Materials and Fabrication of 1¼Cr-½Mo Steel Pressure Vessels for Service above 825 ˚F (440 ˚C)

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Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, D.C. 20005, standards@api.org.

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Introduction

This standard applies to new pressure vessels in petroleum refining, petrochemical, industrial gas, and chemical facilities in which fluids are processed at temperatures in the 825 °F to 1150 °F (440 °C to 620 °C) range. It is based on decades of industry operating experience and the results of recent experimentation and testing conducted by independent manufacturers, fabricators, and users of pressure vessels for this service.

Licensors and owners of process units in which these pressure vessels are to be used may modify or supplement this standard with additional proprietary requirements.

Materials and Fabrication of 1¼Cr-½Mo Steel Pressure Vessels for Service above 825 ˚F (440 ˚C)

1 Scope

This standard includes materials and fabrication requirements for new 1¼Cr-½Mo and 1Cr-½Mo steel pressure vessels, including heat exchanger shells and channels for elevated temperature service. It applies to pressure vessels that are designed, fabricated, and documented in accordance with ASME Code Section VIII, Division 1 or Division 2 (hereafter referred to as “Code”).

This document may also be used as a resource when planning to modify existing pressure vessels.

The interior surfaces of these pressure vessels and heat exchangers (i.e. the surfaces exposed to the process) may or may not have an austenitic stainless steel (SS), ferritic SS, or nickel alloy weld overlay or cladding to provide additional corrosion resistance.

Some 1¼Cr-½Mo and 1Cr-½Mo vessel components with thicknesses greater than 4 in. (100 mm) have been shown to have difficulty meeting the Code toughness requirements. This standard is primarily intended for wall thicknesses less than 4 in. (100 mm); a preferred option for thicker vessel components is to use 2¼Cr-1Mo alloys.

This standard is applicable to shell thicknesses greater than 1 in. (25 mm). Although outside of the scope, this document can be used as a resource for pressure vessels down to lower shell thicknesses with changes defined by the purchaser.

This standard is intended for use for 1¼Cr-½Mo and 1Cr-½Mo equipment operating between 825 °F (440 °C) and 1150 °F (620 °C). The primary in-service materials degradation mechanism addressed by the requirements herein is low creep ductility (LCD) cracking, which can occur at these operating temperatures if not properly addressed. LCD cracking is a form of reheat cracking.

In many cases, 1¼Cr-½Mo and 1Cr-½Mo steel equipment being designed for temperatures >825 °F (>440 °C) operate with stresses below the threshold for brittle fracture [i.e. below 8 ksi (55 MPa) as reported in API 579-1/ASME FFS-1[1], or below 10% of ultimate tensile strength as reported in literature].

Typical equipment covered by the scope of this standard includes catalytic reforming reactors and fluidized catalytic cracking (FCC) unit hot wall reactors. For information on 1¼Cr-½Mo and 1Cr-½Mo equipment operating at lower temperature ranges, refer to API Standard 934-C. Since hydroprocessing units are typically operated at temperatures lower than 825 °F (440 °C), the guidelines in this standard (934-E) do not apply to most hydroprocessing units; instead, they are covered by RP 934-A or API Standard 934-C. Also, since coke drums typically are more susceptible to fatigue than LCD cracking, this standard excludes coke drums from the scope; they are addressed in API Technical Report 934-G.

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 any amendments) applies.

API RP 582, *Welding Guidelines for the Chemical, Oil, and Gas Industries*

ASME[1] *Boiler and Pressure Vessel Code, Section II-Materials—Part C-Specification for Welding Rods, Electrodes, and Filler Metals*

ASME *Boiler and Pressure Vessel Code, Section V-Nondestructive Examination*

ASME *Boiler and Pressure Vessel Code, Section VIII-Rules for Construction of Pressure Vessels, Division 1*

ASME *Boiler and Pressure Vessel Code, Section VIII-Rules for Construction of Pressure Vessels, Division 2-Alternative Rules*

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

ASME SA-20/SA-20M, *Standard Specification for General Requirements for Steel Plates for Pressure Vessels*

ASME SA-182/SA-182M, *Standard Specification for Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service*

ASME SA-263, *Standard Specification for Stainless Chromium Steel-Clad Plate*

ASME SA-264, *Standard Specification for Stainless Chromium-Nickel Steel-Clad Plate*

ASME SA-265, *Standard Specification for Nickel and Nickel-Base Alloy-Clad Steel Plate*

ASME SA-335/SA-335M, *Standard Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service*

ASME SA-336/SA-336M, *Standard Specification for Alloy Steel Forgings for Pressure and High-Temperature Parts*

ASME SA-369/SA-369M, *Standard Specification for Carbon and Ferritic Alloy Steel Forged and Bored Pipe for High-Temperature Service*

ASME SA-387/SA-387M, *Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum*

ASME SA-530/SA-530M, *Standard Specification for General Requirements for Specialized Carbon and Alloy Steel Pipe*

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

ASNT[2] Recommended Practice No. SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing*

ASNT CP-189, *Standard for Qualification and Certification of Nondestructive Testing Personnel*

ASTM[3] G146, *Standard Practice for Evaluation of Disbonding of Bimetallic Stainless Alloy/Steel Plate for Use in High-Pressure, High-Temperature Refinery Hydrogen Service*

[1] ASME International, 3 Park Avenue, New York, New York 10016, www.asme.org.

[2] American Society for Nondestructive Testing, 1711 Arlingate Lane, Columbus, Ohio 43228-0518, www.asnt.org.

[3] ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

AWS[4] A4.2M / ISO 8249MOD, *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*

WRC[5] Bulletin 452, *Recommended Practices for Local Heating of Welds in Pressure Vessels*

WRC Bulletin 519, *Stainless Steel Weld Metal—Prediction of Ferrite Content: An Update of WRC Bulletins 318 and 342*

3 Terms, Definitions, and Acronyms

3.1 Terms and Definitions

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

3.1.1
ASME Code
ASME Boiler and Pressure Vessel Code.

3.1.2
Cold forming
The mechanical forming or rolling of steel vessel components at ambient temperature up to 900 ºF (480 ºC).

