

Welding Guidelines for the Chemical, Oil, and Gas Industries

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Welding Guidelines for the Chemical, Oil, and Gas Industries

1 Scope

1.1 This recommended practice provides supplementary guidelines and practices for welding and welding-related topics for shop and field fabrication, repair, and modification of the following:

- a) pressure-retaining equipment, such as pressure vessels, heat exchangers, piping, heater tubes, and pressure boundaries of rotating equipment and attachment welds;
- b) tanks and attachment welds;
- c) nonremovable internals for process equipment;
- d) structural items attached and related to process equipment;
- e) other equipment or component items when referenced by an applicable purchase document.

1.2 This document is general in nature and augments the welding requirements of ASME *Boiler and Pressure Vessel Code (BPVC)* Section IX, ISO 15614, and similar codes, standards, specifications, and practices, such as those listed in Section 2 of this document. The intent of this document is to be inclusive of chemical, oil, and gas industry standards, although there are many topics not covered herein.

1.3 Welding related to fabrication of the following equipment or components is excluded from the scope of this specification:

- a) structures;
- b) pipelines;
- c) subsea production systems;
- d) marine related equipment (e.g. ballasting pipework, systems covered by classification societies);
- e) wellheads, drilling, and downhole equipment;
- f) bulk material components covered by a manufacturer's material certificate (e.g. seam welded pipe and fittings, clad pipe);
- g) heating, cooling, and air conditioning;
- h) nonmetallic materials;
- i) other fabrication methods (e.g. bending and forming, brazing, and mechanical connections).

1.4 This document is based on industry experience. Restrictions or limitations may be waived or augmented by the owner/operator or purchaser.

1.5 Structural welds that are not welded to process equipment are outside the scope of this document.

1.6 Safety and health issues and concerns are beyond the scope of this recommended practice and, therefore, are not fully addressed herein. Safety and health information is available from other sources, including, but not limited to, the following:

- a) ANSI Z49.1;
- b) AWS Safety and Health Fact Sheets;
- c) other safety and health information on the AWS website;
- d) safety data sheets supplied by materials manufacturers;
- e) operating manuals supplied by equipment manufacturers;
- f) applicable regulatory agencies.

The publications listed in 1.6 a), b), and c) can be downloaded and printed directly from the AWS website at <http://www.aws.org>. The Safety and Health Fact Sheets are revised, and additional sheets are added periodically.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including amendments) applies. Other codes and standards may be specified by the purchaser.

API 510, *Pressure Vessel Inspection Code: In-service Inspection, Rating, Repair, and Alteration*

API 570, *Piping Inspection Code: In-Service Inspection, Rating, Repair, and Alteration of Piping Systems*

API Recommended Practice 577, *Welding Processes, Inspection, and Metallurgy*

API Recommended Practice 578, *Material Verification Program for New and Existing Assets*

API Recommended Practice 579-1/ASME FFS-1, *Fitness-for-Service*

API Standard 620, *Design and Construction of Large, Welded, Low-pressure Storage Tanks*

API Standard 650, *Welded Tanks for Oil Storage*

API Standard 653, *Tank Inspection, Repair, Alteration, and Reconstruction*

API Recommended Practice 751, *Safe Operation of Hydrofluoric Acid Alkylation Units*

API Recommended Practice 934-A, *Materials and Fabrication of 2¹/₄Cr-1Mo, 2¹/₄Cr-1Mo-¹/₄V, 3Cr-1Mo, and 3Cr-1Mo-¹/₄V Steel Heavy Wall Pressure Vessels for High-temperature, High-pressure Hydrogen Service*

API Recommended Practice 934-C, *Materials and Fabrication of 1¹/₄Cr-¹/₂Mo Steel Heavy Wall Pressure Vessels for High-pressure Hydrogen Service Operating at or Below 825 °F (440 °C)*

API Recommended Practice 934-E, *Recommended Practice for Materials and Fabrication of 1¹/₄Cr-¹/₂Mo Steel Pressure Vessels for Service Above 825 °F (440 °C)*

API Technical Report 934-H, *Inspection, Assessment, and Repair of Heavy Wall Reactor Vessels in High-temperature High-pressure Hydrogen Service*

API Technical Report 938-B, *Use of 9Cr-1Mo-V (Grade 91) Steel in the Oil Refining Industry*

API Technical Report 938-C, *Use of Duplex Stainless Steels in the Oil Refining Industry*

API Recommended Practice 941, *Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants*, Eighth Edition, February 2016

API Technical Report 942-A, *Materials, Fabrication, and Repair Considerations for Hydrogen Reformer Furnace Outlet Pigtails and Manifolds*

API Technical Report 942-B, *Material, Fabrication, and Repair Considerations for Austenitic Alloys Subject to Embrittlement and Cracking in High Temperature 565 °C to 760 °C (1050 °F to 1400 °F) Refinery Services*

API Standard 1104, *Welding of Pipelines and Related Facilities*

API Recommended Practice 2201, *Safe Hot Tapping Practices in the Petroleum and Petrochemical Industries*

