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

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Introduction

This recommended practice (RP) applies to new heavy-wall pressure vessels in petroleum refining, petrochemical, and chemical facilities in which hydrogen or hydrogen-containing fluids are processed at elevated temperature and pressure. It is based on decades of industry operating experience and the results of experimentation and testing conducted by independent manufacturers and purchasers of heavy-wall pressure vessels for this service.

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

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

1 Scope

This RP covers materials and fabrication requirements for new 2¹/4Cr and 3Cr steel heavy-wall pressure vessels for high-temperature, high-pressure hydrogen service. For this RP, "heavy-wall" is defined as a shell thickness of 4 in. (100 mm) or greater, and "high-temperature" is considered to be operating temperatures of 650 °F (345 °C) and up to a maximum design temperature where ASME Section II-D:2023 Table 5A defines the threshold time-dependent properties for the given material classification and in compliance with API 941. This RP applies to pressure vessels that are designed, fabricated, certified, and documented in accordance with ASME Section VIII, Division 2, Class 2, including Paragraph 3.4, Supplemental Requirements for Cr-Mo Steels, and ASME Code Case 2151, as applicable.

Although outside of its scope, this RP can be used as a resource for pressure vessels with wall thicknesses below 4 in. (100 mm) or operating at temperatures of less than 650 °F (345 °C), or with maximum design temperature limits above the thresholds given in the paragraph above with changes defined by the purchaser. This document may also be used as a resource when planning to modify an existing heavy-wall pressure vessel.

ASME Section VIII, Division 3 is typically used for much higher-pressure applications (beyond the hydroprocessing range), and a specific ASME Code Case developed for these alloys is also available under Division 3. Division 3 has much stricter design rules (e.g., fatigue and fracture mechanics analyses are required) and material testing requirements, and application of these rules is outside the scope of this document.

Materials covered by this RP are conventional Cr-Mo steels including standard 2¹/4Cr-1Mo and 3Cr-1Mo steels as well as advanced Cr-Mo steels, which include 2¹/4Cr-1Mo-¹/4V, 3Cr-1Mo-¹/4V-Ti-B, and 3Cr-1Mo-¹/4V-Nb-Ca steels. This document may be used as a reference document for the fabrication of pressure vessels made of enhanced steels (i.e., steels with mechanical properties increased by special heat treatments such as ASME SA-542, Grade B, Class 4) at the purchaser's discretion. However, no attempt has been made to cover specific requirements for the enhanced steels, and they may be different than the requirements for vanadium grade steels.

The interior surfaces of these heavy-wall pressure vessels may have an austenitic stainless steel weld overlay lining to provide additional corrosion resistance. A lining of stainless steel cladding using a roll-bonded or explosion-bonded layer on Cr-Mo base metal may be acceptable, but this is outside the scope of this document except as mentioned in 7.5.2.2. Roll-bonded cladding is generally not available with the base metal thicknesses covered by this document. However, if users extend the recommendation of this document to thinner material, roll-bonded cladding may be used. Multilayer vessels are also outside the scope of this document.

Heat exchanger shells and channels that meet the conditions listed above are within the scope of this RP. They are included in the term "pressure vessel" for the purposes of this RP.

This is the fourth edition of RP 934-A. The legacy first edition was API RP 934, *Materials and Fabrication Requirements for 2¹/4Cr-1Mo & 3Cr-1Mo Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service*, published December 2000. The second edition was issued in May 2008, and it was the first version referred to as "934-A." RP 934-A, Second Edition, later incorporated Annex A and then Annex B, which were issued in February 2010 and March 2012 as Addendum 1 and Addendum 2, respectively. The third edition was issued in January 2019 with an Errata in September 2021.

2 Normative References

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any addenda) applies.

API Recommended Practice 582:2023, *Welding Guidelines for the Chemical, Oil, and Gas Industries*

ASME *Boiler and Pressure Vessel Code*,[1] Section II-*Materials*; Part A—*Ferrous Material Specifications*; Part C—*Specifications for Welding Rods, Electrodes and Filler Metals*; Part D—*Properties*

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 2—Alternative Rules*

ASME *Boiler and Pressure Vessel Code*, Section VIII—*Rules for Construction of Pressure Vessels, Division 3—Alternative Rules for Construction of High Pressure Vessels*

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

ASME Code Case 2151-1, *3 Chromium-1 Molybdenum-$^{1}/_{4}$ Vanadium-Columbium-Calcium Alloy Steel Plates and Forgings*

ASME Code Case 2718, *Alternative Minimum Test Temperature for Hydrostatic Testing*

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

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

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

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

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

ASME SA-387, *Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-molybdenum*

ASME SA-508, *Standard Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels*

ASME SA-541, *Standard Specification for Quenched and Tempered Carbon and Alloy Steel Forgings for Pressure Vessel Components*

ASME SA-542, *Standard Specification for Pressure Vessel Plates, Alloy Steel, Quenched-and-Tempered, Chromium- molybdenum, and Chromium-Molybdenum-Vanadium*

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

ASME SA-832, *Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum-Vanadium*

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1 American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, New York 10016-5990, www.asme.org

ASNT RP SNT-TC-1A,[2] *Personnel Qualification and Certification in Nondestructive Testing*

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

AWS A4.2M/*ISO 8249 MOD,* [4] *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 Bulletin 452,[5] *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 Abbreviations

3.1 Terms and Definitions

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

3.1.1
advanced Cr-Mo steel
A Cr-Mo steel grade (typically quenched and tempered) that has had its strength level and other properties improved by the addition of carbide-forming elements (other than Cr and Mo), e.g., vanadium, titanium, and possibly other alloying additions per the applicable material specification. Table 1 shows the specific grades within the scope of this document that are included in this definition. There are other advanced Cr-Mo grades that have their strength level enhanced by thermal processing but they are not included in the scope of this document.

3.1.2
ASME Code
ASME *Boiler and Pressure Vessel Code*, Section VIII, Division 2, including applicable addenda and ASME Code Cases.

3.1.3
cold forming
The mechanical forming or rolling of steel vessel components at ambient temperature up to 900 °F (480 °C).

3.1.4
conventional Cr-Mo steel
A Cr-Mo steel (typically quenched and tempered) that has not had its strength level enhanced by the addition of carbide-forming elements (other than Cr and Mo) e.g., vanadium, titanium, or advanced thermal processing. Table 1 shows the specific grades within the scope of this document that are included in this definition.

3.1.5
final PWHT
The last postweld heat treatment after fabrication of the pressure vessel and prior to placing the pressure vessel in service.

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[2] American Society for Nondestructive Testing, PO Box 28518, 1711 Arlingate Lane, Columbus, Ohio 43228-0518, www.asnt.org.

[3] ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, Pennsylvania 19428-2959, www.astm.org.

[4] American Welding Society (AWS), 8669 NW 36th St., #130, Miami, Florida 33166-6672, www.aws.org.

[5] Welding Research Council (WRC), PO Box 201547, Shaker Heights, Ohio 44122, www.forengineers.org.

3.1.6
hot forming
The mechanical forming of steel vessel components immediately after soaking within the austenitizing temperature range (above the upper critical temperature [Ac3]).

3.1.7
Larson-Miller parameter
Parametric relationship between the 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. 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:

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

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

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

where

T is the temperature in kelvins.

t is the time in hours.

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 may have different constants. LMP is also referred to as the “tempering parameter.”

3.1.8
manufacturer
The firm or organization receiving the purchase order to manufacture the pressure vessel or materials.

3.1.9
maximum PWHT
Specified heat treatment (aggregate temperature and time) of test coupons used to simulate the maximum heat treatment exposures of the vessel alloy or vessel-portion alloy. 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 (480 °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. DHTs 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 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.

3.1.10
minimum allowable temperature (MAT)
The lowest permissible metal temperature for a pressurized component for a given material, stress state (i.e., pressure and other applied loadings), and flaw size based on its resistance to brittle fracture. It may be a single

temperature or an envelope of allowable operating temperatures as a function of pressure. The MAT is derived from mechanical design information, materials specifications, possible embrittlement, and materials data.

3.1.11
minimum design metal temperature (MDMT)
The lowest temperature at which a significant stress can be applied to a pressure vessel before in-service embrittlement.

3.1.12
minimum PWHT
Specified heat treatment (aggregate temperature and time) of test coupons used to simulate the minimum heat treatment exposures of the vessel alloy. 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 (480 °C), e.g., warm forming, 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 effects 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 heating steps that have temperatures outside the PWHT range, the Larson-Miller parameter formula (or Hollomon-Jaffe parameter) may be used (results to be agreed upon by purchaser and manufacturer).

3.1.13
minimum pressurization temperature (MPT)
The lowest temperature at which the pressure vessel can be pressurized to its MAWP or maximum operating pressure during starting up, shutting down and hydrotesting, without the possible risk of brittle fracture of the base metal.

3.1.14
narrow groove welding
A multi-pass weld in which the bevel has a very small groove angle that yields a weld with a high ratio of depth to width.

3.1.15
nonprescreened welds
SAW weld deposits made with heats of flux/wire that have had past cases of RHC or have unknown performance as far as RHC susceptibility (i.e., they have not been tested per Annex B). They shall be assigned by purchaser.

3.1.16
prescreened welds
SAW weld deposits made with heats of flux/wire with no past cases of RHC and test results meeting Annex B (these results indicate that the heat has a negligible susceptibility to RHC) unless test is waived by purchaser as per 6.1.4. They shall be assigned by purchaser.

3.1.17
purchaser
The operator-user that has entered into the pressure vessel purchase order with the manufacturer or their designated representative.

3.1.18
step cooling heat treatment
Specified heat treatment used to simulate and accelerate embrittlement of test specimens for the purpose of evaluating the potential for temper embrittlement of low-alloy steels in high-temperature service.

3.1.19
temper embrittlement
The reduction in toughness due to segregation of impurity elements (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 approximately 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 subsequent hydrotests, start-ups, and shutdowns.

3.1.20
warm forming
The mechanical forming of steel vessel components immediately after soaking within a temperature range of 900 °F (480 °C) to the upper end of the PWHT temperature range.

3.2 Abbreviations

For the purposes of this RP, the following abbreviations apply:

DAC	distance-amplitude correction
DHT	dehydrogenation heat treatment
El %	elongation (%)
FN	Ferrite Number
HAZ	heat-affected zone
HBW	Brinell hardness with tungsten carbide indenter
HV	Vickers hardness
ISR	intermediate stress relief
LMP	Larson-Miller parameter
MDMT	minimum design metal temperature
MT	magnetic particle testing
MTR	material test report
NDE	nondestructive examination
PMI	positive material identification
PQR	procedure qualification record
PT	penetrant testing
PWHT	postweld heat treatment
RHC	reheat cracking
RoA	reduction of area (%)
RT	radiographic testing
SAW	submerged arc welding
SDH	side-drilled holes
SS	stainless steel
TOFD	time-of-flight diffraction (a UT technique)
UT	ultrasonic testing
UTS	ultimate tensile strength (MPa)

WPS	welding procedure specification
YS	yield strength (MPa)

4 Design

4.1 Design and manufacture shall conform to ASME *Boiler and Pressure Vessel Code*, Section VIII, Division 2 and its applicable ASME Code Cases. The latest edition effective through the date of the purchase agreement shall be used.

4.2 The manufacturer's design report (which includes ASME Code strength calculations, and when applicable, local stress analysis for extra loads and other special design analyses) should show compliance with the purchaser's design specification and other technical documents.

4.3 This recommended practice is not intended to cover design issues other than those listed as follows.

a) The minimum required thickness shall not take any credit for the corrosion allowance, weld overlay, or cladding thickness.

b) Weld seam layouts shall provide that welds are accessible for nondestructive examination (NDE), such as radiographic testing (RT), ultrasonic testing (UT), magnetic particle testing (MT), and penetrant testing (PT), both during fabrication and in service. Use of external attachments that cover weld seams should be avoided and shall require purchaser's approval.

c) Attachment welds and weld pads shall not coincide with circumferential or longitudinal welds without purchaser's approval.

d) Nozzle necks shall have transition to the pressure vessel body as shown in ASME Section VIII, Division 2:2023, Table 4.2.13. With purchaser's approval, nozzles with nominal size 4 in. (100 mm) and less may be fabricated in accordance with ASME Section VIII, Division 2:2023, Table 4.2.10, Detail 3 through Detail 6, with integral reinforcement.

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

4.4 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 5.1.2 and 7.1.4.

5 Base Metal Requirements

5.1 Material Specifications

5.1.1 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.

5.1.2 Unless approved in advance by purchaser, different base metals shall not be mixed in the same pressure vessel (e.g., standard 2¹/4Cr-1Mo nozzles should not be used with 2¹/4Cr-1Mo-¹/4V shell plates). Some designs use austenitic stainless steels as part of the outlet nozzle that extends to the outside of the skirt. This results in the nozzle having a dissimilar metal weld. These cases require purchaser approval (also see 7.1.4).

5.1.3 Attachments (such as lugs, clips, etc.) welded directly to the base metal pressure boundary shall be of the same nominal material chemical composition (without the added limits given in 5.3) as the pressure boundary material. It is acceptable for nonpressure parts (such as skirts, lugs, clips, etc.) made of 2¹/4Cr-1Mo to be used on 2¹/4Cr-1Mo-¹/4V pressure parts. For advanced Cr-Mo steels, weld consumables used for internal weld buildup shall be 2¹/4Cr-1Mo-¹/4V, unless approved otherwise by purchaser.

5.2 Steel-making Practice

In addition to the steelmaking practices outlined in the applicable material specifications, the steels shall be vacuum degassed. Plate, piping, and forging materials shall be made to fine grain practice in accordance with the application material specification (such as ASME SA-20 for plates).

Table 1—Base Metal Specifications

Steel		Conventional		Advanced [c d]		
Product Form	**ASME Spec**	**Standard $2^1/4$Cr-1Mo**	**Standard 3Cr-1Mo**	**$2^1/4$Cr-1Mo-$^1/4$V [a]**	**3Cr-1Mo-$^1/4$V-Ti-B [a]**	**3Cr-1Mo-$^1/4$V-Cb-Ca [b]**
Plate	SA-387	Grade 22, Class 2	Grade 21, Class 2	—	—	—
	SA-542 [c]	—	—	Type D, Class 4a	Type C, Class 4a	Type E, Class 4a
	SA-832	—	—	Grade 22V	—	—
Forging	SA-182	Grade F22, Class 3	Grade F21	Grade F22V	Grade F3V	Grade F3VCb
	SA-336	Grade F22, Class 3	Grade F21, Class 3	Grade F22V	Grade F3V	Grade F3VCb
	SA-508 [d]	—	—	—	Grade 3V	Grade 3VCb
	SA-541 [d]	—	—	Grade 22V	Grade 3V	Grade 3VCb
Pipe	SA-335	Grade P22	Grade P21	—	—	—
Pipe (forged or bored)	SA-369	Grade FP22	Grade FP21	—	—	—

[a] Covered by ASME Code, Section VIII, Division 2, Paragraphs 3.3 and 3.4.

[b] Covered in ASME Code Case 2151-1.

[c] ASME SA-542 Type B, Cl. 4 is also permitted by ASME Section VIII, Division 2, Paragraphs 3.3 and 3.4. However, this material has its mechanical properties enhanced by heat treatment, and it is not included in this Recommended Practice.