3.1.3
final post-weld heat treatment (PWHT)
The last PWHT after fabrication of the pressure vessel and prior to affixing the name plate and placing the pressure vessel in service.

3.1.4
fine grain practice
A steelmaking practice where aluminum or other elements are added to steel to provide resistance to grain growth during heat treatments.

NOTE The steps and testing to achieve fine grain practice are defined in the ASME specifications for materials (e.g. ASME SA-20/SA-20M, Paragraph 8).

3.1.5
hot forming
The mechanical forming of steel vessel components immediately after soaking within a temperature range of 900 ºF (480 ºC) to the upper end of the PWHT temperature range.

3.1.6
Larson-Miller parameter (LMP)
Parametric relationship between aggregate elevated temperature exposures (heat treatment(s) temperatures), and times at temperature, LMP can be used to assess the effect of individual or multiple heat treatment(s) on a specific material property, such as strength or toughness. Additional details on LMP are under Section 5.

[4] American Welding Society, 550 NW LeJeune Road, Miami, Florida 33126, www.aws.org.

[5] The Welding Research Council, 3 Park Avenue, 27th Floor, New York, New York 10016-5902, www.forengineers.org.

3.1.7
heat, lot and batch
Are terms meant to establish traceability to an MTR that can assure the same elemental composition is being used/tested, verifying consistency between pre-production lab test results and production weld behavior.

3.1.8
low creep ductility (LCD) cracking
A form of reheat cracking occurring due to long-term exposure to temperatures >825 °F (440 °C) for 1¼Cr-½Mo and 1Cr-½Mo steels. It involves creep cracking of welds or weld heat–affected zones due to carbide precipitation and diffusion of certain elements (As, Cu, P, B, Sb, Sn, Nb, V, Ti, etc.) to grain boundaries. These precipitates result in loss of creep ductility, and significant lowering of the expected creep life.

NOTE This phenomenon is also called "creep embrittlement cracking" in older publications.

3.1.9
master plate
The term used by ASME SA-20/SA-20M to describe starting plates that are subdivided into multiple plates.

3.1.10
maximum PWHT
Specified heat treatment (aggregate temperature and time) of test coupons to simulate the maximum heat-treatment exposures of the vessel alloy or vessel-portion alloy. Additional details on maximum PWHT are under Section 5.

3.1.11
minimum PWHT
Specified heat treatment (aggregate temperature and time) of test specimens to simulate the minimum heat-treatment exposures of the vessel alloy. Additional details on minimum PWHT are under Section 5.

3.1.12
purchaser
The operator-user that has entered into the pressure vessel purchase order with the manufacturer, or their designated representative.

3.1.13
reheat cracking
Creep cracking of welds or weld heat–affected zones after a fabrication heat-treatment step, such as PWHT, or after long-term service at high temperatures. However, in this document, the latter is referred to as low creep ductility cracking. Both forms are due to diffusion of certain elements (P, As, Cu, Sb, Sn, B) to grain boundaries and precipitation of carbides of Mo, Nb, V, Ti in grains. At PWHT temperatures, precipitation of fine carbides strengthens the intragranular matrix, resulting in the strength of the grain exceeding that of the grain boundaries. Additionally, diffusion of tramp elements to the grain boundaries promotes low creep ductility, and can crack at the high temperatures due to the welding residual stresses. Heavier thickness welds are more susceptible, as they develop larger thermal stresses and require longer times to achieve stress relief. This phenomenon is also called "stress relaxation cracking" in other publications.

3.1.14
temper embrittlement
The "reversible" reduction in toughness due to segregation of impurity elelments (such as antimony, phosphorus, tin, and arsenic) to prior austenitic grain boundaries that can occur in some low-alloy steels as a result of long-term exposure in the temperature range of about 650 °F to 1070 °F (343 °C to 577 °C). This change causes an upward shift in the ductile-to-brittle transition temperature as measured by Charpy impact testing. Although the loss of toughness is not evident at operating temperature, equipment that is temper embrittled may, after cooling, be susceptible to brittle fracture during start-up, shutdown, or hydrotesting after weld repair. 1¼Cr-½Mo and 1Cr-½Mo steels are considered to be less susceptible and to have less of a shift than 2¼Cr-1Mo alloys.

3.1.15
Warm forming
The mechanical forming of steel vessel components immediately after soaking within a temperature range of 900 ºF (480 ºC) to the upper end of the PWHT temperature range.

3.2 Acronyms

For the purposes of this document, the following acronyms apply.

CVN Charpy V-notch

DHT dehydrogenation heat treatment

FN ferrite number

HAZ heat-affected zone

HBW Brinell hardness with tungsten carbide indenter

HV Vickers hardness

LCD low creep ductility

LMP Larson-Miller parameter

MDMT minimum design metal temperature

MT magnetic particle testing

MTR material test report

NDE nondestructive examination

PQR procedure qualification record

PT penetrant testing

PWHT post-weld heat treatment

RT radiographic testing

SS stainless steel

UT ultrasonic testing

WPS welding procedure specification

4 Design of Pressure Vessels and Heat Exchangers

4.1 Design and Manufacture

Design and manufacture shall conform to the ASME *Boiler and Pressure Vessel Code,* Section VIII, Division 1 or Division 2 and its applicable Code Cases.

4.2 Coverage of Design Issues

Design issues are typically covered by a manufacturer's design report should conform with the user's design document; ASME Code strength calculations, drawings, and local stress analysis for extra loads; and special design requirements, if required.

This standard is not intended to cover design issues, other than those below.

a) The design thickness (T) shall not include any allowance for extra thickness provided either as corrosion allowance or as a corrosion-resistant liner, such as weld overlay or cladding.

b) Weld seam layouts shall provide that all welds are accessible for NDE, such as RT, UT, MT, and PT, both during fabrication and in service. The use of external attachments that cover weld seams should be avoided, and require purchaser approval.

c) Nozzle necks should have transition to the pressure vessel body as shown in Table 4.2.13 of the ASME Section VIII, Division 2, or be fabricated in accordance with Table 4.2.10, Details 3 through 6 of the ASME , Section VIII, Division 2, with integral reinforcement.

d) Nozzle welds shall be located without intersecting of circumferential or longitudinal welds, unless otherwise approved by purchaser (if approved, the purchaser shall specify and additional NDE and NDE sequence).

e) Plates, forgings, pipe fittings, and flanges and Grade P11 and FP11 pipe may be used for the pressure boundary as indicated in Table 1. Regardless of the class of material used, the ASME Code design allowable stresses shall be based on Class 1 materials. It is acceptable per Code to arbitrarily use lower design allowable stresses. This only has an effect for design temperatures between 850 °F (455 °C) and 900 °F (480 °C), because, at design temperatures ≥ 900 °F (480 °C), the Code design allowable stresses are the same for Class 1 and 2.

