electrode is Composite electrode with composition per AWS A5.23
X	Chemical composition of electrode (Table 1) or weld metal (Table 2) M = carbon steel, medium Mn solid electrode (EM12K) A = carbon-molybdenum weld metal[1] Ni = nickel M = military W = weathering
XX	Number (and letter, if needed) that makes up a part of the electrode classification
N	Indicates that the electrode is intended for the core belt region of nuclear reactor
-	
X	above

N	**Indicates that the weld metal is intended for the core belt region of nuclear reactor vessels, with limited chemistry for phosphorous, vanadium, and copper.**
HZ	**Optional supplemental diffusible hydrogen designator** **H16 = maximum 16 mL / 100 g deposited weld metal** **H8 = maximum 8 mL / 100 g deposited weld metal** **H4 = maximum 4 mL / 100 g deposited weld metal**

[1] **- B3, B4, B5, B6, B6H, B8 are not prequalified in AWS** *D1.1*

5.

a. Process Principles. Gas Tungsten Arc Welding (GTAW), also frequently called TIG (Tungsten Inert Gas) welding, is done using the heat of an arc between a non-consumable tungsten electrode and

external shielding gas or gas mixture. Direct current electrode negative (DCEN) (straight) polarity is used to produce a deep, narrow penetration when welding thicker materials. Direct current electrode positive

metals. Alternating current (AC) is generally used for welding aluminum and magnesium alloys. A high frequency oscillator is usually incorporated into GTAW power supplies to initiate the arc. This reduces

tungsten to the base metal. The process may be performed manually, but may also be used as automatic. The tungsten electrode in the welding “torch” gets very hot under high duty cycles, therefore

deposition rate through the use a continuous filler metal, supplied with current from a separate power source, to preheat the wire using resistance heating.

welding torch are classified in AWS A5.12, *Specification for Tungsten and Tungsten Alloy Electrodes for* . The filler metal used, if any, is rod classified for GMAW in AWS A5.18 or A5.28, with a designation ER at the beginning. Tungsten electrodes are summarized in Table C-17.

spatter, with excellent arc control that is very beneficial for root passes. It can be used on material thicknesses that range from thin sheet metals up to maximum of about 10 mm (3/8 in.). However,

welding processes. Gas shielding is also critical, and wind speeds over 8 km per hour (5 mph) cause quality and mechanical property degradation. GTAW, as an unfluxed welding process, also requires very

Table C-17. AWS A5.12 Classification System for Tungsten Electrodes for GTAW

EWX-X

E	Electrode
W	Tungsten
X-X	Letter (and optionally -number) describing type of tungsten electrode P = pure tungsten Ce = tungsten-cesium alloy La = tungsten-lanthanum alloy Th = tungsten-thorium alloy Zr = tungsten-zirconium alloy G = general, not specified

a. Process Principles. Electroslag Welding (ESW) is used for welding thick sections, typically 50 mm to 500 mm (2 to 20 in.) in thickness, for short to moderate lengths. The plates to be joined are positioned

40 mm (3/4 to 1-1/2 in.), depending on welding equipment and material thickness, with no edge preparation generally required. Water-cooled copper shoes are placed on each side of the joint, forming

used. Shielding of the arc and weld pool is provided by the addition of flux into the joint as welding progresses. To start the weld, an arc is struck in a sump at the bottom of the joint, underneath a deposit

The arc is extinguished by the slag, but the fed electrode wire and adjacent base metal melts from the heat generated by the high electrical resistance of the slag. The weld proceeds as more electrode is fed

weld termination. Both the starting sump and finishing run-off tab are removed after completion of welding.

specified in AWS A5.25, *Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for*
. Electrode wires may be either solid or composite. The classification system is summarized in Table C-18.

deposition rates, in the range of 20 kg (40 lb.) per hour, offering considerable cost and time savings for vertical welding of thick steels. Time and expense is also saved in the avoidance of joint preparation,

distortion upon completion.

(1) ESW, if interrupted during welding, can leave major discontinuities in the joint that are difficult

may cause low toughness properties, as well as make ultrasonic testing more difficult.

