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

API RECOMMENDED PRACTICE 934-A
THIRD EDITION, JANUARY 2019

AMERICAN PETROLEUM INSTITUTE

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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 and/or supplement this RP with additional proprietary requirements.

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

1 Scope

This RP covers materials and fabrication requirements for new $2^{1}/_{4}$Cr 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 above. This RP applies to vessels that are designed, fabricated, certified, and documented in accordance with ASME Section VIII, Division 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 vessels with wall thicknesses below 4 in. (100 mm), and/or operating at temperatures of less than 650 °F (345 °C), 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); however, a specific Code Case developed for these alloys is 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 steels including standard $2^{1}/_{4}$Cr-1Mo and 3Cr-1Mo steels, and advanced steels which include $2^{1}/_{4}$Cr-1Mo-$^{1}/_{4}$V, 3Cr-1Mo-$^{1}/_{4}$V-Ti-B, and 3Cr-1Mo-$^{1}/_{4}$V-Nb-Ca steels. This document may be used as a reference document for the fabrication of vessels made of enhanced steels (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. Multilayer vessels are also outside the scope of this document.

Heat exchanger shells and channels which 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 third edition of RP 934-A. The legacy first edition was API RP 934, *Materials and Fabrication Requirements for $2^{1}/_{4}$Cr-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.

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, *Welding Guidelines for the Chemical, Oil, and Gas Industries*

ASME [1] *Boiler and Pressure Vessel Code*, 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-234, *Standard Specification for Piping Fittings of Wrought Carbon Steel and Alloy Steel for Moderate and 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-435, *Standard Specification for Straight-Beam Ultrasonic Examination of Steel Plates*

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*

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

1 ASME International, Two Park Avenue, New York, New York 10016-5990, www.asme.org.
2 American Society for Nondestructive Testing, PO Box 28518, 1711 Arlingate Lane, Columbus, Ohio 43228-0518, www.asnt.org.

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

AWS [4] A4.2M (ISO 8249:2000 MOD), *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Ferritic-Austenitic Stainless Steel Weld Metal*

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

WRC [5] Bulletin 519, *Stainless Steel Weld Metal—Prediction of Ferrite Content: An Update of WRC Bulletins 318 and 342*

3 Terms, Definitions, and Acronyms

3.1 Terms and Definitions

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

3.1.1
advanced Cr-Mo steel
A CrMo steel grade (typically quenched and tempered) that has had its strength level enhanced by vanadium and possibly other alloying additions. 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 Code Cases.

3.1.3
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 (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.

3.1.4
final PWHT
The last postweld heat treatment after fabrication of the vessel and prior to placing the vessel in service.

3.1.5
hot forming
The mechanical forming of vessel components above the final PWHT temperature.

3.1.6
Larson-Miller parameter
Parametric relationship proportional to the aggregate heat treatment temperature(s) and duration(s). LMP can be used to assess the effect of individual or multiple heat treatment(s) on a specific material property such as strength or

[3] ASTM International, One Hundred Barr Harbor Drive, PO Box C700, West Conshohocken, Pennsylvania 19428-2959, www.astm.org
[4] American Welding Society, 8669 NW Thirty-sixth Street, #130, Miami, Florida 33166-6672, www.aws.org.
[5] Welding Research Council, PO Box 201547, Shaker Heights, Ohio 44122, www.forengineers.org.

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.

$$LMP = T \times (20 + \log t) \qquad \text{Final } LMP = T_i \times [20 + (\log t_i + t_{eqi})] \tag{1}$$

$$t_{eqi} = 10\text{^}\{T_i / T_{eqi} * [20 + \log(t_i)] - 20\} \tag{2}$$

where

T is the temperature in kelvins; and

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."

3.1.7
manufacturer
The firm or organization receiving the purchase order to manufacture the pressure vessel, or materials.

3.1.8
maximum PWHT
Specified heat treatment (aggregate temperature and time) of test coupons used to simulate the maximum heat treatment exposures on 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, maximum PWHT includes all fabrication heat treatments above 900 °F (482 °C), e.g. intermediate stress relief (ISR), all 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. DHT do not need to be included, as they are at temperatures too low to affect material properties.

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

3.1.9
minimum PWHT
Specified heat treatment (aggregate temperature and time) of test coupons used to simulate the minimum heat treatment exposures on 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 all fabrication heat treatments above 900 °F (482 °C), e.g. 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 should be agreed upon by purchaser and manufacturer.

