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 $2^{1}/_{4}$Cr-1Mo, $2^{1}/_{4}$Cr-1Mo-$^{1}/_{4}$V, 3Cr-1Mo, and 3Cr-1Mo-$^{1}/_{4}$V Steel Heavy Wall Pressure Vessels for High-temperature, High-pressure Hydrogen Service*

API Recommended Practice 934-C, *Materials and Fabrication of $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo 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 $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo 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 Facilitie*s

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, S*tandard Specification for Straight-Beam Ultrasonic Examination of Rolled Steel Plates for Special Applications*

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[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.ampp.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 A3.0 [6], *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*

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[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 1011 [7], *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* H_2S*-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*

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[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 $2^{1}/_{4}$Cr-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

PREN = %Cr + 3.3(%Mo + %W/2) + 16%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 ≤ 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 pH < 4;

c) ≥ 1 ppmw total sulfide content and ≥ 20 ppmw free cyanide in the aqueous phase, and 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 ≤ 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 $^1/_2$ 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 $^{1}/_{2}$ 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 $^3/_8$ 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:

a) If base metal %C ≥ 0.18 wt %, then %Cu + %Ni ≤ 0.15 wt %.

b) If base metal %C ≤ 0.18 wt %, or is unknown, then %Cu + %Ni + %Cr ≤ 0.15 wt %.

c) Weld metal %Cu + %Ni + %Cr ≤ 0.15 wt %.

6.2.2 For single-sided welds in HF service, the root and hot passes shall be completed using GTAW. GTAW is used to eliminate slag in the weld. Some owner/operators find it more efficient to complete the weld out with GTAW on pipe NPS 6 and less. ASME/AWS SFA-5.1 E6010/11 root passes shall not be used in HF services.

6.2.3 For double-sided welds in HF service, welding techniques such as GTAW and GMAW are typically used. However, other methods such as SMAW, SAW, or FCAW may also be used with thorough interpass cleaning.

6.2.4 For repair welding and tie-ins to carbon steel which have been exposed to HF service, a 2-hour hydrogen bakeout at 600–650 °F is recommended prior to welding.

6.2.5 While not universal, it is generally recommended to PWHT carbon steel weldments for HF acid service. See Table 7 for temperature and holding time. Some owner/operators do not require PWHT if weld hardness is no greater than 200 Brinell (HB), but impose PWHT if hardness exceeds 200 HB.

6.3 Dissimilar Metal Welding

6.3.1 When joining dissimilar ferritic steels (P-No. 1 though P-No. 5), filler metal shall conform to the nominal chemical composition of either base metal or an intermediate composition. However, when attaching non-pressure-retaining components to pressure-retaining components, filler metal chemical composition shall match the nominal chemical composition of the pressure-retaining component.

6.3.2 When joining ferritic steels (P-No. 1 through P-No. 5) to a) martensitic stainless steels (P-No. 6), b) ferritic stainless steels (P-No. 7), and c) austenitic stainless steels (P-No. 8), the filler metal shall be selected based on the following criteria.

1) Type 309 and Type 309L may be used for design temperatures not exceeding 600 °F (315 °C).

NOTE 1 Due to high differential thermal expansion of austenitic stainless steel, nickel-base filler metals are preferred for temperatures above 600 °F (315 °C). Refer to Table 3 below for application of nickel-base filler metals in sulfidation environments.

NOTE 2 Type 309 Cb (Nb) should not be used when PWHT is required, except for weld overlay.

2) Nickel-base alloy filler materials may be selected using design conditions shown in Table 3, which is applicable to groove and fillet welding. For overlay and clad restoration welding, see NOTE 3 in Table 3.

3) For service conditions exceeding the limits stated in 6.3.2. c) 1) and 6.3.2 c) 2), filler metal selection shall be reviewed with the purchaser.

4) ASME/AWS Classification ER310 (E310-XX) and ASME/AWS Classification ERNiCrFe-6 shall not be used.

5) See Annex F for P-15E.

6.3.3 Dissimilar metal welds joining carbon or alloy steels to stainless or nickel-base alloys should be avoided in severe thermal cycling service, in the immediate vicinity of a high-restraint location, and in sour services per ANSI/NACE MR0103/ISO 17495 or NACE MR0175/ISO 15156.

NOTE The use of dissimilar metal welds (carbon or low-alloy to stainless or nickel alloys) in services corrosive to carbon and low-alloy steel should be carefully evaluated. Failures have been reported due to hydrogen charging of zones exhibiting high hardness adjacent to the fusion line. It is unclear whether the charging is due to corrosion of the carbon or low-alloy steel alone or accelerated due to the presence of a galvanic couple. The dissimilar metal weld may be acceptable if the interface with the ferritic steel is not exposed to the service fluid. In addition, carbon or low-alloy steel to austenitic stainless steel welds might be susceptible to brittle fracture at service temperatures below –20 °F (–29 °C).

Table 3—Application of Nickel-base Electrodes in Sulfidation and Nonsulfidation Environments

ASME/AWS Filler (NOTE 1) **Material Classification**	**Maximum Design Temperature** (NOTE 2) **(Nonsulfidation Environment)**	**Maximum Design Temperature** (NOTE 3) **(Sulfidation Environment)**
ENiCrFe-3	1000 °F (540 °C)	700 °F (370 °C)
ERNiCr-3, ENiCrFe-2	1400 °F (760 °C)	750 °F (400 °C)
ERNiCrMo-3, ENiCrMo-3	1100 °F (590 °C)	900 °F (480 °C)
ERNiCrCoMo-1	1800 °F (982 °C)	1700 °F (927 °C)

NOTE 1 Comparable FCAW consumables may be applied for, provided they are approved by the purchaser.

NOTE 2 Refer to API 939-C for the definition of sulfidation.

NOTE 3 Nickel alloy temperature limits are for through-wall and fillet pressure boundary welds. For weld overlay and clad restoration, these limits may not apply, depending on the user's experience.

6.4 Low-alloy Steel Welding (P-No. 3 to P-No. 5)

Unless otherwise specified, welding guidelines referenced in API 934-A, API 934-C, and API 934-E should be followed for welding Cr-Mo steel pressure vessels. C-Mo and Cr-Mo steel piping systems in high-temperature service (below the creep range, with or without hydrogen present) should be fabricated using the guidelines in AWS D10.8.

6.5 Ferritic and Martensitic Stainless Steel Welding (P-No. 6 and P-No. 7)

Table A.2 provides recommended filler metal selections for typical P-6 (martensitic) and P-7 (ferritic) stainless steel applications.

6.6 Austenitic Stainless Steel Welding (P-No. 8)

For welding austenitic stainless steels (P-No. 8, Group 1), see Annex C.

6.7 Duplex Stainless Steel Welding (P-No. 10H)

For welding duplex stainless steels (DSS) (P-No. 10H), see Annex D.

6.8 9Cr-1Mo-V Welding (P-No. 15E)

For welding 9Cr-1Mo-V alloy steel (P-No. 15E), see Annex F.

6.9 Submerged Arc Welding

6.9.1 SAW procedures shall be requalified whenever the welding flux manufacturer and/or trade name is changed. Equivalence under ASME *BPVC* Section II, Part C, AWS, or ISO filler metal specifications shall not be considered adequate for substitution without requalification.

NOTE 1 It is recognized that fluxes having the same classification can be quite different in their composition. While resultant mechanical properties will generally be the same, operating characteristics can be significantly different. However, nominal flux composition is not included in AWS or ASME specifications/codes and flux suppliers do not normally provide this information. Differences among fluxes of the same classification can result in different and unanticipated weld operating characteristics, possibly leading to an increased risk of defects.

NOTE 2 Experience has shown that issues have occurred when flux production changes from one manufacturing plant to another and also when changing from one country to another. Current experiences show that the owner/operators and/or fabricators have considered requalifying or evaluating PQRs when either one occurs.

6.9.2 Flux trade name and designation used for the procedure qualification shall be specified in both the WPS and PQR. When requested by the purchaser, the country and/or plant of manufacture shall also be specified.

6.9.3 Filler metal/flux classifications specified by the manufacturer for single-pass welding shall not be used for multi-pass welding.

6.9.4 Alloyed submerged arc fluxes shall not be used for welding low-alloy steels. However, fluxes that compensate for alloying elements losses due to the arc are permitted.

6.9.5 Crushed slag is not permitted for welding pressure-retaining components.

6.9.6 Controls shall be in place to ensure that recovered flux is not contaminated in the recovery process and that the process meets the flux manufacturer's requirements for protection from moisture and buildup of fines.

6.9.7 Where flux recycling is applied, the supplier's consumable control procedure shall address new and reused recycling ratios and the number of times a flux may be recycled in accordance with the flux manufacturer's recommendation.

6.9.8 Flux remaining unused (including flux remaining in the machine hoppers) shall be returned to the storage facility, re-baked, and returned to moisture-proof containers in accordance with the flux manufacturer's recommendation.

NOTE In humid environments, the fabricator should consider the use of heated hoppers.

6.9.9 SAW fluxes exposed to moisture shall be reconditioned by baking in accordance with the flux manufacturer's recommendations.

6.9.10 SAW flux shall be clearly identified and stored in moisture-proof containers located indoors per the flux manufacturer's recommendations.

6.9.11 Open containers of SAW flux shall be stored in a humidity-controlled area, with a relative humidity and temperature in accordance with the manufacturer's recommendations.

6.9.12 Fluxes for SAW processes shall be delivered with certification according to ASME *BPVC* Section II, Part C, SFA-5.01, paragraph 5, Schedule 2 or G, or EN 10204 Type 2.2 minimum.

6.10 Electroslag Welding (for Corrosion-resistant Strip Overlay Cladding)

If the manufacturer proposes use of an alloy flux to attain the specified chemical composition, the manufacturer shall submit samples produced at both extreme limits, maximum and minimum, of the specified heat input range. Both samples shall meet the overlay chemical composition specifications.

6.11 Consumable Storage and Handling

6.11.1 A written procedure shall be made documenting storage, baking (if required), and handling of welding consumables in accordance with the manufacturer's recommendations.

6.11.2 Storage and baking of welding consumables shall be carried out in separate ovens. Ovens shall be heated by electrical means and shall have automatic temperature control. Welding consumable storage and baking ovens shall have visible temperature indicators.

6.11.3 Fabricators shall have a documented procedure covering storage, segregation, distribution, and return of welding consumables. Filler metal identity shall be maintained.

6.11.4 Unidentified, contaminated, or otherwise damaged consumables, including those suspected of being damp, which are found in storage or fabrication areas, shall be discarded.

6.11.5 Solid wire filler metals shall be dry and free from rust, scale, oil, or other foreign matter.

6.12 Alloy Consumable Controls

6.12.1 Prior to production welding, each heat, lot, or batch (whichever applies) of alloy consumables shall be subject to positive material identification (PMI) using a weld metal deposit (also called button or pad). Each heat of bare wire, lot of covered electrodes, or lot of flux-cored electrodes shall be PMI tested. Weld button size should be adequate to ensure accurate test results. For solid GTAW and GMAW wire, it is not necessary to test a button if PMI of bare wire can verify the composition before welding.

NOTE Some weld rods have alloying elements contained in the flux and do not meet specification until welded.

6.12.2 After PMI verification, alloy welding consumables shall be segregated and uniquely identified from other consumables. For additional guidance on PMI of welding consumables, see API 578.

6.12.3 Other testing protocols different from 6.12.1 may be substituted as agreed between the fabricator and the purchaser.**Shielding and Purging Gases**

7.1 When shielding gas(es) is used, the WPS shall indicate shielding gas (or gas mixture), composition (percentage), and flow rate.

~~7.2~~ Shielding and purging gases shall meet the purity requirements of ASME/AWS SFA/A5.32 or ISO 14175.

7.3 Shielding and purging gas guidance for austenitic stainless and duplex stainless welding is shown in Annex C and D, respectively.

7.4 Back purging is required for GTAW and GMAW processes for welding materials having a nominal chromium content greater than 2$^1/_4$ % unless the joint is ground or back gouged to sound metal. Exceptions for purging for GMAW-S variations are permitted; see 5.2.3.

a) When a back purge is used, the WPS shall state the gas used, including gas mixture composition and flow rate.

b) Whenever a back purging gas is selected to prevent oxidation or scale formation on the underside of the weld, the purge shall be maintained until at least $^1/_4$ in. (6.5 mm) depth of weld metal has been deposited.

c) For socket, seal, and other attachment welds on base materials less than 1/4 in. (6.5 mm) thick, back purging shall be maintained throughout the welding operation.

7.5 Shielding and back purging shall be applied when welding nonferrous alloys.

7.6 Shielding and back purging gases for titanium shall be argon, helium, or argon-helium mixtures.

7.7 When welding titanium and other refractory alloys, back purging gas and trailing secondary inert gas shields shall be established and maintained over the solidified, cooling weld metal and HAZ until metal temperature falls below 750 °F (400 °C).

NOTE There are a few examples where back purging cannot be applied to titanium, specifically for "batten strip" (also called "pad plates") fillet welds on titanium-clad vessels.

7.8 Verification of Shielding and Purging Gas Effectiveness

7.8.1 Evaluation of surface oxidation of the weld zone in titanium and titanium alloys shall fulfil the criteria specified in Table 4.

Table 4—Maximum Oxidation Levels for Titanium

Weld Color	Significance	Shielding	Comment
Silver	Acceptable weld	Correct shielding	No action
Light straw	Acceptable weld	Fair shielding	Discoloration should be removed with stainless steel brush before starting next weld pass
Blue, grey, or powdery white	Unacceptable weld	Insufficient shielding	See 7.8.2

7.8.2 When weldment oxidation level is deemed unacceptable per Table 4, the weld and the whole oxidized area shall be cut out and a new weld deposited.

7.8.3 When inspection for heat tint is specified by the purchaser, titanium and titanium alloy and nickel and nickel alloy welds cleaned prior to inspection shall be rejected unless otherwise approved by the purchaser.

7.8.4 Evaluation of surface oxidation of completed nickel and nickel alloy weldments shall fulfil the criteria specified in Table 5.

Table 5—Maximum Oxidation Levels for Nickel Alloys

Weld Color	Shielding	Comment
Light brown (tan) to brown	Acceptable shielding	No action
Narrow band of dark brown color and intermittent spots of blue color	Acceptable shielding	No action
Darker or more extensive oxidation colors	Unacceptable shielding	See 7.8.5

7.8.5 When inspection for heat tint is specified by the purchaser, titanium and titanium alloy and nickel and nickel alloy welds cleaned prior to inspection shall be rejected unless otherwise approved by the purchaser.

7.8.6 When weldment oxidation level is deemed unacceptable per Table 5, oxidized surfaces shall be removed by mechanical tools, pickling, or other means specified by the purchaser.

7.8.7 Evaluation of surface oxidation of the weld zone in austenitic stainless steels is shown in C.7 and in DSS is shown in D.3.8 d).

8 Preheating and Interpass Temperature

8.1 Preheating, where required, applies to welding, tack welding, and thermal cutting. Minimum preheat requirements shall comply with applicable codes and recommended practices, such as Appendix R of ASME *BPVC* Section VIII Division 1, Table 330.1.1 of ASME B31.3, API 934-A, API 934-C, API 934-E, Annex XI of AWS D1.1, EN 1011, or ISO/TR 17671. Recommendations or requirements for preheat listed in the relevant code shall be considered mandatory.

8.2 For low-alloy steels, preheat temperature shall be attained and maintained (throughout the entire thickness of the weld plus at least 3 in. [75 mm] on each side of the weld) during welding until PWHT is completed, unless a dehydrogenation heat treatment (DHT) is applied immediately after welding is completed.

NOTE Consideration should be given to lowering the weldment temperature to below M_f (martensite finish temperature) prior to PWHT for 9Cr-1Mo-V low-alloy steel and 12Cr martensitic stainless steel.

8.3 Preheat and interpass temperatures shall be checked by use of thermocouples, temperature-indicating crayons, pyrometers, or other suitable methods. For austenitic stainless steels, DSS, and nickel alloys, digital hand-held contact thermocouples are preferred over temperature-indicating crayons to avoid the potential contamination from tramp elements, such as fluorides, chlorides, and sulfides, which may be contained in the crayons. Thermocouples or pyrometers shall be calibrated.

8.4 Maximum interpass temperatures shall be specified in the WPS and PQR for austenitic stainless steels, DSS, and nonferrous alloys and when impact testing is required for carbon and low-alloy steels. Table 6 provides recommended interpass temperatures for most material groups. Table D.2 shows the recommended interpass temperatures for the various duplex stainless alloys.