4.3 Purchaser shall specify the use of dissimilar metal flanges or a dissimilar metal weld when mating to piping at the outlet nozzle that extends to the outside of the skirt. This is discussed further in section 6.1.2 and 8.1.5.

5 Heat Treatment

5.1 Maximum PWHT

Prior to heat treatment, coupons shall be representative of the as-supplied material (i.e., having the same austenitizing and tempering heat treatment). By definition, maximum PWHT includes all fabrication heat treatments above 900 °F (482 °C) [e.g. warm forming, intermediate stress relief (ISR), planned PWHT cycles, a PWHT cycle for possible shop repairs, and a minimum of one extra PWHT for possible future use by purchaser]. Typically, the ISR and PWHT cycles are aggregated into one single equivalent heat treatment that approximates the sum total effects of time and temperature. Methods to account for the aggregate effects on mechanical properties are discussed in the note below. Dehydrogenation heat treatments (DHT) do not need to be included, as they are at temperatures too low to affect material properties.

NOTE To determine the equivalent time at one temperature (within the PWHT range) of heating steps that have temperatures outside the PWHT range, the Larson-Miller Parameter formula (or Hollomon-Jaffe Parameter) may be used (results are to be agreed upon by purchaser and manufacturer). During future repairs, it is the purchaser's responsibility to assess any changes in properties that may have occurred from high-temperature service and understand how the proposed repair welding and PWHT may impact the pressure vessel.

5.2 Minimum PWHT

Prior to heat treatment, coupons shall be representative of the as-supplied material (i.e. having the same austenitizing and tempering heat treatment). By definition, minimum PWHT includes only the minimum of fabrication heat treatments above 900 °F (482 °C), e.g., warm forming, intermediate stress relieving (ISR) if any, and one PWHT cycle. Typically, the ISR and PWHT cycles are aggregated into one single equivalent heat treatment that approximates the sum total effect of time and temperature. Methods to account for the aggregate effects on mechanical properties are discussed in the note below.

NOTE To determine the equivalent time at one temperature (within the PWHT range) of heat steps outside the PWHT range, the Larson-Miller Parameter formula (or Hollomon-Jaffe Parameter) may be used (results are to be agreed upon by the purchaser and manufacturer).

5.3 Larson-Miller parameter

LMP is employed to evaluate cumulative effects from exposures to varying temperatures during fabrication, including tempering and PWHT, as shown by the second equation below:

$$LMP = T \times (20 + log\, t) \quad (1)$$

$$Final\ LMP = T_i \times \left[20 + log\left(t_i + t_{eqi}\right)\right] \quad (2)$$

$$t_{\text{eqi}} = 10\text{^}\left\{T_i / T_{\text{eqi}} * [20 + log(t_i)] - 20\right\} \quad (3)$$

where

T is the temperature in kelvins;

t is the time in hours; and

t_{eqi} is the equivalent soaking time at temperature T_{eqi} having the same tempering effect as holding at temperature T_{i} for time t_{i}.

NOTE Hollomon-Jaffe parameters can be used in place of LMP parameters, as they use the same concept and formula structure, but have different constants. LMP is also referred to as the “tempering parameter.”

6 Base Metal Requirements

6.1 Material Specification

6.1.1 Pressure boundary base metals shall be in accordance with the applicable ASME specifications indicated in Table 1. Tubing is outside the scope of this document.

Table 1—Base Metal ASME Specifications

Steel	Plate	Forgings	Pipe	Pipe Fittings and Flanges
1¼Cr-½Mo	SA-387 Gr. 11, Cl. 1 or Cl. 2	SA-182 Gr. F11, Cl. 1 or 2 SA-336 Gr. F11, Cl. 1, 2, or 3	SA-335 Gr. P11 SA-369 Gr. FP 11	SA-182 Gr. F11, Cl. 1 or 2 SA-234 Gr. WP11, Cl. 1, 2 or 3
1Cr-½Mo	SA-387 Gr. 12, Cl. 1 or Cl. 2	SA-182 Gr. F12, Cl. 1 or 2 SA-336 Gr. F12 Cl. 1 or 2	SA-335 Gr. P12 SA-369 Gr. FP12	SA-182 Gr. F12, Cl. 1, 2, or 3 SA-234 Gr. WP12, Cl. 1 or 2
NOTE 1 If higher PWHT temperatures are used as discussed in Paragraph 7.6.1, it may be difficult to achieve Class 2 or 3 mechanical properties. NOTE 2 All designs shall be based on Class 1 design allowable stresses per Paragraph 4.2.e.				

6.1.2 Unless approved in advance by the purchaser, different base metals should not be mixed in the same pressure vessel (such as using 21/4Cr-1Mo nozzles in a 11/4Cr-1/2Mo shell or head). There are some designs which use austenitic stainless steels as part of the outlet nozzles, which extend to outside the skirts and involve a dissimilar metal weld outside of the skirt. These cases require purchaser approval (also see 8.1.5).

6.1.3 Attachments (such as skirts, lugs, clips, etc.) welded directly to the pressure boundary shall be of the same material grade as the pressure boundary material.

6.1.4 Nozzles shall be manufactured from forgings.

6.2 Steelmaking Practice

In addition to the steelmaking practice outlined in the applicable specifications, steel plates and heavy forgings made to SA-336/SA-336M shall be vacuum degassed. For pipes, pipe fittings, and pipe flanges made to SA-182/SA-182M, vacuum degassing is not mandatory.