ANSI Z49.1 ¹ *Safety in Welding, Cutting, and Allied Processes*

ANSI/NACE MR0103/ISO 17495 ^{2,3}, *Petroleum, Petrochemical and Natural Gas Industries—Metallic Materials Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Environments*

ASME Boiler and Pressure Vessel Code ⁴, *Section I: Rules for Construction of Power Boilers*

ASME Boiler and Pressure Vessel Code, *Section II: Materials, Part C—Specifications for Welding Rods, Electrodes, and Filler Metals*

ASME Boiler and Pressure Vessel Code, *Section II: Materials, Part D—Properties*

ASME Boiler and Pressure Vessel Code, *Section III: Rules for Construction of Nuclear Facility Components, Subsection NCA—General Requirements for Division 1 and Division 2*

ASME Boiler and Pressure Vessel Code, *Section VIII: Rules for Construction of Pressure Vessels*

ASME Boiler and Pressure Vessel Code, *Section IX: Welding, Brazing, and Fusing Qualifications*

ASME B31.1, *Power Piping*

ASME B31.3, *Process Piping*

ASME PCC-2, *Repair of Pressure Equipment and Piping*

ASTM A262 ⁵, *Standard Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels*

ASTM A488, *Standard Practice for Steel Castings, Welding, Qualifications of Procedures and Personnel*

ASTM A578/578M, *Standard Specification for Straight-Beam Ultrasonic Examination of Rolled Steel Plates for Special Applications*

¹ American National Standards Institute, 1899 L Street, NW, Washington, DC 20036, www.ansi.org.

² Association for Materials Protection and Performance (formerly NACE International), 15835 Park Ten Place, Houston, Texas 77084, www.amp.org.

³ International Organization for Standardization, Chemin de Blandonnet 8, CP 401 – 1214 Vernier, Geneva, Switzerland, www.iso.org.

⁴ American Society of Mechanical Engineers, Two Park Avenue, New York, New York 10016, www.asme.org.

⁵ ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

ASTM A923, *Standard Test Methods for Detecting Detrimental Intermetallic Phase in Duplex Austenitic/Ferritic Stainless Steels*

ASTM E384, *Standard Test Method for Microindentation Hardness of Materials*

ASTM E562, *Standard Test Method for Determining Volume Fraction by Systematic Manual Point Count*

AWS A3.0⁶, *Standard Welding Terms and Definitions—Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*

AWS A4.2M (ISO 8249:2000 MOD), *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Ferritic-Austenitic Stainless Steel Weld Metal*

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

AWS A4.4M, *Standard Procedures for Determination of Moisture Content of Welding Fluxes and Welding Electrode Flux Coverings*

AWS A5.01M/A5.01, *Welding and Brazing Consumables—Procurement of Filler Metals and Fluxes*

AWS A5.2/A5.2M, *Specification for Carbon and Low Alloy Steel Rods for Oxyfuel Gas Welding*

AWS A5.3/A5.3M, *Specification for Aluminum and Aluminum Alloy Electrodes for Shielded Metal Arc Welding*

AWS A5.4/A5.4M, *Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding*

AWS A5.5/A5.5M, *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*

AWS A5.6/A5.6M, *Specification for Copper and Copper-Alloy Electrodes for Shielded Metal Arc Welding*

AWS A5.7/A5.7M, *Specification for Copper and Copper-Alloy Bare Welding Rods and Electrodes*

AWS A5.8M/A5.8, *Specification for Filler Metals for Brazing and Braze Welding*

AWS A5.9/A5.9M, *Specification for Bare Stainless Steel Welding Electrodes and Rods*

AWS A5.10/A5.10M, *Specification for Bare Aluminum-Alloy Welding Electrodes and Rods*

AWS A5.11/A5.11M, *Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding*

AWS A5.12M/A5.12, *Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting*

AWS A5.13/A5.13M, *Specification for Surfacing Electrodes for Shielded Metal Arc Welding*

AWS A5.14/A5.14M, *Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods*

AWS A5.15, *Specification for Welding Electrodes and Rods for Cast Iron*

AWS A5.16/A5.16M, *Specification for Titanium and Titanium Alloy Welding Electrodes and Rods*

AWS A5.17/A5.17M, *Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding*

⁶ American Welding Society, 8669 NW 36 Street, # 130, Miami, Florida 33166, www.aws.org.