Table 6—Recommended Maximum Interpass Temperatures

Material Group	Maximum Interpass Temperature
P-No. 1 (carbon steels)	600 °F (315 °C)
P-No. 3, P-No. 4, P-No. 5A, P-No. 5B, P-No. 5C, and P-No. 15E (low-alloy steels)	600 °F (315 °C)
P-No. 6 (Type 410)	600 °F (315 °C)
P-No. 6 (CA6NM)	650 °F (345 °C)
P-No. 7 (Type 405/410S)	500 °F (260 °C)
P-No. 8 (austenitic stainless steel)	350 °F (175 °C) Also shown in Annex C
P-No. 10H (duplex stainless steels)	Refer to Table D.2
P-No. 11A, Group 1	350 °F (175 °C)
P-No. 34 (Cu-Ni)	350 °F (175 °C)
P-No. 41, P-No. 42	300 °F (150 °C)
P-No. 43, P-No. 44, and P-No. 45	350 °F (175 °C)
P-No. 51, P-No. 52, P-No. 53 (Ti)	300 °F (150 °C)

8.5 When welding high CE forgings and fittings, such as high strength low-alloy steels, special welding procedures, including preheat and cooling rate control for hardness management, shall be developed to reduce the risk of hydrogen assisted cracking.

8.6 Preheat, interpass, and preheat maintenance temperatures shall be measured on the weld metal or on the immediately adjacent base metal. Temperature-indicating crayons are not permitted directly on weld metal or on the joint preparation.

8.7 Where gas burners are used for preheating, temperature equalization throughout the weld zone shall be ensured by using gas burners designed for this purpose.

8.8 Cutting apparatus for oxyfuel systems shall not be used for preheating.

8.9 Welding Interruption

8.9.1 If welding is interrupted for more than 3 minutes without maintenance of minimum preheat, the requirements in 8.9.2 through 8.9.5 shall apply.

8.9.2 If welding is interrupted for more than 3 minutes without maintenance of preheat before a minimum $^{3}/_{8}$ in. of deposit (10 mm) or 25 % of the total joint thickness or is completed (whichever is less), surface NDE (magnetic particle testing [MT] or penetrant testing [PT]) shall be performed before welding is restarted.

8.9.3 During interruption of preheat for ferritic and martensitic steels included in P-No. 3 through 5, P-No. 6, and P-No. 15E and P-No. 10, weldment cooling rates shall be reduced by using insulation to allow hydrogen outgassing.

8.9.4 Preheating shall be restored to the minimum preheat temperature specified in the WPS before welding is restarted.

8.9.5 If welding of thicker wall low-alloy steels is interrupted, a purchaser-approved DHT or intermediate stress relief should be performed before welds are allowed to cool down. Typically, 2 in. (50 mm) thickness is used as the criterion and is based on API 934-A and API 934-C guidelines.

9 Post-weld Heat Treatment

9.1 PWHT procedures shall be reviewed and approved by the purchaser prior to PWHT.

9.2 The WPS specifying PWHT should indicate the following:

a) maximum heating rate;

b) holding temperature range;

c) holding time range;

d) maximum cooling rate and weld thickness.

As an alternative, the WPS may reference a separate project-specific PWHT procedure.

9.3 For special heat-treating methods, such as induction heating and internally fired, PWHT methods and procedures shall be approved by the purchaser prior to production.

9.4 Unless waived by the purchaser, PQR hardness testing shall be performed to verify that hardness requirements can be met following a specified PWHT.

NOTE Hardness testing is often waived when PWHT is performed for reasons such as dimensional stability or construction code thickness requirements.

When hardness testing is performed due to service environments (e.g. wet sour service per NACE SP0472 or as defined by purchaser), testing requirements and methods in 13.6.1 shall be used for PQR testing, unless otherwise specified by the purchaser.

When hardness testing is performed for reasons other than service-related conditions, testing requirements shall be specified by the purchaser.

9.5 Production hardness testing may be required by the purchaser to verify adequacy of heat treatments. The purchaser may specify testing requirements, as noted in 13.6.2, or define company-specific requirements.

9.6 PWHT of austenitic stainless steel, DSS, and nonferrous alloys requires approval by the purchaser. Refer to Annex C and Annex D for more details.

9.7 Table 7 suggests PWHT holding temperatures and times. Code requirements, project specifications, and tempering temperatures should be considered when selecting final PWHT temperature.

Table 7—Recommended Post-weld Heat Treatment Temperatures and Holding Times

P-No.	**Material Type**	**Nominal Thickness at Weld** (in.)	**Service Environment**	**Holding Temperature** (°F) [a]	**Time at Holding Temperature** (hr/in.)
1	Carbon steel	According to code	Code	1100 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	> 1.5 in.	All (see 9.8)	1100 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	All	Wet H_2S	1150 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	When required by API 941 [b]	High temperature H_2	1150 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	All	Caustic	1150 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	All	Amine	1150 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	All	Carbonates	1200 to 1250	1 hr/in., 1 hr minimum
1	Carbon steel	All	HF acid	1150 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	All	Deaerator	1150 to 1200	1 hr/in., 1 hr minimum
1	Carbon steel	All	Ethanol	1150 to 1200	1 hr/in., 1 hr minimum
3	C-$^1/_2$Mo	According to code	Code	1150 to 1200	1 hr/in., 1 hr minimum
3	C-Mn-Mo	All	All	1150 to 1200	1 hr/in., 1 hr minimum
4	1Cr-$^1/_2$Mo, 1$^1/_4$Cr-$^1/_2$Mo	All	For maximum tempering (creep)	1275 to 1325	1 hr/in., 2 hr minimum

P-No.	Material Type	Nominal Thickness at Weld (in.)	Service Environment	Holding Temperature (°F) [a]	Time at Holding Temperature (hr/in.)
4	1Cr-$^1/_2$Mo, 1$^1/_4$Cr-$^1/_2$Mo	All	For optimum high-temperature properties (toughness)	1250 to 1300	1 hr/in., 2 hr minimum
4	1Cr-$^1/_2$Mo, 1$^1/_4$Cr-$^1/_2$Mo	All	Heavy wall pressure vessels for high-pressure hydrogen service operating at or below 825 °F (441 °C)	1225 to 1275	1 hr/in., 2 hr minimum See API 934-C for more details
4	1$^1/_4$Cr-$^1/_2$Mo	All	Pressure vessels for service above 825 °F (440 °C)	1225 to 1275	1 hr/in., 2 hr minimum, See API 934-E for more details
5A	2$^1/_4$Cr-1Mo	All	For maximum tempering (creep)	1300 to 1350	1 hr/in., 2 hr minimum
5A	2$^1/_4$Cr-1Mo	All	For maximum high-temperature properties (toughness)	1275 to 1325	1 hr/in., 2 hr minimum
5A	2$^1/_4$Cr-1Mo	All	Heavy wall pressure vessels for high-temperature, high-pressure hydrogen service	1250 to 1300 (See [g])	1 hr/in., 2 hr minimum, See API 934-A for more details
5B	5Cr-$^1/_2$Mo	All	All	1325 to 1375	1 hr/in., 2 hr minimum
5B	9Cr-1Mo	All	All	1350 to 1400	1 hr/in., 2 hr minimum
5C	2$^1/_4$Cr-1Mo-V	All	Heavy wall pressure vessels for high-temperature, high-pressure hydrogen service	1275 to 1325	8 hr, minimum, See API 934-A for more details
6	Martensitic stainless steels	According to code	All	According to code [c]	1 hr/in., 2 hr minimum
7	Ferritic stainless steels	According to code	All	According to code	1 hr/in., 1 hr minimum
8	Austenitic stainless steels See Annex C	According to code	All	According to code [d]	According to code See Annex C
9A	1$^1/_2$ to 2$^1/_2$ Ni	According to code	All	1100 to 1150	1 hr/in., 1 hr minimum
9B	3$^1/_2$ Ni	According to code	All	1100 to 1150	1 hr/in., 1 hr minimum
10H	Duplex stainless steels See Annex D	According to code	All	According to code	According to code See Annex D
15E	9Cr-1Mo-V	See [e] See Annex F	All	1375 to 1420	See [e], API 938-B, and Annex F
11A	8 Ni, 9 Ni	According to code	All	According to code [f]	1 hr/in., 1 hr minimum
42 and 43	Ni-Cu alloy 400, cast M35-1	All	HF acid	1275 to 1325	2 hr/in., 2 hr minimum
42 and 43	Ni-Cu alloy 400, cast M35-1	All	All except HF acid	1100 to 1150	1 hr/in., 1 hr minimum
44	Alloy 20 stainless Ni Alloy 825	According to code	All	According to code	1 hr/in., 1 hr minimum

P-No.	Material Type	Nominal Thickness at Weld (in.)	Service Environment	Holding Temperature (°F) [a]	Time at Holding Temperature (hr/in.)
45	Alloy, 800, 800H, 800HT	According to code	All	According to code	According to code

[a] For quenched and tempered or normalized and tempered materials, appropriate PWHT time and temperature values shall be chosen to meet required mechanical properties. Tempering temperature may be below, at, or above the PWHT temperature. Plate and forged materials manufacturers are responsible for determining the tempering temperatures required to meet the specified material properties, considering all heat treatment requirements.

[b] PWHT soak temperatures shown are recommended for when PWHT is recommended for high-temperature hydrogen service by the "Carbon steel (nonwelded or welded with PWHT)" curve in Figure 1—Operating Limits for Steels in Hydrogen Service to Avoid High Temperature Hydrogen Attack in API 941, Eighth Edition, 2016.

[c] For Type CA6NM material, a double tempering heat treatment is required. Initial heat treatment at 1225 °F to 1275 °F, followed by air cooling to ambient temperature, and second heat treatment at 1100 °F to 1150 °F and air cooling to ambient temperature.

[d] For Type 321 and Type 347 stainless steels, post-weld thermal stabilization may be specified at 1600 °F to 1675 °F for 2–4 hours. See also Annex C.

[e] For 9Cr-1Mo-V, it is necessary to cool welds to below M_f 93 °C (200 °F) prior to performing PWHT. This is required to maximize austenite transformation to martensite. Austenite that is not transformed before PWHT will transform to martensite upon cooling from PWHT and will lead to high weld hardness. For utility services, PWHT soak time is typically less than that for process service. See 6.4.6.1.3 in API 938-B for more details. See also Annex F.

[f] For 9 % Ni, the entire vessel, assembly, or plate shall be at the PWHT holding temperature at the same time. The cooling rate from the holding temperature shall not be less than 300 °F (167 °C) per hour down to a temperature of 600 °F (315 °C). A local or partial PWHT cannot be used since it results in portions of the structure being in the embrittlement range of 600 °F to 1000 °F (315 °C to 540 °C) for extended periods of time, thereby impairing material toughness.

[g] For enhanced steel with mechanical properties increased by special heat treatments, such as SA-542 Grade B Class 4, the PWHT temperature may be reduced, under the respons bility of plate and forging manufacturers to achieve required mechanical strength.

For alloys/services not listed, PWHT is per code.

9.8 The ASME B31.3 PWHT thickness exemption for P-No. 1 materials is not permitted for material thickness greater than 1.5 in. (38 mm) unless accepted by the owner/operator.

9.9 Local PWHT involving circumferential bands around piping or vessels shall be performed according to AWS D10.10, AWS D10.22, and WRC Bulletin 452, as applicable.

9.10 Local spot PWHT (called a "bull's eye") on vessels or piping shall require approval of the purchaser.

9.11 PWHT procedures should include precautions taken to prevent distortion, collapse, or other damage as appropriate.

9.12 PWHT procedures should include the following information:

a) material and item type;

b) holding temperature ranges and soaking times;

c) heating and cooling rates;

d) methods of heating and cooling (e.g. gas, electrical resistance, induction, and furnace);

e) location and number of thermocouples used to control and record the PWHT;

f) precautions taken to prevent distortion, collapse, or other damage, as appropriate;

g) extent of heating and insulation for local or partial PWHT, including a sketch;

h) parent design code;

i) PWHT type (enclosed locally or fully);

j) atmosphere control, when using gas-fired furnaces rather than electric;

k) chart speed and type of recording;

l) production test piece location, if applicable.

NOTE This ensures that all essential variables are recorded. A change in these variables could alter the mechanical properties of the weld so that the qualification is no longer representative of the mechanical properties obtained after PWHT.

9.13 When PWHT is required, it shall be performed after the completion of all pressure-retaining component welding, including weld repairs, weld overlay, cladding restoration, and welding of internal or external attachments or clips. For revamps or modifications on vessels that required PWHT to comply with code and not for service reasons, PWHT of specific welds can be waived if it meets the exemptions allowed by the applicable code.

NOTE PWHT is a method for reducing and redistributing the residual stresses in the material that have been introduced by welding and shall therefore be performed after completion of all welding.

9.14 Thermocouples shall be used to continuously and automatically record the PWHT temperature on a chart from the start of controlled heating until the end of controlled cooling.

9.15 Exemption of code-required PWHT for ferritic steel base metals based solely on the use of austenitic or nickel-based filler materials is not permitted.

9.16 Code exemption of PWHT for materials not covered in NACE SP0472 (typically P-No. 4 and P-No. 5 alloy steels) in sour service shall be approved by the purchaser. The purchaser shall consider the conditions for sour service (e.g. company specific or reference to ANSI/NACE MR0103/ISO 17945).

9.17 Code exemption of PWHT for materials in high-temperature hydrogen service shall be approved by the purchaser. The purchaser shall consider the conditions for high-temperature hydrogen service (e.g. service temperature and hydrogen partial pressure per API 941).

9.18 Code exemption of PWHT for alloy steels in nonutility services with nominal chromium content of 1 % or greater shall be approved by the purchaser.

10 Repairing a Post-weld Heat Treatment Component Without Post-weld Heat Treatment

10.1 In some instances, PWHT may potentially have adverse effects on equipment and piping. In those cases, CDW may be used in lieu of PWHT where PWHT is inadvisable. See Annex G of this recommended practice for more requirements for CDW for repairing a component without PWHT.

10.2 The repair of a previously PWHT'd component without PWHT shall follow the applicable construction code requirements or shall follow the rules for the alternative welding methods within NBIC NB-23 Part 3 or ASME PCC-2 Article 209, or follow the rules for CDW within API 510. Purchaser approval shall be obtained prior to performing the repair. Procedure qualifications shall be done in accordance with ASME *BPVC* Section IX, QW-290.

10.3 If CVN toughness testing, such as that established by ASME *BPVC* Section VIII, Division1, Parts UG-84 and UCS-66, is required by the original code of construction, PQR tests should include CVN toughness testing as well and the variables under Column B (where toughness testing is specified) in ASME *BPVC* Section IX—Table QW-290 should be considered essential variables.

10.4 If special hardness limits are necessary for stress corrosion/environmental cracking resistance (e.g. NACE SP0472 and ANSI/NACE MR0103/ISO 17945), the PQR shall include hardness tests. In addition, the variables in ASME *BPVC* Section IX—Table QW-290 under Column A (where hardness testing is specified) shall be considered essential variables.

10.5 The ASME B31.3 PWHT thickness exemption for P-No. 1 materials is not permitted for material thickness greater than 1.5 in. (38 mm) unless accepted by the owner/operator.

10.6 Exemptions of PWHT required by code for repair of ferritic steels in environmental cracking services covered in NACE SP0472 or in high-temperature hydrogen service shall be approved by the owner/operator. See 9.15, 9.16, and 9.17.

11 Cleaning and Surface Preparation

11.1 Laminations identified on the bevel surface by visual examination shall be investigated by NDE and reported to the purchaser for resolution prior to removal.

11.2 Burrs, nicks, dents, and surface defects shall be removed from weld bevels.

11.3 Surfaces to be welded shall be free of moisture, greases, oils, paints, rust blooms, and embedded iron or other substances. Organic contaminants such as oils, cutting fluids, or crayon marks shall be removed with appropriate solvents prior to welding.

11.4 Welding shall not be performed when the base metal surface is wet or damp.

11.5 Arc strikes outside of the weld area shall be removed by light grinding. Avoid grinding below minimum wall thickness when removing arc strikes. The purchaser should specify if MT or PT inspection of the ground area is required.

11.6 For double-welded joints, the backside of the joints shall be ground or gouged to sound metal. If gouged, the surface shall be ground to a bright finish.