[d] ASME SA-508, Gr. 22, Cl 3 and ASME SA-541, Gr. 22, Cl. 3 are also permitted by ASME Section VIII, Division 2, Paragraphs 3.3 and 3.4. However, these materials have their mechanical properties enhanced by heat treatment, and they are not included in this Recommended Practice.

5.3 Chemical Composition Limits

To minimize susceptibility to temper embrittlement, the chemical composition of base metals shall be limited as follows (these chemical composition limits apply to each heat analysis):

$$\text{J-factor} = (\text{Si} + \text{Mn}) \times (\text{P} + \text{Sn}) \times 10{,}000 \leq 100 \text{ (with Si, Mn, P, and Sn in wt \%) Cu} = 0.20 \text{ wt \% max.} \quad (4)$$

$$\text{Ni} = 0.30 \text{ wt \% max. for conventional Cr-Mo steels and } 0.25 \text{ wt \% max. for advanced Cr-Mo steels.} \quad (5)$$

Intentional additions of unspecified elements (especially if done to meet specified mechanical properties) should be submitted for purchaser approval. If approved, these elements shall be shown on the material test report (MTR).

5.4 Heat Treatment

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

a) normalized and tempered (N&T): slow cooled in air from the austenitizing temperature range and then tempered in order to achieve grain refinement and improved homogenization;

b) quench and tempered (Q&T): accelerated cooling from the austenitizing temperature range by quenching (liquid or air-blasting) and then tempered (Q&T is preferred for wall thickness outlined in the scope of this document).

The appropriate heat treatment shall be chosen to meet the required mechanical properties. Tempering temperature may be below, at, or above the postweld heat treatment (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 3.1.12 and 3.1.9). The cumulative effects of the various heat treatments can be evaluated by using the equivalent LMP approach and confirmed with mechanical property testing in 5.5.2, 5.5.3, and 6.2.

5.5 Mechanical Properties

5.5.1 Test Specimens

5.5.1.1 Location of Test Specimens

Test specimens for establishing the tensile and impact properties shall be removed from the following locations (where *T* is the maximum thickness of the material at the time of heat treatment).

a) Plate—from each plate, at the $^{1}/_{2}T$ location and at the $^{1}/_{4}T$ location in accordance with ASME SA-20 if required by ASME Code ($^{1}/_{2}T$ is acceptable per ASME Code for ASME SA-387 and ASME SA-542 materials by specifying Supplementary Requirement S53). Specimens shall be oriented transverse to the rolling direction, in accordance with ASME SA-20. Distance from plate edges shall be 1*T*.

b) Forging—from each heat (except as allowed by 5.5.1.1.c), $^{1}/_{2}T$ of the prolongation or of a separate test block (In both cases, the sample location from side edges shall be per ASME Code). Specimen shall be oriented transverse to the major working direction. A separate test block, if used, shall meet ASME Code and 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 forgings shall be heat treated in the same furnace charge and under the same conditions as the production forgings.

c) For thick and complex forgings that are contour shaped or machined to essentially the finished product configuration prior to heat treatment, specimens shall be removed in accordance with ASME Section VIII, Division 2, Paragraph 3.10.4.2(c).

d) Pipe—from each heat and lot of pipe, at $^{1}/_{2}T$. Specimens shall be oriented transverse to the major working direction in accordance with ASME SA-530.

e) If the purchaser specifies hot tensile and base metal step cooling tests (they are not required by this RP or by ASME Code), test specimen locations shall be as defined above.

5.5.1.2 Heat Treatment of Test Specimens

a) Test specimens shall be heat treated to simulate minimum and maximum heat treatment as specified in Table 2.

b) A simulated heat treatment is not necessary for the hot forming operation if a subsequent full austenitizing heat treatment after forming is performed (such as in Q&T or N&T supplied materials). If any other heat treatment is used after hot forming, test specimens shall be subjected to a simulated hot forming heat treatment prior to the heat treatment specified in Table 2

NOTE Where warm forming is used, simulation heat treatment on test coupons is required by the definition of maximum or minimum PWHT (see 3.1.9 and 3.1.12).

c) Use of shorter or longer than the recommended maximum PWHT time shall be agreed between the purchaser, the manufacturer, and the base material supplier. Shorter times can be considered to ensure material properties are not degraded. ASME Code requirements shall be met.

d) Materials qualified to longer soaking time than maximum will be considered to meet the maximum PWHT requirements.

e) Materials qualified for shorter soaking time than minimum will be considered to meet the minimum PWHT requirements.

Table 2—Heat Treatment of Test Specimens [a]

Steel	Base Metal and PQR Tensile Tests	Base Metal, Weld Metal, and PQR Impact Tests	Step Cooling Tests (on Weld Metal)
Conventional	Minimum and maximum PWHT	Minimum and maximum PWHT	Minimum PWHT
Advanced	Minimum and maximum PWHT [a]	Minimum and maximum PWHT [b]	Minimum PWHT

[a] No testing of materials as supplied to the manufacturers is needed, as testing materials with these heat treatments is more meaningful and is acceptable per the ASME Code.

[b] These heat treatments shall meet or exceed the requirements of ASME Section VIII, Division 2, Paragraph 3.4 and ASME Code Case 2151-3.

5.5.2 Tensile Properties

5.5.2.1 Ambient temperature tensile properties after the heat treatments specified in 5.5.1.2 shall comply with the applicable code(s) and the following additional requirements. This RP does not require testing of materials in the as-supplied condition (as supplied to the vessel manufacturer). It can be detrimental to ask for testing on the materials in the as-supplied condition and to require the special properties listed below, as this will change the mill heat treatment.

a) Tensile strength shall not exceed the following limits:

— conventional Cr-Mo steels: 100 ksi (690 N/mm^2);

— advanced Cr-Mo steels: 110 ksi (760 N/mm^2).

b) Yield strength shall not exceed the following limits:

— conventional Cr-Mo steels: 90 ksi (620 N/mm^2);

— advanced Cr-Mo steels: 90 ksi (620 N/mm^2).

5.5.2.2 Elevated temperature tensile tests are not required by this RP or by the ASME Code. However, if elevated temperature tensile tests are specified by the purchaser, the tests should be performed at the equipment design temperature, and test specimens should be in the maximum PWHT condition. If tests are required, the minimum acceptance values are 85 % of values for the tensile strength listed in ASME *Boiler and Pressure Vessel Code*, Section II-D: 2023, Table U for the test temperature unless otherwise specified by the purchaser.

5.5.3 Impact Properties

5.5.3.1 General

Average impact energy values at –20 °F (–29 °C) of three Charpy V-notch test specimens heat treated in accordance with 5.5.1.2 shall not be less than 40 ft-lb (55 J), with no single value below 35 ft-lb (48 J). If the minimum design metal temperature (MDMT) is lower than –20 °F (–29 °C), testing is required at the MDMT. If testing performed at a lower temperature gives results which meet or exceed 40/35 ft-lb (55/48 J) criteria, then retesting at –20 °F (–29 °C) is not required. The percent ductile fracture and lateral expansion (in mils or mm) should also be reported. If impact test results do not meet specification only one retest shall be permitted for each product form (i.e., according to ASME SA-20 clause 16.2 for plate). Where it is suspected that the test methods 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 ASME SA-20 for plates).

5.5.3.2 Step Cooling Tests

Step cooling tests of the base metals are not required (only weld materials are required to be tested, as stated in 6.2.4). If the purchaser imposes step cooling tests of base metals, the test procedure and acceptance criteria should be in accordance with 6.2.4. The purchaser may opt to require that step cooling tests be performed only on the heat with the highest J-factor.

If the purchaser requires step cooling tests of base metals, the purchaser may substitute (as an alternative) impact testing at –80 °F (–62 °C). The average impact energy values at −80 °F (−62 °C) shall not be less than 40 ft-lb (55 J) with no single value below 35 ft-lb (48 J). The percent ductile fracture and lateral expansion (in mils or mm) should also be reported. When this testing is invoked and the test data is satisfactory, the results may be considered to take the place of the testing described in 5.5.3.1.

All test results before step cooling for each test temperature at −20 F (−29 C) and warmer shall meet 40ft-lb (55 J) average with no single value below 35ft-lb (48 J).

6 Welding Consumable Requirements

6.1 Material Requirements

6.1.1 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.

6.1.2 The chemical composition of deposited weld metal samples shall meet the following limits to improve resistance to temper embrittlement. These limits apply to the heat analysis:

$$\text{X-bar} = (10P + 5Sb + 4Sn + As)/100 \leq 15 \text{ (P, Sb, Sn, and As are in ppm)} \quad (6)$$

$$Cu = 0.20 \text{ wt \% max.} \quad (7)$$

$$Ni = 0.30 \text{ wt \% max.} \quad (8)$$

6.1.3 Low-hydrogen welding consumables, including fluxes, having a maximum diffusible hydrogen of 8 ml/100 g of weld metal per AWS A4.3 shall be used. Welding consumables shall be baked, stored, and used in accordance with consumable manufacturer's instructions or if approved by purchaser, dedicated instructions supported by experimental data (holding in electrode oven, length of time out of oven, etc.).

NOTE These acceptable consumables are often designated with suffixes of H4 or H8.

6.1.4 For $2^1/4$Cr-1Mo-V submerged arc welding (SAW) wire and flux combinations, testing for reheat cracking (RHC) is required, unless waived by purchaser, and shall be performed per Annex B of this practice.

NOTE While the K-factor (based on ASME PVP paper 2009-78144, "Prevention of Weld Metal Reheat Cracking During Cr-Mo-V Heavy Reactors Fabrication") is also a good indicator for indicating RHC susceptibility due to Pb/Bi contamination, the sub-ppm accuracy required of the laboratory test methods is only available using very specialized testing, and (as of this writing) only a few labs around the world have this equipment (based on API SCCM 934 meeting September 2012, "A Study on the K-Factor Analysis of 2 1/4Cr-1Mo-V Steel Weld Metal" and IIW Weld World 2014 DOI 10.1007/s40194-014-0147-6, "Round Robin of Trace Elements"). Also, the K-factor does not screen for possible RHC caused by other element(s). Therefore, purchaser can evaluate if testing of the K-factor is cost effective and provides the necessary information to prevent RHC instead of performing the Annex B test referenced above.

$$\text{K-factor, } Kf = Pb + Bi + 0.03Sb \text{ (element concentrations expressed in ppm)} \quad (9)$$

6.2 Mechanical Properties

6.2.1 Tensile Properties

Tensile properties of deposited weld metal shall meet base metal tensile properties in accordance with 5.5.2. The maximum yield strength limit for deposited weld metal when using advanced Cr-Mo steels may be raised to a higher limit with purchaser approval.

6.2.2 Stress Rupture

Where design temperatures are above 825 °F (440 °C), which is outside the scope of this document, weld metal stress rupture tests for each SAW wire and flux combination for Category "A" welds are required per ASME Section VIII, Division 2, Paragraph 3.4.4.5. Specimens parallel (all weld metal) and transverse to the weld axis (with base metal included) are required by the ASME Code. Per ASME Code, if a failure occurs in the base metal (which includes the heat-affected zone [HAZ]) before the weld metal has met the specified time to failure during the transverse stress rupture test, the test can be repeated with different heats of base metal. This paragraph is not meant to exceed ASME Code requirements but only to highlight the code requirements.

6.2.3 Impact Properties

Each lot of electrodes, heat of filler wire, and combination of batch of flux and heat of wire shall be impact tested (for both conventional and advanced Cr-Mo steels) and shall meet the requirements of 5.5.3.1.

6.2.4 Step Cooling Tests

6.2.4.1 Prior to the start of fabrication, step cooling tests shall be performed on the weld metal as specified below to determine its susceptibility to temper embrittlement. Each lot of electrodes, heat of filler wire, and combination of batch of flux and heat of wire shall be tested.

Two sets of Charpy V-notch test specimens, with a minimum of 24 specimens per set, shall be prepared from test coupons subjected to the following heat treatments:

Set 1—minimum PWHT only, to establish a transition temperature curve before step cooling.

Set 2—minimum PWHT plus the step cooling heat treatment specified below, to establish a transition temperature curve after step cooling.

Step cooling heat treatment should be as stated in the following steps (all hold temperature tolerances are ±15 °F [8.3 °C]):

1) Heat to 600 °F (316 °C), heating rate is not critical.

2) Heat at 100 °F (56 °C)/hour maximum to 1100 °F (593 °C).

3) Hold at 1100 °F (593 °C) for one hour minimum.

4) Cool at 10 °F (6 °C)/hour maximum to 1000 °F (538 °C).

5) Hold at 1000 °F (538 °C) for 15 hours minimum.

6) Cool at 10 °F (6 °C)/hour maximum to 975 °F (524 °C).

7) Hold at 975 °F (524 °C) for 24 hours minimum.

8) Cool at 10 °F (6 °C)/hour maximum to 925 °F (496 °C).

9) Hold at 925 °F (496 °C) for 60 hours minimum.

10) Cool at 5 °F (3 °C)/hour maximum to 875 °F (468 °C).

11) Hold at 875 °F (468 °C) for 100 hours minimum.

12) Cool at 50 °F (28 °C)/hour maximum to 600 °F (316 °C).

13) Cool to ambient temperature in still air.

6.2.4.2 After the test coupons are heat treated, sets of Charpy V-notch test specimens shall be prepared and impact tested at eight selected test temperatures to establish a transition temperature curve. One of the tests should be performed at –20 °F (–29 °C). Three specimens should be tested at each test temperature. The transition temperature curve should be established with at least two test temperatures on both the upper and lower shelf and a minimum of four intermediate test temperatures. For the minimum PWHT condition, results at −20 °F (−29 °C) and higher test temperatures shall meet the criteria given in 5.5.3.1

6.2.4.3 The 40 ft-lb (55 J) transition temperatures should be determined from the transition temperature curves established from the two sets of Charpy V-notch specimens. Impact properties shall meet the following requirement:

$$CvTr40 + 2.5\,\Delta CvTr40 \leq 50\ °F\ (10\ °C) \tag{10}$$

where

$CvTr40$ is the 40 ft-lb (55 J) transition temperature of material subjected to the minimum PWHT only; and

$\Delta CvTr40$ is the shift of the 40 ft-lb (55 J) transition temperature of material subjected to the minimum PWHT plus the step cooling heat treatment.

NOTE 1 Techniques such as the hyperbolic tangent equation can be used for fitting Charpy vs temperature data (See Paragraph 9F.2.3 in API 579-1/ASME FFS-1:2021), to generate the transition temperature curve required by 6.2.4.2.

NOTE 2 It is preferred to use all Charpy data for evaluating the hyperbolic tangent curve fit (not just the average value from each test temperature).

7 Welding, Heat Treatment, and Production Testing

7.1 General Forming and Welding Requirements

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

Welded joints, including nonpressure attachments to the pressure vessel body shall:

a) be full penetration joints;

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 should propose alternate NDE methods to verify weld quality for purchaser's approval);

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

7.1.2 Welding shall be completed prior to final PWHT. Welding of attachments to the internal austenitic stainless steel weld overlay or to external stainless steel weld buildup or subsequent layers of weld overlay may occur after PWHT when permitted by purchaser. For these attachment welds, a procedure qualification record (PQR) or mockup test shall be performed to verify that this does not produce a HAZ in the base metal, unless waived by purchaser.