(2) ESW can be used for joints over 12 mm (1/2 in.) thick, but generally does not become the most

including the number of joints to be welded. ESW is not prequalified under AWS *D1.1*
qualification testing following AWS *D1.1*
vertical require special setups and procedures, although ESW has been performed at angles to 45 degrees.

Table C-18. AWS A5.25 Classification System for Electrodes and Fluxes for ESW

FESXX-XXX

FES	**Flux for Electroslag Welding**
X	**Minimum tensile strength in units of 10 ksi (70 MPa)** **6 = 60 ksi (420 MPa)** **7 = 70 ksi (480 MPa)**
X	**Temperature in °F at or above the impact strength meets or exceeds 15 ft-lbf (20 J)** **Z = no impact strength test required** **0 = tested at 0°F (-18°C)** **2 = tested at -20°F (-29°C)**
-	
XXX	**Electrode classification used (EM5K-EW, for example), see AWS A5.25**

7.

a. Process Principles. Electrogas Welding (EGW) is very similar to Electroslag Welding (ESW), and is used for welding thick sections, typically 50 mm to 500 mm (2 to 20 in.) in thickness, for short to

opening gap at the joint is generally set to approximately 22 mm (7/8 in.), depending on welding equipment and material thickness, with no edge preparation generally required. Water-cooled copper

current electrode negative (DCEN) currents of 500 to 700 amperes are commonly used. The electrode is either a solid wire, composite (cored) wire, or a flux cored wire designed for EGW. For solid wires,
or an argon-CO_2 mix.
When flux cored wires are used, the shielding gas may or may not be necessary, depending upon the

weld pool and allows the welding arc to stabilize before reaching the actual joint. The arc is maintained, and the fed electrode wire and adjacent base metal melts from the heat generated by the arc. The weld

Both the starting sump and finishing run-off tab are removed after completion of welding.

b. Filler Metal Designation, Specification and Certification. Filler materials, electrodes and fluxes
Specification for Carbon and Low-Alloy Steel Electrodes and Electrogas Welding
classification system is summarized in Table C-19.

c. Advantages, Disadvantages and Limitations. Electrogas Welding (EGW) provides very high

vertical welding of thick steels. Time and expense is also saved in the avoidance of joint preparation, preheating and interpass temperature control, and interpass cleaning. The joint is also free from angular

(1) EGW, if interrupted during welding, can leave major discontinuities in the joint that are difficult to access and repair. The large grain size from the substantial heat input, and subsequent slow cooling,

disadvantage, compared to ESW, of requiring protection of the joint from wind over 8 km per hour (5 mph).

economical choice until a thickness of around 50 mm (2 in.) is welded, depending upon several factors including the number of joints to be welded. EGW is not prequalified under AWS , therefore qualification testing following AWS Section 4 is required. Angles beyond 10 to 15 degrees from vertical may require special setups and procedures.

Table C-19. AWS A5.26 Classification System for Electrodes for EGW

EGXXX-XXX

EG	Electrogas Welding
X	Minimum tensile strength in units of 10 ksi (70 MPa) 6 = 60 ksi (420 MPa) 7 = 70 ksi (480 MPa) 8 = 80 ksi (550 MPa)
X	Temperature in °F at or above the impact strength meets or exceeds 20 ft-lbf (27 J) Z = no impact strength test required 0 = tested at 0°F (-18°C) 2 = tested at -20°F (-29°C)
X	S = solid wire T = tubular wire
-	
XXX	Electrode classification used, see AWS A5.26

APPENDIX D

1. VISUAL TESTING (VT).

a. Method Description. Visual inspection, as a form of nondestructive testing, is the visual observation

the first nondestructive testing method applied, and if the inspected item fails to meet visual criteria, more extensive nondestructive testing should not be conducted until the visual criteria is satisfied.

and other enhancements. Such instruments tend to distort the perception of the inspector. When surface discontinuities such as cracks are suspected, the use of magnifying devices to further investigate the

(2) Visual inspection includes the measurement of the work, which may include the smoothness of thermally cut edges, and the measurement of root openings, groove angles, weld size, convexity and

such as weld gauges are required.

b. Advantages and Disadvantages.

arc strikes, excessive convexity, overlap, toe cracks, undersized welds, undercut, seams and laminations at exposed edges. Not all listed discontinuities are structurally significant, but they may provide indication

(2) Visual inspection cannot reveal subsurface discontinuities such as cracks, incomplete fusion, slag inclusions, incomplete penetration, buried laminations or lamellar tearing. See Table D-1.

surrounding heat-affected zone (HAZ).