11.7 Slag shall be completely removed from the backside of each completed austenitic stainless steel or nickel-base alloy weld, unless otherwise permitted by the purchaser. See also C.7.5.

11.8 Aluminum flake weld-through primers may be used for weld joint surface protection. When used, the WPS should indicate the weld-through primer by type and brand. Use of other types of weld-through primers or coatings is not permitted, unless approved by the purchaser. The purchaser may require additional procedure qualifications or weldability tests.

11.9 Carbon or alloy steel wire brushes or other carbon or alloy steel tools shall not be used on stainless steel, DSS, or nonferrous materials. See also C.7.6, D.3.1, and D.3.2.

11.10 For nickel alloy steels (e.g. 1.5 % to 9 % Ni), thermally cut edges shall be machined or ground to remove dross and burn serrations.

11.11 For nickel alloy steels (e.g. 1.5 % to 9 % Ni) in refrigerated liquid or vaporized liquified gas service, grit blasting or other suitable means shall be used to remove mill scale from surfaces before fillet welds are made. In addition, grit blasting or other suitable means are required to remove slag for the first pass if SMAW electrodes are used.

11.12 If magnetic tools are used to lift or move 9 % Ni, the steel shall be degaussed prior to welding.

12 Special Procedure Qualification Requirements/Testing

12.1 General

12.1.1 PQRs shall be in accordance with ASME *BPVC* Section IX, Form QW-483 or ISO 15614-1, Annex B.

When specified by the purchaser, PQRs should include the following:

a) preliminary WPS;

b) laboratory test reports, including photomicrographs;

c) parent material certificates;

d) consumable certificates;

e) PWHT records, if applicable;

f) NDE reports, if applicable.

12.1.2 PQRs shall include the results of additional testing, when specified. Some examples are as follows.

a) Hardness testing—Record hardness results and location (e.g. weld metal, HAZ, and base metal).

b) CVN impact testing—Record the absorbed energy values with test temperature, specimen size, percent shear energy, and lateral expansion (when required) for each specified notch location (e.g. weld metal and HAZ).

c) Corrosion testing—Record sample dimensions, weights, and other data per the applicable corrosion test standard.

12.1.3 When specified by the purchaser, mockups simulating production conditions shall be made and tested whenever geometry, accessibility, or restraint of the standard code qualification coupon fails to simulate production conditions.

12.1.4 For special applications determined by the purchaser, such as, but not limited to, severe corrosion service or high-temperature service, special qualification tests (e.g. stress corrosion cracking or temper embrittlement tests) may be specified.

12.2 Tube-to-Tubesheet Welding

12.2.1 For tube-to-tubesheet designs where strength welds are specified, WPSs shall be qualified and tested in accordance with ASME *BPVC* Section IX, QW-193 and QW-288, or ISO 15614-8. Vendors shall submit a complete fabrication plan (including assembly, cleaning, weld preparation, rolling, and testing) to the purchaser for approval.

12.2.2 WPSs for seal welding of tube-to-tubesheets shall be qualified in accordance with ASME *BPVC* Section IX, QW-202.6a, b, or c, or ISO 15614-8.

12.2.3 Strength welded tube-to-tubesheet welds shall have a minimum of two weld passes, with start/stop points offset by at least 30°.

12.3 Macroscopic Examination

12.3.1 When required by the purchaser, a macroetched sample shall be prepared. This sample shall be prepared and etched such that the entire cross section of the weld, including the HAZ, adjacent parent material, and individual weld passes is visible. Macroetched samples shall be prepared in this same manner when hardness surveys are required by the purchaser.

12.3.2 Macroscopic examination shall be performed per ASME *BPVC* Section IX, QW 193.1.3, with a magnification between 10x and 20x.

12.3.3 Acceptance criteria shall be per applicable code, such as ISO 15614-1 Level 2.

13 Other Items

13.1 Backing Materials

13.1.1 Where metallic backing material is permitted, the P-Number or its nominal chemical composition shall be specified in the WPS and/or the applicable fabrication drawing. For joints between similar materials, in the case of a permanent backing strip, the chemical composition of backing materials shall match the nominal base metal chemical composition. Alternate methods and materials require purchaser or owner/operator approval.

13.1.2 Permanent backing strips should be avoided when possible.

13.1.3 When removable backing strips are used, the backing strip material should have the same composition as the base metal. In some cases, a backing strip of a closely similar material may be considered (e.g. in the case of $2^1/_4$Cr-1Mo-$^1/_4$V base metal, a temporary backing strip of $2^1/_4$Cr-1Mo material), providing the welding condition and weld material would be the same foreseen for the pressure-retaining component and such option is authorized by the purchaser.

13.1.4 After the removal of temporary fusible backing strips, the weld root shall be ground smooth.

13.1.5 Alternate backing materials (e.g. ceramics) and methods require purchaser or owner/operator approval.

13.2 Peening

Peening is permitted only with the approval of the purchaser.

13.3 Weld Overlay and Clad Restoration (Back Cladding)

Requirements for weld overlays and back cladding are located in Annex B.

13.4 Temporary Attachments

13.4.1 Temporary attachments welded to the base metal shall be of the same nominal chemical composition or same material grade as the base metal, and welded in accordance with a qualified weld procedure. In case of $2^1/_4$Cr-1Mo-$^1/_4$V base metal, a temporary attachment of $2^1/_4$-Cr -1Mo material may be used, providing the welding condition and weld material would be the same foreseen for the pressure parts and such option is authorized by the purchaser.

13.4.2 Temporary attachments shall be removed by gouging or grinding, taking care to prevent damage to the base metal. The base metal shall be restored to its original condition before final heat treatment (if required), pressure testing, and final acceptance. The base metal shall be inspected with MT or PT upon removal of the attachment.

NOTE Attaching thermocouples for PWHT using capacitor discharge is not considered as temporary attachment. However, after removal of thermocouple, the area is typically ground and inspected with MT or PT.

13.4.3 As an alternative option, a different material, such as carbon steel can be used, provided that a buffer layer is deposited using the same weld filler material grade used for welding the pressure-retaining components, before the welding of the temporary attachment.

13.5 Stud Welding

13.5.1 Automatically timed arc and resistance stud welding for attaching load-carrying studs shall be per UW-27, UW-28, and UW-29 of ASME *BPVC* Section VIII, Division 1 or AWS D1.1, Section 7, for structural attachment. A production test sample of at least five consecutively welded studs shall be tested at the beginning of each shift and after performing maintenance operations on the stud welding equipment.

NOTE Adjustments might be necessary due to increased power draw during the shift.

13.5.2 Automatically timed arc and resistance stud welding for attaching non-load-carrying studs (such as extended heat transfer surfaces and insulation attachment pins) shall be qualified on materials having the same nominal chemical composition as the production welds and a WPS shall be prepared. A production test sample of at least five consecutively welded studs shall be tested at the beginning of each shift and after performing maintenance operations on automatic equipment.

13.5.3 Testing of production welds shall consist of bend or hammer tests in accordance with ASME *BPVC* Section IX, QW-192. When permitted by the purchaser, joints with less than 100 % fusion may be accepted.

13.6 Hardness Testing—Weld Procedure Qualification and Production Testing

13.6.1 When specified by the purchaser, hardness testing on the PQR coupon and/or the production welds shall be performed in accordance with the latest edition of ANSI/NACE MR0103/ISO 17945 or

NACE MR0175/ISO 15156. For production weld testing, the percentage or extent of welds to be tested shall be specified.

13.6.2 Hardness testing results shall comply with the latest edition of NACE SP0472 and NACE MR0103 or the purchaser's requirements.

13.7 Single-pass Welds

Single-pass welds on pressure-retaining components are not permitted, unless approved by the purchaser.

13.8 Welding and Hot Tapping Equipment or Piping In-service

Welding on in-service equipment, tanks, or piping (including hot tapping) can be safely performed with some, but not all, services and materials. Proposals for welding on in-service equipment shall be reviewed and approved by the owner/operator. These reviews should address the condition of the material to be welded, to develop acceptable welding and testing procedures, and to have recommended precautions in place during welding.

Hot tapping shall be performed per the guidance of API 2201.

The owner/operator and their welding contractor should also review API 577. In addition to the welding guidelines, minimum thickness limits, process flow considerations, and materials factors, both documents cover the hazards and concerns associated with some particular process streams (such as amines, ethylene, hydrogen, wet H_2S, HF acid, etc.).

NOTE ASME PCC-2 and API 1104—Annex B are two other excellent resources for guidance on these topics.

13.9 Seal Welded Threaded Connections and Seal Welded Repairs

Seal welds of threaded connections and seal welded repairs shall comply with the requirements of the applicable code (e.g. ASME B31.3, ASME B31.1) and consist of two passes with offset starts and stops (minimum of approximately 30°).

13.10 Calibration of Welding and Measuring Equipment

Welding and welding parameter measuring and recording equipment shall be calibrated at least every 12 months, or more often if required by the equipment manufacturer's recommendations.

Annex A
(informative)

Welding Consumables for Shielded Metal Arc Welding

Table A.1 and Table A.2 provide generally accepted electrode selections for the base materials shown. They do not attempt to include all possible choices. Welding consumables not shown for a particular combination of base materials shall be approved by the purchaser.

For austenitic stainless steels, see Annex C.

For duplex stainless steels, see Annex D.

Table A.1—Filler Metals for Carbon and Low-alloy Steel

Base Material (See NOTES 1, 2, and 4)	**Carbon Steel**	**Carbon-molybdenum Steel**	**1 and 1 1/4 Cr-1/2 Mo Steel**	**2 1/4 Cr-1 Mo Steel**	**5 Cr-1/2 Mo Steel**	**9 Cr-1 Mo Steel**	**2 1/4 Nickel Steel**	**3 1/2 Nickel Steel**	**9 % Nickel Steel**
Carbon steel	AB (See NOTE 3)	AC	AD	ADE	ADEF	ADEFH	AJ	AK	*
Carbon-molybdenum steel		C	CD	CDE	CDE	CDEFH	*	*	*
1 and 1 1/4Cr-1/2Mo steel			D	DE	DEF	DEFH	*	*	*
2 1/4Cr-1Mo steel				E	EF	EFH (See NOTE 4)	*	*	*
5Cr-1/2Mo steel					F	FH	*	*	*
9Cr-1Mo steel						H (See NOTE 4)	*	*	*
9Cr-1Mo-V steels (See Annex F)									
2 1/4 nickel steel							J	JK	LM
3 1/2 nickel steel								K	LM
9 % nickel steel									LM

Key

A ASME/AWS SFA/A5.1, Classification E70XX low hydrogen (see NOTE 5).

B ASME/AWS SFA/A5.1, Classification E6010 for root pass (see NOTE 5).

C ASME/AWS SFA/A5.5, Classification E70XX-A1, low hydrogen.

D ASME/AWS SFA/A5.5, Classification E70XX-B2L (see NOTE 6) or E80XX-B2, low hydrogen.

E ASME/AWS SFA/A5.5, Classification E80XX-B3L (see NOTE 6) or E90XX-B3, low hydrogen.

F ASME/AWS SFA/A5.5, Classification E80XX-B6 or E80XX-B6L (see NOTE 6), low hydrogen.

H ASME/AWS SFA/A5.5, Classification E80XX-B8 or E80XX-B8L (see NOTE 6), low hydrogen.

J ASME/AWS SFA/A5.5, Classification E80XX-C1 or E70XX-C1L, low hydrogen.

K ASME/AWS SFA/A5.5, Classification E80XX-C2 or E70XXC2L, low hydrogen.

L ASME/AWS SFA/A5.11, Classification ENiCrMo-3.

M ASME/AWS SFA/A5.11, Classification ENiCrMo-6, ENiCrFe-4, ENiCrFe-9, ENiCrMo-3, ENiCrMo-4, ENiCrMo-10, ENiMo-8, or ENiMo-9.

* An unlikely or unsuitable combination. Consult the owner/operator’s engineer if this combination is needed.

NOTE 1 This table refers to coated electrodes. For bare and cored wire welding (SAW, GMAW, GTAW, FCAW), use equivalent electrode classifications (ASME/AWS SFA/A5.14, SFA/A5.17, SFA/A5.18, SFA/A5.20, SFA/A5.23, SFA/A5.28, SFA/A5.29, SFA/A5.34). Refer to the text for information on other processes.

NOTE 2 Higher-alloy electrode, specified in the table, should normally be used to meet required tensile strength or toughness after PWHT. The lower-alloy electrode specified may be required in some applications to meet weld metal hardness requirements.

NOTE 3 Other E60XX and E70XX welding electrodes may be used if approved by the purchaser.

NOTE 4 This table does not cover modified versions of Cr-Mo alloys.

NOTE 5 See 6.1.3.

NOTE 6 PWHT can cause the strength of these filler metals to drop below minimum requirements. Care should be taken to ensure adequate strength in the PWHT condition.

Table A.2—Filler Metals for Copper-nickel and Nickel-base Alloys

Base Material (See NOTE 1)	70-30 and 90-10 Cu-Ni	Alloy 400 (N04400)	Nickel 200 (N02200)	Alloy 800 (N08800), 800H (N08810), 800HT (N08811)	Alloy 600 (N06600)	Alloy 625 (N06625)	Alloy 825 (N08825)	Alloy C-22 (N06022)	Alloy C276 (N10276)	Alloy B-2 (N10665) or B-3 (N10675)	Alloy G-3 (N06985)	Alloy G-30 (N06030)
Carbon and low-alloy steel	BC	BC	C	A	A	AJ	AJ	D	E	F	G	H
300 series stainless steel	BC	AC	AC	A	A	AJ	AJ	D	E	F	G	H
400 series stainless steel	B	B	AC	A	A	A	A	D	E	F	G	H
70-30 and 90-10 Cu-Ni	B	B	C	C	C	C	C	*	*	*	*	*
Alloy 400 (N04400)		B	BC	A	A	A	A	A	A	F	A	A
Nickel 200 (N02200)			C	AC	AC	AC	AC	CD	CE	CF	CG	CH
Alloy 800 (N08800), 800H (N08810), 800HT (N08811) (See NOTE 2)				K	A	A	A	DJ	EJ	FJ	GJ	HJ
Alloy 600 (N06600)					A	AJ	A	DJ	EJ	FJ	GJ	HJ
Alloy 625 (N06625)						J	J	DJ	EJ	FJ	GJ	HJ
Alloy 825 (N08825)							J	DJ	EJ	FJ	GJ	HJ
Alloy C-22 (N06022)								D	EJ	FJ	GJ	HJ
Alloy C-276 (N10276)									E	FJ	GJ	HJ
Alloy B-2 (N10665) or B-3 (N10675)										F	GJ	HJ
Alloy G-3 (N06985)											G	HJ
Alloy G-30 (N06030)												H

Key

A ASME/AWS SFA/A5.11, Classification ENiCrFe-2 or -3.
B ASME/AWS SFA/A5.11, Classification ENiCu-7.
C ASME/AWS SFA/A5.11, Classification ENi-1.
D ASME/AWS SFA/A5.11, Classification ENiCrMo-10.
E ASME/AWS SFA/A5.11, Classification ENiCrMo-4.
F ASME/AWS SFA/A5.11, Classification ENiMo-10.
G ASME/AWS SFA/A5.11, Classification ENiCrMo-9.
H ASME/AWS SFA/A5.11, Classification ENiCrMo-11.
J ASME/AWS SFA/A5.11, Classification ENiCrMo-3.
K ASME/AWS SFA/A5.11, Classification ENiCrCoMo-1 or matching filler.
* An unlikely or unsuitable combination. Consult the purchaser’s engineer if this combination is needed.

NOTE 1 Table A.2 refers to coated electrodes. For bare or cored wire welding (SAW, GMAW, GTAW, FCAW), use equivalent electrode classification (ASME/AWS SFA/A5.14, SFA/A5.34). Refer to the text for information on other processes.

NOTE 2 For Alloys 800, 800H, and 800HT, if sulfidation or stress relaxation cracking is a concern, use matching filler metals.

NOTE 3 Alloy B-2 not commercially available anymore. It is still listed here for existing equipment.

Annex B
(normative)

Weld Overlay and Clad Restoration (Back Cladding)

B.1 General

B.1.1 Weld overlays and clad restoration procedures shall be qualified in accordance with ASME *BPVC* Section IX.

B.1.2 WPSs for weld overlay shall include the chemical composition ranges of the major elements for the particular alloy.

B.1.3 Single-sided welding of clad or weld overlaid material shall be qualified using clad or overlaid materials.