6.3 Chemical Composition Limits

For 1¼Cr-½Mo and 1Cr-½Mo steels, all plate, piping, and forging materials should be made to fine grain practice per ASME SA-20/SA-20M (no grain size measurement is required if the chemical analysis requirements of SA-20/SA-20M 8.3.2 are met). The steel shall meet the following additional chemical analysis by heat analysis:

X-bar $\leq$ 15 ppm

Where X-bar = (10P + 5Sb + 4Sn + As)/100 [with P, Sb, Sn, and As in ppm]

C = 0.15 wt. %, maximum

P = 0.010 wt. %, maximum

S = 0.007 wt. %, maximum

Cu = 0.20 wt. %, maximum

Ni = 0.30 wt. %, maximum

Nb = 0.006 wt. %, maximum

V = 0.025 wt. %, maximum

Ti = 0.02 wt. %, maximum

NOTE While the J-factor is used to mitigate temper embrittlement in 2¼Cr-1Mo steels, it is not applicable to 1¼Cr-½Mo and 1Cr-½Mo steels, and an X-bar limit has been adopted as a means of restricting the concentration of elements that contribute to temper embrittlement, reheat cracking, and LCD cracking. The chemistry restrictions described above, along with other aspects of this standard, are designed to provide the steel with resistance to reheat and LCD cracking, balanced with the other desired properties. API Publication 938-A was used as a basis for these requirements, and the optimum limits have been compiled. The MPC-05 and MPC-07 formulas discussed in Publication 938-A are too complicated for steelmakers to develop strategies to consistently meet, and hence, it would be extremely impractical to add to purchasing requirements.

6.4 Heat Treatment

Pressure-boundary components, regardless of product form, shall be either:

a) annealed;

b) normalized and tempered (N&T);

c) quenched and tempered (Q&T); or normalized with accelerated cooling and tempered (N+Ac+T)] to meet the required mechanical properties.

For thicknesses >2 in. (50 mm), Q&T or N+Ac+T may be required to meet fracture-toughness specifications. Tempering temperature may be below, at, or above PWHT temperature.

NOTE Plate and forged materials manufacturers are responsible for determining the tempering temperatures required to meet the specified material properties, considering all heat-treatment requirements (i.e. including the minimum and maximum PWHT as defined in 5.1 and 5.2). The cumulative effects of the various heat treatments shall be evaluated by using the equivalent LMP approach as required for mechanical property testing in 6.5.2.a, 6.5.3, and 6.2.

6.5 Mechanical Properties

6.5.1 Location of Tensile Test Specimens

Test specimens for establishing the tensile properties shall be removed from the following locations:

a) Plate—from each master plate, at the ½T location (½T is acceptable per Code by specifying SA-387 Supplementary Requirement S53). Specimens shall be oriented transverse to the rolling direction in accordance with SA-20/SA-20M.

NOTE If multiple plates are cut from one master plate, only one set of specimens from the master plate (i.e. one set from each heat and heat-treatment batch) is required.

b) Forging—from each heat, at ½T of the prolongation or of a separate test block (sample distance from side edges shall be per Code). Specimens shall be oriented transverse to the major working direction in accordance with ASME SA-182/SA-182M or ASME SA-336/SA-336M. A separate test block, if used, shall be made from the same heat, and shall receive substantially the same reduction and type of hot working as the production forgings that it represents, and shall be of the same nominal thickness as the production forgings. The separate test forging shall be heat treated in the same furnace charge and under the same conditions as the production forgings.

c) Pipe—from each heat and lot of pipe, at ½T. Specimens shall be oriented transverse to the major working direction in accordance with ASME SA-530/530M.

6.5.2 Tensile Test Requirements

Tensile testing of plates and forging materials shall conform with the applicable code(s) and the following additional requirements:

— Test coupons for N&T, Q&T, and N+Ac+T steels shall be heat treated to represent the maximum PWHT as defined in 5.1, in addition to any requirements of the applicable code. Coupons from annealed steels can be tested at minimum or maximum PWHT.

— Tensile values at room temperature shall meet the requirements of the applicable code(s).

6.5.3 Impact Testing Requirements

Charpy V-notch (CVN) impact testing shall be performed for all 1¼Cr-½Mo and 1Cr-½Mo steel material used for pressure-containing components. Impact testing is required for all material thickness and minimum design metal temperature (MDMT) combinations, and shall be performed on test coupons heat treated to represent the maximum PWHT as defined in 5.1, in addition to any requirements of the applicable code. One exception is that coupons from annealed steels can be tested at minimum or maximum PWHT.

CVN impact tests shall be performed at the pressure vessel MDMT or lower, and shall conform with the testing procedures and criteria given in the applicable code(s). Test coupons shall be from the ½T location.

If impact test results do not meet specification only one re-test shall be permitted for each product form (i.e. according to SA-20 clause 16.2 for plate). Where it is suspected that the test methods and or samples were done incorrectly, and if approved by the purchaser, initial results can be voided and retesting can be performed. Repeating the heat treatment is also permitted (according to SA-20 for plates).

7 Welding Consumable Requirements

7.1 Material Requirements

7.1.1 Deposited weld metal, from each lot or batch of welding electrodes, each heat of filler wires, and each combination of filler wire and flux, shall match the nominal chemical composition of the base metal to be welded.

7.1.2 The following chemical composition of deposited weld metal samples shall be controlled to improve resistance to temper embrittlement, reheat cracking, and low creep ductility cracking. The chemical composition restriction applies to the heat analysis.

X-bar = (10P + 5Sb + 4Sn + As) / 100 ≤ 15 ppm

Where P, Sb, Sn, and As are in ppm

C = 0.15 wt.% maximum

Cu = 0.20 wt.% maximum

Ni = 0.30 wt.% maximum

B = 0.001 wt % maximum

7.1.3 Consumables with a B2L suffix shall not be used.

7.1.4 Low hydrogen welding electrodes, having a maximum diffusible hydrogen of 8 mL per 100 g of weld metal per AWS A4.3, shall be used. Welding consumables shall be baked, stored, and used in accordance with manufacturer's instructions (for holding in electrode oven, length of time out of oven, use of electrically-heated quivers, etc.).