(4) The cost of visual inspection is usually less, per unit length of weld, that the other methods of

rather than simple verification measurements and recording of unsatisfactory workmanship.

Table D-1. Visual Inspection

	Most Applicable	Applicable	Least Applicable
Discontinuity	Microcracks Shrinkage Cavity Undercut Excessive Reinforcement Excessive Convexity Excessive Penetration Misalignment Burn-Through Underfilled Groove Irregular Bead Root Concavity Poor Restart Miscellaneous Surface Discontinuities (Spatter, etc.)	Crater Cracks Group Discontinuous Cracks Branching Cracks Surface Pore Crater Pipe Incomplete Penetration Overlap	Longitudinal Cracks Transverse Cracks Radiating Cracks Uniform Porosity Linear Porosity Elongated Cavity “Worm Hole” Incomplete Fusion (Sidewall or Interpass) Incomplete Fusion (Root)
Joint Geometry	Lap, < 6 mm (< 0.2 in.)	Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

2. PENETRANT TESTING (PT).

a. Method Description. Penetrant testing, also called dye penetrant or liquid penetrant testing, is the use of a liquid penetrating dye to detect discontinuities at the surface of a weld or base metal. The penetrant is applied to the surface, allowed to remain on the surface for a specified dwell time to penetrate cracks, pores, or other surface-breaking discontinuities, and then is carefully removed. A developer is then applied to the surface, which draws the penetrant out of the discontinuities. This leaves a visible contrasting indication in the developer, which is then removed for closer visual examination of the area providing indications. One method of penetrant testing uses a visible dye, usually red, which contrasts with the developer, usually white. The second method uses a flourescent dye, visible under ultraviolet light. Flourescent methods are usually more sensitive, but require a darkened area for testing.

b. Advantages and Disadvantages.

(1) Penetrant testing is relatively economical compared to ultrasonic testing, and especially economical when compared to radiographic testing.

(2) Testing materials are small, portable, and inexpensive, with no specialized equipment required unless an ultraviolet light is used.

(3) A relatively short period of training is necessary for technicians who will be performing PT.

(4) PT can be performed relatively quickly, depending upon the penetrant used and the required dwell time.

(4) A disadvantage with some penetrants and developers is the safe handling and disposal of used liquids and cleaning rags.

(5) Cleaning after inspection to remove residual penetrant and developer prior to weld repairs or the application of coating systems can sometime be difficult and time-consuming.

(6) Rough surface conditions, and irregular profile conditions such as undercut and overlap, can sometimes provide false indications of weld toe cracks when cleaning is not thoroughly performed. Weld spatter can also make surface removal of the penetrant more difficult.

(7) PT cannot be performed when the surface remains hot, unless special high-temperature PT materials are used, so waiting time is sometimes necessary with PT that would not be required with magnetic particle testing.

(8) Existing coatings should be removed prior to PT because the coating may bridge narrow cracks, preventing the entry of the penetrant.

(9) PT is especially effective with small surface-breaking cracks, such as toe cracks, and also surface-breaking piping porosity, crater cracks, laminations along exposed edges and joint preparations, and other surface discontinuities.

(10 PT is ineffective for any discontinuity below the surface, such as buried cracks, slag inclusions, lack of fusion, or incomplete penetration. See Table D-2.

Table D-2. Penetrant Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity	Radiating Cracks Surface Pore\ Crater Pipe Overlap Miscellaneous Surface Discontinuities (Spatter, etc.)	Longitudinal Cracks Transverse Cracks Crater Cracks Group Discontinuous Cracks Branching Cracks Uniform Porosity Linear Porosity Shinkage Cavity Incomplete Fusion (Sidewall or Interpass) Incomplete Fusion (Root) Incomplete Penetration Undercut Burn-Through	Microcracks Elongated Cavity “Worm Hole”
Joint Geometry		Lap, < 6 mm (< 0.2 in.) Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