B.1.4 For most welding processes, weld overlays shall be deposited with a minimum of two layers. Machine or automated single-layer overlays using either the ESW or strip SAW process are permitted when the fabricator demonstrates successful fusion and adherence to chemical composition limits and are approved by the purchaser.

B.1.5 ESW or strip SAW is permitted for weld overlay applications, provided that the following conditions are met.

a) The PQR metallographic examination, carried out in accordance with ASME *BPVC* Section IX, QW-382.1 (b), indicates that at least 5 % penetration (based on the overlay thickness) has been achieved.

NOTE Even though QW-382.1 (b) addresses hardfacing, it is being used to evaluate corrosion resistant overlays by this API 582.

b) Welding procedure production tests required by the purchaser include metallographic examination of overlay cross sections to verify that the overlay penetrated into the base metal with no lack of fusion present.

c) After welding and PWHT, spot UT is performed. For vessels, perform UT on at least four strips, approximately 3.2 in. (80 mm) wide, along the full length of the shell and one strip approximately 3.2 in. (80 mm) wide across each head on weld overlay. UT shall meet the requirements of ASTM A578, Level C.

B.1.6 Overlap range of adjacent weld deposits shall be considered an essential variable. The amount of overlap shall be agreed to by the fabricator and the purchaser.

B.1.7 PQR chemical analysis shall report all elements for which specific values are given for the consumable in ASME *BPVC* Section II, Part C/AWS filler metal specifications.

B.1.8 Production weld overlay shall have the chemical composition checked using either:

a) a physical sample (e.g. drillings, chips) removed for quantitative analysis, or

b) a portable spectrometer approved by the purchaser.

B.1.9 Elements specified for the production overlay chemical composition shall be analyzed and reported, (except for carbon and nitrogen) using the X-ray fluorescence method. When carbon and nitrogen tests are required by the purchaser, a physical sample (e.g. chips) is required for quantitative analysis. Alternatively, an optical emission spectrometer may be used to check all required elements, including carbon and nitrogen. Specified elements and chemical composition acceptance criteria for production overlay and back cladding are found for various alloy(s) in B.3 through B.6.

B.1.10 The purchaser shall establish the method of measurement and requirements for the extent of chemical composition tests on production welds. The purchaser shall also specify the location and depth into the overlay that chemical analysis will be performed.

B.1.11 The purchaser shall establish the method of measurement and requirements for the extent of ferrite tests on production welds. Sampling frequency for production overlay ferrite testing shall be specified by the purchaser. If PWHT is performed, ferrite measurements shall be taken prior to PWHT.

B.1.12 For SAW overlay, deliberate additions of principal alloying elements through the flux are prohibited, except for compensation of losses of alloying elements due to the welding arc.

B.1.13 Weld overlays shall be 100 % liquid penetrant examined. If the component is PWHT, this examination shall be performed after PWHT. The acceptance criteria for weld overlay PT examination shall be zero cracks or cracklike indications and zero open defects of any size.

B.1.14 Consumables for commonly used cladding and overlay systems are shown in Table B.1. Use of other systems should be approved by the purchaser.

Table B.1—Filler Metals for Overlay of Carbon and Low-alloy Steels

Cladding Material	Weld Overlay Materials [a] [e]	
	First Layer	Top Layer(s)
405/410 S	ENiCrFe-2 or -3 or ERNiCr-3 [b]	
405/410 S	E/ER309/309L [d]	E/ER309/309L or E/ER308/308L [d]
405/410 S	E/ER430/430Nb 15Cr-1Nb-0.05C [c]	E/ER409/409Nb/410 13Cr-1Nb-0.05C [c]
304L SS	E/ER/EQ309L	E/ER/EQ308L
316L SS	E/ER/EQ309LMo	E/ER/EQ316L
317L SS	E/ER/EQ309LMo	E/ER/EQ317L
321/347 SS	E/ER/EQ309L/E309Nb (Cb)	E/ER/EQ347
Alloy 20-Cb3	E/ER/EQ320LR	E/ER/EQ320LR
Alloy 400	ENi-1 or ERNi-1	E/ERNiCu-7
Alloy 625	E/ERNiCrMo-3	E/ERNiCrMo-3

[a] Use of this table is limited to carbon and low-alloy steel backing materials.

[b] Refer to Table 3 for suitability in high-temperature sulfidation. Note that these nickel alloys have been used successfully for clad restoration in coke drums, even though peak drum temperatures exceed the limits of Table 3. In addition, there have been a few refining organizations that recently have utilized E/ERNiCrMo-3 (Alloy 625) for coke drum overlays.

[c] Nb/C should be 7 to 15, depending on welding procedure. PWHT is recommended.

[d] Non-low-carbon stainless steel grades (e.g. E/ER/EQ308, E/ER/EQ316, or E/ER/EQ317) are not normally used in the PWHT'd condition. The purchaser shall approve the use of all non-low-carbon stainless steel grades in the PWHT condition.

[e] Table B.1 refers to coated electrodes and bare wires. For SAW and FCAW, use equivalent electrode classifications (ASME/AWS SFA/A5.9, SFA/A5.14, SFA/A5.22, and SFA/A5.34). Refer to the text for information on other processes.

B.1.15 When repairs are made to cladding or overlay welds on low-alloy steels, a minimum remaining clad or overlay thickness of $^{3}/_{16}$ in. (4.8 mm) is required in order to exempt PWHT, unless it can be demonstrated that no new HAZ is formed in the base metal with thinner overlay.

NOTE Repairs have been successfully done to overlay and cladding of 1/8" minimum without PWHT provided low-heat input processes are used as documented in API 934-H.

B.1.16 When base metal PWHT is required, PWHT does not have to be performed for welding attachments to the overlay/clad when the actual overlay/clad thickness is $^{3}/_{16}$ in. (4.8 mm) or greater. When the overlay/clad is less than $^{3}/_{16}$ in. (4.8 mm) thick, a specially qualified WPS shall be provided to verify that the attachment weld does not affect the base material.

NOTE 1 This requirement may be waived for P-No. 1 base metals when PWHT is a requirement due to base metal thickness and not for process reasons.

NOTE 2 Attachments have been successfully welded to overlay and cladding of 1/8" minimum without PWHT provided low-heat input processes are used as documented in API 934-H.

B.1.17 Electrode nominal diameter for rod and wire fillers and thickness and width for strip fillers, plus ASME/AWS classification, shall be considered essential variables.

B.1.18 The minimum thickness of cladding or overlay welding shall be as required by the minimum thickness qualified of the WPS/PQR or 0.125 in. (3 mm), whichever is greater after machining.

B.1.19 When PWHT is required for base materials with austenitic stainless steel weld overlay, corrosion testing of samples for weld procedure qualifications may be performed per the ASTM A262 Practice (e.g. Practice A, Practice C, etc.) specified by the purchaser.

B.1.20 Test coupons for corrosion testing shall be heat treated prior to testing with at least twice the fabrication heat treatment soak time as specified for the equipment.

B.2 Clad Restoration (Back Cladding)

B.2.1 Cladding shall be stripped back for a minimum distance of $^{3}/_{16}$ in. (4.8 mm) from the edge of the weld bevel. The cladding edge shall be rounded with a minimum radius of $^{1}/_{16}$ in. (1.5 mm) or tapered at a minimum angle of 30°. For carbon and low-alloy steel backing material the stripped-back area shall be etched with either a nitric acid or copper sulfate solution to ensure complete removal of cladding.

B.2.2 When the clad stripback depth impinges upon the minimum backing material design thickness, the overlay shall be qualified as a composite joint in accordance with QW-217 of ASME *BPVC* Section IX or ISO 15614-7.

B.2.3 During welding of the pressure-retaining backing material, positive steps shall be taken to ensure that the weld does not come into contact with cladding material.

B.2.4 Back clad areas shall include cladding thickness measurements together with ferrite (if applicable) or PMI measurements. Measurements shall include one measurement for the first 36 in. (85 cm) of weld and one at each additional 36 in. (85 cm) interval.

B.3 Austenitic (300 Series) Stainless Steel Overlay

B.3.1 Austenitic stainless steel overlays or back cladding shall have a first layer that is predominantly austenitic and free of cracks.

B.3.2 For PQR and/or production overlays, the final layer shall have the chemical composition given in Table B.2. The purchaser shall specify chemical compositions of austenitic overlay systems not shown in Table B.2.

Table B.2—Chemical Composition Requirements for Austenitic Stainless Steel Overlays

Overlay Type	% C (max.)	% Cr (min.)	% Ni (min.)	% Mo	% Cb (Nb)
308	0.08	18.0	8.0		
308L	0.04	18.0	8.0		
316	0.08	16.0	10.0	2.0 to 3.0	
316L	0.04	16.0	10.0	2.0 to 3.0	
317L	0.04	18.0	11.0	3.0 to 4.0	
347	0.08	17.0	9.0		8 × C min. to 1.0 max.

NOTE Testing of carbon for production welds may be waived by the purchaser.

B.3.3 For the overlay alloys listed in Table B.2, ferrite content of the final layer of weld overlay shall be in the range of 3 FN (Ferrite Number) to 10 FN, except for Type 347 that shall have a range of 5 FN to 11 FN. Minimum FN for Type 347 may be reduced to 3 FN, provided the fabricator submits data verifying that hot cracking will not occur using the lower FN consumable to be used in production, and this is approved by the purchaser. Ferrite requirements for overlay alloys not listed in Table B.2 shall be agreed to by the fabricator and the purchaser.

B.3.4 Ferrite measurements shall be taken before PWHT.

B.3.5 Magnetic instruments for measuring ferrite shall be calibrated annually per AWS A4.2M.

B.3.6 The maximum interpass temperature shall be specified in the WPS and PQR for austenitic stainless steel overlays onto carbon and alloy steels. For material group P-No. 8 (austenitic stainless steel), the recommended maximum interpass temperature is 480 °F (250 °C). Note that this is higher than the maximum interpass temperature for a through-wall weld of austenitic stainless steel (see C.4.2.1).

B.4 Ferritic Stainless Steel Alloys

The purchaser shall specify the requirements for ferritic stainless steel overlays.

B.5 Nickel-copper Alloy 400 (67Ni-30Cu)

B.5.1 The PQR shall report Ni, Cu, and Fe content. The Fe content shall not exceed 7.0 %. For HF service, the Fe content shall comply with API 751 requirements. Other chemical composition requirements (in addition to Fe) for the production overlay shall be specified by the purchaser.

B.5.2 Where ferricyanide testing for the presence of free iron contamination on production welds is required, it is to be specified by the purchaser in a separate document.

B.5.3 Single-layer overlays are not permitted.

B.6 Nickel-base Alloys Other Than Ni-Cu Alloy 400

B.6.1 The chemical composition requirements for overlay with nickel-base alloys other than Ni-Cu Alloy 400 shall be specified by the purchaser.

B.6.2 With the exception of iron, the chemical composition for overlay with nickel-base alloys shall meet the chemical requirements of the equivalent base materials.

B.6.3 Maximum iron content in the weld deposit for Alloy C276 and Alloy 625 overlay shall be specified by the purchaser.

Annex C
(normative)

Additional Considerations for Welding Austenitic Stainless Steel Alloys

C.1 General Fabrication

Fabrication of austenitic stainless steels shall be performed in a dedicated workshop or sections of a workshop reserved exclusively for those types of materials (adequately isolated from carbon and low-alloy steel fabrication).

C.2 Welding Processes

For single-sided welded joints, welding processes using fluxes (e.g. SMAW, FCAW, flux-coated GTAW wire, etc.), which are sometimes used in lieu of backing gas, should not be used for root pass welding unless approved by the purchaser, or unless slag can be removed from the process side of root passes and the area is inspected for slag removal.

C.3 Dissimilar Welding

When joining austenitic stainless steels (P-No. 8) to ferritic steels (P-No. 1 through P-No. 5 and P-No. 15E), the filler metal shall be selected based on the criteria shown in 6.3.2.

C.4 Austenitic Stainless Steel Welding

C.4.1 General

C.4.1.1 Table C.1 provides recommended filler metal selections for typical austenitic stainless steel applications.

C.4.1.2 Comparable low-carbon austenitic stainless consumables shall be used when welding low-carbon “L” grade base materials (e.g. Type 304L, Type 316L).

C.4.1.3 Comparable niobium-stabilized austenitic stainless consumables (e.g. ER347, E347) shall be used when welding stabilized austenitic base materials (e.g. Type 321, Type 347).

C.4.1.4 For austenitic stainless steels 6Mo and 904L, consumables shall have an enhanced (higher) molybdenum content compared to the base material (e.g. ERNiCrMo-3).

C.4.1.5 For austenitic stainless steels 6Mo and 904L, consumables shall have a sulfur content no greater than 0.015 %.

Table C.1—Austenitic Stainless Steel Alloy Filler Metals

Base Material (See NOTES 1–6)	**Type 405 Stainless Steel**	**Type 410S Stainless Steel**	**Type 410 Stainless Steel**	**Type 304 Stainless Steel**	**Type 304L Stainless Steel**	**Type 304H Stainless Steel**	**Type 310 Stainless Steel**	**Type 316 Stainless Steel**	**Type 316L Stainless Steel**	**Type 317L Stainless Steel**	**Type 321 Stainless Steel**	**Type 347 Stainless Steel**	**Type 347H Stainless Steel**
Carbon and low-alloy steel	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 405 stainless steel	ABC	ABC	ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 410S stainless steel		ABC	ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 410 stainless steel			ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 304 stainless steel				D	DH	DJ	A	DF	DGH	DI	DE	DE	DE
Type 304L stainless steel (See NOTE 5)					GHL	DHJ	A	DF	GH	HI	DE	DE	DE
Type 304H stainless steel (See NOTE 6)						JL	A	DFJ	DGHJ	DIJ	DEJ	DEJ	EJ
Type 310 stainless steel							K	AK	A	A	A	A	A
Type 316 stainless steel								F	FG	FI	EF	EF	EF
Type 316L stainless steel									G	GI	EG	EG	EG
Type 317L stainless steel										I	EI	EI	EI
Type 321 stainless steel											E (See NOTE 1)	E	E
Type 347 stainless steel (See NOTE 6)												E	E
Type 347H stainless steel (See NOTES 6 and 7)													E

Key

A ASME/AWS SFA/A5.4, Classifications E309-XX or E309L-XX.
B ASME/AWS SFA/A5.11, Classification ENiCrFe-2 or -3 or ENiCrMo-3 (see NOTE 4).
C ASME/AWS SFA/A5.4, Classification E410-XX (0.05 % C max.) (heat treatment at 1400 °F required).
D ASME/AWS SFA/A5.4, Classification E308-XX or E308L-XX.
E ASME/AWS SFA/A5.4, Classification E347-XX (see NOTE 6).
F ASME/AWS SFA/A5.4, Classification E316-XX.
G ASME/AWS SFA/A5.4, Classification E316L-XX.
H ASME/AWS SFA/A5.4, Classification E308L-XX.
I ASME/AWS SFA/A5.4, Classification E317L-XX.
J ASME/AWS SFA/A5.4, Classification E308H-XX.
K ASME/AWS SFA/A5.4, Classification E310-XX.
L ASME/AWS SFA/A5.4, Classification E16-8-2.

NOTE 1 This table refers to coated electrodes. For bare wire or cored welding (SAW, GMAW, GTAW, FCAW), use equivalent electrode classifications (ASME/AWS SFA/A5.9, SFA/A5.14, SFA/A5.22, SFA/A5.34). Refer to the text for information on other processes. Either ER347 or ER321 may be used for GTAW or PAW of Type 321 stainless steel.

NOTE 2 The higher-alloy electrode specified in the table is normally preferred.

NOTE 3 See Section 6 weld metal delta ferrite requirements.

NOTE 4 See Table 3 for the temperature limitation for nickel-base filler metals.

NOTE 5 E16-8-2 is often specified for cryogenic service to reduce ferrite content.

NOTE 6 E16-8-2 is often specified to minimize ferrite when the weld deposit will be exposed to high temperatures and high creep strains where sigma phase may affect performance.

NOTE 7 E347-XX classification shall contain > 0.04 % carbon.

C.4.2 General

C.4.2.1 For welding austenitic stainless steels (P-No. 8, Group 1), the following guidelines and restrictions apply.

C.4.2.2 Except for Type 309 weld overlays and unless otherwise specified below, materials requiring PWHT or materials operating at temperatures greater than 1000 °F (538 °C), Ferrite Number (FN) for deposited weld metal shall not exceed 9 FN.