7.1.3 Weld repairs to base metal, weld joints, and weld overlay shall be performed using a repair welding procedure (qualified in accordance with 7.2 and this procedure) and shall meet all the requirements that applied to the original fabrication welds. The location and dimensions of repairs shall be documented in accordance with 11.4 i).

7.1.4 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.

7.1.5 Welding of plates before rolling shall only be performed if approved by the purchaser. Purchaser shall carefully consider manufacturer's experience in rolling welded plates of comparable materials, heat treatment conditions, use of ISR, and thicknesses. Experience in welding plates before rolling of conventional Cr-Mo steel is not equivalent to rolling of welded plates of vanadium-modified Cr-Mo steel. When approved, use of ISR after plate welding and before rolling for vanadium-modified Cr-Mo steels is required.

7.1.6 For advanced Cr-Mo steel shells formed from plates that require correction for out-of-roundness and peaking, ISR of the long seams shall be completed before any corrections to peaking or out of roundness are made at the weld seams. All corrections shall be made prior to welding the circumferential seams.

7.1.7 Temporary attachments to the base metal which are not essential for subsequent lifting shall be removed before final postweld heat treatment. Removal of temporary attachments after PWHT shall not introduce a HAZ into the base metal.

7.2 Welding Procedure Qualification

7.2.1 Welding procedures shall be qualified in accordance with the following:

— conventional Cr-Mo steels: ASME Section IX;

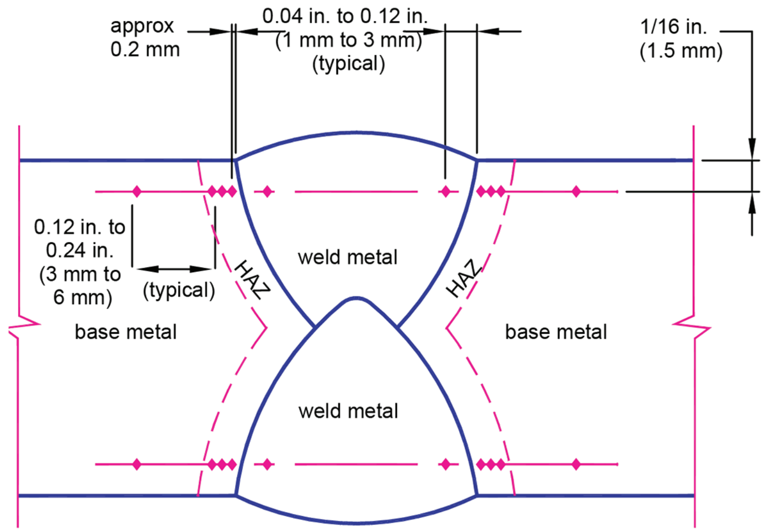
— advanced Cr-Mo steels: ASME Section IX; ASME Section VIII, Division 2, Paragraph 3.4; or ASME Code Case 2151-3, as applicable.

7.2.2 Base metal for welding procedure qualification tests shall be made from the same ASME Code material specification and the same P-number, group number, and nominal chemical composition as specified for the pressure vessel, except that either plate or forging may be used to qualify both. The welding consumable combination (electrodes, wire, and flux, whichever are applicable) shall be of the same type and brand as those to be used in production welding.

7.2.3 Charpy V-notch impact testing shall be performed on weld metal and HAZ of the heat-treated test plate with specimen heat treatment in accordance with Table 2. These impact tests should be performed for each welding procedure and each welding process and should meet the impact test temperature and acceptance requirements in 5.5.3.1. Location of impact specimens shall also be as per ASME Section VIII Division 2 Paragraph 3.11.8.

7.2.4 Step cooling tests shall be performed on the weld metal and HAZ for each welding procedure and process as specified for the weld metal in 6.2.4. Previously qualified welding procedure specifications (WPSs) with step cooling tests can be accepted by purchaser, based on WPSs complying with 7.2.1.

7.2.5 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 hardness shall not exceed 235 HV10 for conventional Cr-Mo steels and 248 HV10 for advanced Cr-Mo steels.



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

7.2.6 A tensile test, transverse to the weld, shall be performed on a weld joint of the heat-treated test plate in the maximum PWHT condition. The tensile test should meet the ambient temperature properties specified for the base metal in 5.5.2.1.

7.2.7 WPSs/PQRs shall be submitted to 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.

7.3 Preheat and Heat Treatments during Base Metal Forming and Welding

7.3.1 Preheat

7.3.1.1 Base metal should be heated to a minimum of 400 °F (205 °C) for both conventional and advanced Cr-Mo steels prior to and during welding operations (except as modified for weld overlay; see 7.5.4). Lower preheat values can be proposed and submitted to the purchaser for approval along with data from past experience but shall not be less than 300 °F (150 °C) for the conventional grades and 350 °F (175 °C) for the advanced grades prior to welding.

NOTE The 400 °F (205 °C) preheat for welding is based on the ASME Section VIII, Division 2:2023 nonmandatory Table 6.7 (see Paragraph 6.4.1.2 of the ASME Code). Lower preheat values have been used successfully in the past by numerous manufacturers. Lower preheat values can be proposed to the purchaser for approval along with data on past experience.

7.3.1.2 Base metal shall be heated to a minimum of 300 °F (150 °C) for conventional Cr-Mo steels and 350 °F (177 °C) for advanced Cr-Mo steels prior to and during thermal cutting and gouging operations.

7.3.1.3 Preheating at a minimum of 300 °F (150 °C) for conventional Cr-Mo steels and 350 °F (177 °C) for advanced Cr-Mo steels 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.

7.3.1.4 During welding, the preheat temperature shall be maintained until PWHT, ISR, or dehydrogenation heat treatment (DHT) in accordance with 7.3.2. The purpose is to minimize the risk of hydrogen cracking and to minimize problems due to low as-welded toughness.

7.3.1.5 For butt-welding and attachment welding, preheat temperatures shall be maintained through the entire plate thickness for a distance of at least one 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.

7.3.2 Intermediate Stress Relief/Dehydrogenation Heat Treatment

7.3.2.1 General

ISR or DHT is required before cooling below preheat temperature prior to PWHT for all joints. ISR is required for the following joints unless approved otherwise by purchaser:

— all nozzle welds for advanced Cr-Mo steels;

— nozzle welds for conventional Cr-Mo steels with shell or head thicknesses 6 in. (150 mm) and greater;

— weld buildup for advanced Cr-Mo steels (e.g., for catalyst support rings or skirt attachments).

DHT can be considered for:

— nonrestrained joints (i.e., standard circumferential and longitudinal seams and head petal welds) for conventional or advanced Cr-Mo steels; or

— conventional Cr-Mo steel nozzle welds less than 6 in. (150 mm) thick.

A higher level of concern with DHT is typically applied to all weld types in advanced Cr-Mo steels, as they can have low as-welded toughness. Although a DHT will reduce hydrogen, it will not sufficiently restore toughness, especially for advanced Cr-Mo steels, which have low toughness during pre-PWHT handling at room temperature.

Factors to be considered when reviewing use of DHT in lieu of ISR are the degree of weld restraint, weld joint thickness, experience of the manufacturer, and type of steel.

7.3.2.2 Maintaining Preheat before ISR

In some cases, it may be impractical to maintain preheat when transporting pressure vessels to the furnaces for ISR. This should be reported by manufacturer to purchaser before the order is awarded, along with details of the proposed heat treating steps (e.g., a DHT may be proposed just before transporting to the furnace for ISR) and duration of time the pressure vessel welds may be below preheat temperature before ISR. Purchaser shall approve the proposed heat treating steps for each pressure vessel.

7.3.2.3 Intermediate Stress Relief

ISR shall be performed in a furnace unless otherwise approved by the purchaser. ISR shall be performed at the following metal temperatures:

— conventional Cr-Mo steels: 1100 °F (593 °C) minimum for two hours minimum;

— advanced Cr-Mo steels: 1200 °F (650 °C) minimum for four hours minimum, or 1250 °F (680 °C) minimum for two hours minimum.

7.3.2.4 Dehydrogenation Heat Treatment (DHT)

The DHT shall be performed at a minimum metal temperature of 570 °F (300 °C) for conventional Cr-Mo steels and 660 °F (350 °C) for advanced Cr-Mo steels, when approved by purchaser. The duration should be agreed upon between manufacturer and purchaser; however, in no case should the duration be less than one hour for conventional Cr-Mo steels and four hours for advanced Cr-Mo steels. For tack welds, DHT can be reduced to preheat temperatures, for a minimum duration of one hour.

7.4 Production Testing of Base Metal Welds

7.4.1 Chemical Composition of Production Welds

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

7.4.1.2 The chromium, molybdenum, vanadium, and niobium concentrations (as applicable) of weld deposits shall be within the ranges specified in ASME Section II, Part C and ASME Section VIII, Division 2:2023, Table 3.2, for the specified electrodes or wires.

7.4.2 Hardness of Weld Deposit

7.4.2.1 After final PWHT (see 7.6), hardness testing shall be performed on 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.

7.4.2.2 Each hardness test result 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.

7.4.2.3 Hardness values shall not exceed:

— 225 HBW or equivalent (conventional Cr-Mo steels),

— 235 HBW or equivalent (advanced Cr-Mo steels).

Hardness tests shall be performed on each 10 ft (3 m) 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 Testing of base metal adjacent to the fusion line (including the HAZ) is not required, as HAZ hardness test measurements on vessel production weldments are typically an average of the HAZ, weld deposit, and base metal hardnesses, and as the test indentation is generally larger than the HAZ width due to the limitations of the test method.

7.4.3 Weld Metal Production Impact Tests

7.4.3.1 Production test plates subjected to the minimum PWHT shall meet ASME Section VIII, Division 2, Paragraph 3.11.8.4. Additional production test plate material, subjected to the maximum PWHT, shall also be tested and should meet the same requirements of ASME Section VIII, Division 2, Paragraph 3.11.8.4. The impact test temperature and acceptance criteria shall also be in accordance with 5.5.3.1.

NOTE When welding production test plates, the recording of a welding log is optional, but it is beneficial in the analysis of welding issues that may arise as described in 7.2.7.

7.4.3.2 If impact testing results do not meet specification, only one retest shall be permitted for each production test plate. Where it is suspected that the test methods or samples were done incorrectly, and if approved by the purchaser, initial results can be voided and retesting can be performed.

7.5 Weld Overlay

7.5.1 Material Requirements and Number of Layers

7.5.1.1 The ferrite content of austenitic stainless steel weld overlay shall be between 3 Ferrite Number (FN) and 10 FN, as determined in accordance with WRC Bulletin 519, prior to PWHT, except that the minimum FN for Type 347 weld deposits shall be 5 FN. This limit may be reduced to 3 FN, provided:

— the manufacturer submits data on the specific welding consumable brand and product number verifying that hot cracking will not occur, and

— this is approved by the purchaser.

7.5.1.2 Single layer overlays applied with automatic welding processes are commonly used and are acceptable as long as the requirements herein and the requirements in API 582:2023, Annex B are met.

7.5.2 Disbonding Tests

7.5.2.1 When required by purchaser, hydrogen disbonding tests on proposed overlay weld procedures shall be performed per ASTM G146 at the testing conditions defined in Table 4 in this document.

NOTE 1 Vanadium-modified grades have been shown to be very resistant to disbonding of weld overlay for all domains indicated in Table 3 (based on NACE International 2005, Paper 05573 “Hydrogen Induced Disbonding: From Laboratory Tests to Actual Field Conditions”).

NOTE 2 Disbonding tests can also be done on clad plate, but requirements for this testing are outside of the scope of this document. Notwithstanding, testing of explosion bonding cladding has been shown to be resistant up to domain B on base metals of 2¼Cr-1Mo-V.

7.5.2.2 When applicable, results of disbonding tests should be available prior to fabrication for each overlay welding procedure to be used on the pressure vessel shell rings and heads. Previously qualified disbonding test results can be submitted for review by purchaser if representative of the proposed WPS and operating conditions. Disbonding test coupons shall be in the maximum PWHT condition.

7.5.2.3 When testing is required by purchaser, the test parameters should result in hydrogen charging that meets or exceeds the hydrogen charging from operation. Since the sample size and geometry are different than the actual pressure vessel, the test conditions will also need to be adjusted. Proposed testing conditions (hydrogen partial pressure, temperature, and cooling rates) to meet or exceed the “equivalent” hydrogen charging of the actual maximum operating service are indicated in Table 3. Six domains of test conditions, depending on the pressure vessel wall thickness, pressure, and temperature, are defined in Table 4.

7.5.2.4 For conventional 2¼Cr-1Mo steel pressure vessels where the operating conditions fall into the D, E, and F domains, the risk of disbonding is very low. Purchaser shall determine if testing is necessary.

7.5.2.5 Acceptance criteria for the test results shall be an area ranking A, per ASTM G146.

Table 3—Proposed Testing Conditions at 842 °F (450 °C) to Simulate Hydrogen Charging from Maximum Operating Conditions

Pressure Vessel Service Conditions		Max. Operating Temperature		
Thickness in. (mm)	Max. Operating Hydrogen Partial Pressure psia (bar)	≥ 842 °F (450 °C)	797 °F to 840 °F (425 °C to 449 °C)	< 797 °F (425 °C)
≥ 9.84 (250)	≥ 2465 (170)	A	B	C
	≥ 2030 < 2465 (≥ 140 < 170)	B	C	D
≥ 7.09 < 9.84 (≥ 180 < 250)	≥ 2030 (140)	B	C	D
	≥ 1595 < 2030 (≥ 110 < 140)	C	D	E
	≥ 1160 < 1595 (≥ 80 < 110)	D	E	F
≥ 5.12 < 7.09 (≥ 130 < 180)	≥ (1595) 110	C	D	E
	≥ 1160 < 1595 (≥ 80 < 110)	D	E	F
	≥ 870 < 1160 (≥ 60 < 80)	E	F	F
	< 870 (60)	F	F	F
≥ 3.94 < 5.12 (≥ 100 < 130)	≥ 1160 (80)	D	E	F
	≥ 870 < 1160 (≥ 60 < 80)	E	F	F
	< 870 (60)	F	F	F
≥ 3.15 < 3.94 (≥ 80 < 100)	≥ 870 (60)	E	F	F
	< 870 (60)	F	F	F
< 3.15 (80)	< 870 (60)	F	F	F

Table 4—Test Conditions Domains

Domain	Testing Conditions		
	Temperature °F (°C)	Hydrogen Partial Pressure psia (bar)	Cooling Rate °F/h (°C/h)
A[a]	842 (450)	2175 (150)	1215 (675)
B	842 (450)	2175 (150)	270 (150)
C	842 (450)	1740 (120)	270 (150)
D	842 (450)	1305 (90)	270 (150)
E	842 (450)	1015 (70)	270 (150)
F	842 (450)	725 (50)	270 (150)

[a] For Domain A, the following equivalent testing conditions may be used as an alternate:
— temperature, 842 °F (450 °C);
— hydrogen partial pressure, 2538 psi (175 bar);
— cooling rate, 270 °F/h (150 °C/h).