3.1.10
narrow groove welding
A multi-pass weld in which the bevel has a very small groove angle, which yields a weld with a high ratio of depth to width.

3.1.11
purchaser
The firm or organization that has entered into the purchase order with the manufacturer, or their designated representative.

3.1.12
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.

3.1.13
temper embrittlement
The reduction in toughness due to a metallurgical change 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 be susceptible to brittle fracture during subsequent hydrotests, start-ups, and shutdowns.

3.2 Acronyms

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

DAC	distance-amplitude correction
DHT	dehydrogenation heat treatment
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
PQR	procedure qualification record
PT	penetrant testing
PWHT	postweld heat treatment
RHC	reheat cracking
RT	radiographic testing
SDH	side-drilled holes
TOFD	time-of-flight diffraction (a UT technique)
UT	ultrasonic testing
WPS	welding procedure specification

4 Design

4.1 Design and manufacture shall conform to ASME Section VIII, Division 2 and its applicable 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, and/or weld overlay or cladding thickness.

b) Weld seam layouts shall provide that all 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. The 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 vessel body as shown in ASME Section VIII, Division 2, 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, Table 4.2.10, Detail 3 through Detail 6, with integral reinforcement.

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

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 should not be mixed in the same vessel (e.g. standard $2^1/_4$Cr-1Mo nozzles should not be used with $2^1/_4$Cr-1Mo-$^1/_4$V 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 Section 7.1.5).

5.1.3 External attachments (such as lugs, clips, etc.) welded directly to the pressure boundary shall be of the same nominal material chemical composition (without the added limits given in Section 5.3) as the pressure boundary material. It is acceptable for non-pressure parts (such as skirts, lugs, clips, etc.) made of $2^1/_4$Cr-1Mo to be used on $2^1/_4$Cr-1Mo-$^1/_4$V pressure parts.

5.2 Steel-making Practice

In addition to steel-making practices outlined in the applicable material specifications, the steels shall be vacuum degassed, and all 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 1/4Cr-1Mo**	**Standard 3Cr-1Mo**	**2 1/4Cr-1Mo-1/4V [a]**	**3Cr-1Mo-1/4V-Ti-B [a]**	**3Cr-1Mo-1/4V-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] 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] SA-508, Gr. 22, Cl 3 and 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

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

$$\text{J-factor} = (\text{Si} + \text{Mn}) \times (\text{P} + \text{Sn}) \times 10^4 \leq 100 \text{ (with Si, Mn, P, and Sn in wt \%)}$$

$$\text{Cu} = 0.20 \text{ wt \% max.}$$

$$\text{Ni} = 0.30 \text{ wt \% max. for conventional steels and } 0.25 \text{ wt \% max. for advanced steels.}$$

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); or

b) accelerated cooled from austenitizing and then tempered, with the accelerated cooling by air blasting or liquid quenching. In this case, the steel is often referred to as “quenched and tempered” (Q&T).

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 3.1.8 and 3.1.9). The cumulative effects of the various heat treatments shall be evaluated by using the equivalent LMP approach, as required for 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 $^1/_2T$ location, and at the $^1/_4T$ location in accordance with ASME SA-20 if required by Code ($^1/_2T$ is acceptable per Code for SA-387 and SA-542 materials by specifying Supplementary Requirement S53). Specimens shall be oriented transverse to the rolling direction, in accordance with SA-20. Distance from plate edges shall be $1T$.

b) Forging—from each heat (except as allowed by 5.5.1.1.c), $^1/_2T$ of the prolongation or of a separate test block (sample location from side edges shall be per Code). Specimen shall be oriented transverse to the major working direction. A separate test block, if used, shall meet Code and shall be made from the same heat and should receive substantially the same reduction and type of hot working as the production forgings that it represents, and should 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, the 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 $^1/_2T$. Specimens shall be oriented transverse to the major working direction in accordance with ASME SA-530.

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

5.5.1.2 Heat Treatment of Test Specimens

Test specimens shall be heat treated as specified in Table 2. If the base metal is heat treated after hot forming, test specimens should be subjected to a simulated hot forming heat treatment prior to the heat treatment specified in Table 2. If the heat treatment after hot forming consists of full austenitizing such as in quenching or normalizing, and is higher than the hot forming temperature, simulated hot forming heat treatment is not necessary.