NOTE Whenever FN measurements are required in this document, they are to be taken prior to PWHT and shall be measured with an instrument calibrated to, and listed in, AWS A4.2M. Measurements shall be taken on surfaces that have been machined or ground smooth. FN may also be estimated by actual, as-deposited chemical composition using WRC 1992 (FN) diagram.

C.4.2.3 FN range for deposited weld metal of the following alloys shall be as follows.

a) Type 308, 316, and 317 (3–10 FN).

b) Type 310 and 320 (0–4 FN).

c) Type 347 (5–11 FN).

NOTE The minimum FN for Type 347 may be reduced to 3 FN, provided the fabricator submits data verifying that hot cracking will not occur using the lower FN consumable to be used in production and this is approved by the purchaser.

a) Type 16-8-2 (1–5 FN).

b) When joining stainless steels for cryogenic service, nonmagnetic applications, or special corrosive service, weld deposits with a lower FN may be required and will be specified by the purchaser.

C.4.2.4 When austenitic stainless steel FCAW weld filler materials are exposed to temperatures above 1000 °F (538 °C) during fabrication and/or during service.

a) Filler materials shall not intentionally contain bismuth.

b) Bismuth in the deposited weld metal shall not exceed 0.002 %.

C.4.2.5 When welding thick-wall components of chemically stabilized stainless steels (e.g. Type 321, Type 347, and Type 316Cb), grain size of the base metal (forgings and plate) and welding heat input should be controlled, as required by the purchaser, to reduce the risk of stress relaxation, reheat, or liquation cracking.

To minimize susceptibility to liquation cracking in the HAZ of thick-wall Type 347 stainless steel, some users have used lower heat input. Some have specified chemistry controls on base metal such as phosphorus limits and grain size limits. Some have used Liquation Number. See WRC 421 for further details.

C.5 Preheating and Interpass Temperature

C.5.1 Preheat (when specified) and interpass temperatures shall be checked by use of thermocouples, temperature-indicating crayons, pyrometers, or other suitable methods. For austenitic stainless steels, digital hand-held contact thermocouples are preferred over temperature-indicating crayons to avoid the potential contamination from tramp elements, such as fluorides, chlorides, and sulfides, which may be contained in the crayons. If crayons are used, they shall be the ones shown to be acceptable for stainless steel (see C.7.2 for recommended impurity limits).

C.5.2 Preheat, interpass, and preheat maintenance temperatures shall be measured on the weld metal or on the immediately adjacent base metal. Temperature-indicating crayons are not permitted directly on weld metal or on the joint preparation.

C.5.3 Maximum interpass temperature shall be specified in the WPS and PQR for austenitic stainless steels. For material group P-No. 8 (austenitic stainless steel), the recommended maximum interpass temperature is 350 °F (175 °C), except for weld overlays where the recommended maximum interpass temperature is 480 °F (250°C).

C.6 Post-weld Heat Treatment

C.6.1 In general, weldments of austenitic stainless steels do not need PWHT. There are a few cases where PWHT is desirable. Common exceptions include the following:

a) stabilization anneal of Type 321 and 347 stainless for certain services (e.g. polythionic acid);

b) prevention of in-service stress relaxation cracking.

C.6.2 When austenitic stainless is welded to other alloys, PWHT may be needed. Two common examples include the following:

a) pressure boundary welds to hardenable carbon and low-alloy steels;

b) weld overlays onto carbon and low-alloy steels.

In many cases, these will need PWHT for code or service requirements for the hardenable steel (see B.1.9 for more details on overlays).

C.6.3 PWHT of austenitic stainless steel requires approval by the purchaser.

C.6.4 Except for weld overlays, PQR tests for austenitic stainless steel to ferritic steel welds shall employ the maximum PWHT temperature limit specified in the welding procedure whenever the stainless steel is PWHT above 1300 °F (705 °C).

C.6.5 When austenitic stainless is welded to carbon or low-alloy steel, repairing a PWHT'd component without PWHT requires that the repair meet applicable construction code requirements or follow NBIC NB-23 or API 510. Purchaser approval shall be obtained prior to performing the repair. Procedure qualifications shall be done in accordance with ASME *BPVC* Section IX.

NOTE If PWHT was originally conducted due to service requirements, specifically environmental cracking prevention, PWHT of the repair should be strongly considered.

C.6.6 Table C.2 lists suggested PWHT holding temperatures and times for austenitic stainless steel. Code requirements, project specifications, and tempering temperatures should be considered when selecting final PWHT temperatures.

Table C.2—Post-weld Heat Treatment Temperatures and Holding Times for Austenitic Stainless Steel

P-No.	**Material Type**	**Nominal Thickness at Weld** (in.)	**Service Environment**	**Holding Temperature** (°F)	**Time at Holding Temperature** (hr)
8	Austenitic stainless steels	According to code	All	According to code	According to code

NOTE 1 Generally, austenitic stainless steels do not need PWHT, except for very specialized applications. PWHT of austenitic stainless should be reviewed by an experienced metallurgical engineer. If PWHT is requested, it should be clearly specified in the design and purchasing documents.

NOTE 2 For stabilized grades of stainless such as Type 321 and Type 347 in certain environments (e.g. refinery services resulting in polythionic acid), post-weld thermal stabilization may be specified at 1600–1675 °F (871–913 °C) for 2–4 hours when the expected operating temperature exceeds 825 °F (440 °C).

C.7 Cleaning and Surface Preparation

C.7.1 When found or present, low melting point metallic contaminants, such as copper, lead, and zinc, shall be removed before welding.

NOTE Grinding is not generally recommended since heat from grinding can drive low melting point contaminants further into the stainless steel. Low melting point contaminants can be liquified by welding heat, then can penetrate into the grain boundaries, and embrittle the austenitic stainless steel. Other techniques, such as chemical removal or abrasive flapper discs, have been used successfully to remove these low melting point contaminants.

C.7.2 Surfaces shall be protected from chlorides and other halides. Marking, painting, coating, or inspection materials should contain as few halides as possible.

NOTE MIL-STD-2041D and DOE RDT-F-7-3T have adopted the following for limits in markers and paints:

< 200 ppm halogens;

< 250 ppm each, low melting point metals;

< 300 ppm total low melting point metals;

< 200 ppm sulfur.

The purchaser or owner/operator should specify what limits are acceptable.

C.7.3 In the beveling process, HAZs formed during plasma-arc cutting shall be removed. During machining operations, only a cutting fluid compatible with stainless steel (i.e. sulfur and chloride free) shall be used.

C.7.4 Slag shall be removed from all sides of each completed austenitic stainless steel alloy weld, unless otherwise permitted by the purchaser.

C.7.5 Carbon and alloy steel wire brushes or other tools shall not be used on austenitic stainless steel. Wire brushes and other tools to be used for austenitic stainless steel shall be stainless steel. Also, stainless brushes or tools that have been previously used on carbon or low-alloy steel shall not be used on austenitic stainless steel.

C.7.6 If carbon-arc cutting or gouging is used on austenitic stainless steels, the surface shall be ground to a bright finish.

NOTE Poor gouging technique can allow localized spots to absorb carbon. These spots are prone to sensitization and can result in a pit initiation site.

C.8 Quality of Final Surface Finish

C.8.1 Discoloration—Depending on the amount of heat tint and the intended service, it may be necessary to remove discolored surface oxides by pickling or mechanical polishing. The need and method for removing the discoloration should be specified by the owner/operator.

AWS D18.2 charts can be used as reference for heat tint color acceptance criteria. The figure in AWS D18.2 shows levels from No. 1 that has no heat tint (perfect shielding) to No. 10 that has heavy heat tint. The AWS D18.2 chart is for austenitic stainless steel only. It is not to be used for other alloy systems such as aluminum, titanium, or nickel.

Discoloration on welds, HAZs, or areas adjacent to the HAZ should not exceed level 4 of the AWS D18.2 chart for aqueous corrosive service and should be lower than level 7 for noncorrosive service. The definition of corrosive versus noncorrosive shall be determined by the owner/operator, based on the specific service experience (e.g. aqueous chlorides, acids, etc.).

Note that other fabricators and owner/operators have found that different oxygen levels in the purge gas coupled with different welding heat inputs may result in different visual oxidation results compared to the AWS D18.2 chart shown above.

C.8.2 Arc strikes and weld spatter on base metal should be avoided. If they exist, they shall be removed. Welder shall strike the arc in the weld instead of next to the weld.

C.8.3 For the process side of welded surfaces, the purchaser should use the applicable code or establish acceptance limits for visual inspection acceptance of pores or inclusions.

C.9 Other Items

C.9.1 Weld Overlay and Clad Restoration (Back Cladding)

Annex B provides detailed requirements (e.g. production chemical composition sampling) and guidelines for performing weld overlay and clad restoration (back cladding).

C.9.2 Corrosion Testing of Welded 6 % Mo Stainless Steel

Corrosion tests for 6Mo stainless steel weld PQR/WPS shall be performed and assessed in accordance with the requirements for super duplex stainless (25Cr) in ISO 17781.

Annex D
(normative)

Welding Guidelines for Duplex Stainless Steel

D.1 General Note

Welding of DSS is more complicated than welding austenitic stainless steels. Paying attention to details is important to maintain both corrosion resistance and mechanical properties of both the weld metal and HAZ. Failures have occurred due to formation of harmful metallurgical phases in the weldment. (The reader is directed to refer to API 938-C and AWS D10.18 for further best practices information.) Awareness, training, and quality control are critical. This annex provides guidelines for welding various grades of DSS (lean, standard, super, and hyper).

D.2 Definitions

pitting resistance equivalent number
PREN
PREN = %Cr + 3.3 x (%Mo + 0.5%W) + 16 x %N

DSS
Duplex stainless steel; when used in this annex, it refers to all forms of duplex stainless including lean, standard, super, and hyper DSS unless otherwise stated.

lean DSS
DSS with nominally 20 % Cr and PREN < 30.0. Examples are S32101, S32202, S32304, S32003, S82011, and S82441.

Type 20Cr duplex Group A
DSS with 24.0 ≤ PREN < 28.0.

Type 20Cr duplex Group B
DSS with 28.0 ≤ PREN < 30.0.

NOTE Alloy S32003 has added molybdenum for enhanced pitting resistance and may have increased sigma phase formation susceptibility.

standard DSS
DSS with nominally 22 % Cr and 30.0 ≤ PREN < 40.0 and Cr ≥ 19 %. Examples are S31803, S32205, J92205, and J93372.

super DSS
DSS with nominally 25 % Cr and 40.0 ≤ PREN < 48.0. Examples are S32520, S32550, S32750, S32760, S32906, J93380, and J93404.

hyper DSS
DSS with 48.0 ≤ PREN ≤ 55.0 and Cr ≤ 33.0 %. Typically, these contain nominally 27 % Cr. Examples are S32707 and S33207.

D.3 Cleaning and Surface and Weld Preparation

D.3.1 DSS fabrication and components should be separated from carbon and low-alloy steel fabrication and components, when possible.

D.3.2 Iron and steel contamination of the duplex stainless surface should be prevented. Contamination during lifting and handling should be prevented by use of proper equipment (e.g. by use of nylon slings, rather than carbon steel chains). Do not mix tools (e.g. grinding discs) between DSS and carbon and low-alloy steel fabrication. Do not use the same grit blasting media as used for iron and nonstainless steel. Rolling, forming, and other handling operations typically use carbon or alloy steel tools and machines that can embed iron and steel in the surface of the DSS. The embedded iron and steel cannot be reliably removed by brushing with a stainless steel wire brush, nor by light grinding, therefore pickling or electropolishing should be used to remove the embedded iron and steel. Failure to do so can result in rust blooms where the contamination occurred.

D.3.3 Carbon-arc cutting or gouging is prohibited on DSS unless subsequently grinding to white metal on the arc-affected surface and where dross is found.

NOTE Poor gouging technique can promote localized absorption of carbon, making the alloy prone to pit initiation.

D.3.4 In the beveling process, HAZs formed during plasma-arc cutting shall be removed. During machining operations, only a cutting fluid compatible with stainless steel (i.e. sulfur and chloride free) shall be used.

D.3.5 Weld repairs to bevel shall not be permitted, unless approved by the purchaser. If approved for super and hyper DSS, only one repair attempt shall be allowed in the same area.

D.3.6 Beveled edges and a minimum of at least 1 in. (25 mm) from the bevel on both internal and external surfaces shall be cleaned per 11.2 and 11.3.

D.3.7 Surfaces shall be protected from chlorides and other halides. Marking, painting, coating, or inspection materials should contain as few halides as possible.

NOTE MIL-STD-2041D and DOE RDT-F-7-3T have adopted the following for limits in markers and paints:

< 200 ppm halogens;

< 250 ppm each, low melting point metals;

< 300 total low melting point metals;

< 200 ppm sulfur.

The purchaser or owner/operator should specify what limits are acceptable.

D.3.8 Post fabrication cleaning shall include the following:

a) removal of dirt, oil, paint, marking, and other surface contamination;

b) removal of arc strikes, weld spatter, flux, and slag;

c) removal of iron (surface deposits or embedded iron particles due to aggressive grinding);

d) removal of heat tint (other than straw/light yellow color) on the process side (if accessible) by blasting, grinding, brushing; pickling or electropolishing can be used if required by specification/purchase documents; grinding shall be light grinding with fine grit wheel; brushing shall be with a stainless steel wire wheel or brush.

D.4 Welding Processes

D.4.1 Autogenous welding shall not be performed without approval from the purchaser. This includes tack welds and tube-to-tubesheet welds.

D.4.2 To maintain acceptable corrosion resistance in DSS, open root passes shall be GTAW for single sided welds with filler metal addition, with the next pass using a lower heat input than the root pass. The second pass should aim to be about 75 % of the heat input of the root pass to avoid overheating of the root pass (this lower heat input second pass is often called a "cold pass"; see Figure D.1). The cold pass should be a single bead.

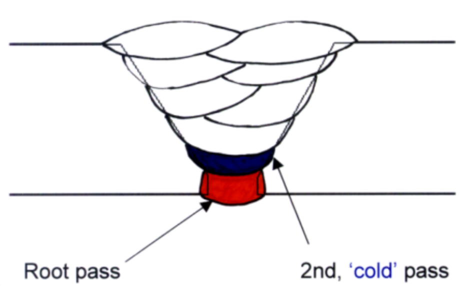

Figure D.1—Root and "Cold Pass" Schematic

D.5 Chemical Composition Requirements of Consumables and As-welded Deposits

D.5.1 Commonly used filler metals are shown in Table D.1.

NOTE Even though the weld filler metals used for welding of standard DSS Grade 2205 have higher nominal nickel content (9 %) than the base metal (5 % nominal), they are often referred to as "matching."

Table D.1—Welding Consumables for Duplex Stainless Steels [a]

Process	Lean DSS [b]	Standard DSS	Super DSS [d]	Hyper DSS [c]
SMAW	SFA 5.4 E2209	SFA 5.4 E2209, E2553	SFA 5.4 E2594, E2595	Not applicable
GTAW/GMAW	SFA 5.9 ER2209	SFA 5.9 ER2209, ER2553	SFA 5.9 ER2594	As recommended by alloy supplier
SAW	SFA 5.9 ER2209 with a flux designed for DSSs	SFA 5.9 ER2209 with a flux designed for DSSs	SFA 5.9 ER2594 with a flux designed for DSSs	As recommended by alloy supplier
FCAW	SFA 5.22 E2209TX-X or EC2209	SFA 5.22 E2209TX-X, E2553X-X, EC2209, EC2553	SFA 5.22 E2594TX-X, EC2594	Not applicable

[a] This table does not cover some of the specialized 25 % Cr alloys. The alloy suppliers' recommendations on welding consumables shall be followed.
[b] Most lean DSS producers recommend welding with 2209 filler per the above restrictions. Additional proprietary matching grades may be available from manufacturers.
[c] ISO and AWS filler metals designations for hyper DSS are being pursued. Proprietary grades are available.
[d] The user is instructed to ensure that the minimum %Mo and PREN of the selected filler metal are compatible with the base metal.

D.5.2 SAW flux shall be a basic flux and the designation of "basic flux" from the flux supplier is generally sufficient to meet this requirement.

NOTE When the purchaser specifies a more-accurate measure, the basicity index (BI) can be calculated from the chemical components of the flux (in weight percent):

$$BI = \frac{CaF_2 + CaO + MgO + BaO + SrO + Na_2O + K_2O + Li_2O + 0.5(MnO + FeO)}{SiO_2 + 0.5(Al_2O_3 + TiO_2 + ZrO_2)}$$

A basic flux is one where BI is greater than 1.2.[12] Some users experience suggests that as much as 1.8 BI may be necessary to effectively reduce oxygen content to ensure code-required elongation.