3. MAGNETIC PARTICLE TESTING (MT).

a. Method Description. Magnetic particle testing uses the relationship between electricity and magnetism to induce magnetic fields in the steel. Magnetic particles, commonly in the form of iron powder colored for better visibility, are dusted onto the magnetized surface. Cracks and other discontinuities on or near the surface disturb the lines of magnetic force, essentially acting as poles of a magnet, attracting the magnetic particles. After the area has been magnetized, the particles are applied, then removed with gentle dusting or application of air. Particles attracted to discontinuities remain on the surface at the discontinuity, attracted to the magnetic poles. The MT technician then evaluates the location and nature of the indicating particles. Tight lines are indicative of surface cracks or other discontinuities. Subsurface cracks and slag inclusions would show a broader indication. A permanent record of detected discontinuities can be made with the use of transparent adhesive tape or photography.

(1) The magnetic fields can be induced using either prods, which directly magnetize the steel through direct contact with the steel and the induction of current flow in the steel, or with a yoke, which does not transfer electrical current but provides magnetic flux between the two elements of the yoke.

(2) MT equipment may be operated either DC (rectified AC) or AC. DC provides higher magnetization levels which allows for inspection for discontinuities somewhat below the surface. Inspection with AC is generally limited to surface-breaking and very near-surface discontinuities, and is considered more effective for surface discontinuities because the particles are more mobile.

b. Advantages and Disadvantages.

(1) MT is relatively fast and economical.

(2) The equipment is relatively inexpensive, compared with ultrasonic or radiographic equipment.

(3) A source of electric power is necessary.

(4) Inspection costs are generally equal to or slightly more than PT, but considerably less than UT or RT.

(5) More training is necessary for MT, compared to PT, but substantially less than that required for UT or RT.

(6) MT can be performed effectively while the joint is still warm from welding or postheating.

(7) After inspection, removal of magnetic particles is quick and thorough, not delaying repairs or affecting coating application.

(8) Existing coatings may reduce the effectiveness of MT.

(9)The depth of inspectability depends upon the equipment, selection of current, and the type of particles used. Although opinions vary as to the maximum depth that can be effectively inspected using MT, 8 mm (5/16 in.) is generally considered the deepest discontinuity that can be detected under good conditions.

(10) MT is effective for detecting surface-breaking discontinuities such as cracks and laminations. It is also effective for cracks, laminations, incomplete fusion, slag inclusions, and incomplete penetration

if slightly below the surface. Rounded discontinuities such as porosity do not disturb the magnetic flux lines sufficiently to be effectively detected. See Table D-3.

Table D-3. Magnetic Particle Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity		Longitudinal Cracks Transverse Cracks Radiating Cracks Crater Cracks Group Discontinuous Cracks Branching Cracks Surface Pore Shrinkage Cavity Crater Pipe Incomplete Fusion (Sidewall or Interpass) Incomplete Fusion (Root) Incomplete Penetration Undercut Overlap	Microcracks Uniform Porosity Linear Porosity Elongated Cavity “Worm Hole” Burn-Through Miscellaneous Surface Discontinuities (Spatter, etc.)
Joint Geometry	Lap, < 6 mm (< 0.2 in.)	Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

4. ULTRASONIC TESTING (UT).

a. Method Description. Ultrasonic testing requires specialized equipment to produce and receive precise ultrasonic waves induced into the steel using piezoelectric materials. The unit sends electric pulses into the piezoelectric crystal, which converts electrical energy into vibration energy. The vibration is transmitted into the steel from the transducer using a liquid couplant. The vibration is introduced into the steel at a known angle, depending upon the design of the transducer, with a known frequency and waveform. The speed of travel of the vibration in steel is also known. The vibration pulse travels through the steel until it strikes a discontinuity, or the opposite face of the steel, either of which reflects energy back to the transducer unit or another receiving transducer. Using a system of calibration and measurements, the location, relative size and nature of the discontinuity, if any, can be determined by close evaluation of the reflected signals. Small reflections are generally ignored, unless located in specific regions such as along edges. Locations of discontinuities can be determined using the display screen scale and simple geometry.

(1) AWS *D1.1* Section 6, Part F provides the UT inspection procedures, including calibration, scanning methods, scanning faces, and transducer angles, and weld acceptance criteria, including reflected signal strength, discontinuity lengths and locations for weld discontinuities. Report forms, generally hand written, are prepared by the UT technician, recording weld discontinuities and other material discontinuities that exceed the acceptance criteria specified.