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 fabricators is needed, as testing materials with these heat treatments is more meaningful and is acceptable per the Code.

[b] These heat treatments shall meet or exceed the requirements of ASME Section VIII, Division 2, Paragraph 3.4 and ASME Code Case 2151-1.

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 fabricator). 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 steels: 100 ksi (690 N/mm^2);

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

b) Yield strength shall not exceed the following limits:

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

— advanced 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, test specimens should be in the maximum PWHT condition, and acceptance values should be as specified by the purchaser. Typically, if tests are required, the minimum acceptance values are 85 % of values listed in ASME Section IID, Table U for the test temperature.

5.5.3 Impact Properties

5.5.3.1 General

Average impact 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 temperature. If testing done 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.

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 shown in 6.2.4). If the purchaser decides to impose the step cooling tests of base metals, the test procedure and the acceptance criteria should be in accordance with 6.2.4. The purchaser may opt to require that the step cooling tests be performed only on the heat with the highest J-factor.

If the purchaser is requiring step cooling tests of base metals, the purchaser may substitute (as an alternative) impact testing at –80 °F (–62 °C) with results of 40 ft-lb (55 J) average minimum and 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.

6 Welding Consumable Requirements

6.1 Material Requirements

6.1.1 The deposited weld metal, from each lot or batch of welding electrodes and 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 shall meet the following limits to improve resistance to temper embrittlement. These limits apply to the heat analysis:

$$\text{X-bar} = (10P + 5Sb + 4Sn + As)/100 \leq 15 \text{ (P, Sb, Sn, and As are in ppm)}$$
$$Cu = 0.20 \text{ wt \% max.}$$
$$Ni = 0.30 \text{ wt \% max.}$$

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

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

NOTE While the K-factor (based on ASME PVP paper 2009-78144 [1]) is also a good indicator for indicating RHC susceptibility due to Pb/Bi contamination, the required sub-ppm accuracy needed in the laboratory test methods is only available using very specialized testing, and only a few labs around the world have this equipment. Therefore, specifying testing of the K-factor is not recommended.[2] Also, the K-factor does not screen for possible RHC caused by other contaminating element(s). For reference, $Kf = Pb + Bi + 0.03Sb$ (element concentrations expressed in ppm).

6.2 Mechanical Properties

6.2.1 Tensile Properties

The tensile properties of the deposited weld metal shall meet those of the base metal in accordance with 5.5.2. The maximum yield strength limit for deposited weld metal when using advanced 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), weld metal stress rupture tests for each SAW wire and flux combination are required per ASME Section VIII, Division 2, paragraph 3.4.4.5. Both specimens parallel (all weld metal) and transverse to the weld axis (with base metal included) are required by the 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.

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 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 follows [all hold temperature tolerances are ±15 °F (8.3 °C)].

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

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

STEP 3 Hold at 1100 °F (593 °C) for 1 hour minimum.

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

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

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

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

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

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

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

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

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

STEP 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.

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. The impact properties shall meet the following requirement:

$$CvTr\,40 + 2.5\,\Delta CvTr40 \leq 50\ °F\ (10\ °C);$$

where:

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

$\Delta CvTr\,40$ 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.

7 Welding, Heat Treatment, and Production Testing

7.1 General 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.

7.1.2 Welded joints, including non-pressure attachments to the 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; and

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

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

7.1.4 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 shall meet all the requirements that applied to the original fabrication welds.

7.1.5 No pressure-containing 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 if allowed on a case-by-case basis 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. Depending on the process temperature and line size, there are cases where a dissimilar metal pipe-to-pipe weld is preferred over dissimilar metal flanges.