D.5.3 To obtain improved corrosion resistance in welds, over-alloyed filler metals may be used if approved by the purchaser. Recommendations by the filler metal supplier should be carefully followed.

D.6 Procedure Specification and Qualification Requirements

D.6.1 General requirements for DSS welds include:

a) WPSs and PQRs shall be qualified per 4.2.

b) Welds (including tack and fit-up) shall be deposited per 4.3.

c) Procedure qualification testing shall be performed using coupons from the same DSS base metals (i.e. same UNS number) as will be used in production.

d) For SAW and FCAW welding processes, consumables used for production welds shall be the same as used for weld procedure qualification (i.e. same material manufacturer and manufacturer trade name/product number).

e) Backing gas composition shall be considered an essential variable. Changes to backing gas composition shall require requalification of the WPS.

f) Repair welding procedures shall be approved by the purchaser before repair welds are performed. Details of defect removal technique and method for verifying complete removal of defects shall be supplied to the purchaser for review and authorization prior to proceeding with the repair.

g) Weld maps shall be submitted per 4.4 and 4.5.

h) For manual and semi-automatic welding, WPSs shall be qualified in the vertical-up position (3G) unless waived by the purchaser. If welding is to be performed only in the flat (1G) position, then only qualification in the 1G position is required.

D.6.2 The WPS shall contain information required by ASME *BPVC* Section IX, QW-250, and the following:

a) specific welding process or combination of processes to be used in production;

b) specific manufacturer(s) and trade name(s) for filler metal(s) to be used in production (same as detailed in PQR);

c) tack welding technique/details (where applicable);

d) electrical characteristics of welding (i.e. current and voltage range and polarity for each diameter of filler metal);

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[12] Tuliani S.S., Boniszewski T., and Eaton N., "Welding and Metal Fabrication," Vol 37, p. 327. Cited in Kou S., 2003, *Welding Metallurgy*, John Wiley & Sons, Hoboken, NJ.

e) heat input range for each pass;

f) welding head travel speed for each pass;

g) maximum interpass temperature.

D.6.3 Essential variables for procedure qualification shall be in accordance with ASME *BPVC* Section IX, QW-250, including supplemental essential variables for notch toughness, and those listed below. Changes in an essential variable or an approved WPS shall require requalification.

a) Joints:

    1) A change from double-sided to single-sided welding. Single-sided welding with backing strip is equivalent to double-sided welding.

    2) A decrease in the groove angle of more than 10° where this results in a groove angle that is less than 50°.

    3) A deviation from qualified groove angle of more than ±2.5° if the qualified angle is < 30° (except for portions of compound bevels).

b) A change in UNS number, except that dual certified UNS S31803/UNS S32205 are interchangeable.

c) A change in thickness range (see D.6.4).

d) A change in consumable brand name when impact testing is required except for solid wire.

e) An increase in wire diameter for FCAW-G.

f) A change in flux brand name for SAW, unless the specific brand and trade name of the consumable used in production has been qualified on supporting PQRs with impact test results meeting the minimum design code requirements, or test reports on a Certified Material Test Report have been performed per A/SFA 5.01.

g) Welding position:

    1) A change from vertical uphill to vertical downhill welding and vice versa.

    2) For mechanized and automated welding processes, a position different than the position qualified.

    3) For manual and semi-automatic welding, a change in position according to ASME *BPVC* Section IX, QW-461.9 shall be considered an essential variable for procedure qualification.

h) An increase in interpass temperature from the temperature used during WPS qualification.

i) Gas:

    1) Addition or removal of backing gas.

    2) A change in composition of shielding, backing, or purge gas.

j) Heat input:

    1) Heat input shall not exceed the maximum value recorded during WPS qualification.

2) Minimum heat input shall not be lower than 75 % of the lowest value recorded on the PQR.

k) A change in transfer mode (e.g. dip/short circuit, globular, spray).

l) Welding equipment: a change in make, model, and program settings for GTAW-P or GMAW-P.

m) When impact testing is required, a change from stringer bead to weaving technique or vice versa.

n) A change between manual, semi-automatic, mechanized, and automatic welding.

D.6.4 Thickness Qualified

The minimum and maximum qualified weld thickness (t) shall be as follows:

a) For t < or = $^5/_8$ in. (16 mm), the minimum qualified thickness shall be the thickness of the qualification test coupon (T) and the maximum qualified thickness shall be 2T, up to a maximum of $^5/_8$ in. (16 mm).

b) For t > $^5/_8$ in. (16 mm), but < $1^1/_8$ in. (29 mm), the minimum and maximum qualified thicknesses may be qualified by qualification test coupons within this range.

c) For t > or = $1^1/_8$ in. (29 mm), the minimum qualified thickness is T and the maximum qualified thickness shall be 1.2T.

D.6.5 Mechanical, Corrosion, Ferrite, and Microstructural Testing and Requirements

D.6.5.1 Mechanical, corrosion, and ferrite testing and microstructural evaluation shall be per the latest edition of ISO 17781.

D.6.5.1.1 For new WPS qualification, impact testing shall be per 4.3 and 5.4 of ISO 17781, and acceptance shall be per 5.4, Level QLI. For existing WPS, procedures qualified with impact testing per ASTM A923 are also acceptable.

D.6.5.1.2 Unless otherwise specified by the purchaser, test conditions and acceptance criteria for each set of three tests in the HAZ shall be per the base metal values for the particular alloy in Table 2 of ISO 17781.

D.6.5.1.3 In addition to the ISO 17781 limits on ferrite content in base metals and weld deposits, the HAZ ferrite content limit shall be 40–65 %, unless otherwise specified by the purchaser.

D.6.5.2 Measurement of the ferrite to austenite content in the deposited weld metal and HAZ shall be performed according to ASTM E562 and at a magnification of 400–500x. The number of fields and points per sampled area shall be in agreement with the guidance displayed in the 10 % relative accuracy column in ASTM E562—Table 3. As a guideline, magnification should be based on the initial determination of the sample areas to be tested to ensure that the microstructure can be clearly resolved without having adjacent grid points fall over the same constituent feature. A 100-point grid mapped over 10 fields in a target area (weld/HAZ) may be considered sufficient for material with 30 % or greater ferrite content.

NOTE Due to discrepancies in comparing metallographic point counts to ferrite gauge measurements, it is recommended that the purchaser assess the potential difference when using ferrite gauge measurement for acceptance of production welds.

D.6.6 Preheat, Interpass Temperature, Heat Input, and Post-weld Heat Treatment

D.6.6.1 Preheat temperature shall not exceed 120 °F (50 °C).

D.6.6.2 Preheat and interpass temperatures shall be checked by use of thermocouples, temperature-indicating crayons, pyrometers, or other suitable methods. For DSS, digital hand-held contact thermocouples are preferred over temperature-indicating crayons to avoid the potential contamination from tramp elements, such as fluorides, chlorides, and sulfides, which may be contained in the crayons. If crayons are used, they shall be the ones shown to be acceptable for stainless steel.

D.6.6.3 The maximum interpass temperatures are given in Table D.2.

Table D.2—Maximum Recommended Interpass Temperatures for Duplex Stainless Steels

Base Metal or Component Thickness	Maximum Interpass Temperature	
	Lean and Standard DSS (e.g. UNS S32101/S32205)	Super and Hyper DSS (e.g. UNS S32750 and S33207)
< 1/8 in. (3 mm)	120 °F (50 °C)	120 °F (50 °C)
< 1/4 in. (6 mm)	160 °F (70 °C)	160 °F (70 °C)
< 3/8 in. (9.5 mm)	210 °F (100 °C)	210 °F (100 °C)
> or = 3/8 in. (9.5 mm)	300 °F (150 °C)	250 °F (120 °C)
NOTE For P-No. 10H material, production interpass temperatures shall not exceed the interpass temperature used during WPS qualification.		

D.6.6.4 Heat input ranges to meet performance requirements (corrosion and/or mechanical testing) are dependent on the specific product thickness, joint design, and welding process. Heat input ranges in Table D.3 are a general guideline from API 938-C and specific procedure range guidelines are available from material suppliers.

See ASME *BPVC* Section IX, QW-409.1(c) and its Appendix H for waveform-controlled welding.

Table D.3—Heat Input Guidelines for Duplex Stainless Steels

DSS Alloy Family	Heat Input
Lean DSS	15–76 kJ/in. (0.5–3.0 kJ/mm)
Standard DSS	12.7–63.5 kJ/in. (0.5–2.5 kJ/mm)
Super DSS	12.7–38.1 kJ/in. (0.5–1.5 kJ/mm)
Hyper DSS	5–25 kJ/in. (0.2–1.0 kJ/mm)

NOTE These ranges are starting points. Heat input selection should be based on actual testing during welding procedure qualification as required by D.6.3 h).

D.6.6.5 For SMAW, weaving beyond three times the electrode diameter should be avoided to prevent excessive exposure to elevated temperature.

D.6.6.6 Generally, PWHT is not recommended for DSS. In the rare cases where PWHT needs to be considered, it requires the approval of the purchaser. If solution annealing of duplex stainless weldments made using weld metal with enhanced nickel content (e.g. 9 % Ni) is required, the minimum solution annealing temperature should be at least 2015 °F (1100 °C), which is higher than used for the corresponding alloy with 5–6 % Ni.

D.6.7 Requirements for Shielding and Back Purging Gases

The requirements are as follows.

a) Shielding gases shall be argon or an argon/nitrogen mixture. Note that argon/nitrogen mixtures may be preferred for certain aggressive corrosive services. Other shielding gases may be used if approved by the purchaser.

b) Backing (purge) gases shall be an argon/nitrogen mixture with minimum 2 % nitrogen. Other backing gases may be used if approved by the purchaser.

c) Single-sided open root joints shall be welded with a back-purged GTAW or GMAW root pass. Back purging shall continue until a minimum 0.25 in. (6 mm) of weld metal has been deposited. The seller shall submit details of the method and equipment to be used for measuring and monitoring oxygen content as part of the WPS.

d) Backing gas oxygen content at the weld shall have no greater than 0.10 % (1000 ppm) oxygen before welding.

e) An oxygen content monitoring system should be used. While some heat tint may be noted, ASTM G48 testing shows insignificant lowering of CPT for welds deposited with backing gas at this content.

D.7 Production Welding Requirements

D.7.1 ASME *BPVC* Section VIII, Division 1 required production test plates—Each heat of plate used to fabricate shell and head segments shall be subjected to production testing. Test plates shall be made from the same heat as the base material and installed as run-off tabs at the end of longitudinal weld seams. Test plates shall be of sufficient size to provide the same temperature gradient during cooling from weld temperatures as the component being welded. Sample coupons shall be subjected to ferrite determination and CVN impact testing as required in ISO 17781.

D.7.2 Pressure-retaining welds shall have ferrite measurements made by using a ferrite measuring instrument calibrated in accordance with AWS A4.2M. A total of five measurements shall be taken in the center of each weld cap surface, and, if accessible, the root pass. The weld cap and root pass shall be prepared as recommended by the testing equipment manufacturer. Acceptance criteria shall be per ISO 17781.

D.7.3 Unless waived by the purchaser, whenever ferrite testing is required for production welds, the number of tests shall be as follows.

a) For piping, each circumferential weld shall be tested, and the number of tests for circumferential welds shall be per Table D.4.

Table D.4—Ferrite Test Requirements for Duplex Stainless Steel Piping Joints

Pipe Size	Number of Tests/Joint	Orientation
NPS ≤ 24	2	180°
24 < NPS ≤ 36	3	120°
NPS > 36	4	90°

b) For equipment, main pressure-retaining welds shall be tested at least once in every 10 ft. (3.0 m) of linear weld. Nozzle connection welds shall have one test per weld.

D.8 Additional Requirements for Wet H_2S or Other Hydrogen Charging Environments

Services in wet H_2S environments as defined by, but not limited to, ANSI/NACE MR0103/ISO 17945 or NACE MR0175/ISO 15156 have occasionally resulted in HAZ cracking failures in DSS. In addition, high-pressure hydrogen leak testing prior to startup of refinery hydroprocessing services has resulted in HAZ cracking failures in DSS. Therefore, for hydrogen charging environments such as these, the following requirements shall be required.

a) PQR hardness testing:

1) Microstructural examination of one randomly selected weld section from each PQR plate or pipe shall be assessed using the procedures detailed in D.6.5.

2) Hardness (HV10) readings shall be taken in the weld deposit and base metal, and HV5 readings shall be taken in the HAZ. A minimum of six readings shall be taken on each of the weld joints prepared for metallography.

b) Maximum allowable PQR hardness:

1) Lean and standard DSS, 320 HV10 maximum.

2) Super and hyper DSS, 350 HV10 maximum.

For services not defined by ANSI/NACE MR0103/ISO 17945 or NACE MR0175/ISO 15156 ANSI/NACE MR0103/ISO 17945 or NACE MR0175/ISO 15156, the owner/operator shall define what constitutes hydrogen charging service.

D.9 Special Requirements

D.9.1 PQRs for tube-to-tubesheet joints shall include the following:

a) In addition to the macro-examination required by ASME *BPVC* Section IX, QW-193, microstructural examination (including determination of ferrite by point-count method) of one randomly selected weld section shall be assessed using the procedures detailed in D.6.5.

b) Test assemblies shall simulate each step of production, including both rolling and welding. In addition, if production tube-tubesheet seal/strength welding is to be performed through the plug sheet, this shall be simulated in the test assembly (access hole diameter and distance from hole to tubesheet shall be equal to production distances ±10 %).

c) Hardness (HV10) readings shall be taken in the weld deposit and tubesheet base metal, and HV5 readings shall be taken in the HAZ. A minimum of six readings shall be taken on each of the tube-to-tubesheet joints prepared for metallography. Hardness values shall be per D.8 b).

d) For standard and super DSS heat exchangers, a quadrant section of a tube-to-tubesheet weld shall be corrosion tested in accordance with D.6.5, when required by the purchaser. No pitting is allowed. This does not apply to dissimilar tube-to-tubesheet welds.

D.9.2 Welding of DSS to other metals requires additional considerations, some of which are shown below:

a) Generally accepted filler metals for SMAW of DSS are shown in Table D.5. No attempt has been made to include all possible choices. Welding consumables not shown for a particular combination of base materials shall be approved by the purchaser.

b) In most cases, DSS can be welded to carbon and low-alloy steel, austenitic stainless steel, and other grades of DSS. The filler metal should have strength and corrosion resistance superior to at least one of the dissimilar metals and achieve a phase balance to produce a tough weld. A duplex filler is generally used for welding DSS to carbon steel or austenitic stainless steel, but austenitic stainless steel filler metals have also been satisfactory. Ni-based filler metals are sometimes used, but they may promote a fully ferritic zone adjacent to the fusion line in DSS, which tends to reduce toughness along the fusion line.

c) When welding DSS to carbon or low-alloy steel, there can be detrimental effects due to the preheating or PWHT required by the carbon or low-alloy steel. Preheating may slow the cooling of the DSS HAZ enough that intermetallic phases form. Preheating should not be used unless approved by the purchaser. Most PWHT temperatures for steel will lead to formation of intermetallic phases in DSS which reduce toughness and corrosion resistance. One solution is to butter carbon steel or low-alloy weld bevels with austenitic filler metal (e.g. E309L), PWHT, and then weld to the DSS using a DSS filler metal without PWHT.

d) When welding DSS alloyed with nitrogen (e.g. 22Cr Duplex, 25Cr Duplex), weld consumables shall not contain deliberate additions of niobium (columbium) such as ENiCrMo-3. This is due to precipitation of niobium nitrides and other intermetallics that have resulted in low weld metal toughness and solidification cracking. In addition, niobium-containing filler metals may degrade the ductility and corrosion properties of the weldment due to changing the ferrite/austenite balance in the DSS fusion line and HAZ. Note that other nickel-based filler metals with less than 0.5 wt. % Nb (e.g. ENiCrMo-4, ENiCrMo-10, ENiCrMo-13, and ENiCrMo-14) have been used successfully.