AWS A5.18/A5.18M, *Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding*

AWS A5.19, *Specification for Magnesium Alloy Welding Electrodes and Rods*

AWS A5.20/A5.20M, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*

WS A5.21/A5.21M, *Specification for Bare Electrodes and Rods for Surfacing*

AWS A5.22/A5.22M, *Specification for Stainless Steel Flux Cored and Metal Cored Welding Electrodes and Rods*

AWS A5.23/A5.23M, *Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding*

AWS A5.24/A5.24M, *Specification for Zirconium and Zirconium-Alloy Welding Electrodes and Rods*

AWS A5.25/A5.25M, *Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding*

AWS A5.26/A5.26M, *Specification for Carbon and Low-Alloy Steel Electrodes for Electrogas Welding*

AWS A5.28/A5.28M, *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*

AWS A5.29/A5.29M, *Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding*

AWS A5.30/A5.30M, *Specification for Consumable Inserts*

AWS A5.31M/A5.31, *Specification for Fluxes for Brazing and Braze Welding*

AWS A5.32/A5.32M, *Welding Consumables—Gases and Gas Mixtures for Fusion Welding and Allied Processes*

AWS A5.34/A5.34M, *Specification for Nickel-Alloy Electrodes for Flux Cored Arc Welding*

AWS A5.35/A5.35M, *Specification for Covered Electrodes for Underwater Wet Shielded Metal Arc Welding*

AWS A5.36/A5.36M, *Specification for Carbon and Low-Alloy Steel Flux Cored Electrodes for Flux Cored Arc Welding and Metal Cored Electrodes for Gas Metal Arc Welding*

AWS A5.39, *Specification for Flux and Electrode Combinations for Submerged Arc and Electroslag Joining and Surfacing of Stainless Steel and Nickel Alloys*

AWS D1.1, *Structural Welding Code—Steel*

AWS D1.6, *Structural Welding Code—Stainless Steel*

AWS D1.8, *Structural Welding Code—Seismic Supplement*

AWS D10.4, *Recommended Practices for Welding Austenitic Chromium-Nickel Stainless Steel Piping and Tubing*

AWS D10.8, *Recommended Practice for Welding of Chromium-Molybdenum Steel Piping and Tubing*

AWS D10.10, *Recommended Practices for Local Heating of Welds in Piping and Tubing*

AWS D10.18, *Guide for Welding Ferritic/Austenitic Duplex Stainless Steel Piping and Tubing*

AWS D10.22, *Specification for Local Heating of Welds in Creep Strength-Enhanced Ferritic Steels in Piping and Tubing Using Electric Resistance Heating*

AWS D18.2, *Guide to Weld Discoloration Levels on Inside of Austenitic Stainless Steel Tube*

EN 1011⁷, *Welding—Recommendations for welding of metallic materials*

⁷ European Committee for Standardization (CEN), Rue de la Science 23, B - 1040 Brussels, Belgium, www.cen.eu.

EN 10204, *Metallic products—Types of inspection documents*

IOGP S-619 ⁸, *Specification for Unfired, Fusion Welded Pressure Vessels*, August 2018

ISO 3690, *Welding and allied processes—Determination of hydrogen content in arc weld metal*

ISO 3834-2, *Quality requirements for fusion welding of metallic materials—Part 2: Comprehensive quality requirements*

ISO 6507, *Metallic materials—Vickers hardness test—Part 1: Test method*

ISO 9001, *Quality management systems—Requirements*

ISO 9606, *Qualification testing of welders—Fusion welding*

ISO 10474, *Steel and steel products—Inspection documents*

ISO 14175, *Welding consumables—Gases and gas mixtures for fusion welding and allied processes*

ISO 14344, *Welding consumables—Procurement of filler materials and fluxes*

ISO 14731, *Welding coordination—Tasks and responsibilities*

ISO 14732, *Welding personnel—Qualification testing of welding operators and weld setters for mechanized and automatic welding of metallic materials*

ISO 15609, *Specification and qualification of welding procedures for metallic materials—Welding procedure specification—Part 1: Arc welding*

ISO 15614, *Specification and qualification of welding procedures for metallic materials—Welding procedure test—Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys*

ISO/IEC 17025 ⁹, *General requirements for the competence of testing and calibration laboratories*

ISO/TR 17671, *Welding—Recommendations for welding of metallic materials—Part 1: General guidance for arc welding*

ISO 17781, *Petroleum, petrochemical and natural gas industries—Test methods for quality control of microstructure of ferritic/austenitic (duplex) stainless steels*

NACE MR0175/ISO 15156, *Petroleum and Natural Gas Industries—Materials for Use in H₂S-containing Environments in Oil and Gas Production—Parts 1, 2, and 3*

NACE SP0178, *Design, Fabrication, and Surface Finish Practices for Tanks and Vessels to Be Lined for Immersion Service*

NACE SP0472, *Methods and Controls to Prevent In-service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments*

National Board NB-23 ¹⁰, *National Board Inspection Code*

SFA-5.01M/SFA-5.01, *Welding and Brazing Consumables—Procurement of Filler Materials and Fluxes*

⁸ International Association of Oil & Gas Producers, City Tower, 40 Basinghall Street, London EC2V 5DE, United Kingdom, www.iogp.org.

⁹ International Electrotechnical Commission, 3 Rue de Varembé, CH-1211, Geneva 20, Switzerland, www.iec.ch.

¹⁰ National Board of Boiler and Pressure Vessel Inspectors, 1055 Crupper Avenue, Columbus, Ohio 43229, www.nationalboard.org.