7.2 Mechanical Requirements

7.2.1 Tensile Properties

Tensile properties of deposited weld metal shall meet that of the base metal in accordance with 6.5.2.

7.2.2 Impact Properties

Whenever CVN impact testing is required for base materials per 6.5.3, each lot of electrodes, heat of filler wire, and combination of lot of flux and heat of wire, shall be screened by impact testing of weld deposit prior to the start of fabrication. Impact testing shall be done on test coupons heat treated to represent the minimum and maximum PWHT as defined in 5.1 and 5.2, in addition to any requirements of the applicable code.

CVN impact tests shall be performed at the pressure vessel MDMT or lower, and shall conform with the testing procedures and criteria required for the base metals.

8 Welding, Heat Treatment, and Production Testing

8.1 General Welding Requirements

8.1.1 Base metal surfaces prior to welding or applying weld overlay shall consist of clean metal prepared by machining, grinding, or blast cleaning.

8.1.2 Welded joints, including non-pressure attachments to the pressure vessel body, shall:

a) be full-penetration joints, except for external attachments greater than 19 mm (3/4 in.) thick when allowed by Code and approved by the purchaser. If approved, the gap between the attachment and shell or head shall be vented;

b) be located so that full ultrasonic examination of welds can be made after fabrication and after the equipment has been in service. In cases where this is not practical, the manufacturer shall propose alternate NDE methods to verify weld quality for purchaser approval;

c) be made sufficiently smooth to facilitate nondestructive examination (MT, PT, UT, or RT), as applicable.

8.1.3 Welding shall be completed prior to final PWHT. Welding of attachments to the internal corrosion-resistant weld overlay or cladding, or to external stainless steel weld buildups, or subsequent layers of weld overlay may occur after PWHT when permitted by purchaser. For these attachment welds, a PQR or mockup test shall be performed to verify that this does not produce a HAZ in the base metal, unless waived by purchaser. The location and dimensions of repairs shall be documented in accordance with Paragraph 11.

8.1.4 Weld repairs to base metal, weld joints, and weld overlay shall be performed using a repair welding procedure qualified in accordance with 8.2, and shall meet all the same requirements as the normal fabrication welds. Repairs to correct weld defects shall be made using the same procedure used for the original weld or another weld procedure if reviewed and approved by purchaser.

8.1.5 No pressure-retaining dissimilar metal welds of ferritic to austenitic alloys shall be allowed, especially at stress riser sites such as the nozzle-to-shell, nozzle-to-head, or nozzle-to-flange welds, except on a case-by-case basis, approved by purchaser. Dissimilar metal welds should be avoided at nozzle-to-pipe connections with constraint mismatch and also at thickness transitions. In some cases, purchasers have allowed dissimilar metal welds in the outlet nozzles (typically in pipe-to-pipe or pipe-to-elbow welds) that are located outside of the skirts but preferably at locations where access allows for NDE. Depending on the process temperature and line size, there are cases in which a dissimilar metal pipe-to-pipe weld is preferred over dissimilar metal flanges.

8.2 Welding Procedure Qualification

8.2.1 Welding procedures shall be qualified in accordance with ASME *Code* Section IX, with the following additional requirements.

8.2.2 Base metal for welding procedure qualification tests shall be made from the same ASME base metal specification (same P-number and Group number) and be similar in chemical composition as specified for the pressure vessel, but either plate or forging may be used. The welding consumable combination (electrodes, wire, and flux—whichever are applicable) shall be of the same type and similar in chemical composition as those to be used in production welding.

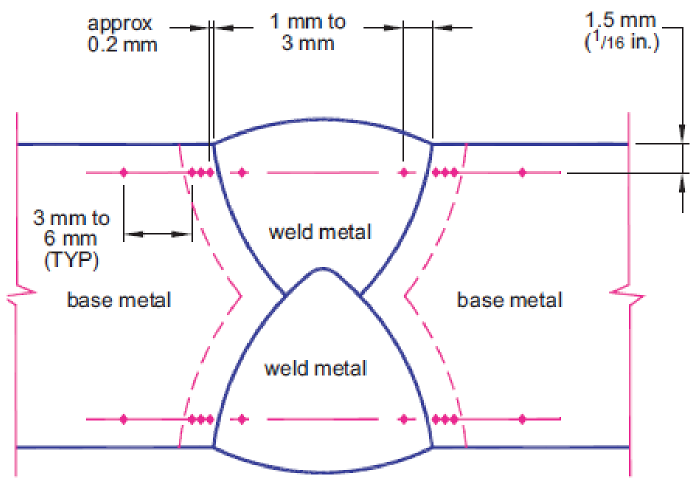
8.2.3 Vickers hardness traverses of weld joints shall be made on weld samples in the minimum PWHT condition. These hardness traverses shall be performed at locations similar to those shown in Figure 1. If previously qualified WPS/PQRs are proposed, purchaser shall decide if the hardness test locations are sufficient. The PQR hardness shall not exceed 248 HV10.

8.2.4 Tensile testing, transverse to the weld, shall be performed on a weld joint of the heat-treated test plate in the maximum PWHT condition, and shall meet the ambient temperature ultimate tensile strength specified for the base metal in 5.5.2. One exception is that coupons from annealed steels can be tested at minimum or maximum PWHT.

8.2.5 Charpy V-notch impact testing shall be performed on weld metal and HAZ of the heat-treated test plate in the minimum and maximum PWHT conditions. These impact tests shall be performed for each welding procedure and shall meet the impact test temperature and acceptance requirements in 5.5.3. Location of impact specimens shall also be as per ASME Sec VIII Div 2 Paragraph 3.11.8.

8.2.6 WPSs/PQRs shall conform with ASME Section IX and this standard, and shall be submitted to the purchaser for review and acceptance prior to fabrication.

NOTE When qualifying new procedures, recording of a welding log is optional, but it is beneficial in the analysis of welding issues that may arise. The welding log may include variables for each weld bead, such as current, voltage, welding travel speed, heat input, preheat, interpass temperature, filler metals heat/lot. Sketch of weld beads sequence or macro of cross section may also be prepared to qualitatively show weld geometry, weld bead dimensions and bead heights.