7.5.3 Weld Overlay Procedure Qualification

7.5.3.1 The selected weld overlay process and the number of layers (including single layers) shall be qualified in accordance with ASME Section IX, and API 582:2023, Annex B.

7.5.3.2 Procedure qualification tests shall be made on base metal of the same ASME specification (same P number and group number) and similar chemical composition as specified for the pressure vessel, but either plate or forging may be used. Thickness of the test coupons shall not be less than one-half the thicknesses of the pressure vessel base metal or one in. (25 mm), whichever is less. The welding electrode, wire, and flux used for the weld overlay procedure qualification shall be the same type and brand to be used in production.

7.5.3.3 The qualification test plates shall be subjected to the maximum PWHT condition.

7.5.3.4 The chemical composition of the weld overlay shall be checked by laboratory chemical analysis or by using a portable analyzer of acceptable accuracy and precision when approved by purchaser. Samples shall be taken at the minimum specified thickness from the process side, and the composition shall meet the specified composition of the weld overlay (which may vary from the filler metal specification if a higher-alloy filler metal was used to account for dilution). The chemical composition, determined by these samples, should be used to calculate the ferrite content following the WRC Bulletin 519 1992 diagram, and the ferrite content shall meet the limits given in 7.5.1.

7.5.3.5 Weld buttering as part of a pressure-retaining weld shall be qualified separately per ASME Section IX, QW-283.

7.5.4 Preheat and Heat Treatments during Weld Overlay

Base metal shall be preheated to 200 °F (94 °C) for the first layer of weld overlay. The maximum interpass temperature for weld overlay shall be 480 °F (250 °C). No preheating is required for the second and any subsequent layers of weld overlay.

NOTE Performing an ISR after overlay welding is not applicable.

7.5.5 Production Testing of Weld Overlay

7.5.5.1 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.

7.5.5.2 Ferrite Content of Weld Overlay

7.5.5.2.1 A magnetic instrument calibrated to AWS A4.2M/ISO 8249 MOD 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 8249 MOD may 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 ten locations, selected at random, for each shell ring and head;

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

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

7.5.5.2.4 Ferrite values at each location shall meet the requirements in 7.5.1. If readings are outside of the specification, corrective actions shall be determined by the manufacturer and approved by purchaser.

7.6 Final Postweld Heat Treatment

7.6.1 The fabricated pressure vessel should be postweld heat treated 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 ASME Section VIII, Division 2, Paragraph 6.4.3.

Final PWHT temperature and holding time shall be as shown in Table 5.

7.6.2 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.

Table 5—PWHT Holding Temperature and Time

Material	PWHT Temperature	Holding Time
Conventional Cr-Mo steels	1275 °F ± 25 °F (690 °C ± 14 °C)	see footnote [a]
Advanced Cr-Mo steels	1300 °F ± 25 °F (705 °C ± 14 °C)	8 hours minimum [b]

[a] Holding time shall meet ASME Section VIII, Division 2:2023, Table 6.11 and the filler metal manufacturer's specified minimum PWHT holding time.

[b] The electrode manufacturers have developed their materials for thicker welds, and even with thinner welds, this longer heat treatment is needed to meet toughness and tensile properties. ASME Section VIII, Division 2:2023 requirements (Table 6.11) shall also be met if stricter.

8 Nondestructive Examinations

8.1 General

NDE personnel shall be qualified in accordance with ASNT RP 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.

8.2 NDE prior to Fabrication

8.2.1 Ultrasonic Testing (UT)

8.2.1.1 As required by ASME Section VIII, Division 2, Paragraph 3.3.3, bare and clad base metal plates should be ultrasonically examined with 100 % scanning before any forming in accordance with ASME Section V and ASME SA-578, Level C, Supplementary Requirement S1.

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

8.2.2 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 ASME Section VIII, Division 2, Paragraph 7.5.6 or by PT in accordance with ASME Section VIII, Division 2, Paragraph 7.5.7. Examination should be after finish machining but before welding.

8.2.2.2 For rolled shell plates and formed heads, the internal and external surfaces and the surfaces prepared for welding shall be examined by either MT or PT after forming. Procedures and acceptance standards shall be in accordance with ASME Section VIII, Division 2, Paragraph 7.5.6 for MT, or with ASME Section VIII, Division 2, Paragraph 7.5.7 for PT. Examination should be after finish machining but before welding.

8.3 NDE during Fabrication

8.3.1 MT shall be performed after completion of welds excluding stainless weld overlay. This includes pressure-retaining base metal welds, weld buildup deposits, and attachment welds. MT shall also be performed after gouging or grinding operations, including back gouging of root passes. MT shall be in accordance with ASME Section VIII, Division 2, Paragraph 7.5.6.

8.3.2 Areas where internal attachment welds will be welded directly to overlay or cladding shall be examined by straight-beam UT to inspect for possible lack of bonding between the overlay and base metal exceeding the criteria in 8.4.2. If detected, repairs shall be done before internal attachments are welded to the area.

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

8.4 NDE after Fabrication and prior to Final PWHT

8.4.1 Base Metal Welds

8.4.1.1 Pressure-retaining butt welds and vessel-to-support skirt welds shall be fully examined by RT or UT before final PWHT. RT shall be in accordance with ASME Section VIII, Division 2, Paragraph 7.5.3. UT in lieu of RT shall meet the requirements of ASME Section VIII, Division 2, Paragraph 7.5.5.

8.4.1.2 When RT is not practical for nozzle and skirt attachment welds, UT in accordance with Paragraph 7.5.5 of ASME Section VIII, Division 2 shall be applied in lieu of RT.

8.4.1.3 For advanced Cr-Mo steel SAW welds that are categorized as “prescreened” for minimizing transverse RHC as defined in Annex A, the UT required by Annex A can be performed after ISR in lieu of after final PWHT per 8.5.1.1.

NOTE For SAW welds categorized as “nonprescreened” as defined in Annex A, the special UT is suggested to be done both after ISR and after PWHT, as described in Annex A.

8.4.2 Weld Overlay

Spot UT shall be done over four test strip patterns on the shell and one strip across the head. The shell strips shall be equally spaced and approximately 3.2 in. (80 mm) wide along the full length of the pressure vessel shell. The head strip shall be approximately 3.2 in. (80 mm) wide. UT should be in accordance with ASME SA-578, Level C.

8.5 NDE after Final PWHT

8.5.1 Base Metal Welds

8.5.1.1 Advanced Cr-Mo steel pressure-retaining base metal welds, including nozzles, shall be fully examined for transverse RHC by UT in accordance with Annex A (unless done after ISR per 8.4.1.3 and as allowed in Annex A).

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

8.5.1.3 Accessible welds shall be examined by MT. An alternating current yoke method shall be used to prevent arc strikes. PT may be substituted for MT whenever MT is impractical.

8.5.1.4 Internal weld surfaces (groove and fillet) on unclad or nonoverlaid pressure-retaining parts in services shall receive 100 % MT inspection, where accessible.

8.5.2 Weld Overlay

8.5.2.1 Entire surfaces of austenitic stainless steel weld overlay (full surface coverage) and attachments welded to the overlay shall be examined by PT in accordance with ASME Section VIII, Division 2, Paragraph 7.5.7.

8.5.2.2 Spot UT should be performed as described in 8.4.2.

8.6 Positive Material Identification

PMI should be performed in accordance with purchaser's PMI specification.

9 Hydrostatic Testing

9.1 Pressure-retaining welded joints shall be free from any coatings, scale, or other foreign material before testing. Dirt, scale, sand, or other foreign material shall be removed from the pressure vessel.

9.2 Test water shall not contain more than 50 ppm chlorides for SS-lined pressure vessels unless otherwise approved by purchaser.

9.3 During the hydrostatic testing, the pressure vessel metal temperature shall be 60 °F (15 °C) or warmer, unless otherwise approved by purchaser.

NOTE This temperature is substantially warmer than 30 °F (17 °C) above the impact testing temperature of –20 °F (–29 °C), and hence meets the ASME Code. Even though ASME BPVC, Section VIII (Division 2, paragraph 8.2.4) states that the hydrotest temperature shall be 30 °F (17 °C) above the MDMT, the ASME Code Case 2718 (*Alternative Minimum Test Temperature for Hydrostatic Testing*, Section VIII, Division 2) also states that 30 °F (17 °C) above the impact testing temperature may be used whenever the impact testing temperature is lower than the MDMT.

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

10 Preparations for Shipping

10.1 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 contaminants from the hydrotest water.

10.2 Pressure vessel openings shall be sealed with a steel cover and gasket, and either a desiccant system or vapor phase inhibitor shall be used or the pressure vessel shall be filled with dry nitrogen gas at a suggested pressure of 5 psig (34.5 kPa). If nitrogen is applied, the nitrogen pressure should be maintained during transportation, erection, and pre-commissioning.

WARNING The pressure vessel should be marked. A conspicuous warning tag should be attached at each manway stating, "THE PRESSURE VESSEL IS FILLED WITH NITROGEN—DO NOT ENTER."

10.3 For preservation during transportation, exposed machined surfaces (e.g., flange faces, bolting, and stainless steel surfaces) shall be protected by applying suitable grease, rust preventative oil, or coating.

11 Documentation

11.1 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.

11.2 For review prior to materials procurement:

a) materials purchase specification;

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

11.3 For review and approval prior to fabrication:

a) MTRs showing chemical composition, 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); it 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.

11.4 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;

j) minimum pressurization temperature (MPT) determination report (see Annex C for additional information).

12 Summary Material Examination and NDE Requirements

See Table 6 for a summary of API RP 934-A material examination and NDE requirements.

Table 6—Summary of API RP 934-A Material Examination and NDE Requirements

Materials and Locations for Testing or Inspection	Material Examination Requirements										
	Tensile Testing	Impact Testing	PMI	Chemical Composition	Ferrite	RT	UT	MT	PT	Hardness	Other
Base Material and Weld Metal Testing—Prior to Fabrication											
Plates (including SS-clad plates)	5.5.2.1	5.5.3.1	8.6	5.3	—	—	8.2.1.1	8.2.2.2 [a, f]	8.2.2.2 [a, f]	—	—
Forgings	5.5.2.1	5.5.3.1	8.6	5.3	—	—	8.2.1.2	8.2.2.1 [a]	8.2.2.1 [a]	—	—
Pipe and Fittings	5.5.2.1	5.5.3.1	8.6	5.3	—	—	—	—	—	—	—
Cr-Mo Filler Metal	6.2.1	6.2.3 6.2.4	8.6	6.1.2	—	—	—	—	—	—	6.1.3 6.1.4 6.2.2 Annex B
Weld Qualification Test Plates											
Base Metal Weld	7.2.6	7.2.3 7.2.4	—	—	—	—	—	—	—	7.2.5	7.2.2
Weld Overlay [b]	—	—	—	7.5.3.4	7.5.1 7.5.3.4	—	—	—	—	—	—
Production Pressure Welds											
Surfaces Prepared for Welding	—	—	—	—	—	—	—	8.2.2.1 [a] 8.2.2.2 [a, f]	8.2.2.1 [a] 8.2.2.2 [a, f]	—	—
Back-gouged Surfaces, Prior to Back Welding	—	—	—	—	—	—	—	8.3.1	—	—	—
Before PWHT	—	—	7.4.1 8.6	7.4.1	—	8.4.1.1 [c]	8.4.1.1 [c] 8.4.1.2 [d]	8.3.1	—	—	—
After PWHT	—	—	—	—	—	—	8.5.1.1 8.5.1.2 Annex A	8.5.1.3 8.5.1.4	8.5.1.3 [e]	7.4.2	—
After Hydrotest	—	—	—	—	—	—	—	—	—	—	—
Production Weld Overlay											
Before Overlay Welding	—	—	—	—	—	—	—	8.2.2.1 [a] 8.2.2.2 [a, f]	8.2.2.1 [a] 8.2.2.2 [a, f]	—	—
Before PWHT	—	—	7.5.5.1 8.6	7.5.5.1	7.5.5.2	—	8.4.2	—	—	—	—
After PWHT	—	—	—	—	—	—	8.5.2.2	—	8.5.2.1 [g]	—	—

Table 6—Summary of API RP 934-A Material Examination and NDE Requirements (Continued)

Materials and Locations for Testing or Inspection	Material Examination Requirements										
	Tensile Testing	Impact Testing	PMI	Chemical Composition	Ferrite	RT	UT	MT	PT	Hardness	Other
Production Test Plates											
Base Metal Welds	—	7.4.3	—	—	—	—	—	—	—	—	—
Miscellaneous											
Locations of Temporary Attachments	—	—	—	—	—	—	—	8.3.3 [a, h]	8.3.3 [a, h]	—	—
Vessel-to-skirt Welds Prior to PWHT	—	—	—	—	—	8.4.1.1	8.4.1.2 [d]	—	—	—	—
Location of internal attachments	—	—	—	—	—	—	8.3.2 [i]	—	—	—	—

a Alternative to use MT or PT.

b Disbonding tests are not typically required; if desired by purchaser, purchaser should define testing requirements and acceptance criteria (7.5.2).

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

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

e PT may be substituted for MT whenever MT is impractical.

f MT or PT is required on internal and external surfaces of rolled plates, formed head plates, and surfaces prepared for welding.

g Stainless steel weld overlay and attachments welded to the overlay.

h Areas where temporary attachments have been removed.

i Areas where internal attachments welds will be welded directly to overlay or cladding.

Annex A
(informative)

Guidance for Inspection for Transverse Reheat Cracking

A.1 Foreword

This annex was issued in response to widespread fabrication problems with 2^{1}/4Cr-1Mo-V pressure vessels that occurred in 2008. The problems were determined to be RHC in newly fabricated SAW and involved many short transverse cracks in the weld deposits. If this type of cracking were to reoccur during future new fabrication, one concern is that it would not be flagged for evaluation or rejection by currently required ASME inspection programs using UT or RT (i.e., ASME Section VIII, Division 2). The objective of this annex is to provide a means for detection of this cracking (to be performed in addition to the ASME Code-required NDE) and to suggest appropriate evaluation/rejection criteria. Since it may be difficult to detect *all* the reheat cracks in some welds, prudent weld removal and repair decisions need to be made if some cracks are detected.

Research on the root cause of the cracking and the prevention steps was performed, and the results were incorporated into this document. These inspection guidelines will help in detecting welds with RHC. Then welds made with the same heat of welding consumables can be thoroughly evaluated.

A.2 Brief Description of the Cracking Conditions and Morphology

The "reheat cracking" that caused the major problems at multiple (but not all) pressure vessel fabrication shops in 2008 can be described as:

— subsurface in SAW weld deposits;

— transverse to welding direction and perpendicular or at a slight angle to the surface;

— possibly having slight branching;

— occurring in circumferential, longitudinal, head meridian, and nozzle welds;

— typically very small crack size—most are 0.16 in. (4 mm) to 0.39 in. (0 mm) in length and 0.08 in. (2 mm) to 0.20 in. (5 mm) in height);

— typically having many cracks present in an affected weld (can be hundreds of cracks);

— occurring at various depths and various locations across the width of the weld;

— often occurring as "clusters" with many parallel cracks lined up in the same plane (Figure A.1);

— only developing after the first heat treatment step at >1150 °F (620 °C), such as ISR, reheating for rerolling, or PWHT;

— not occurring after welding or DHT;

— not historically occurring on less restrained weld procedure qualification tests or production test plates (even with some attempts to add restraint on these tests).