(2) More expensive and sophisticated UT equipment can be operated in digital mode, recording and printing display screen images with input data. Very sophisticated automated UT equipment can record the transducer location and the corresponding reflections, then use computer software systems to produce representative two-dimensional images, from various directions, of the inspected area and discontinuities. Such equipment is rarely used in normal construction inspection applications, but is available and sometimes used for very complex and critical inspections.

(3) Even with conventional equipment, more complex inspection methods can be used to locate, evaluate and size weld discontinuities. These techniques include tip diffraction and time-of-flight techniques, and can be incorporated into project inspection through the use of AWS *D1.1* Annex K provisions. Annex K requires the use of written UT procedures specific to the application, with experienced and qualified UT technicians tested in the use of the procedures, and also provides for alternate acceptance criteria in lieu of the tables found in Section 6, Part F of AWS *D1.1*. Such provisions are necessary when using miniature transducers, alternate frequencies, or scanning angles other than those prescribed.

b. Advantages and Disadvantages.

(1) Ultrasonic testing is a highly sensitive method of NDT, and is capable of detecting discontinuity in welds and base metal in a wide variety of joint applications and thicknesses.

(2) AWS *D1.1* provisions are applicable for thickness ranges from 8 mm (5/16 in.) to 200 mm (8 in.) Both thinner and thicker materials may be examined and evaluated using UT, but Annex K must be used for technique and acceptance.

(3) Although capable of locating discontinuities and measuring discontinuity length, it is less capable of directly sizing discontinuities or determining discontinuity height without the use of advanced techniques.

(4) A primary disadvantage of ultrasonic testing is that it is highly dependent upon the skill of the UT technician.

(6) The cost of the equipment is considerably more that MT, but also much less than RT. The cost of more sophisticated UT units capable of computer-generated imaging approaches, and sometimes exceeds, the cost of RT equipment.

(7) UT indications are difficult to interpret in certain geometric applications. It is ineffective for fillet welds unless very large, and then only for the root area for fillet welds above approximately 18 mm (3/4 in.). When backing bars remain in place, it is difficult to distinguish between the backing bar interface and cracks, slag lines, or lack of penetration or fusion at the root. With partial joint penetration groove welds, it is difficult to distinguish between the unfused root face and discontinuities near the root. In welded beam-to-column moment connections, the interference of the web with inspection of the bottom flange makes direct evaluation of the area beneath the weld access hole difficult. Second-leg inspections, not as accurate or as reliable as first-leg inspections, are necessary to evaluate the entire depth of many welds unless the weld face is ground flush. Discontinuities located just below the weld or material surface are also difficult to detect.

(8) UT is best suited for planar discontinuities such as cracks and lack of fusion, discontinuities which are generally most detrimental to joint performance when oriented transverse to the direction of loading. These discontinuities tend to be irregular with rough surfaces, and therefore reflect signals even when not exactly perpendicular to the direction of the pulse. Laminations and lamellar tears are also easily detected. Smooth surfaces, such as unfused root faces, would redirect a signal and provide a weak response unless oriented perpendicular to the pulse. Rounded and cylindrical discontinuities such as porosity disperse the signal, also providing a weak response, but such rounded discontinuities are rarely detrimental to joint performance. Slag inclusions are irregular and provide easily identifiable responses. See Table D-4.

(9) The cost of ultrasonic testing is considerably more than PT or MT, and considerably less than RT. However, UT is the best method for detection of the most serious weld discontinuties in a wide variety of thicknesses and joints. The time, and therefore cost, of UT inspection can vary greatly, depending upon the quality of the weld to be inspected. A good quality weld will provide few responses, requiring little evaluation time. A difficult configuration, or a poor quality weld, will require numerous time-consuming evaluations and recording of test data.