NOTE HV10 measurement for HAZ requires 0.04 in. (1 mm) minimum spacing between indentations. In some cases, it is acceptable that hardness measurement location is off the line in order to satisfy the minimum spacing requirements.

Figure 1—Location of Vickers Hardness Indentations

8.3 Preheat and Dehydrogenation Heat Treatment

8.3.1 Preheat During Fabrication Steps Other than Welding

8.3.1.1 Base metal shall be heated to a minimum of 300F (150C) prior to, and during, thermal cutting and gouging operations.

8.3.1.2 Preheating at a minimum of 300F (150C) is also required for rolling, cold forming and pressing operations. Rolling, forming and pressing operations without preheating may be considered based on review of material toughness in the as supplied condition, edge preparation, ambient temperature and the manufacturer's experience with similar or more severe degree of forming.

The request to waive preheat shall be submitted by the manufacturer to the purchaser before starting fabrication along with details on prior relevant experience.

8.3.2 Preheat During Welding

Base metals should be heated to a minimum of 400 °F (200 °C) during welding operations (except as modified for weld overlay; see 8.5.4). For butt welding and attachment welding, this preheat temperature shall be maintained through the entire plate thickness for a distance of at least four plate thickness on either side of the weld, but need not extend more than 4 in. (100 mm) in any direction from the edges to be welded.

During welding, the preheat temperature shall be maintained until PWHT or dehydrogenation heat treatment (DHT) is performed in accordance with 8.3.3.

Lower preheat values can be proposed and submitted to purchaser for approval along with data from past experience but shall not be less than 300 ºF (150 ºC) prior to welding.

NOTE The 400 °F (205 °C) preheat for welding is based on the ASME Sec. VIII, Div. 2 non-mandatory Table 6.7 (see Paragraph 6.4.1.2 of the Code). Lower preheat values have been used successfully in the past by numerous manufacturers. Proposed lower preheat values can be proposed to the purchaser for approval along with data on past experience.

8.3.3 Dehydrogenation Heat Treatment (DHT)

The DHT shall be performed at a minimum metal temperature of 570 °F (300 °C) for a minimum duration of one hour. In lieu of a DHT for tack welds, preheat shall be held for a minimum of 15 minutes after completion of tack weld. Additional situations (i.e. small attachments, tube-to-tube sheet welds, especially if made with the gas shield process) may use the same holding of preheat at the discretion of the purchaser.

8.4 Production Testing of Base Metal Welds

8.4.1 Chemical Composition of Production Welds

8.4.1.1 The chemical composition of weld deposits representing each different welding procedure shall be checked by either laboratory chemical analysis or by using a portable analyzer of equivalent accuracy and precision.

8.4.1.2 The chromium and molybdenum concentrations (as applicable) of weld deposits shall be within the ranges specified in ASME *Code* Section II, Part C, for the specified electrodes or wires.

8.4.2 Hardness of Weld Deposit

8.4.2.1 After final PWHT (see 8.6), hardness testing shall be performed for each pressure-retaining weld using a portable hardness tester. The hardness testing instrument (method, manufacturer and model) and procedure shall be submitted to purchaser for approval.

8.4.2.2 Reported test results at each hardness test location shall be the average of three impressions at each test location. The test locations shall include weld metal only. Hardness values of all three locations should be reported.

8.4.2.3 Average hardness results at each test location shall not exceed 225 HBW. Hardness testing methods that give results in other units can have the results converted to HBW.

8.4.2.4 Hardness tests shall be performed on each 10-foot (3-meter) length of weld, or fraction thereof. Where the side exposed to the process environment is weld overlaid, hardness testing of welds shall be performed on the nonoverlaid side.

NOTE HAZ hardness test measurements on vessel production weldments are typically an average of the HAZ, weld deposit, and base metal hardnesses, as the test indentation is generally larger than the HAZ width due to the limitations of the test method.

8.4.3 Weld Impact Tests

Production test plates are only required if required by Code.

8.5 Weld Overlay or Integral Clad

To provide a corrosion layer on the internal surface of the equipment, one or more of the following options can be used:

— austenitic SS weld overlay,

— nickel alloy weld overlay,

— austenitic SS integral cladding (refer to ASME SA-264),

— ferritic or martensitic SS integral cladding (refer to ASME SA-263), or

— nickel alloy integral cladding (refer to ASME SA-265)

The following special requirements shall apply.

8.5.1 Material Requirements

The ferrite content of austenitic stainless steel weld overlay shall be between 3 FN and 10 FN, as determined in accordance with WRC Bulletin 519, prior to any PWHT, but the ferrite content for Type 347 SS shall be between 5 and 10 FN (in accordance with API RP 582).

8.5.2 Disbonding Tests

Experience indicates that the risk of disbonding is low at the thicknesses and hydrogen charging levels at which 1¼Cr-½Mo and 1Cr-½Mo steels are used; hence, testing is not required by this standard. If testing is considered, API RP 934-A can be consulted as a resource, and the purchaser shall define testing requirements and acceptance criteria (refer to ASTM G146).

8.5.3 Weld Overlay Procedure Qualification

7.5.3.1 The selected weld overlay process and the number of layers shall be qualified in accordance with ASME Section IX.

7.5.3.2 Procedure qualification tests shall be made on base metal of the same ASME specification as specified for the pressure vessel, but either plate or forging may be used. Thickness of the test specimen shall not be less than one half the thickness of the equipment base metal or 1 in. (25 mm), whichever is less. The welding electrode, wire/strip, and flux used for the weld overlay procedure qualification shall be the same type to be used in production.

7.5.3.3 The qualification test plates shall be subjected to the maximum PWHT condition. One exception is that coupons from annealed steels can be tested at minimum or maximum PWHT.

7.5.3.4 Weld overlay chemical composition shall be determined for each overlay WPS at an agreed-upon depth (or distance from fusion line) and at the final surface [see ASME IX, Figure QW-462.5(a)]. Weld composition at the agreed-upon depth shall meet the filler-metal specification or other requirements as defined by the purchaser.