SFA-5.02/SFA-5.02M, *Specification for Filler Metal Standard Sizes, Packaging, and Physical Attributes*

SFA-5.1/SFA-5.1M, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*

WRC Bulletin 412 ¹¹, *Challenges and Solutions in Repair Welding for Power and Process Plants*

WRC Bulletin 421, *Welding Type 347 Stainless Steel—An Interpretive Report*

WRC Bulletin 452, *Recommended Practices for Local Heating of Welds in Pressure Vessels*

WRC Bulletin 525, *Fabrication and Repair of Low Alloy Steel Pressure Equipment*

David Abson, Adrienne Barnes, Sayee Raghunathan, and Steve Jones, "Temper Bead Qualification Hardness Acceptance Criteria," TWI Ltd and Rolls-Royce plc., ASME Standards Technology, LLC-2013

W.E. Erwin and J.G. Kerr, "The Use of Quenched and Tempered 2¹/₄Cr-1Mo Steel for Thick Wall Reactor Vessels in Petroleum Refinery Processes," Welding Research Council Bulletin WRC 275, 1982

Surajit Ghosal, "Failure Analysis of Reactor Effluent Air Cooler (REAC) in Hydrocracker Unit," NACE Corrosion 2014, Paper No. 3730

Briony Holmes, "Guidelines for Measuring the Amount of Ferrite in Duplex Stainless Steels," Materials Technology Institute, Inc., 2018

Vahid A. Hosseini, Kjell Hurtig, Daniel Eyzop, Agneta Östberg, Paul Janiak, and Lief Karlsson, "Ferrite Content Measurement in Super Duplex Stainless Steel Welds," *Welding in the World*, 2019, 63, pp. 551–563

Hiroyuki Iwamoto, Fumiyoshi Minami, "Japanese Welding Guideline for Duplex Stainless Steels," ASME PVP 2019, Paper PVP2019-93022, San Antonio, Texas, July 14–19, 2019

David E. Moore, "Fabrication of 2205 Duplex Stainless Steel REACs in Refinery Hydroprocessing Units," Materials Technology Institute, Inc., 2015

W.J. Sperko, "Exploring Temper Bead Welding," *Welding Journal*, 2005, 84(7), pp. 37–40

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1

applicable code

The code or standard specified by the purchaser to which the equipment shall conform.

3.1.2

backing gas

(also called purge gas)

Gas that is used on the backside of a weld to prevent reaction with the atmosphere.

¹¹ Welding Research Council, P.O. Box 201547, Shaker Heights, Ohio 44122, www.forengineers.org.

3.1.3 **carbon equivalent** **CE**

$$CE = \%C + \%Mn/6 + (\%Cr + \%Mo + \%V)/5 + (\%Cu + \%Ni)/15$$

NOTE This CE formula was developed by the International Institute of Welding, and historically has been used for most applications; however, there are other CE formulas also in use.

3.1.4 **controlled-deposition welding** **CDW**

Welding techniques used to obtain controlled grain refinement and tempering of the underlying heat-affected zone (HAZ) in the base metal; various CDW techniques are used, such as temper bead, surface temper bead, and half bead.

3.1.5 **duplex stainless steel** **DSS**

Stainless steels with Cr and Ni contents balanced to produce microstructures with about 50 % ferrite and 50 % austenite; there are four categories of DSS that are defined in 3.1.8, 3.1.11, 3.1.18, and 3.1.20.

3.1.6 **half bead technique**

A controlled deposition method characterized by the removal by grinding of approximately one-half thickness of the previously deposited weld metal layer, so that the heat from the second layer of weld metal effectively tempers the entire previous layer's heat affected zone.

3.1.7 **high-temperature hydrogen service**

Service where the combination of temperature and partial pressure of hydrogen are greater than what is acceptable for the applicable alloy in API 941; typically, most owner/operators define high-temperature hydrogen service by drawing a curve 50 °F below and 25 psia to the left of the operating limit curve (Nelson Curve) in API 941.

3.1.8 **hyper duplex stainless steel**

Duplex stainless steels with 33 % Cr or less and a pitting resistance equivalent number (PREN) of 48-55; examples of hyper duplex stainless steel are UNS S32707 and UNS S33207.

3.1.9 **included angle**

The total angle between the two weld faces, adding both sides of the bevel.

3.1.10 **inspector**

The purchaser's representative.

3.1.11 **lean duplex stainless steel**

Duplex stainless steels with either lower Cr, Ni, or Mo than the standard 2205 grade; typically, lean duplex has nominal 20 % Cr and PREN less than 30. Common lean duplex stainless steels are UNS S32101, UNS S32202, UNS S32304, UNS S32003, UNS S82011, and UNS S82441. Lean duplex grades are primarily used as an alternative to 304L and 316L stainless.

3.1.12**low-alloy steel**

Steels with alloy additions, where chromium content ranges from 1.0 percent nominal to 9.0 percent nominal (e.g. P-number 3 to 5, and P-number 15E).

3.1.13**owner/operator**

The owner/operator is responsible for the reliable operation of the welded component in a specific facility or site; the owner/operator may be represented by a person or a group of people.