Table D.5—Filler Metals for Shielded Metal Arc Welding of Duplex Stainless Steels

<table>
<tr><th>Base Metals</th><th colspan="6">Duplex Alloys</th><th colspan="3">Undermatched Alloys</th><th colspan="3">Overmatched Alloys</th></tr>
<tr><th>UNS</th><th>S32304</th><th>S31803
S32205
J92205</th><th>S32550</th><th>S32760
J93380</th><th>S32750</th><th>S39274</th><th>P1-P5</th><th>P8
(TP 304)</th><th>P8
(TP 316)</th><th>P8
(TP 254
SMO)</th><th>P43
(IN 625)</th><th>P45
(IN 825)</th></tr>
<tr><td>S32304</td><td>A-DF</td><td>A-DF</td><td>A-DF</td><td>A-DF</td><td>A-DF</td><td>A-DF</td><td>AEF</td><td>AEF</td><td>AF</td><td>GHI</td><td>GHI</td><td>GHI</td></tr>
<tr><td>S31803</td><td></td><td rowspan="2">A-D</td><td rowspan="2">A-D</td><td rowspan="2">A-D</td><td rowspan="2">A-D</td><td rowspan="2">A-D</td><td rowspan="2">AEF</td><td rowspan="2">AEF</td><td rowspan="2">AF</td><td rowspan="2">GHI</td><td rowspan="2">GHI</td><td rowspan="2">GHI</td></tr>
<tr><td>S32205</td><td></td></tr>
<tr><td>J92205</td><td></td><td>A-D</td><td>A-D</td><td>A-D</td><td>A-D</td><td>A-D</td><td>AEF</td><td>AEF</td><td>AF</td><td>GHI</td><td>GHI</td><td>GHI</td></tr>
<tr><td>S32550</td><td></td><td></td><td>B-D</td><td>B-D</td><td>B-D</td><td>B-D</td><td>ABEF</td><td>ABEF</td><td>ABF</td><td>GHI</td><td>GHI</td><td>GHI</td></tr>
<tr><td>S32760</td><td></td><td></td><td></td><td>CDGHI</td><td>CDGHI</td><td>CDGHI</td><td>A-DEF</td><td>A-DEF</td><td>A-DF</td><td>GHI</td><td>GHI</td><td>GHI</td></tr>
<tr><td>J93380</td><td></td><td></td><td></td><td>CDGHI</td><td>CDGHI</td><td>CDGHI</td><td>A-DEF</td><td>A-DEF</td><td>A-DF</td><td>GHI</td><td>GHI</td><td>GHI</td></tr>
<tr><td>S32750</td><td></td><td></td><td></td><td></td><td>CDGHI</td><td>CDGHI</td><td>A-DEF</td><td>A-DEF</td><td>A-DF</td><td>GHI</td><td>GHI</td><td>GHI</td></tr>
<tr><td>S39274</td><td></td><td></td><td></td><td></td><td></td><td>CDGHI</td><td>A-DEF</td><td>A-DEF</td><td>A-DF</td><td>GHI</td><td>GHI</td><td>GHI</td></tr>
</table>

Key

A ASME SFA 5.4, Classification E2209—duplex filler material.
B ASME SFA 5.4, Classification E2553—duplex filler material.
C ASME SFA 5.4, Classification E2594—duplex filler material.
D DP3W (unclassified)—duplex filler material.
E ASME SFA 5.4, Classification E309L—high-alloy austenitic filler material.
F ASME SFA 5.4, Classification E309LMo—high-alloy austenitic filler material.
G ASME SFA 5.11, Classification ENiCrMo-10—nickel-base filler material.
H ASME SFA 5.11, Classification ENiCrMo-14—nickel-base filler material.
I ASME SFA 5.11, Classification ENiCrMo-13—nickel-base filler material.

NOTE 1 This table refers to coated electrodes. For bare and cored wire welding (SAW, GMAW, GTAW, FCAW), use equivalent electrode classification (ASME/AWS SFA/A5.9, SFA/A5.14, SFA/A5.22, and SFA/A5.34). Refer to the text for information on other processes.

NOTE 2 At times, ENiCrMo-10, ENiCrMo-13, and ENiCrMo-14 are used for duplex and super duplex weld joints when severe corrosion is anticipated.

Annex E
(normative)

Welding of High-temperature Heat-resistant Alloys

E.1 General Notes

E.1.1 High-temperature heat-resistant alloys (heat-resistant alloys) are those that contain major alloying elements of chromium and nickel and carbide-forming elements. These alloys are intended for use in high-temperature applications where time dependent (creep) mechanisms are operative. Heat-resistant alloys are often castings, either centrifugal or static, including cast piping and furnace tubes or headers. However, they can also be supplied as plates or wrought fittings. The cast versions contain more carbon for better high-temperature resistance that can make weldability more difficult. Additional information is found in AWS D10.4—Annex A.

Typical chemical compositions and product forms are shown in Table E.1.

Table E.1—Typical Chemical Composition and Product Forms for High-temperature Heat-resistant Alloys [a]

Nominal Chemical Composition	Standard ASTM/ASME Casting Designation [b]	UNS Wrought Equivalent Designation [b]	Product Form	P-Number
25Cr-20Ni-Fe Balance	HK	S31000	Wrought or cast	8 or Unassigned
20Cr-32Ni-Fe Balance	HT	N08800, N08810, N08811	Wrought or cast	45 or Unassigned
26Cr-35Ni-Fe Balance	HP		Wrought or cast	Unassigned
25Cr-45Ni-Fe Balance	Proprietary grades	N06333	Wrought or cast	Unassigned
35Cr-45Ni-Fe Balance	Proprietary grades	None	Cast	Unassigned

[a] There are numerous high-temperature alloys with a wide range of Cr and Ni contents. This list is only a small portion of the more widely used ones.

[b] Cast and wrought materials compositions will not exactly match. Shown are the nearest equivalents. Wrought versions, if available, have much lower carbon content.

E.1.2 This annex provides recommendations for welding of new (unaged) material and is not intended to be a guideline for repairing aged material after high-temperature service. Aged material requires significantly different preheat and/or solution annealing practices prior to repair welding. This is due to the precipitation of various metallurgical second phases in the aged material that tend to embrittle the alloy making it more difficult to weld.

E.2 Welding Process

In addition to the acceptable welding processes listed in Section 5 of this recommended practice, electron beam welding is acceptable for welding centrifugal casting products, subject to approval by the owner/operator.

E.3 Welding Procedures and Performance Qualifications

E.3.1 Welding procedures and performance qualifications for each alloy shall be in accordance with the requirements of ASME *BPVC* Section IX with the additional requirements stated within this annex. In the event assigned P-Numbers are not available to create a welding test plate, base metals for procedure qualifications and the base metals qualified based on their use are shown in Table E.2. This typically occurs for specialized or proprietary furnace tubes and other furnace components and may represent a deviation from ASME *BPVC* Section IX.

Table E.2—Base Metals Used for Procedure Qualification and Qualified Materials

NOTE This table is for welds such as furnace components governed by API 560 (and API 561, which will be published shortly) that are not required by the purchaser to conform to the ASME Code.

Base Metal(s) Used for Procedure Qualification Coupon	Base Metals Qualified
Unassigned P-Number 35Cr-45Ni-Fe Balance to the same Unassigned P-Number 35Cr-45Ni-Fe Balance	Alloys with Unassigned P-Number 35Cr-45Ni-Fe Balance to the same Unassigned P-Number 35Cr-45Ni-Fe Balance, or 25Cr-35Ni-Fe Balance, or any P-No. 45 alloys or Unassigned P-Number 20Cr-32Ni-Fe Balance
Unassigned P-Number 35Cr-45Ni-Fe Balance to Unassigned P-Number 25Cr-35Ni-Fe Balance	Alloys with Unassigned P-Number 35Cr-45Ni-Fe Balance to alloys with Unassigned P-Number 25Cr-35Ni-Fe Balance Alloys with Unassigned P-Number 35Cr-45Ni-Fe Balance to the same Unassigned P-Number 35Cr-45Ni-Fe Balance Alloys with Unassigned P-Number 25Cr-35Ni-Fe Balance to the same Unassigned P-Number 25Cr-35Ni-Fe Balance
Unassigned P-Number 25Cr-35Ni-Fe Balance to the same Unassigned P-Number 25Cr-35Ni-Fe Balance	Alloys with Unassigned P-Number 25Cr-35Ni-Fe Balance to the same Unassigned P-Number 25Cr-35Ni-Fe Balance, or any P-No. 45 alloy or Unassigned P-Number 20Cr-32Ni-Fe Balance
Unassigned P-Number 25Cr-35Ni-Fe Balance to P-No 45 or Unassigned P-Number 20Cr-32Ni-Fe Balance	Alloys with Unassigned P-Number 25Cr-35Ni-Fe Balance to any P-No 45 or Unassigned P-Number 20Cr-32Ni-Fe Balance Alloys with Unassigned P-Number 25Cr-35Ni-Fe Balance to the same Unassigned P-Number 25Cr-35Ni-Fe Balance Any P-No. 45 metal or Unassigned P-Number 20Cr-32Ni-Fe Balance to any P-No. 45 metal or Unassigned P-Number 20Cr-32Ni-Fe Balance
P-No 45 or Unassigned P-Number 20Cr-32Ni-Fe Balance to P-No 45 or Unassigned P-Number 20Cr-32Ni-Fe Balance	P-No. 45 alloy or Unassigned P-Number 20Cr-32Ni-Fe Balance to any P-No. 45 alloy or Unassigned P-Number 20Cr-32Ni-Fe Balance

NOTE Some of these heat-resistant alloys have low-carbon and high-carbon versions. In general, carbon contents below 0.20 % C are considered low, and carbon contents above 0.35 % C are considered high carbon and weldability is different. The owner/operator should consider requiring a separate PQR for the higher carbon grades using test samples of the high-carbon version.

E.3.2 When conducting performance qualifications for welders/welding operators, alternate base materials may be utilized. Those alternate base materials are shown in Table E.3. When a base metal shown in the left column is used for performance qualifications, the welder/welding operator is qualified to weld combinations of base metals shown in the right column, including unassigned metals of similar chemical composition to these metals.

Table E.3—Alternate Base Materials for Welder Qualifications

Base Metal(s) Used for Performance Qualification	Base Metals Qualified
Castings of Unassigned P-Number 35Cr-45Ni-Fe Balance, 25Cr-35Ni-Fe Balance, or 20Cr-32Ni-Fe Balance	Unassigned P-Number 35Cr-45Ni-Fe Balance, 25Cr-35Ni-Fe Balance, or any P-No. 45 metal or Unassigned P-Number 20Cr-32Ni-Fe Balance
NOTE Some of these alloys have low-carbon and high-carbon versions. In general, carbon contents below 0.20 % C are considered low, and carbon contents above 0.35 % C are considered high carbon. In general, the required skill to weld versions greater than 0.35% C is greater than that necessary to weld versions with less than 0.20 % C. The owner/operator should consider requiring a performance test for the higher carbon grades using test samples of the high-carbon version.	

E.3.3 Filler Metals for Welding Heat-resistant Alloys

E.3.3.1 Autogenous automated-GTAW root pass welding is permitted only for joining centrifugal castings to themselves and for centrifugal-to-static castings.

E.3.3.2 Welding heat-resistant alloys with commercially available, nonclassified filler metals (complying with ASME/AWS specifications) that conform to the nominal chemical composition of the base metal's major alloying elements is permitted, provided that weld metal creep properties at the design temperature are acceptable to the designer. This is valid for welding a heat-resistant alloy to itself or welding two different heat-resistant alloys. Alternatively, nickel-base filler metals as those listed in Table 3 of this recommended practice can be used if acceptable to the designer.

E.3.4 Procedure Qualification Guided Bend Tests

Guided bend tests of cast heat-resistant alloy weld coupons shall be performed in accordance with the requirements of ASTM A488—8.2.4. When the base metal will not withstand the 180° guided bend required by ASME *BPVC* Section IX, a qualifying welded specimen is required. Specimens shall consist of base metal heat treated to the ductility and strength requirements of the applicable specification. The base metal specimens shall then be bent to failure. The guided bend weldment specimens shall be capable of being bent to within 5° of the result for the base metal angle or greater. In the case of joining two different alloys, both base alloys shall be tested as described above, then the guided bend weldment specimen shall be capable of being bent to within 5° of the result from the less ductile base metal bend or greater. Guided bend tests may also be waived subject to approval by owner/operator's engineer.

Annex F
(normative)

Welding Guidelines for P91 (9Cr-1Mo-V) Steels

F.1 Scope

This annex covers 9Cr-1Mo-V alloy steel piping, also known as ASME piping Grade P91. At this time, the scope covers piping, headers, and tubes. Other API Task Groups are investigating the use of Grade 91 for plate for pressure equipment, but have not codified requirements yet. This material is also classified ASME *BPVC* Section IX as P-No. 15-E.

F.2 Welding Processes

The welding processes are as follows.

a) The use of FCAW, GMAW, GTAW, SAW, and SMAW processes is permitted for the welding of P91 pressure boundary equipment. Other processes may be proposed to the purchaser for approval.

b) Use of GMAW-S for welding of the root pass shall be subject to the approval of the purchaser. If GMAW-S is selected, filler wire shall have minimum silicon (Si) content of 0.35 %.

F.3 Shielding Gas

For shielding gas, the following applies.

a) For FCAW and GMAW, a combination of 75 to 80 % Ar and balance CO_2 should be used as the shielding gas.

b) $Ar/CO_2/O_2$ mixture gas shall not be used for FCAW.

F.4 Composition and Mechanical Requirements of Consumables and Weld Deposits

The requirements are as follows.

a) The chemical composition shall meet the requirement of respective AWS SFA specification.

b) SMAW electrodes shall be certified to the H4 designation.

NOTE In some geographic areas, H5 is also considered acceptable. H4 means 4 ml of diffusible hydrogen per 100 grams of weld deposit, whereas H5 means 5 grams of diffusible hydrogen per 100 grams of weld deposit. The purchaser should ask for a PQR or other demonstration that H5 is acceptable.

a) During procedure qualification, in addition to applicable code requirements, weld deposits for SAW or FCAW shall be impact tested for each lot number (or tradename, as applicable) of flux for SAW and heat number of filler metal for both SAW and FCAW. Acceptance criterion is an average of 20 ft-lb (27.1 J) with no value less than 16 ft-lb (21.7 J) at 70 °F (21 °C). When impact testing is not required by code, such as steam or power applications, the owner/operator may waive this requirement.

b) A basic flux should be used for SAW. For P91 piping, B31.3 mandates flux with a basicity index of ≥ 1.0. The owner/operator or purchaser can specify a higher basicity index if they prefer.

c) Rutile flux is permitted for FCAW if adequate toughness per F.4 c) can be demonstrated.

d) Electrodes from packaging that has been punctured or torn shall be dried in accordance with the electrode manufacturer's recommendations or shall not be used for welds requiring consumables with an H4 diffusible hydrogen classification.

e) For FCAW, if welding is interrupted, the manufacturer's recommendations to determine if the filler wire needs to be discarded shall be followed.

NOTE For humid climates, the filler wire should be discarded if not used within 8 hours. For other climates, the allowable time may be longer.

f) For manual GTAW process, the diameter of the filler material shall be limited to a maximum of 3.2 mm (0.125 in.).

g) For P-15E (9Cr-1Mo-V) welding consumables, the nickel plus manganese content shall be no greater than 1.20 %.

F.5 Procedure Qualification Hardness Requirements

The weld deposit, HAZ, and base metal of a PQR test plate shall be hardness tested per the latest edition of ANSI/NACE MR 0103/ISO 17495—Annex C. Hardness requirements are as follows.

a) Minimum hardness for P91 shall be 196 HV10.

NOTE There are discrepancies when trying to convert Vickers (HV) hardness values to Brinell (HB) values.

b) For nonsour services in the PWHT condition, maximum hardness shall be 290 HV10 for 9Cr-1Mo-V steel (P91, T91).

NOTE P91 material is generally not recommended for wet, sour services.

F.6 Preheating and Interpass Temperature

F.6.1 Minimum recommended preheat temperature shall meet code requirements. Currently, ASME B31.1 and ASME B31.3 mandate minimum preheat temperature of 400 °F. ASME *BPVC* Section VIII treats preheat temperature requirements as nonmandatory, but recommends 400 °F.

NOTE Newer research, such as cited in EPRI 3002018025—2.6.1, has shown that the following preheat temperature guidelines have been acceptable in steam services.

a) Irrespective of process, where the thickness is greater than 0.5 in. (12.7 mm), preheat shall be 400 °F (205 °C) minimum.

b) For welds deposited using either the GMAW process or the GTAW process with a solid wire filler metal, preheat shall be 300 °F (150 °C) minimum.

c) For welds deposited using the SMAW process, preheat shall be 350 °F (175 °C) minimum.

d) For welds deposited using the FCAW process or the SAW process or for highly restrained components, preheat shall be 400 °F (205 °C) minimum.