Table D-4. Ultrasonic Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity	Longitudinal Cracks Incomplete Fusion (Sidewall or Interpass)	Transverse Cracks Radiating Cracks Elongated Cavity Solid Inclusion Slag or Flux Inclusion Oxide Inclusion Metallic Inclusion Incomplete Fusion (Root) Incomplete Penetration Burn-Through Irregular Bead Poor Restart	Microcracks Crater Cracks Group Discontinuous Cracks Branching Cracks Uniform Porosity Linear Porosity “Worm Hole” Surface Pore Shrinkage Cavity Crater Pipe Undercut Excessive Reinforcement Excessive Convexity Excessive Penetration Overlap Misalignment Underfilled Groove Root Concavity
Joint Geometry		Lap, < 6 mm (< 0.2 in.) Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) One-Side Only Access Single-V Groove

5. RADIOGRAPHIC TESTING (RT).

a. Method Description. Radiographic Testing (RT) uses a radioactive source and, typically, a film imaging process similar to X-ray film. The film provides a permanent record of the inspection. When a weld is exposed to penetrating radiation, some radiation is absorbed, some scattered, and some transmitted through the weld onto the film. Image Quality Indicators (IQIs) are used to verify the quality and sensitivity of the image. Most conventional RT techniques involve exposures that record a permanent image on film, although other image recording methods are also used. Real-time radiography uses a fluoroscope to receive radiation, then presents an on-screen image for evaluation. The two types of radiation sources commonly used in weld inspection are x-ray machines and radioactive isotopes.

(1) X-rays are produced by portable units capable of radiographing relatively thin objects. A large 2000 kV X-ray unit is capable of penetrating approximately 200 mm (8 in.) of steel, a 400 kV unit to 75 mm (3 in.), and a 200 kV unit to 25 mm (1 in.) of steel.

(2) Radioisotopes are used to emit gamma radiation. The three most common RT isotopes are cobalt 60, cesium 137, and iridium 192. Cobalt 60 can effectively penetrate up to approximately 230 mm (9 in.) of steel, cesium 137 to 100 mm (4 in.), and iridium 192 to 75 mm (3 in.) of steel.

b. Advantages and Disadvantages.

(1) RT can detect subsurface porosity, slag, voids, cracks, irregularities, and lack of fusion. See Table D-5.

(2) Accessibility to both sides of the weld is required.

(3) RT is limited to butt joint applications by AWS *D1.1*. Because of the constantly changing thickness for the exposure, RT is not effective when testing fillet welds or groove welds in tee or corner joints.

(4) To be detected, an imperfection must be oriented roughly parallel to the radiation beam. As a consequence, RT may miss laminations and cracks parallel to the film surface. Because they are usually volumetric in cross-section, discontinuities such as porosity or slag are readily detected.

(5) The limitations on RT sensitivity are such that discontinuities smaller than about 1½ percent of the metal thickness may not be detected.

(6) The radiographic images provide a permanent record for future review, and aid in characterizing and locating discontinuities for repair.

(7) RT is generally unaffected by grain structure, particularly helpful with ESW and EGW welds.

(8) RT is a potential radiation hazard to personnel, and strict safety regulations must be monitored and enforced.

(9) The cost of radiographic equipment, facilities, safety programs, and related licensing is higher than any other NDT process.

(10) There is usually a significant waiting time between the testing process and the availability of results.

Table D-5. Radiographic Testing

	Most Applicable	Applicable	Least Applicable
Discontinuity	Longitudinal Cracks Transverse Cracks Radiating Cracks Crater Cracks Group Discontinuous Cracks Branching Cracks Uniform Porosity Linear Porosity Elongated Cavity “Worm Hole” Solid Inclusion Slag or Flux Inclusion Oxide Inclusion Metallic Inclusion Incomplete Fusion (Root) Incomplete Penetration	Surface Pore Shrinkage Cavity Crater Pipe Incomplete Fusion (Sidewall or Interpass) Undercut Excessive Reinforcement Excessive Convexity Excessive Penetration Burn-Through Underfilled Groove Root Concavity Miscellaneous Surface Discontinuities (Spatter, etc.)	Microcracks Overlap
Joint Geometry	Lap, 6-15 mm (0.2 - 0.6 in.) Both-Side Access Double-V Groove	Lap, < 6 mm (< 0.2 in.) Lap, 16 - 50 mm (0.6 - 2 in.) Lap, > 50 mm (> 2 in.) Single-V Groove	

6. OTHER METHODS.

Because of severe limitations in applicability, the use of eddy current, acoustic emission, or other methods not mentioned above is discouraged.