3.1.14**P-number (shown as P-No. in this document)**

Base metals have been grouped by P-numbers assigned by the ASME *BPVC* Section IX Committee; for current P-numbers, ASME *BPVC* Section IX should be consulted.

3.1.15**pitting resistance equivalent number****PREN**

A semi-quantitative method of categorizing relative resistance to halide pitting in stainless steels, where

$$\text{PREN} = \% \text{Cr} + 3.3(\% \text{Mo} + \% \text{W}/2) + 16\% \text{N}$$
(with elements in weight percent).

3.1.16**procedure qualification record****PQR**

A record of welding variables used to produce an acceptable test weldment and the results of tests conducted on the weldment to qualify a welding procedure specification (WPS).

3.1.17**purchaser**

The party that issues the purchase order; this may be the owner/operator of the equipment or component, or the owner/operator's designated agent (e.g. the engineering contractor).

3.1.18**standard duplex stainless steel**

Duplex stainless steels with nominal 22 % Cr and with $30.0 \leq \text{PREN} < 40.0$. UNS S31803 and UNS S32205 (known as Alloy 2205) are the most widely used wrought versions; UNS J92205 (ASTM A890 Grade 4A, CD3MN) and UNS J93372 (ASTM A890 Grade 1B, CD4MCuN) are the most common cast versions.

3.1.19**sour service**

Sour service conditions exist when either H_2S or the HS^- ion are present in significant quantities in aqueous water. There is no general agreement on the threshold H_2S or HS^- that defines sour service, however. ANSI/NACE MR0103/ISO 17495 cites the following conditions known to promote sour service cracking in carbon steels:

- a) > 50 ppmw total sulfide content in the aqueous phase;
- b) ≥ 1 ppmw total sulfide content in the aqueous phase and $\text{pH} < 4$;
- c) ≥ 1 ppmw total sulfide content and ≥ 20 ppmw free cyanide in the aqueous phase, and $\text{pH} > 7.6$;
- d) > 0.3 kPa absolute (0.05 psia) partial pressure H_2S in the gas phase associated with the aqueous phase of a process.

3.1.20

super duplex stainless steel

Duplex stainless steels with nominal 25 % Cr and with $40.0 \leq \text{PREN} < 48.0$; some common examples are UNS S32760 (Zeron 100), UNS S32750 (Alloy 2507), and UNS S32550 (Ferralium 255). Common super duplex stainless steel castings are UNS J93380 (ASTM A890 Grade 6A, CD3MWCuN) and UNS J93404 (ASTM A890 Grade 5A, CE3MN).

3.1.21

surface temper bead reinforcing layer

Surface temper bead reinforcing layer is a subset of temper bead welding (TBW) in which one or more layers of weld metal are applied on or above the surface layers of a component and are used to modify the properties of previously deposited weld metal or the HAZ; surface layer may cover a surface or only the perimeter of the weld.

3.1.22

temper bead welding

TBW

CDW techniques involving the sequencing of weld passes such that the heat input from subsequent weld beads temper the HAZ microstructure formed by previous weld passes; weld beads are placed at specific locations for the purpose of tempering the previously deposited weld metal and its HAZ. Temper beads may be placed above, flush with, or below the surrounding base metal surface. If above the base metal surface, the beads may cover all or only part of the weld deposit and may or may not be removed following welding.

3.1.23

waveform-controlled welding

A process modification using software to purposely manipulate the output welding waveform.

3.1.24

weld zone

A grouping of weld passes with similar parameters and function (i.e. root, fill, and cap are each weld zones).

3.1.25

welding procedure specification

WPS

A document providing the required welding variables for a specific application to ensure repeatability by properly trained welders and welding operators.

3.2 Acronyms and Abbreviations

BPVC *Boiler and Pressure Vessel Code*

CDW controlled-deposition welding

CE carbon equivalent

CVN Charpy V-notch

DHT dehydrogenation heat treatment

DSS duplex stainless steel

EGW electrogas welding

ESW	electroslag welding
FCAW	flux-cored arc welding
FCAW-G	flux-cored arc welding—gas shielded
FCAW-S	flux-cored arc welding—self shielded (no gas shielding)
FN	Ferrite Number
GMAW	gas metal arc welding
GMAW-G	gas metal arc welding—globular transfer
GMAW-P	gas metal arc welding—pulsed arc
GMAW-S	gas metal arc welding—short circuiting transfer
GMAW-Sp	gas metal arc welding—spray transfer
GTAW	gas tungsten arc welding
GTAW-P	gas tungsten arc welding—pulsed
HAZ	heat-affected zone
HF	hydrofluoric
M_f	martensite finish temperature
MT	magnetic particle testing
NDE	nondestructive examination
PAW	plasma arc welding
PMI	positive material identification
PQR	procedure qualification record
PREN	pitting resistance equivalent number
PT	penetrant testing
PWHT	post-weld heat treatment
SAW	submerged arc welding
SMAW	shielded metal arc welding
TBW	temper bead welding
WPS	welding procedure specification

4 General Welding Requirements

4.1 When approved by the purchaser (engineer), welding procedures for certain welds between structural members of an attachment but not welded to the pressure boundary shall either comply with D.1, D.6, and D.8 or may be qualified per ASME *BPVC* Section IX.