In the past, the most common form of RHC in Cr-Mo welds resulted in longitudinal cracking in the coarse-grain area of weld HAZs, but there were also reports of transverse or longitudinal cracking in weld deposits. This inspection guideline is focused on detecting only transverse reheat cracks occurring in the SAW weld deposits and should be performed in addition to ASME Code-required RT and UT examinations. The ASME Code-required inspections are used to detect other forms of longitudinal or transverse weld defects.

The fact that cracking only occurs after heat treatment gave the cracking its name and also the alternative labels of “stress relief” or “stress relaxation” cracking. The presence of cracking has been confirmed by metallographic testing and by dye penetrant testing (PT) after grinding.

Both single and tandem wire SAW welds have experienced cracking. Cracking has not been experienced with other welding processes using flux-containing welding consumables, such as SMAW or FCAW.

A.3 Recommended Inspection Strategy and Timing

A.3.1 General Strategy

The techniques described in this annex are focused on detecting transverse reheat cracks occurring in the SAW weld deposits. The default inspection mode will be from the outside diameter (OD). However, if the weld has not been overlaid by stainless steel, the technique is equally valid when applied from the inside diameter (ID).

This procedure uses ultrasonic time-of-flight diffraction (TOFD) for initial detection. RHC has been characterized in TOFD B-scans (Figure A.2) as intermittent co-planar (in the through-wall direction) reflectors typically appearing in cluster configurations. For indications that are not rejected by TOFD and need further clarification, manual pulse-echo shear wave angle beam UT examination can be used to characterize flaws and determine their primary orientation. Flaws that are found to be planar and transverse in their primary orientation should be considered reheat cracks.

If a weld shows cracking at any depth and the inspection has not conclusively and reliably indicated that the other depths are crack-free then the entire weld depth should be gouged/ground out and redeposited.

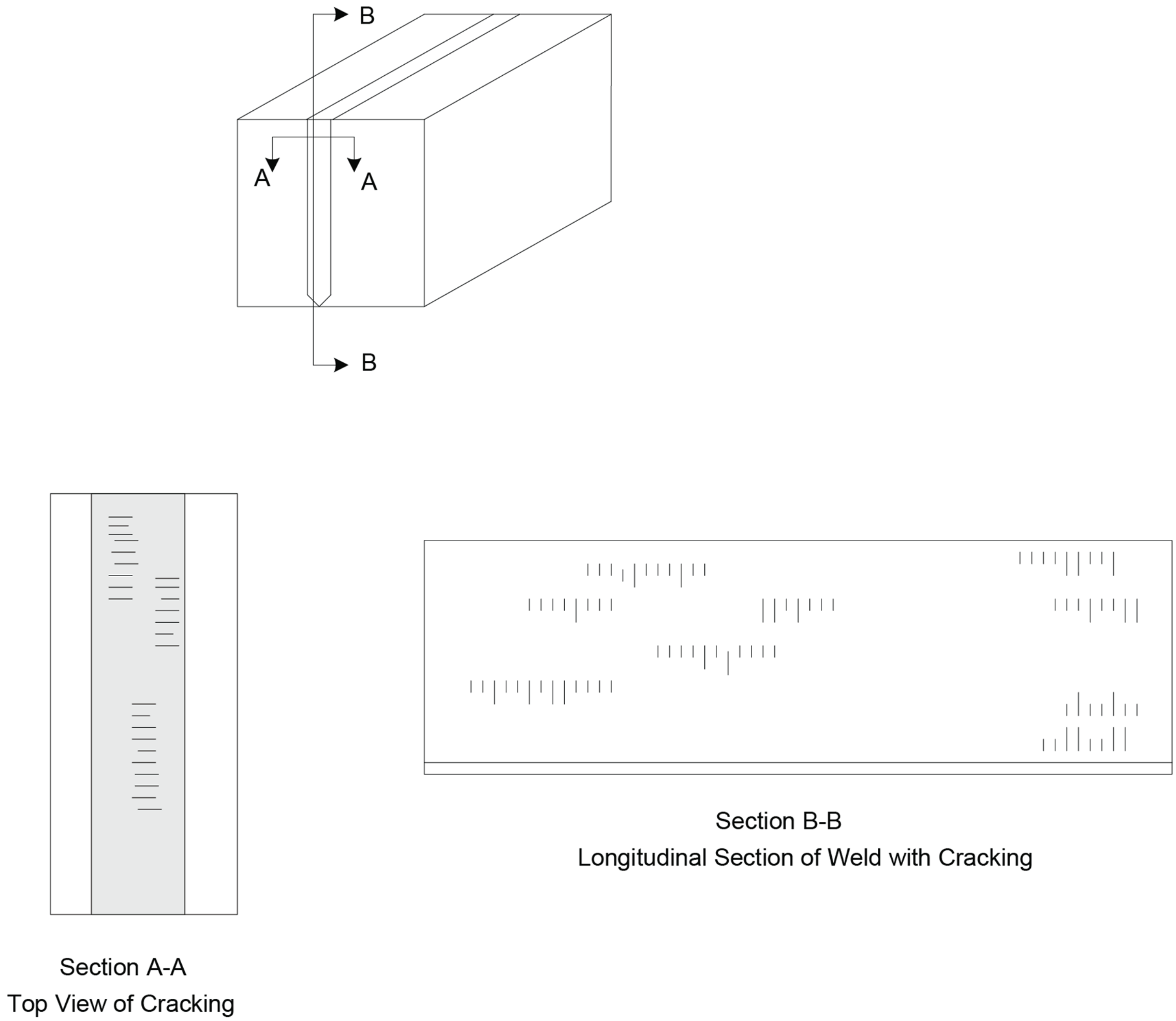


Figure A.1—Schematic Showing Reheat Cracking Locations

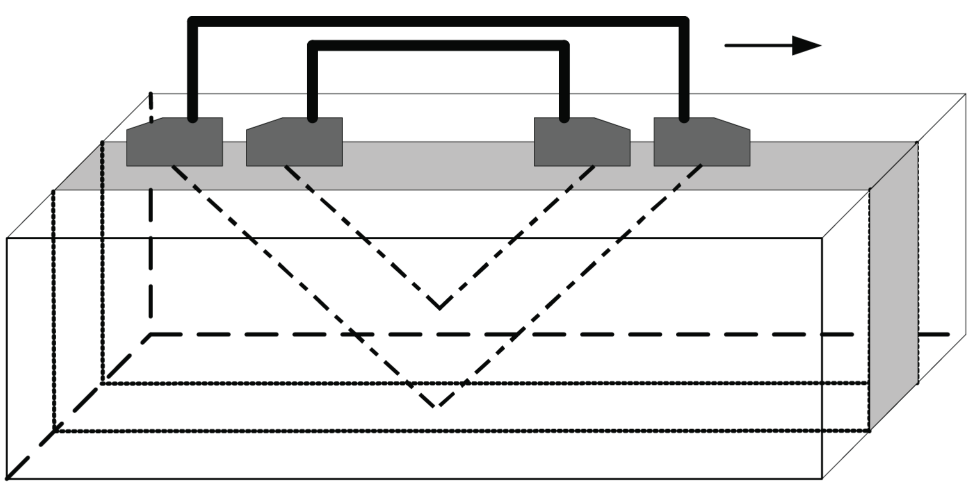


Figure A.2—B-scan for Detecting Transverse Defects with TOFD

A.3.2 Special Inspection Timing/Frequency

a) UT inspection (see A.4) should be performed on 100 % of nonprescreened SAW welds, before PWHT but after ISR or other >1150 °F (620 °C) reheating steps are completed.

b) On the nonprescreened welds, an ISR is suggested even if the weld initially received only DHT and would not have required ISR before PWHT.

c) After PWHT on nonprescreened welds, reinspection with these special TOFD procedures should be performed on the following:

— 100 % of SAW welds that have been repaired due to RHC;

— 10 % minimum of SAW welds that showed no RHC; if RHC is detected, the inspection should be increased to 100 % for this heat of flux.

d) TOFD should be performed per A.4.1 on circumferential and longitudinal seams, and pulse-echo UT should be performed per A.4.3 on the nozzle welds. Pulse-echo UT should also be used to characterize indications found by TOFD, per A.4.2.

e) For prescreened welds, 100 % of SAW welds should be scanned using at least one probe setup from either the TOFD or pulse-echo UT options listed in A.4.1 or A.4.2. Scanning shall be performed after a heat treatment cycle >1150 °F (620 °C) but can be done at whatever point after this or subsequent heat treatments that is optimum for the production cycle. This inspection may or may not provide scanning of the full weld thickness and width, but scanning of at least part of the thickness is considered to be acceptable for this case.

It is understood that this inspection may disrupt a manufacturer's previous production process; however, it is recommended that this inspection timing and frequency be the default unless otherwise approved by purchaser. Prior to commencement of any examinations, the manufacturer should develop comprehensive procedures and demonstrate the procedure capabilities and personnel competency in accordance with ASME Section V, Article 4 and this annex.

A.3.3 Reporting and Documentation

The results of this inspection should be promptly reported to purchaser, and the final reports (with a summary of the procedure) should be included in the pressure vessel inspection package.

A.4 Inspection Methods and Guidelines

A.4.1 TOFD UT

TOFD for detecting transverse RHC should be performed with probes aligned on the weld axis to provide a B-scan view with the scanning travel direction along the weld length (see Figure A.2). D-Scans, with the probes aligned transverse to the weld and the scanning travel parallel to the weld, are not useful for detecting these transverse cracks. For prescreened welds, a minimal amount of offset alignment between the probes (e.g., <10° to 20°) can be used (see Figure A.3), provided adequate performance is demonstrated on the sensitivity demonstration block described in Table A.1. If it is properly demonstrated, the offset probe setup will avoid the requirement of flush grinding the welds.

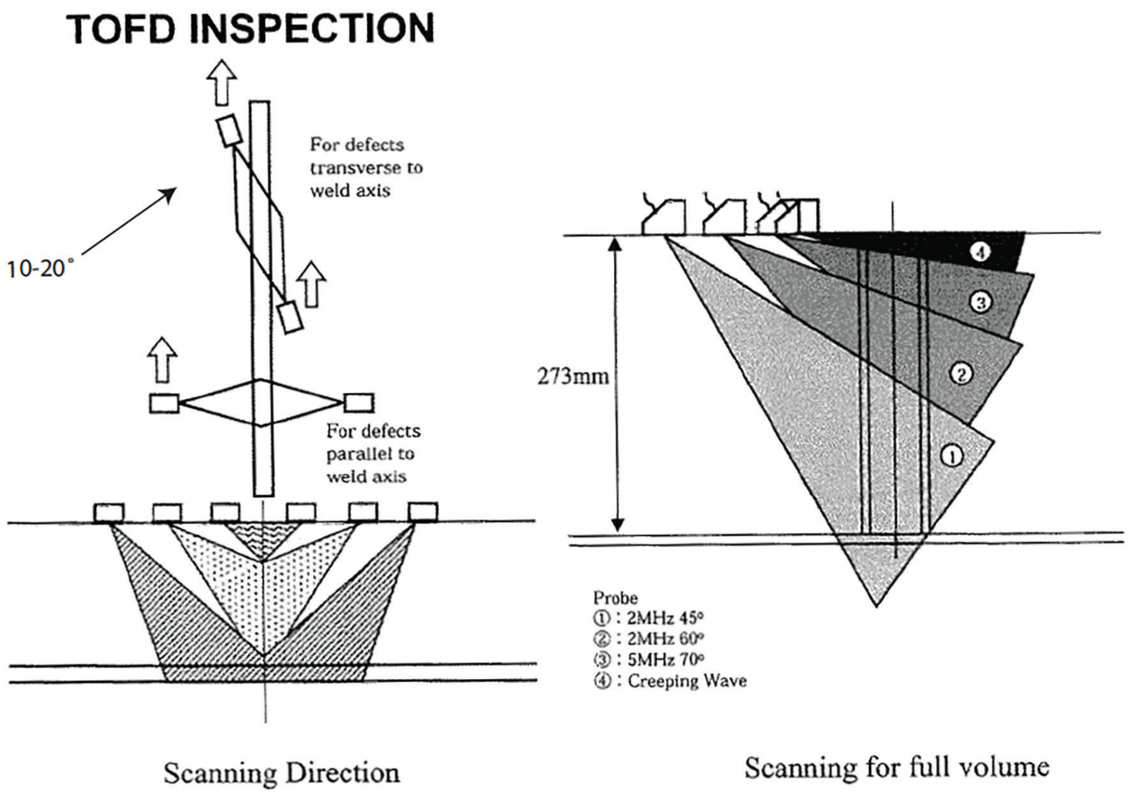


Figure A.3—Alternate Probe Setup with Offset for Detecting Transverse Defects

These reheat cracks are very small in most cases and can be difficult to detect, especially when situated at depths near the range limits of the TOFD setups. Therefore, an adequate number of TOFD setups shall be used to enable coverage of the full weld thickness and width as shown by the performance demonstration required in Table A.1 on a sensitivity demonstration block with an adequate number of flaws. The flaw sizes found in ASME Section V, Article 4:2023, Appendix III diffract far too much sound energy in comparison with reheat cracks to be useful indicators of adequate sensitivity. Tests showed that even 0.12 in. (3 mm) side-drilled holes (SDH) on a 9.8 in. (250 mm) block produced a signal at maximum depths that far exceeded the response from deep reheat cracks. Hence, the recommended sensitivity demonstration/calibration block is described in Table A.1. The block should be made of base metal with similar heat treatment as the welds. TOFD also has difficulty detecting near surface flaws, and a creeping wave setup may be required to cover this area (or if accessible, a TOFD scan can be done from both surfaces).

The procedure and calibration from Section V, Article 4:2023, Appendix III should be followed along with the requirements in Table A.1. This method can be used on circumferential and longitudinal seams on shells and heads but is not practical for most nozzle welds. Personnel performing and evaluating UT examinations should be qualified and certified with their employer's written practice. Only ASNT RP SNT-TC-1A Level II or Level III personnel should analyze the data and interpret results, and before analyzing production welds they should perform a procedure demonstration on the block described in Table A.1.