F.6.2 Maximum interpass temperature shall be 600 °F (316 °C).

F.6.3 After completion of DHT (see F.8), weldments should be cooled below 200 °F (93 °C) prior to PWHT.

NOTE 200 °F (93 °C) is the martensite finish temperature (M_f).

F.7 Interruption of Heating Cycle

Interruption of the heating cycle should be avoided if possible. If interruption is unavoidable, refer to 8.9.

F.8 Dehydrogenation Heat Treatment

For DHT during fabrication, after welding and before cooling to room temperature, the weldment shall not be allowed to cool to below 200 °F (93 °C) before heating to 660 °F (350 °C) for 1 hour per inch with 1 hour minimum for hydrogen degassing. After the DHT is completed, weldments shall be cooled in still air to below 200 °F (93 °C) prior to PWHT. For tack welds, DHT can be reduced to preheat temperatures, held for a minimum of 1 hour.

F.9 Post-weld Heat Treatment

For PWHT, the following applies.

a) PWHT temperature and holding time are essential variables within the limits of ± 25 °F (± 14 °C) and ± 1 hour, respectively.

b) PWHT temperature shall be performed following applicable code requirements.

c) Welds shall be cooled to below the martensite finish temperature prior to PWHT.

d) The maximum allowable PWHT temperature shall not exceed 1420 °F (770 °C).

e) The PWHT holding time is 2 hours per inch (25 mm) of thickness, but not less than 2 hours.

f) Heating and cooling rate shall be no greater than 200 °F/hr (110 °C/hr) per inch thickness.

g) Follow ASME *BPVC* Section I Appendix, "Nonmandatory Appendix C Local Heating of Welds in Cylindrical Components of P-No.15E Materials When Using Electric Resistance Heating."

F.10 Production Welding Requirements

The requirements are as follows.

a) For production welds, hardness testing shall be performed after preparing the weld surface to make it free from scale, slag, and surface roughness. Weld hardness readings shall be taken at the centerline of the weld cap.

b) For piping, each weld shall be hardness tested, and the number of tests for circumferential welds shall be as follows: for NPS up to 24, two hardness tests; for NPS 26 through NPS 36, three hardness tests; and for NPS 38 and larger, four hardness tests. Branch connection welds shall have one test per weld.

c) Hardness acceptance criteria are 190 HB minimum, 270 HB maximum.

F.11 Dissimilar Metal Welding

For dissimilar metal welding, the following applies.

a) Dissimilar metal welds should be prohibited in 9Cr-1Mo-V for severe thermal cycling service, in the immediate vicinity of a high-restraint location and in sour services, unless accepted by the owner/operator or purchaser.

NOTE The owner/operator and purchaser should consider what is severe thermal cycling and high restraint.

b) For dissimilar metal welds between 9Cr-1Mo-V and lower-alloy steel (e.g. 2$^1/_4$Cr-1Mo), consideration should be made to insert a small transition piece (e.g. 5Cr-$^1/_2$Mo) to allow a lesser gradient in the chemical composition to minimize decarburization of the lower alloy during high-temperature operation. Welding parameters (e.g. pre-heat, interpass, PWHT) shall follow the higher alloy requirements.

c) For dissimilar metal welds between 9Cr-1Mo-V and austenitic stainless steels or between 9Cr-1Mo-V and nickel-base alloys:

1) It is often common practice to weld a "butter" layer of a nonhardening alloy, such as ERNiCrFe-2, ERNiCrFe-3, or ERNiCr-3, onto the 9Cr-1Mo-V prior to completing the butt weld. Once the butter layer is applied, the buttered pipe can be PWHT'd per standard 9Cr-1Mo-V practice. After the PWHT, the butt weld can be completed using the same filler metals or an alloy matching the other side of the joint, with no need for PWHT.

2) For circumferential welds of 0.5 inch (12.7 mm) thick or thinner, a wide bevel/cap (see Figure F.1) shall be used to extend the toe of the weld in the 9Cr-1Mo-V steel beyond the fusion boundary and HAZ in the 9Cr-1Mo-V steel.

3) For welds thicker than 0.5 in. (12.7 mm) nominally in piping components, a "step bevel" (see Figure F.2) configuration combined with a wide cap is recommended if there exists enough access to complete the weld.

4) For welding 9Cr-1Mo-V to stainless steels or nickel-base alloys, the preferred electrode/rods are ERNiCrFe-2, ERNiCrFe-3, or ERNiCr-3 (as shown in Table 3).

5) Where a thickness transition exists between the 9Cr-1Mo-V and austenitic stainless steel or nickel-base alloy, a transition piece should be utilized. The purchaser should specify the details of the joint. This transition piece should be a higher alloy, either matching in composition to the austenitic stainless steel or a nickel-base alloy.

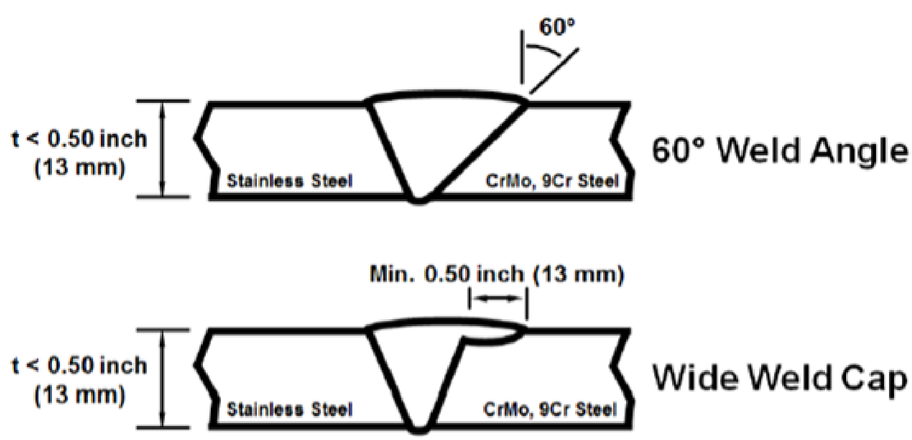

Figure F.1—Wide Bevel or Wide Cap for Welding P91 to Austenitic Stainless or Nickel-base Alloys

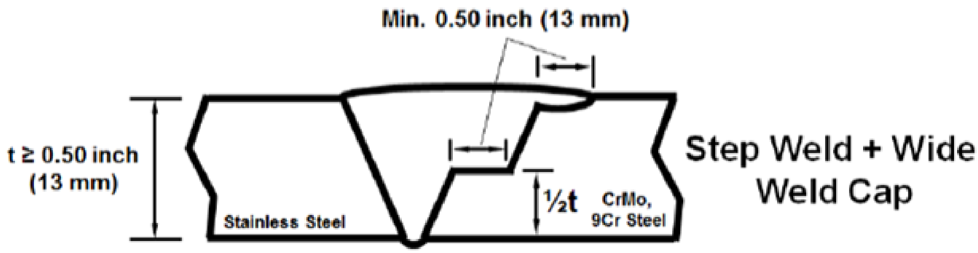

Figure F.2—Step Bevel for Welding P91 to Austenitic Stainless or Nickel-base Alloys

Annex G
(normative)

Controlled-deposition Welding as an Alternative to Post-weld Heat Treatment of Weld Repairs

G.1 Introduction

The principle of CDW is that weld beads in the first layer are overlapped such that at least part of the coarse-grained, hardened region produced by the previous bead is replaced with fine-grained and tempered HAZ. A second layer, with appropriate penetration, can achieve further refinement, and further layers may be added to achieve tempering.

G.2 Scope

G.2.1 This annex provides recommendations for the application of preheat and CDW to repair welding when invoked by API 510, API 570, API 653, NBIC NB-23, or ASME PCC-2 Article 209.

G.2.2 CDW may be used in conjunction with base metal chemical composition controls and preproduction weld procedure hardness controls and testing as an alternative to PWHT. The thermal control used during CDW can produce repair weld HAZ with lower hardness in lower hardenability steels.

G.3 Codes and Standards

There are circumstances where welded repairs to pressure equipment may be carried out without a subsequent PWHT, provided that the procedure complies with the requirements of relevant industry standards and purchaser's specifications. Certain codes and standards allow CDW repairs, provided that certain requirements are met, such as preheating, or the maximum depth or area of the repair. These standards include the following:

a) ASME *BPVC* Section I—PW-40.3;

b) API 510;

c) API 570;

d) NBIC Part 3, Method 6 and Supplement 8 (see Welding Methods 2, 3, and 4, temper bead methods).

G.4 Preheat Limits and Restrictions

G.4.1 The preheating method, when performed in lieu of PWHT, is limited to the following materials and weld processes.

a) The materials shall be limited to P-No. 1, Groups 1, 2, and 3 and to P-No. 3, Groups 1 and 2 (excluding Mn-Mo steels in Group 2), as permitted for welded construction by the applicable rules of the original code of construction.

b) The welding shall be limited to the SMAW, GMAW, FCAW, and GTAW processes.

G.4.2 The preheat method shall be performed as follows:

a) The weld area shall be preheated and maintained at a minimum temperature of 300 °F (150 °C) during welding.

b) The 300 °F (150 °C) temperature should be checked to ensure that 4 in. (100 mm) of the material or four times the material thickness (whichever is greater) on each side of the groove is maintained at the minimum temperature during welding. The maximum interpass temperature shall not exceed 600 °F (315 °C).

c) When the weld does not penetrate through the full thickness of the material, the minimum preheat and maximum interpass temperatures need only be maintained at a distance of 4 in. (100 mm) or four times the depth of the repair weld, whichever is greater on each side of the joint.

G.5 Controlled-deposition Welding Limits and Restrictions

G.5.1 Testing has shown that CDW may not sufficiently reduce residual stress and, therefore, should not be considered as a substitute for thermal stress relief. This is especially true in services where residual stress is a critical factor (e.g. alkaline stress corrosion cracking), and in cases like this, CDW should not be used unless demonstrated to be acceptable by testing and validation, and acceptance by the owner/operator.

G.5.2 Materials considered for CDW shall be limited to ASME P-No. 1 (carbon steel), ASME P-No. 3 (carbon-$^{1}/_{2}$Mo steel), and ASME P-No. 4 (1Cr-$^{1}/_{2}$Mo and 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo steel).

G.5.3 ASME P-No. 5A steels (2$^{1}/_{4}$Cr-1Mo and 3Cr-1 Mo) may be considered for CDW except for sour service, high-temperature hydrogen services, high-pressure hydrogen services, where hydrogen embrittlement is a concern and services where residual stress is a critical factor (e.g. alkaline stress corrosion cracking).

G.5.4 Welding processes for CDW are limited to those allowed by ASME *BPVC* Section IX and the applicable post-construction code.

G.5.5 In-service welding (e.g. hot tap welds, buttering) using CDW is permitted.

G.6 Application of Preheat and Controlled-deposition Welding as an Alternative to Post-weld Heat Treatment of Weld Repairs

G.6.1 Application of preheat and CDW shall be based on technical consideration of the adequacy of CDWs in the as-welded condition at operating and hydrotest conditions.

G.6.2 Requirements for service conditions, materials used, design of joints, preheating, PWHT, metallurgical effects of welding, acceptance criteria for weld quality, and related examinations shall be addressed by the purchaser's experienced welding engineer or metallurgical engineer using the codes, standards, specifications, or contract documents that invoke this annex. Review should consider factors including the reason for the original PWHT, susceptibility to environmental cracking, stresses in the weld location, susceptibility to high-temperature hydrogen attack, susceptibility to creep, etc. When the requirements of this annex conflict with those of construction codes, they should be resolved by an experienced welding engineer or metallurgical engineer. Specifications or contract documents that are required to follow this annex may add additional requirements, and the organization shall comply with both sets of requirements.

G.7 Qualification of Controlled-deposition Welding Procedures as an Alternative to Post-weld Heat Treatment of Weld Repairs

G.7.1 The main factors affecting CDW are the weld bead size (weld volume) and the extent of bead overlap. Control of the bead size is achieved by the choice of diameter of the electrode rod or wire and by the welding parameters, which is usually achieved by depositing weld beads at a consistent specified heat input. The WPS parameters should be chosen to achieve the optimum bead size and overlap to avoid hard HAZs.

G.7.2 A WPS shall be developed for each CDW application. An existing PQR may be used provided the test material meets the following requirements in G.7.2.1. and G.7.2.2.

G.7.2.1 Test material for the PQR shall be of the same material specification (including specification type, grade, class) as the original material specification for the repair. Test material used should conform as much as possible to the material used for construction, but in no case shall the test material be lower in strength, lower in carbon content, or lower in CE than the materials used in construction.

G.7.2.2 If the original material specification is obsolete, the test material for the PQR shall conform as much as possible to the material used for construction, but in no case shall the test material be lower in strength, lower in carbon content, or lower in CE than that of the material to be welded.

G.7.3 CDW procedures shall define the minimum preheat temperature during welding, the maximum interpass temperature and the post-heating (e.g. DHT) temperature/time requirements. Qualification thickness for test plates and repair grooves shall be in accordance with Table G.1.

Table G.1—Controlled-deposition Welding as an Alternative to Post-weld Heat Treatment Qualification Thicknesses for Test Plate and Repair Grooves

Depth *t* of Test Groove Welded [a]	Repair Groove Depth Qualified	Thickness of T of Test Coupon Welded	Thickness of Base Metal Qualified
t	< *t*	< 50 mm (2 in.)	≤ T
t	< *t*	≥ 50 mm (2 in.)	50 mm (2 in.) to unlimited

[a] The weld groove depth used for procedure qualifications shall be deep enough to allow removal of the required test specimen.

G.7.4 When notch toughness testing is required by the applicable repair code (e.g. NB-23), the PQR shall include CVN impact tests to determine if weld metal and HAZ toughness in the as-welded condition are adequate at the minimum design metal temperature (i.e. the criteria used in ASME *BPVC*, Section VIII, Division I, Parts UG-84 and UCS 66, or ASME B31.3). If special hardness limits are necessary (i.e. NACE SP0472, ANSI/NACE MR0103/ISO 17945, and NACE MR0175/ISO 15156), the PQR shall include hardness test results.

G.7.5 WPS shall include the following additional requirements.

a) Minimum requirements of ASME *BPVC* Section IX QW-290, NBIC NB-23 or ASME PCC-2 Article 209, as applicable.

b) Maximum weld heat input for each layer shall not exceed that used in the procedure qualification test.

c) Minimum preheat temperature for welding shall not be less than that used in the procedure qualification test.

d) Maximum interpass temperature for welding shall not be greater than that used in the procedure qualification test.

e) For CDW, preheat temperature shall be checked to ensure that 100 mm (4 in.) of the material or four times the material thickness (whichever is greater) on each side of the weld joint will be maintained at the minimum temperature during welding. When the weld does not penetrate through the full thickness of the material, the minimum preheat temperature need only be maintained at a distance of 100 mm (4 in.) or four times the depth of the repair weld, whichever is greater.

f) Consumables for the alloys and welding processes permitted by this annex shall have a maximum diffusible hydrogen level as specified in Table 2.

g) When shielding gases are used, the gas shall exhibit a dew point that is no higher than −60 °F (−50 °C). Surfaces on which welding is to be performed shall be maintained in a dry condition during the welding and free of rust, mill scale, and hydrogen-producing contaminants, such as oil, grease, and other organic materials.

h) For welds made by FCAW or SMAW, after completion of welding and without allowing the weldment to cool below the minimum preheat temperature, the temperature of the weldment shall be raised to a minimum temperature of 315 °C (600 °F) for a period of two to four hours to assist outgassing of diffusible hydrogen picked up during welding. Hydrogen bake-out treatments may be omitted provided the electrode used is classified by the filler metal specification with an optional supplemental diffusible hydrogen designator of H4/H5.

i) For filler metals requiring tempering, the final CDW reinforcement layer shall be removed after welding and cooling to ambient temperature. In addition, for all CDW repairs, weldments shall be ground so that there is no notch at the interface between weld and base metal, and the weld shall be ground to remove excessive reinforcement per the ASME Code criteria.

Bibliography

[1] API Standard 560, *Fired Heaters for General Refinery Service*

[2] API Recommended Practice 939-C, *Guidelines for Avoiding Sulfidation (Sulfidic) Corrosion Failures in Oil Refineries*

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