4.2 WPSs and procedure qualification records (PQRs) shall be qualified in accordance with ASME *BPVC* Section IX and the requirements of this recommended practice. Existing WPSs/PQRs, or parts of existing WPSs/PQRs, may be acceptable, provided the requirements of this specification are satisfied.

4.3 Welds (including tack and fit-up) shall be deposited using approved and qualified weld procedures, approved materials, and certified welders.

4.4 WPSs and welding PQRs and weld maps (including effective thickness data) shall be submitted to the purchaser for review and approval prior to the start of fabrication or construction unless submittal is waived by the purchaser. Weld maps, similar guides, or fabrication drawings that clearly identify the application of each WPS, indicating where and how these WPSs will be used, shall be included in the submittal. An owner/operator does not take over the responsibility and liability evolving from a formal approval of WPSs, PQRs, or weld maps.

4.5 Weld maps, similar guides, drawings, or other documentation shall be updated during fabrication to clearly indicate the welder(s) or welding operator(s) that deposited each weld. Similarly, the location of nondestructive examination (NDE) performed during fabrication shall be recorded. In addition, the heat number, lot number, batch number, or other applicable identification of consumables used for each weld shall be recorded..

4.6 Pressure boundary welds or welds to the pressure boundary shall comply with the specified design code, plus any applicable API standard or recommended practice.

4.7 WPSs using waveform-controlled welding shall have the heat input measured using instantaneous power or instantaneous energy, per ASME *BPVC* Section IX.

4.8 Pressure-retaining groove welds shall be full penetration and two layers minimum.

4.9 Welder and Welding Operator Qualifications

4.9.1 Welders, including tack welders, shall be qualified in accordance with applicable parts of ASME *BPVC* Section IX or ISO 9606, whichever is applicable.

4.9.2 Welding operators shall be qualified in accordance with ASME *BPVC* Section IX or ISO 9606, whichever is applicable.

5 Welding Processes

5.1 Acceptable Welding Processes

Acceptable welding processes are as follows:

- a) shielded metal arc welding (SMAW);
- b) gas tungsten arc welding (GTAW) and pulsed GTAW (GTAW-P);

- c) gas metal arc welding (GMAW) with solid wire and metal cored electrodes for the following transfer modes:
 - 1) spray (GMAW-Sp);
 - 2) short circuiting (GMAW-S);
 - 3) GMAW-P;
 - 4) globular (GMAW-G);
 - 5) other transfer modes approved by the purchaser;
- d) submerged arc welding (SAW);
- e) electrogas welding (EGW);
- f) electroslag welding (ESW), limited to weld overlay onto P-No. 1 through P-No. 5 and P-No. 15E base materials;
- g) flux-cored arc welding (FCAW);
- h) plasma arc welding (PAW);
- i) other welding processes approved by the purchaser.

5.2 Limitations of Fusion Welding Processes

5.2.1 General

Fusion welding processes listed in 5.1 are acceptable with the restrictions and notes stated in 5.2.2 through 5.2.7.

5.2.2 Gas Tungsten Arc Welding—Pulsed

- a) When used for root pass, fill pass, and/or cover pass welding of single-sided joints, GTAW-P should be performed with the same make and model of equipment, using the same program settings as those used in the procedure qualifications. These requirements shall be stated on the WPS.

NOTE The need to specify the make and model, program, equipment settings, and pulse waveform is based upon the effects these variables have on welding arc performance, especially sidewall fusion and out-of-position welding. Studies have shown considerable variation in arc characteristics between different makes or models of welding systems. This variation can lead to welding defects, some of which can be difficult to detect using radiography.

- b) GTAW-P machines shall be equipped with arc starting devices (e.g. high-frequency starting unit), crater-elimination, slope-in and slope-out control, and pre-gas and post-gas flow.

5.2.3 Gas Metal Arc Welding—Short Circuiting

The use of GMAW-S shall be limited as follows.

- a) GMAW-S shall not be used for branch connections, nozzle-to-shell welds, or socket welds.

- b) GMAW-S may be used for root pass welding where the backside of the weld is not accessible. Root pass welding with GMAW-S for other applications is permitted, provided the root pass is completely removed from the backside, or as approved by owner/operator.
- c) Entire fillet welds and the fill and cap passes for butt welds may be welded with this process, provided the thickness of the welded component does not exceed 3/8 in. (9.5 mm), and vertical welding is performed with uphill progression.
- d) For vertical welding, the root pass and second pass progression for a material of any thickness may be either uphill or downhill.
- e) Variations of GMAW-S shall have the same limitations as outlined above. Proposals to use GMAW-S variations without back purging shall be approved by the owner/operator's engineer.
- f) For piping in fixed position, GMAW-S should not be used for pipe sizes under NPS 4.