Table A.1—TOFD Guideline for Identifying Transverse Reheat Cracks

Parameter	Recommendation	Comments
Surface condition of welded joint	Flush ground on both inside (ID) and outside (OD).	For nonprescreened welds, the grinding shall be good quality and smooth enough to achieve good probe contact. For prescreened welds, grinding can be avoided if TOFD with offset probes is properly qualified per A.4.1.
Sensitivity demonstration block	A series of 0.157 in. × 0.157 in. × 0.0157 in. (4 mm × 4 mm × 0.4 mm) vertical, transversely oriented embedded EDM notches at depths per Figure A.4	Notches are positioned at each 10 % (0.1*T*) of specimen thickness and offset by 10 % of specimen thickness. An additional notch should be placed within 0.24 in. (6 mm) of the near surfaces.
Probe alignment/ scanning location	B-Scan (Figure A.2) from OD. Probes centered on the weld and aligned along its length.	If the weld is wide, probes may need to be offset to one side and then the other.
Zone of beam coverage through weld thickness and width	Adjust probe frequencies, angles, probe center spacing (PCS), and probe diameter to ensure complete coverage through thickness; often requires multiple probe setups (such as shown in Figure A.3).	TOFD setups should be evaluated using the sensitivity demonstration block described above. Scans should be run in the direction of successive notches on the block with the flaws centered at first and then on successive runs (as many as necessary to match the width of the weld and HAZ being examined) offset by increments equal to probe diameter, until the A-scan response amplitude is less than the 20 % of centered run. Zones of coverage are demonstrated by the ability to obtain responses from successive notches that are at least equal to 20 % of the highest amplitude obtained from notches with the setup. The information gathered should be used to adjust probe setups and scanning positions on the welds as necessary. It is possible that more than one scan will be required to ensure the entire weld width and HAZ is covered. A creeping wave set up may be required to detect the near surface flaw.
Scanning direction	One direction (along the length of the weld)	—
Rejection criteria	1) Single point reflectors: Single point reflectors should be evaluated by manual pulse-echo angle beam shear wave according to A.3.2. 2) Clusters: If three indications (point reflectors) are observed in the same through-thickness plane (±0.098 in. [±2.5 mm]) and separated by 2 in. (50 mm) or less, they should be considered reheat cracks, unless pulse-echo ultrasonic examination can demonstrate that they are not planar and not transverse. 3) Straight line indications: Phase-reversed solid indications of 2 in. (50 mm) or longer noted near and above the back wall signal may be caused by small clusters of RHC near the ID and should be investigated by examination from the near side or other UT methods.	When clusters are investigated by manual pulse-echo UT at depths where the primary detection angle of 70° is unable to reach the flaws due to vessel curvature, there should be no minimum distance-amplitude correction (DAC) consideration. Lower angles do not adequately reflect the signal. Unless a cluster is definitely demonstrated to not be RHC, it should be rejected.

An example probe setup for a 9.8 in. (250 mm) thick wall is shown in Table A.2:

Table A.2—Example Probe Setup for 9.8 in. (250 mm) Thick Wall

Probe Angle	Probe Diameter	Probe Frequency	Probe Center Spacing (PCS)
60°	¼ in. (6 mm)	5 MHz	3.42 in. (87 mm)
45°	½ in. (12.5 mm)	2 MHz	7.87 in. (200 mm)
25°	½ in. (12.5 mm)	2 MHz	11.81 in. (300 mm)

Repair welds may become wider than original welds (especially narrow gap welds), and in some cases, TOFD scans along the weld centerline may not cover the entire weld width. For example, welds >2 in. (50 mm) wide may need multiple scans with the same probe setup (on the sides of the weld centerline) to achieve full coverage. The need for multiple scans is determined by demonstration testing on the calibration block as described in Table A.1.

TOFD Sensitivity Demonstration Block for Detection Block for Detection of Transverse Reheat Cracks

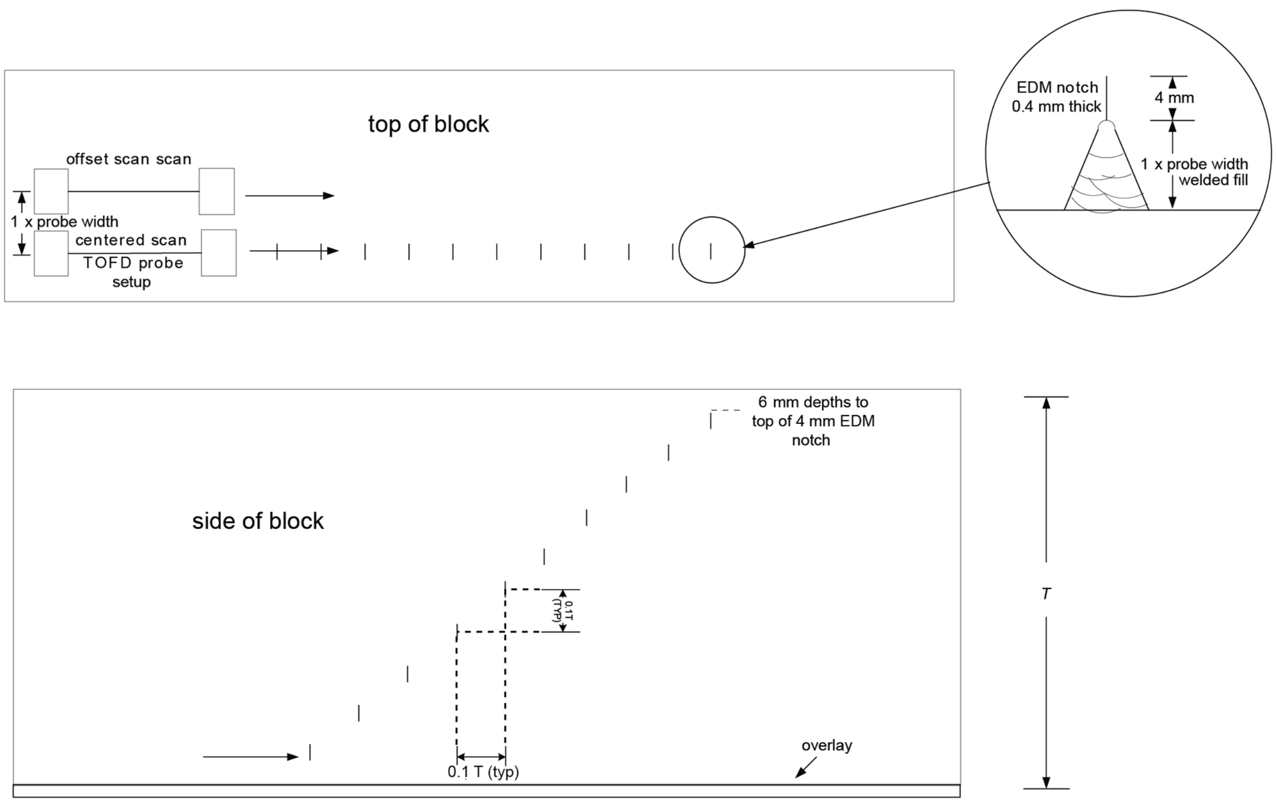


Figure A.4—TOFD Sensitivity Demonstration Block

A.4.2 Manual Pulse-echo Shear Wave UT

Table A.3 lists the recommended steps and rejection criteria for pulse-echo shear wave UT. Manual pulse-echo UT examinations are performed along flush-ground welds in the longitudinal direction. Scanning in both directions along the weld (e.g., clockwise and counter-clockwise for a circumferential seam) is recommended; however, weld metal reheat cracks are often detected in only one direction. Close attention shall be paid to areas near the surface zones that are within the TOFD blind zones.

Table A.3—Manual Pulse-echo Shear Wave Guideline for Identifying Transverse Reheat Cracks

Parameter	Recommendation	Comments
Surface condition of welded joint	Flush ground	—
Probe frequency	2 to 4 MHz (focused if necessary to achieve adequate resolution at maximum depths)	Transducer frequency should be 4 MHz for near side examination and 2 MHz for depths greater than 4 in. (100 mm)
Probe angles	70° (primary detection angle), 60° and possibly 45°	Multiple probes are used to “cover” the near and far zones: — 70° covers about 0.4 in. (10 mm) to 4 in. (100 mm); — 60° covers about 2 in. (50 mm) to 6 in. (150 mm); and — 45° covers the deeper areas.
Calibration reference	0.12 in. (3 mm) SDH (DAC set-up); or calibration block shown in Figure A.4	Holes at multiple depths (per ASME Section V, Article 4 as a minimum) and some EDM notches are typically included
Scanning sensitivity	+ 14 dB above reference level	—
Evaluation sensitivity	+ 14 dB above reference level	—
Probe alignment/ scanning location	Along flush-ground weld; probes aligned parallel to the weld; UT beam shall be directed as perpendicular as possible to the plane where the indications are found.	Scanning for transverse flaws or “A-scan”; however, this terminology is not consistent worldwide.
Scanning direction	Both directions along weld	Forward and backward from welding direction.
Flaw characterization	Based on ISO 23279 (except no minimum amplitude and no echodynamic evaluation)	Primary objective is to determine if indication is planar and transverse. Look for >9 dB difference between the 70° and 60° scans ([45° and 60° for depths greater than 4.75 in. [120 mm]). If >9 db (Hdmax-Hdmin), then classify as planar. Compare maximum signal obtained from transverse and parallel directions with the same probe that produced the maximum signal (see Figure A.5); if the difference is >9 dB, the defect can be considered transverse.
Rejection criteria	1) Greater than 20 % DAC — record. 2) 10 % to 20 % DAC — investigate and characterize.	Reject except if classified as another type of defect and passing ASME Code requirements.

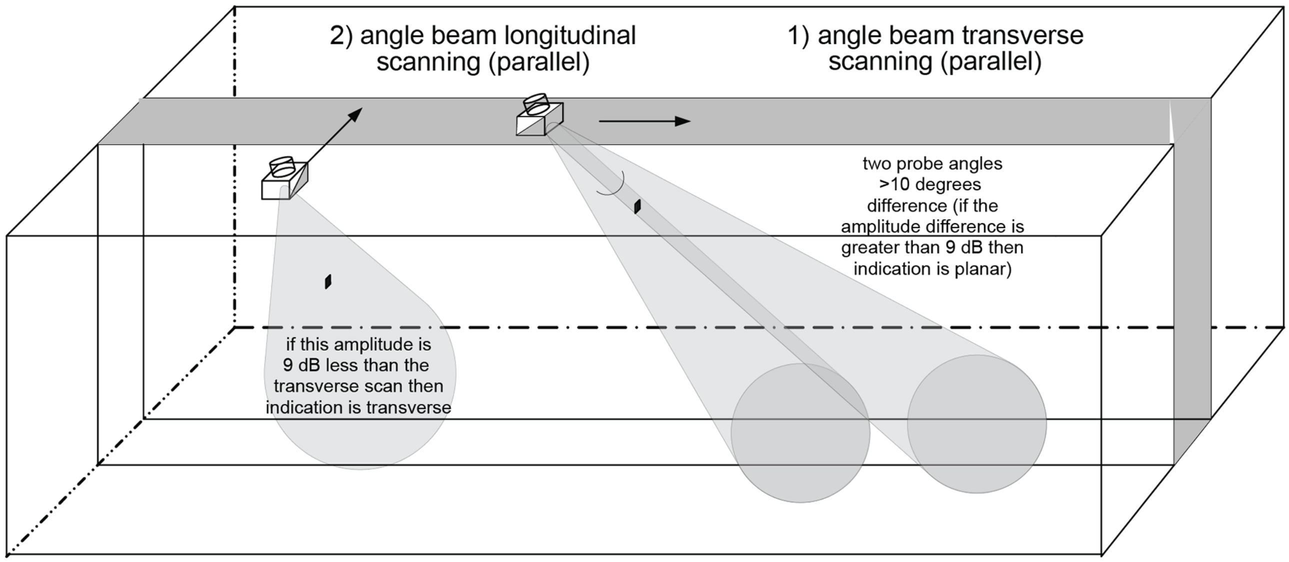


Figure A.5—Characterization of Reheat Cracks Using Pulse-echo UT

One of the primary areas in which the guideline in Table A.3 exceeds ASME Code Section V, Article 4 requirements is in the calibration standard. Whereas the code requires calibration on an SDH with a diameter, which is a function of the wall thickness and ranges from 0.24 in. (6 mm) to 0.39 in. (10 mm) for typical pressure vessel wall thicknesses, this guideline requires a 0.12 in. (3 mm) SDH. This results in detection of much smaller indications.

The disadvantages of this method are that it is very operator-dependent and there is no permanent record. Pulse-echo UT is prone to a reduction in probability of detection (POD) as a result of operator fatigue. However, pulse-echo UT is used to characterize reflectors (as there are often some reflectors that are other types of noninjurious defects) and to scan the TOFD blind zones. On nozzle welds, where TOFD often cannot be done, 100 % pulse-echo UT is necessary to inspect for weld metal RHC. There is no documented experience using phased array to detect RHC; however, it may be used with purchaser approval and proper procedure development and demonstration that flaw characterization and orientation can be made as consistently and effectively as with single element examination. Additional research would be required to fully incorporate it into this guideline.

Personnel performing and evaluating pulse-echo UT examinations should possess a UT shear wave qualification from API (e.g., API QUTE) or an equivalent qualification approved by purchaser. Only ASNT RP SNT-TC-1A Level II or III personnel should analyze the data and interpret results, and before analyzing production welds they should perform a procedure demonstration on the block described in Table A.3.

A.4.3 UT of Nozzle Welds

In most nozzle welds that have shown RHC, the magnitude of cracking found after partial inspection has been extensive enough to justify a full repair. Nozzle welds that require inspection for RHC should be 100 % inspected using pulse-echo UT. As a minimum, scanning should be done with two beam angles, including 70° as the primary detection angle (2 MHz to 4 MHz calibrated to a 0.12 in. [3 mm] SDH). For follow-up, phased array UT S-scans can be considered; however, phased array UT will require procedure development and calibration before using. Proposed procedures and calibrations should be submitted for approval by the purchaser. If a nozzle weld shows cracking at any depth and the inspection has not conclusively and reliably indicated that the other zones are clean, the entire weld should be replaced.

A.4.4 Other Inspection Methods

Radiography has not been able to detect these cracks, which aligns with expectations.

Annex B
(informative)

Weld Metal/Flux Screening Test for Reheat Cracking Susceptibility

B.1 Foreword

This annex is being issued in response to widespread fabrication problems with $2^1/4$Cr-1Mo-V pressure vessels that occurred from January 2008 through at least August 2008 due to transverse RHC. Additional background on the problem is given in Annex A. Annex A also gives guidance on inspection methods for detecting transverse RHC and suggests that the extent of inspection can vary based on nonprescreened versus prescreened welds determined by a screening test of the weld metal and flux heats. Initially, the screening test used was the "Gleeble® test,"[6] which is a high-temperature tensile test done at a set strain rate using specialized testing equipment. Since these testers are generally used for research and are not standardized, only a limited number of laboratories could conduct the tests, and although each tester distinguished between susceptible and non-susceptible materials, the threshold for acceptable material varied for each tester.

To develop an acceptable screening test that is repeatable between multiple laboratories, a joint industry sponsored research program (JIP) was formed in February 2010. The JIP sponsors included numerous oil companies, pressure vessel manufacturers, weld metal suppliers, steel suppliers, licensors, and an engineering company. The program included developing the details of the test method, running sensitivity tests on numerous test variables, and conducting round robin tests at multiple laboratories to ensure that the results were repeatable. At each stage, "good," "bad," and "borderline" materials were compared, to show that the test procedure could distinguish between these materials.

This procedure is applicable to $2^1/4$Cr-1Mo-V submerged arc welding (SAW) wire and flux combinations (by heat) and is solely for screening for fabrication RHC susceptibility. The test criteria apply only to samples prepared and tested completely in accordance with this procedure and is not applicable to the previously used Gleeble test[6] methods. The screening test has the benefit of testing for almost all possible weld metal causes of fabrication RHC. The purchaser should decide on whether the screening test and other RHC tests are required, and the purchaser and pressure vessel manufacturer should decide which party will coordinate the testing and determination of acceptable laboratories.