8.5.4 Preheat and Heat Treatments During Weld Overlay

For weld overlay with austenitic stainless steel or nickel-based alloy, the base metal shall be preheated to and maintained at or above 200 °F (94 °C) for the first layer of weld overlay. No preheating is required for the second and subsequent layers of weld overlay.

8.5.5 Production Testing of Weld Overlay

8.5.5.1 Chemical Composition of Weld Overlay

The chemical composition of weld overlays shall be checked by laboratory chemical analysis, or by using a portable positive material identification (PMI) analyzer, of samples taken at minimum specified thickness. This composition shall meet the specified composition of the overlay material (C, Cr, Ni, Mo, and Nb, as applicable). At least one analysis shall be required for each welding process for nozzles and for each shell ring and head. This sampling/testing will result in repairs being needed on the overlay.

8.5.5.2 Ferrite Content of Austenitic Stainless Weld Overlay

7.5.5.2.1 A magnetic instrument calibrated to AWS A4.2M/ISO 8249MOD shall be used to check the ferrite content of the production weld overlay prior to any PWHT.

7.5.5.2.2 Calibration for the steel backing material in accordance with AWS A4.2M/ISO 8249MODmay be used.

7.5.5.2.3 A minimum of six ferrite readings shall be taken on the surface at each of the following locations:

a) at least 10 locations, selected at random, shall be checked for each shell ring and head;

b) two locations for each nozzle overlay (one at each end); and

c) one location on cladding or overlay restoration of each category A, B, and D weld joint, if applicable.

7.5.5.2.4 The value of all ferrite readings at each location shall meet the requirements of 8.5.1.

8.6 Final Post-weld Heat Treatment

7.6.1 PWHT shall conform with the minimum requirements of the applicable code, except that 1¼Cr-½Mo and 1Cr-½Mo weld joints shall be PWHT at 1225 ˚F (663 ˚C) to 1275 ˚F (690 ˚C). The use of PWHT temperatures higher than the Code minimum requirements helps to prevent reheat and LCD cracking. PWHT at 1275 ˚F (690 ˚C) to 1325 ˚F (720 ˚C) can be considered when the primary failure mechanism expected for the service is creep. However, the use of PWHT 1275 ˚F (690 ˚C) to 1325 ˚F (720 ˚C) temperatures may result in lower steel tensile strength and impact toughness (the testing requirements in this Standard and within the Code will confirm whether the base materials and weld deposit have met the required mechanical properties). Designers and fabricators are cautioned to consider PWHT temperatures and the possible difficulties in meeting material properties when they are selecting between Class 1 and Class 2 materials (also note that all designs, with either Class 1 or 2 materials, shall be based on Class 1 design allowable stresses per Paragraph 4.3.e).

7.6.2 The fabricated pressure vessel shall be PWHT as a whole in an enclosed furnace whenever possible. When pressure vessel size does not allow a furnace PWHT as a whole, PWHT may be performed sectionally according to the ASME Section VIII, Division 2, Paragraph 6.4.3. Local PWHT shall follow the required heating, and gradient control band widths and thermocouple placements of WRC Bulletin 452 unless otherwise approved by purchaser.

7.6.3 The PWHT temperature shall be strictly controlled. The temperature shall be measured using thermocouples attached to the inside and outside of the pressure vessel including portions of the pressure vessel outside of the furnace. Those sections of the pressure vessel outside the furnace shall be insulated such that the temperature gradient does not affect the mechanical integrity (e.g., physical condition, mechanical properties) of the pressure vessel.

7.6.4 Continuous time-temperature records of all PWHT operations shall be documented. The records shall meet ASME Section VIII, Division 2, Paragraph 6.4.4.

9 Nondestructive Examination (NDE)

9.1 General

8.1.1 NDE personnel shall be qualified in accordance with ASNT Recommended Practice SNT-TC-1A or ASNT CP-189 or other agencies with purchaser approval. For ASME Section VIII, Division 2, pressure vessels, NDE personnel shall be qualified per Paragraph 7.3 of Section VIII, Division 2. Personnel interpreting and reporting results should also be qualified to the same practice.,

8.1.2 Where references to ASME Section VIII, Division 2 inspection requirements are listed, they shall be applied to ASME Section VIII, Division 1 or Division 2, pressure vessels and heat exchangers.

9.2 NDE Prior to Fabrication

9.2.1 Ultrasonic Testing (UT)

8.2.1.1 Bare and clad base metal plates shall be ultrasonically examined with 100% scanning in accordance with ASME Section V and SA-578/SA-578M, Level C, Supplementary Requirement S1, before forming.

8.2.1.2 Forgings for shell rings, nozzles, and manways shall be ultrasonically examined with 100% scanning in accordance with Paragraph 3.3.4 of ASME Section VIII, Division 2.

9.2.2 Magnetic Particle Testing (MT) or Dye Penetrant Testing (PT)

8.2.2.1 Entire surfaces of forgings, including welding surfaces, shall be examined by MT in accordance with Paragraph 7.5.6 or by PT in accordance with Paragraph 7.5.7 of ASME Section VIII, Division 2. Examination should be after finish machining, but before welding.

8.2.2.2 For formed plates to be welded for shell rings and heads, welding edges shall be examined by MT or PT.

8.2.2.3 Where nozzle welds intersect circumferential and longitudinal welds (if approved per Paragraphs 4.2.d and 8.1.2.b), weld preparation surfaces (beveled edges) shall receive PT or MT inspection.

9.3 NDE During Fabrication

8.3.1 MT shall be performed after completion of welds, including pressure-retaining base metal welds, weld build-up deposits, and attachment welds. MT shall also be performed after any gouging or grinding operation, including back gouging of root passes. MT shall be in accordance with Paragraph 7.5.6 of ASME Section VIII, Division 2.

8.3.2 Temporary attachments should be minimized. Areas where temporary attachments have been removed shall be examined by MT or PT in accordance with Paragraph 7.5.6 or Paragraph 7.5.7 of ASME Section VIII, Division 2, as applicable.

9.4 NDE After Fabrication and Prior to Final PWHT

9.4.1 Base Metal Welds

8.4.1.1 Pressure-retaining butt welds and vessel-to-support skirt welds shall be fully examined by RT in accordance with Paragraph 7.5.3 of ASME Section VIII, Division 2, or UW-51 of ASME Section VIII, Division 1, before final PWHT, as applicable.