5.2.4 Gas Metal Arc Welding—Pulsed

GMAW-P may be used for any material thickness in any position. Welding shall be performed with the same make and model of welding equipment and using the same program settings as those used in the procedure qualification. These requirements shall be stated on the WPS.

NOTE It is recommended that whenever the welding system is changed or the settings on existing equipment significantly altered, that the fabricator verify weld properties. The extent of verification or testing should be as agreed between the purchaser and the fabricator.

5.2.5 Flux-cored Arc Welding

5.2.5.1 Self-shielding FCAW (FCAW-S) shall not be used for carbon and low-alloy steel pressure-retaining welds.

5.2.5.2 FCAW with external gas shielding (FCAW-G) may be used for pressure-retaining welds, structural welds, or weld overlays (see Annex B for overlays).

5.2.5.3 When rutile type (i.e. E71T-1 type) consumables are used with impact testing required, test reports on a Certified Material Test Report should be required per A/SFA 5.01. Alternatively, the specific brand and trade name of the consumable used in production should be qualified on supporting PQRs with impact test results meeting the minimum design code requirements.

NOTE For FCAW procedures in critical services requiring either impact or hardness testing, it is advisable to review weld metal properties with the consumable manufacturer to ensure the original qualified properties continue to be met. Minor variations that occur over time with FCAW consumable formulations (e.g. raw material and microalloying changes) do not adversely affect the ability of these products to perform as intended. However, small changes in microalloying additions can have significant effects on properties, especially after heat treatment.

5.2.5.4 Welding consumables shall be limited to the ASME/AWS or ISO classification used in the PQR. These requirements shall be stated on the WPS.

5.2.6 Electrogas Welding

The use of EGW shall be limited by the following conditions.

- a) EGW shall be used only with filler materials specifically intended for the EGW process (ASME/AWS SFA/A5.26).

- b) Welding consumables shall be limited to the classification and manufacturer's trade name used in the PQR. These requirements shall be stated on the WPS.
- c) Only filler materials having specified minimum impact test requirements shall be used.

5.2.7 Submerged Arc Welding

5.2.7.1 Manually held (semiautomatic) SAW is not permitted for welding pressure-containing parts, unless approved by the purchaser.

5.2.7.2 A separate qualification is required for SAW welds in which any pass thickness is greater than $\frac{1}{2}$ in. (13 mm).

5.2.7.3 Run-on and run-off plates (tabs) shall have the same P-No. as the base metal. Exceptions are permitted when the end of base metal adjoining the run-on or run-off plate/tabs will be cut off.

5.3 Single-sided Welded Joints

For single-sided welded joints, welding processes using fluxes shall not be used for root pass welding of stainless steels, nonferrous alloys, and nickel-base alloys, unless slag can be removed from the process side of root passes and the area inspected for slag removal. Residual slag may produce fluoride corrosion of these alloys. Acceptance of slag-producing weld processes for these alloys shall be per agreement between the purchaser and the fabricator.

5.4 Combining Filler Metals of Different Compositions

Combining two or more welding processes using alloy filler metals of different nominal compositions, other than ASME weld metal classifications A-Numbers 1 through 5, requires qualification as a combination procedure.

5.5 Automated Welding Processes

5.5.1 Orbital machine welding and similar fully automated welding processes require separate programming weld schedules for the specific joint geometry, diameter, wall thickness, and welding position. These weld schedules shall report essential and nonessential variables needed to accurately describe motions (e.g. travel and oscillation), timing, and electrical functions of the welding system. Specific weld schedules relevant to each welding procedure shall be noted on the WPS or as a supplementary table attached to the WPS.

5.5.2 A change in position according to ASME *BPVC* Section IX, QW-461.9 shall be considered an essential variable for procedure qualification.

6 Welding Consumables (Filler Metal and Flux)

6.1 General

6.1.1 Filler metals shall be specified in each WPS by ASME *BPVC* Section II, Part C/AWS, or ISO specification and classification. Filler metals that do not conform to an ASME/AWS or ISO specification shall be submitted to the purchaser for approval. When the brand name is an essential variable, the brand name shall be specified in the WPS.

NOTE Annexes A, C, and D provide general guidance and recommended filler metal selections.

6.1.2 Testing is required to verify consumable mechanical properties whenever:

- a) the deposited filler metal does not fall within ASME/AWS or ISO filler metal specifications;
- b) the manufacturer's typical consumable certification or other supplier certifications are not available.

When this testing is done, tensile strength, yield strength, and elongation shall meet the specified minimum code and design requirements.

When post-weld heat treatment (PWHT) is required for either 6.1.2 a) or 6.1.2 b), test coupons of weld metal only shall be PWHT'd with the nominal temperature and maximum time the same as to be used in production. Tensile strength, yield strength, and elongation shall meet the specified minimum code and design requirements. When impact testing is required, it shall also meet the specified minimum code and design requirements.

NOTE 1 Refer to ASME *BPVC* Section IX, QW-202 for guidance on mechanical testing.