All other requirements from the material specifications for the weld wire and flux should still be met.

B.2 General

This testing procedure covers the assessment of the RHC susceptibility of $2^1/4$Cr-1Mo-V SAW weld metal. This testing procedure should be used if specified by the purchaser as a screening test for each heat-of-wire/batch-of-flux combination. It is not intended to add any additional testing to weld procedure qualifications or production test plates.

The values stated in SI (metric) units are to be regarded as the standard.

B.3 Test Apparatus

B.3.1 Testing Machine

Machines used for tension testing shall conform to the requirements of ASTM E4 or ISO 376.

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[6] The inclusion of the Gleeble test is not intended to endorse it specifically or limit users from considering other applications.

The forces used in determining tensile strength and yield strength shall be within the verified force application range of the testing machine as defined in ASTM E4 or ISO 376.

The testing machine shall be equipped with a means of measuring and controlling either the strain rate, the rate of crosshead motion, or both to meet the requirements in B.6.5. It shall also be equipped with a means of heating and controlling the temperature to meet the requirements in B.6.3.

B.3.2 Gripping Devices

B.3.2.1 General

Various types of gripping devices may be used to transmit the measured force applied by the testing machine to the test specimens. To ensure axial tensile stress within the gage length, the axis of the test specimen should coincide with the center line of the heads of the testing machine. Any departure from this requirement may introduce bending stresses that are not included in the usual stress computation (force divided by cross-sectional area).

The gripping device should be attached to the heads of the testing machine through properly lubricated spherical-seated bearings or duly aligned following requirements of ASTM E1012.

A schematic diagram of a gripping device for threaded-end specimens using lubricated spherical-seated bearings is given in Figure B.1.

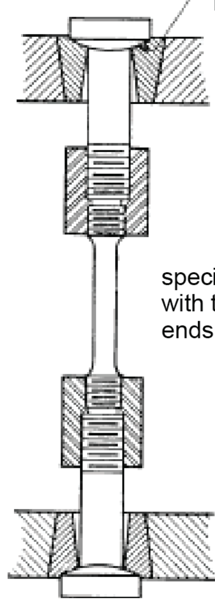


Figure B.1—Example of a Gripping Device Devoted to Threaded-end Specimens

B.3.2.2 Effects of Testing Temperature on Gripping Device

Gripping devices and pull rods may oxidize, warp, and creep with repeated use at elevated temperatures. Increased bending stresses may result. Therefore, grips and pull rods should be periodically retested for axiality and reworked when necessary.

The use of high-temperature-resistant alloys for extension/gripping rods is mandatory in order to avoid yielding and also to control the strain rate in the specimen. Yielding of the rods may have a strong effect on test results by transferring deformation from the specimen gage length to the rods.

As examples, ASTM B637, UNS N07080 (formerly grade 80A), AISI 310S (EN 1.4845/X8 Cr Ni 25 21), and AISI 314 (EN 1.4841/X15 Cr Ni Si 25-21) have been successfully used. Other refractory or high-temperature-resistant alloys may also be used.

B.3.3 Dimension-measuring Devices

Micrometers, calipers, and other devices used for measuring linear dimensions shall be accurate and precise to at least one half the smallest unit to which the individual dimension is required to be measured. Since the measurements shall be to the nearest 0.0008 in. (0.02 mm) (per B.6.7), the accuracy shall not be larger than 0.0004 in. (0.01 mm).

B.3.4 Extensometers

The use of extensometers is mandatory for verification of the strains. They shall record the actual deformation in the gage length and shall be used for determining the yield strength (YS). They should not be used for controlling the test strain rate.

Extensometers used in tension testing shall conform to the requirements of ASTM E83 or ISO 9513 for the testing conditions specified for this test method. ASTM E83 or ISO 9513 shall be used for selecting the required sensitivity and accuracy of extensometers. The extensometer shall also be tested to ensure its accuracy when used in conjunction with a furnace at elevated temperature.

B.3.5 Heating Apparatus and Testing Atmosphere

The apparatus for and method of heating the specimens should provide the temperature control necessary to satisfy the requirements specified in B.6.4.

Heating shall be by an electric resistance, inductive, or radiation furnace with the specimen in air at atmospheric pressure unless another test media is specifically agreed upon in advance.

The recommended media for testing is air (room atmosphere) but the following media can also be applied as alternatives without significant influence on the test results:

— vacuum;

— helium (standard industrial quality); or

— argon (standard industrial quality).

The test atmosphere shall be reported as required in B.8.

B.3.6 Temperature-measuring Apparatus

The method of temperature measurement shall be sufficiently sensitive and reliable to ensure that the temperature of the specimen is within the limits specified in B.6.4.

Temperatures should be measured with thermocouples in conjunction with the appropriate thermometer device and settings. Thermocouples shall have a known calibration. When base-metal thermocouples are used, representative thermocouples should be calibrated for each lot of wires.

Temperature-measuring, -controlling, and -recording instruments shall be verified periodically against a secondary standard, such as a precision potentiometer and, if necessary, recalibrated. Lead-wire error should be checked with the lead wires in place as they normally are used.

B.4 Welding of Screening Test Coupons

B.4.1 Weld Joint Details and Welding Parameters

Weld metal screening test coupons should be prepared with each heat/batch of wire and flux combination proposed to be used for production welding. The base metal and backing plates can be made of:

— carbon steel (CS)-recommended, regardless of pressure vessel material;

— 2^{1}/4Cr-1 Mo or 2^{1}/4Cr-1 Mo-V; or

— CS with the bevel area buttered with 2^{1}/4Cr-1 Mo or Cr-1 Mo-V weld metal.

Welding of the test coupon shall be as summarized in Table B.1 and Figures B.2 and B.3.

Table B.1—Welding Parameters to be Used for Welding of Screening Test Coupons

Specified Welding Conditions		
Wire diameter [a]	0.125 in. (3.2 mm)	0.16 in. (4 mm)
Automatic vs manual welding [b]	Machine / SAW Auto.	
Heat input	49.53 KJ/in. to 54.61 KHJ/in. (1.95 KJ/mm to 2.15 KJ/mm)	
Voltage (V)	30 to 32	
Amperage (A)	500 to 520	540 to 560
Travel speed	19.7 in. ± 0.8 in. (50 ±2 cm/min)	
Polarity (ac or dc +/−)	ac	
Joint preparation	See Figure B.2	
Welding position	1G	
Stick-out	0.9 in. (23 mm)	1.2 in. (30 mm)
Use of strongbacks to minimize distortion (yes or no)	Yes - see Figure B.4 for example	
Preheating	392 °F (200 °C) minimum	
Interpass temperature min./max.	392 °F/572 °F (200 °C/300 °C)	
Post heating or DHT	660 °F ± 50 °F (350 °C ± 10 °C) for 4 hours, minimum	

[a] Either 0.125 in. (3.2 mm) or 0.16 in. (4 mm) wire may be used from a given heat of wire (for a given flux batch) and should match production welding.

[b] Single or tandem wire shall match what will be used for production welding.

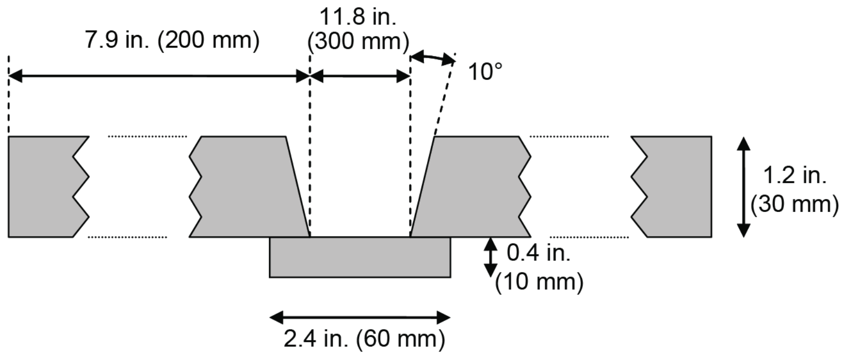


Figure B.2—Geometry of the Weld Joint To Be Used for the Screening Test Coupon

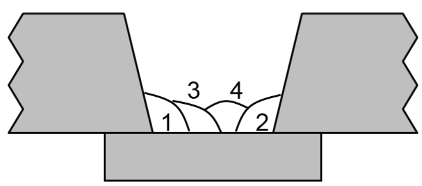
The weld coupon shall use a 1.2 in. (30 mm) thickness plate butt-welding joint with a 10° bevel angle and 1.2 in. (30 mm) root opening, with a backing plate and filling with four beads per layer (see Figure B.2 and Figure B.3).

NOTE This test is not a weld procedure qualification test nor is it relevant to production test plates, and only test coupons welded with these parameters are indicative and valid. The welding parameters do not reflect production welding, and thicker plates should not be used.

B.4.2 Heat Treatment of Test Coupons

Welding step shall be followed by DHT (also referred to as "post heating") at 350 °C ± 10 °C for four hours minimum.

The welded coupon shall not be exposed to high-temperature heat treatment, such as ISR or PWHT. Any deviation will lead to nonvalidity of the results.



NOTES:

a) Four beads per layer.
b) Welding direction reversed after each bead deposit.
c) Coupon's position fixed.

Figure B.3—Welding Sequence To Be Used for the Screening Test

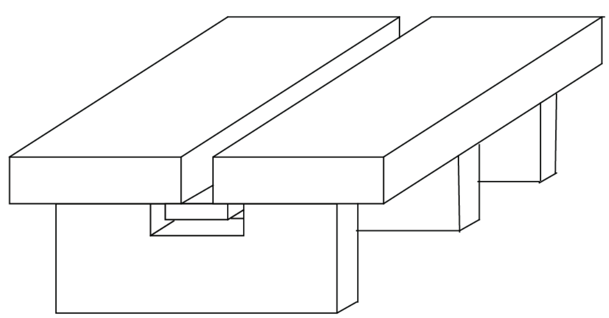


Figure B.4—Example of Strongbacks Used to Minimize Coupon Distortion

B.5 Specimens and Sampling

B.5.1 Sampling

Two parallel RHC test specimens shall be longitudinally machined from the welded joint (see Figure B.5 and Figure B.6). The gap between the two pre-forms shall be 0.08 in. (2 mm). The length of the pre-forms shall be 4.75 in. (120 mm) minimum, and they shall be extracted at least 2 in. (50 mm) from the ends of the test plates. These sample locations can be used for any of the plate and backing materials allowed in B.4.1.

Two in. (50 mm) of each end of the welded joint shall be removed in order to avoid sampling on nonrepresentative microstructures (due to non-stabilized welding parameters during depositing of beads).

B.5.2 Machining and Specimen Dimensions

RHC specimens are machined according to usual techniques (either classical lathe or numerically controlled lathe). Dimensions of the specimens are given by Figure B.7. Calibrated lengths of the specimen as per Figure B.7 are mandatory. Small deviations are acceptable only at the threaded ends as shown. If deviations are required, the axis of the specimen shall be coincident with the axis of the 0.47 in. × 0.47 in. × 4.75 in. (12 mm × 12 mm × 120 mm) pre-form described in B.4.1.

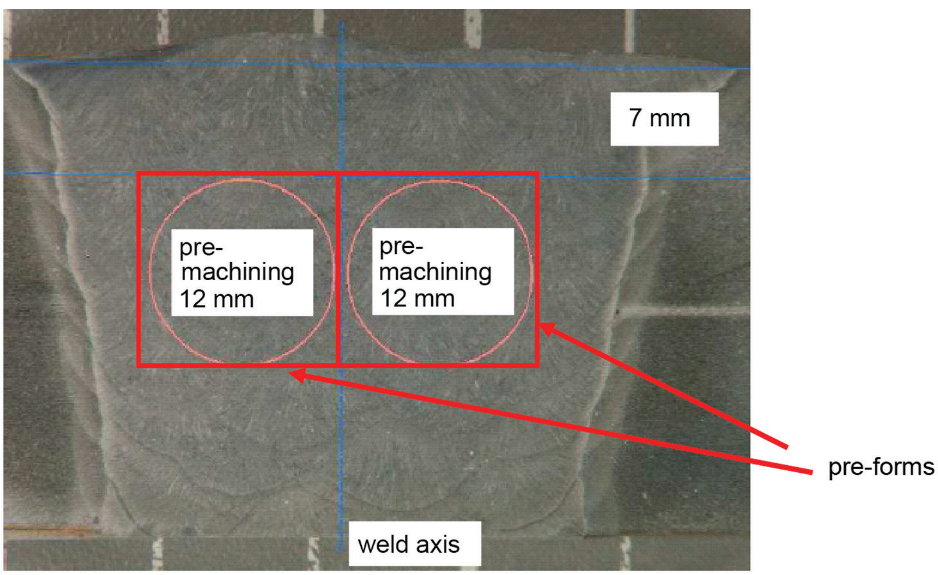


Figure B.5—Position of Pre-forms inside the Welded Zone (Macrographic View)

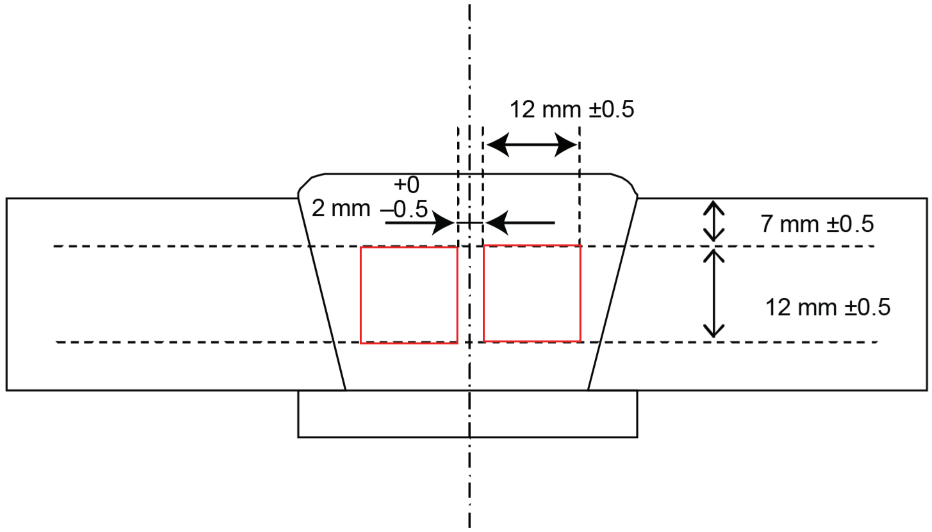


Figure B.6—Position of Pre-forms inside the Welded Zone (Schematic View)

B.6 Test Procedures

B.6.1 Cleaning Specimen

Carefully clean the specimen in fresh alcohol, acetone, or other suitable solvent that will not affect the metal being tested.