8.4.1.2 UT may be applicable in lieu of RT when the UT procedure fulfills the requirements of Paragraph 7.5.5 of ASME Section VIII, Division 2.

8.4.1.3 When RT is not practical for nozzle and skirt attachment welds, UT may be applied in lieu of RT.

9.4.2 Weld Overlay

Spot UT—four strips approximately 3.2 in. (80 mm) wide along the full length of the pressure vessel shell and one (1) strip approximately 3.2 in. (80 mm) wide across each head—shall be performed on weld overlay. UT shall be in accordance with ASME SA-578, Level C.

9.5 NDE After Final PWHT

9.5.1 Base Metal Welds

8.5.1.1 Pressure-retaining base metal welds, including nozzles, shall be fully examined by UT in accordance with Paragraph 7.5.4 of ASME Section VIII, Division 2.

8.5.1.2 Accessible welds shall be examined by MT. An AC yoke method shall be used to prevent arc strikes. PT may be used instead of MT whenever MT is impractical.

8.5.1.3 Internal weld surfaces (groove and fillet) on unclad or non-overlayed pressure-containing parts in services with >50 psia (3.45 bara) hydrogen partial pressure shall receive 100% MT inspection.

9.5.2 Weld Overlay

Entire surfaces of stainless steel and nickel-based weld overlay, and attachments to the overlay, shall be examined by PT in accordance with Paragraph 7.5.7 of ASME Section VIII, Division 2.

9.6 Positive Material Identification

PMI shall be performed in accordance with the purchaser's PMI specification.

10 Hydrostatic Testing

Pressure-retaining welded joints shall be free from any scale and other foreign matter before testing. All dirt, scale, sand, and other foreign material shall be removed from the pressure vessel.

Test water shall not contain more than 50 ppm chlorides for stainless steel lined pressure vessel sunless otherwise approved by purchaser.

During the hydrostatic testing, the pressure vessel metal temperature shall be at least 30 °F (17 °C) above the MDMT, or 60 °F (15 °C), whichever is warmer.

The pressure vessel shall be drained and thoroughly dried immediately after testing.

11 Preparation for Shipping

Immediately after completion of final examination of the pressure vessel, the interior of the pressure vessel shall be cleaned and dried. Heat drying or other evaporative means shall not be used due to possible chloride contamination of stainless overlay or clad pressure vessels.

All openings shall be sealed with a steel cover and gasket, and the pressure vessel shall be filled with a minimum 5 psig (34.5 kPa) of dry nitrogen gas or use a desiccant system. If nitrogen is used, the nitrogen pressure shall be maintained during transportation, erection, and pre-commissioning. A non-removable tag shall be attached, with a warning stating that the pressure vessel is filled with nitrogen.

For preservation during transportation, exposed machined surfaces, such as flange faces, shall be protected by applying suitable grease, rust preventative compound, or coating.

12 Documentation

The following documentation should be available for Purchaser review at the following indicated fabrication stages. Final documentation shall be submitted to the purchaser at the completion of the project:

11.1 For review prior to materials procurement

a) Materials Purchase Specification

b) Heat treatment calculations (i.e., basis for determining the minimum and maximum PWHT)

11.2 For review and approval prior to fabrication

a) MTRs showing chemical composition and mechanical test result, and heat/batch/lot number. This applies to materials for all pressure containing parts, attachment materials welded to pressure containing parts and weld filler metals. This shall include:

- J-factors, (if applicable)
- X-bars (if applicable)
- impact test results (before and after step cooling if applicable)
- Step cooling results (if applicable)
- hot tensile test results (if applicable)

b) welding procedure specifications (WPS) with applicable procedure qualification records (PQR) including overlay disbonding testing.

c) DHT procedure (if applicable)

d) ISR procedure (if applicable)

e) Furnace PWHT procedure and local PWHT procedure (if applicable)

f) NDE (Including scan plans), PMI and hardness test procedures

g) Inspection and test plan that:

- Is organized by fabrication and testing sequence
- Includes material procurement, inspection, and testing
- Includes any loose pressure boundary components (e.g. reactor dump caps, top reactor manway inlet spools etc.)
- Includes internals installation at Manufacturer's facility, if applicable
- Includes the location where each activity is taking place if other than the Manufacturer's shop

11.3 For review and approval during fabrication

a) PMI results

b) hardness test results

c) NDE results

d) Chemistry and ferrite examination reports for weld overlay and back cladding

e) heat treatment charts, showing hold times and temperatures for PWHT, ISR, and DHT

f) production test plate results

g) Material traceability record connecting each component and weld to an MTR

h) Repair procedure for each case of a major repair

i) Weld and base metal repair map with sufficient detail to locate the repair, show the size of the grind out and indicate whether the repair was completed from the inside or outside surface

Bibliography

[1] API 579-1/ASME FFS-1, *Fitness-For-Service*

[2] API RP 934-A, *Materials and Fabrication of 2¼Cr-1Mo, 2¼Cr-1Mo-¼V, 3Cr-1Mo, and 3Cr-1Mo-¼V Steel Heavy Wall Pressure Vessels for High-Temperature, High-Pressure Hydrogen Service*

[3] API Standard 934-C, *Materials and Fabrication of 1¼Cr-½Mo Steel Heavy Wall Pressure Vessels for High-pressure Hydrogen Service Operating at or Below 825 °F (441 °C)*

[4] API TR 934-D, *Materials and Fabrication Issues of 1¼Cr-½Mo and 1Cr-½Mo Steel Pressure Vessels*

[5] API TR 934-G, *Design, Fabrication, Operational Effects, Inspection, Assessment, and Repair of Coke Drums and Peripheral Components in Delayed Coking Units*

[6] API Publication 938-A, *An Experimental Study of Causes and Repair of Cracking of 1¼Cr-½Mo Steel Equipment*

[7] ASME[6] *Boiler and Pressure Vessel Code, Section II-Materials, Part A—Ferrous Material Specifications,* and *Part D—Properties*

[6] ASME International, 3 Park Avenue, New York, New York 10016, www.asme.org.