NOTE 2 The testing described in 6.1.2 does not apply to weld overlays.

6.1.3 Groove and/or fillet welds using flux-based processes shall be made with filler metals producing low-hydrogen deposits as defined in Tables 1 and 2. Some industry codes/standards (e.g. API 650) may be more restrictive for certain materials and/or specific applications. In such cases, governing industry codes and standards take precedence over this recommended practice. However, for the following conditions, non-low-hydrogen, cellulose-type SMAW electrodes are permitted:

- a) for API 620 and API 650 storage tank fabrication and erection, where the carbon steel base metal thickness is less than $\frac{1}{2}$ in. (13 mm) and the minimum specified tensile strength of the base material is less than 70 ksi (483 MPa);
- b) for pipe welding of ASME P-No. 1, Group 1 (carbon steel base metal), the root pass and second pass of single-sided welds, regardless of base metal thickness, may be welded with cellulose-type coated electrodes.

6.1.4 For carbon steel pressure-retaining welds, if base metal is exempt from impact testing, weld metal shall have a Charpy V-notch (CVN) toughness equal to or greater than 20 ft-lb (27 J) at either 0 °F (–18 °C) or the minimum design metal temperature, whichever is lower. Weld metal toughness shall be certified by the filler metal manufacturer according to ASME *BPVC* Section II, Part C/AWS filler metal specifications, or if approved by the purchaser, can be established by the PQR as long as the PQR is using the same heat or lot of filler metals as will be used for the production welding.

6.1.5 Procedures using consumables with “G” classifications should require impact reports on a Certified Material Test Report per A/SFA 5.01, or alternatively be restricted to the brand and type of consumable used for the PQR. The nominal chemical composition of the specified brand and type of consumable should be identified on the WPS.

6.1.6 Welding consumables shall be clearly identified by ASME, AWS, or ISO classification, or trade name, where applicable, and the identity shall be maintained until consumed.

6.1.7 Welding consumables shall be used only for the welding process applications recommended in the ASME *BPVC* Section II, Part C/AWS or ISO filler metal specification, or by its manufacturer (e.g. filler metals designed for “single-pass welding” shall not be used for multiple pass applications, and fluxes designated for non-PWHT applications shall not be used for PWHT applications).

6.1.8 Table A.1 provides recommended filler metal selections for typical P-No. 1 through P-No. 5, P-No. 9, and P-No. 11 materials.

6.1.9 Welding consumables shall be purchased only from manufacturers operating a quality management system approved by the purchaser.

6.1.10 Filler metals shall be delivered with their product data sheet and heat, lot, or batch certificate, including chemical analysis, according to ASME *BPVC* Section II, Part C, SFA-5.01, minimum Sch. 3 or H or ISO 10474/EN 10204 minimum Type 3.1, except as modified in 6.9.12.

6.1.11 For FCAW welding of carbon steel, low-alloy steel, and 2.5–3.5 % Ni alloy steel pressure-retaining equipment with wall thickness in excess of $\frac{3}{8}$ in. (9.5 mm), the diffusible hydrogen limit for consumables (as manufactured) shall meet the requirements in Table 1.

Table 1—Diffusible Hydrogen Limits for Hydrogen-controlled FCAW Consumables for Carbon, Low-alloy, and 2.5–3.5 % Ni Alloy Steels

Specified Minimum Tensile Strength for the Base Metal	Maximum Diffusible Hydrogen Designation (per ASME/AWS SFA/A5.20 or SFA/A5.29) (ml of diffusible hydrogen per 100 g weld metal)
≤ 70 ksi (483 MPa)	H16
> 70 ksi (483 MPa) and ≤ 85 ksi (587 MPa)	H8
> 85 ksi (587 MPa)	H4

6.1.12 For any welding process, consumables considered to be low hydrogen for carbon and low-alloy steels, plus ferritic and martensitic stainless steels, shall achieve a maximum diffusible hydrogen level as specified in Table 2.

NOTE This table does not apply to rutile or cellulositic consumables.

Table 2—Diffusible Hydrogen Limits for Low-hydrogen Consumables

Base Material	Specified Minimum Yield Strength for the Base Material	Maximum Diffusible Hydrogen (ml diffusible hydrogen per 100 g weld metal)
Carbon and low-alloy steel	≤ 60 ksi (415 MPa)	H8
Carbon and low-alloy steel	> 60 ksi (415 MPa)	H4/H5
Ferritic and martensitic stainless steel	All	H4/H5

6.2 Welding of Carbon Steel for Hydrofluoric Acid Service

6.2.1 For carbon steel in hydrofluoric (HF) acid service, consult API 751 for guidance on filler metal chemical composition.

NOTE Currently, the optimum chemical composition limits are as follows:

- If base metal %C ≥ 0.18 wt %, then %Cu + %Ni ≤ 0.15 wt %.
- If base metal %C ≤ 0.18 wt %, or is unknown, then %Cu + %Ni + %Cr ≤ 0.15 wt %.
- Weld metal %Cu + %Ni + %Cr ≤ 0.15 wt %.