(all units, unless specified otherwise, are in mm)

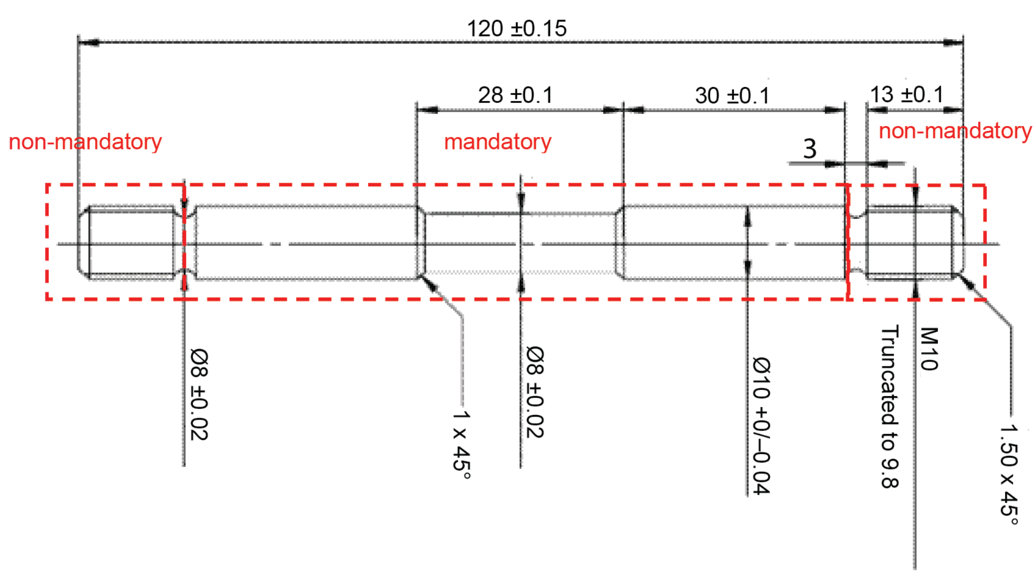


Figure B.7—Detailed Geometry of RHC Standard Specimen

B.6.2 Connecting Specimen to the Machine

It is critical to not introduce nonaxial forces while installing the specimen. Specimens should not be turned to the end of the threads.

B.6.3 Testing Temperature

For the purpose of this RHC screening test procedure, testing temperature shall be equal to 1200 °F (650 °C) ± 5.4 °F (3 °C).

B.6.4 Temperature Control and Heating of the Specimen

The thermocouple beads shall be formed in accordance with ASTM E633.

In attaching thermocouples to the specimen, the junction shall be kept in intimate contact with the specimen and shielded from radiation. Ceramic insulators should be used on the thermocouples in the hot zone. Sheathed thermocouples can be used, keeping in mind the need of intimate contact with the specimen. The use of base-metal thermocouples welded directly on the specimen is also acceptable.

The use of three thermocouples is mandatory: one in the middle of the gage length and one at each end of the reduced section (see Figure B.6).

The temperature difference between the three thermocouples should not exceed ±5.4 °F (3 °C).

For the whole duration of the test (defined as the time from the application of force until fracture), the difference between the measured temperature given by TC1 and the nominal testing temperature (i.e., 1200 °F (650 °C)] shall not exceed ±5.4 °F (±3 °C).

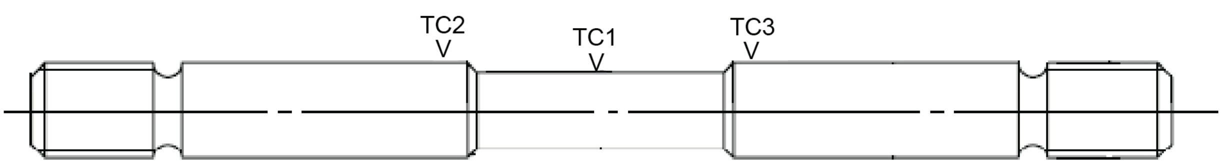


Figure B.8—Location of the Thermocouples on the RHC Standard Specimen

During testing, internal heating due to plastic working may raise the temperature of the specimen above the specified limits. This situation should be minimized by using an adequate heating regulation system or by adjusting the temperature during the test.

The measured test temperature for reporting per B.8 shall be the average of the three thermocouples.

The heating phase of the specimen, from room temperature to stabilized test temperature, shall be achieved in 40 minutes maximum. The heating time shall be reported and the tests which exceed 40 minutes should be considered nonvalid.

The holding time at temperature prior to the start of the test shall be 10 minutes ±1 minute. The start of holding time shall be defined as the time when temperature measured by TC1 (see Figure B.8) reaches the target temperature minus 5.4 °F (3 °C). The time to attain test temperature and the time at temperature before testing shall be reported as required by B.8.

Figure B.9 summarizes the heating of the specimen.

NOTE 1 It is highly recommended that a spare specimen be used in order to set the parameters to obtain homogeneity and relevant conditions.

NOTE 2 The heating characteristics of the furnace and the temperature control system should be studied to determine the power input, temperature set point, proportioning control adjustment, and control-thermocouple placement necessary to limit transient temperature overshoots.

NOTE 3 For resistance furnaces, it is very useful to preheat the furnace at the target temperature and then insert the specimen into the test machine. This facilitates reaching the test temperature within the maximum allowed time.

B.6.5 Strain Measurement and Strain Rate

The tensile properties of tested materials at elevated temperature, as well as their ductility, are strongly affected by the rate of deformation.

Tests shall be performed at constant crosshead displacement rate of 0.03 in. (0.8 mm)/min ±20 % using the standard specimens shown in B.4.2. This displacement rate corresponds to an estimated average strain rate equal to 0.0005 s^{-1}. The displacement rate shall be controlled and reported.

B.6.6 Recording Maximum Force

If an automatic recorder of force and extension is used, the recording of force shall be continued until the sensing element of the extensometer is removed. In all cases (and as a minimum), the maximum force shall be observed and recorded manually.

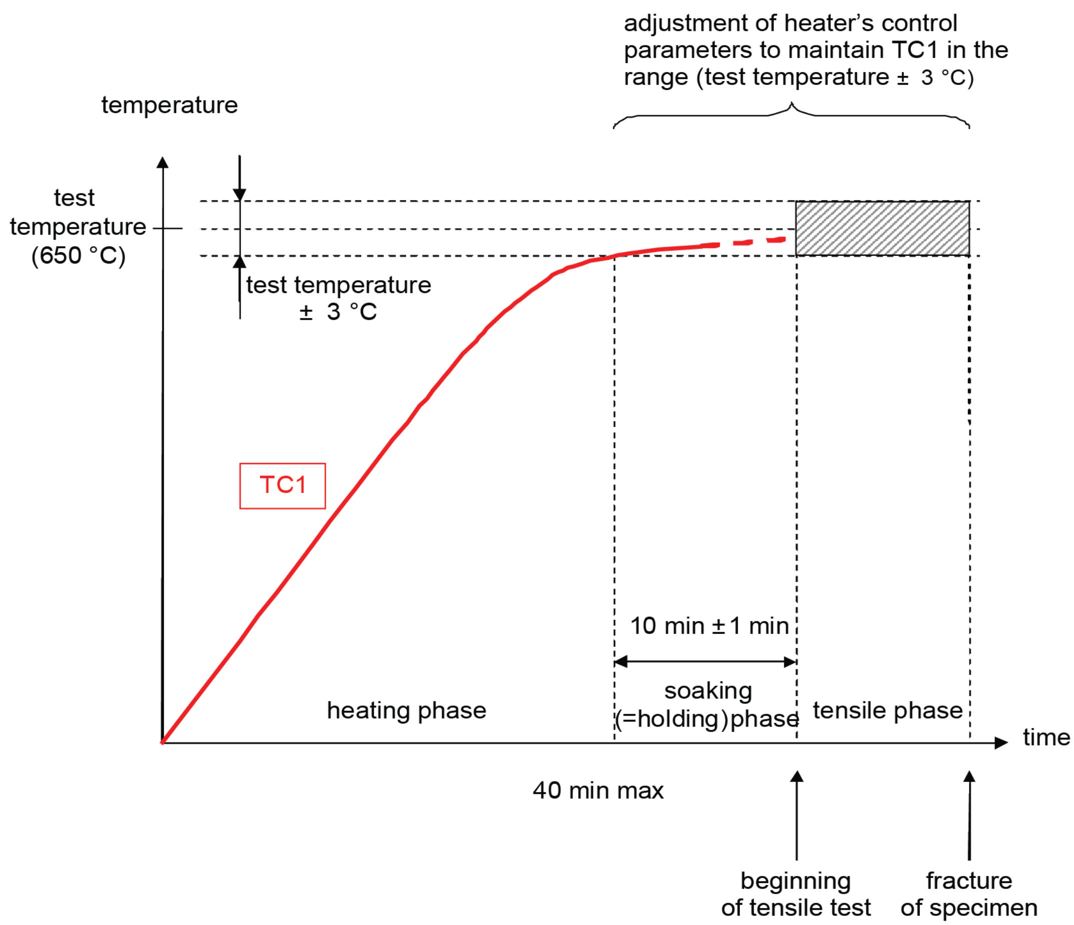


Figure B.9—Illustration of Heating Requirements on Test Specimens

B.6.7 Measurements of Specimen After Test

For determining the reduction of area (RoA) of specimens, diameter of the broken specimen shall be measured at room temperature after cooling down. Diameter shall be measured using a duly calibrated sliding caliper (not a micrometer) and by fitting the ends of the fractured specimen together carefully.

The minimum diameter shall be measured to the nearest 0.0008 in. (0.02 mm) with five (5) measurements minimum at different locations around the circumference. The average of the measurements shall be recorded.

If the fracture cross section is not circular, sufficient diameter measurements shall be made to establish the cross-sectional area at fracture. To account for cases with ovality (variation between two or more measurements), calculation of cross-sectional area after breaking should be done with the elliptic area formula:

$$\text{area} = \pi * (a * b)/4 \tag{11}$$

where

a is the grand axis of the ellipse, and

b is the small axis of the ellipse

Instead of the disc area formula:

$$\text{area} = \pi * D^2/4 \tag{12}$$

where

D is the average diameter.

If elongation is being reported (it is optional), the gage length ($L\text{o}$) should be taken equal to 1.02 in. (26 mm), assuming the deformation is restricted to the reduced diameter length of the specimen.

Fracture should occur in the middle of the gage length (in the central third of the specimen gage length). If the fracture occurs at a fillet or gage mark, the RoA may not be representative of the material, and the test should be declared invalid.

B.6.8 Precision and Bias

The results from each of the two specimens removed from a given weld sample and the average of the two results shall be reported as required in B.8.

B.7 Test Criteria

For a wire-flux combination to be deemed acceptable for RHC resistance:

— the average RoA of the two specimens shall be 32 % min, and

— the RoA of individual specimens shall be 29 % min.

B.8 Report

The report shall include the following (for each individual specimen):

— the description of the material tested with all specified processing information;

— identification of the specimen(s);

— as-built specimen dimensions, including cross-sectional dimensions;

— the temperature of test;

— the test atmosphere;

— the time to attain test temperature and the time at temperature before testing;

— the total duration of the tensile phase of the specimen;

— other special conditions, such as nonstandard atmosphere and heating methods, exceptions to required dimensional accuracy and axiality of loading, and the amount and duration of temperature overshoot;

— the reduction of area for each individual sample and for each test average;

— yield strength and tensile strength.

— when required, elongation and gage length. If elongation was measured from gage marks not on the reduced section of the specimen, this fact should be included in the designation of the quantity, for example, “elongation from shoulder measurements” or “elongation from over-all measurements.” If elongation was measured from the extensometer record at fracture instead of after fracture, this should be noted;

— the location and description of fracture. The description should include any defects, evidence of corrosion, and type of fracture (such as cup and cone, brittle, or shear);

— identification of the equipment used, including make and capacity of testing machine, make and class of extensometer, make and size of furnace, type of temperature controller, and description of thermocouples; and

— name of the test technician and date of the test.

A test certificate shall be issued with this information. A sample certificate is shown in Figure B.10. This certificate and these test results are not required to be included on—and generally will be separate from—the material mill certifications.

Weld Metal/Flux Screening Test Results for Reheat Cracking Susceptibility Tested in accordance with API 934-A, Annex B		
Test Sample Information	Specimen 1	Specimen 2
Identification of the specimen		
Description of material tested with all specified processing information: Manufacturer Wire heat/Flux batch Filler metal classification/diameter (mm)		
As-built specimen dimensions: Original gage length, gage diameter (mm)		
Test Conditions		
Temperature of test (°C)		
Test atmosphere		
Time at heating phase (minutes, seconds)		
Time at soaking/holding phase (minutes, seconds)		
Total duration of the tensile loading phase after soaking/holding phase (minutes, seconds)		
Any special conditions [a]		
Test Results		
Diameter at Fracture-5 readings min. (mm)		
Diameter—average (mm)		
Reduction of area (%)		
Yield strength (MPa)		
Tensile strength (MPa)		
When required, gage length (mm) [b]		
When required, elongation (%) [b]		
Location and description of fracture [c]		
Test Certification		
Make and capacity of testing machine		
Make and class of extensometer		
Make and size of furnace		
Type of temperature controller		
Type of thermocouples		
Name of test technician and date of test		

[a] Examples: nonstandard atmosphere and heating methods, exceptions to required dimensional accuracy and axiality of loading, or amount and duration of temperature overshoot. Some of these factors will result in the test results being rejected.
[b] If elongation was measured from the extensometer record at fracture or from gage marks not on the reduced section of the specimen, for example "elongation from shoulder measurements" or "elongation from over-all measurements."
[c] The description should include any defects, evidence of corrosion, and type of fracture (such as cup and cone, brittle, or shear).

Figure B.10—Sample Test Certificate

B.9 Acknowledgement and Publications

This test procedure was developed quickly and efficiently in response to a definite industry need. Appreciation is given to the JIP sponsors who agreed to promptly publish this procedure to help the industry. The test data and round robin laboratory test results that went into the development of this procedure are published in an ASME PVP Conference 2012 paper by ArcelorMittal Industeel (PVP2012-78030). Additional background is given in ASME paper PVP2009-78144.

Annex C
(informative)

Minimum Pressurization Temperature (MPT) Determination

MPT in this document is considered a form of the Minimum Allowable Temperature (MAT) and methods to determine these parameters are described in API 579-1/ASME FFS-1:2021, Annex 9J.

Development of MPT is an evaluation that considers all credible damage mechanisms, including the susceptibility of hydroprocessing reactor materials to the combined effects of temper embrittlement and hydrogen embrittlement also the calculation is based on the as-fabricated pressure materials properties. MPT calculations are generally performed by the fabricator and are reviewed by the purchaser.

Determination of an accurate MPT is important for operators-user as lower MPT values or curves reduce start-up and shutdown times.

Bibliography

[1] API TR 934-F, Part 1, *Impact of Hydrogen Embrittlement on Minimum Pressurization Temperature for Thick-wall Cr-Mo Steel Reactors in High-pressure H_2 Service—Initial Technical Basis for RP 934-F,* 1st Edition, September 2017

[2] API TR 934-F, Part 2, *Literature Review of Fracture Mechanics-based Experimental Data for Internal Hydrogen-assisted Cracking of Vanadium-modified 21/4Cr-Mo Steel,* 1st Edition, October 2017

[3] API TR 934-F, Part 3, *Subcritical Cracking of Modern 21/4Cr-1Mo-1/4V Steel Due to Dissolved Internal Hydrogen and H_2 Environment, Research Report,* 1st Edition, December 2017

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