7.2 Welding Procedure Qualification

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

— conventional steels: ASME Section IX; or

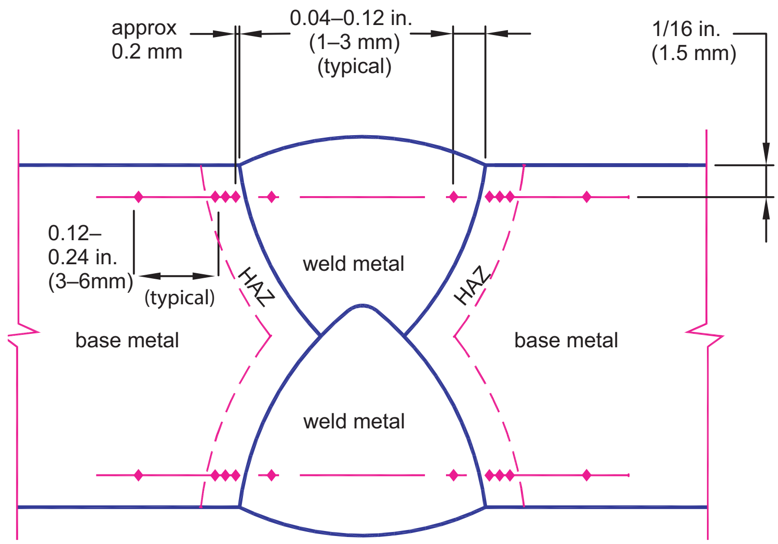
— advanced steels: ASME Section IX and ASME Section VIII, Division 2, Paragraph 3.4, or ASME Code Case 2151-1, as applicable.

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 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.

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 the weld joint shall be made on a weld sample 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, the purchaser shall decide if the hardness test locations are sufficient. The hardness shall not exceed 235 HV10 for conventional steels and 248 HV10 for advanced 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, and should meet the ambient temperature properties specified for the base metal in 5.5.2.

7.2.7 WPSs/PQRs shall be submitted to purchaser for review and acceptance prior to fabrication.

7.3 Preheat and Heat Treatments During Base Metal Forming and Welding

7.3.1 Preheat

7.3.1.1 Base metal shall be heated to a minimum of 400 °F (205 °C) for both conventional and advanced steels prior to and during all welding operations (except as modified for weld overlay; see 7.5.4).

NOTE The 400 °F (205 °C) preheat for welding is based on the ASME Sec. VIII, Div. 2 non-mandatory Table 6.7 (see Paragraph 6.4.1.2 of the Code). Lower preheat values have been used successfully in the past by numerous fabricators. Proposed 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 steels and 350 °F (177 °C) for advanced steels prior to, and during, all thermal cutting and gouging operations.

7.3.1.3 Preheating at a minimum of 300 °F (150 °C) for conventional steels and 350 °F (177 °C) for advanced steels is also required for rolling, forming, and pressing operations, unless the manufacturer proposes no preheat, considering the material toughness, edge preparation, ambient temperature, and their experience, and submits this for approval to the purchaser.

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, this preheat temperature 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 is required before cooling below preheat temperature prior to PWHT, unless purchaser approves the use of DHT. ISR should not be waived for restrained joints such as all nozzle welds for advanced grades and nozzle welds in conventional grades with shell or head thicknesses 6 in. (150 mm) and greater, unless approved by purchaser after careful review.

Approval of DHT in lieu of ISR can be considered for nonrestrained joints for conventional or advanced grades, or for conventional grade nozzle welds less than 6 in. (150 mm) thick, but should be granted only after careful consideration of the metallurgical factors and possible risks. A higher level of concern with DHT is typically applied to advanced steels, as they can have low as-welded toughness. Although a DHT will reduce hydrogen, it will not sufficiently restore toughness, especially for advanced materials which remain very brittle during pre-PWHT handling. To approve the use of DHT, the purchaser should require test and/or experiential data such as past case histories of welded pressure vessels by this manufacturer (with details on materials, thicknesses, and weld joints receiving DHT, data concerning hydrogen controls for procurement and handling of welding consumables, and the planned NDE of the weld joints). Purchaser may require the manufacturer to demonstrate and use high-sensitivity ultrasonic examination procedures to detect flaws at weld joints after using a DHT.

Factors to be considered when reviewing possible use of DHT are the degree of weld restraint, weld joint thickness, experience of the manufacturer, and type of steel. DHT is commonly allowed for conventional steels on nonrestrained welds such as shell welds and shell-to-head welds.

In some cases, it may be physically impractical to fully maintain preheat during transporting of the reactor to the furnace 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 reactor welds may be below preheat temperature before ISR. Purchaser can then decide if the proposed heat treating steps are acceptable for each reactor on a case-by-case basis.

7.3.2.2 Intermediate Stress Relief

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

— conventional steels: 1100 °F (593 °C) minimum for 2 hours minimum;

— advanced steels: 1200 °F (650 °C) minimum for 4 hours minimum, or 1250 °F (680 °C) minimum for 2 hours minimum.

7.3.2.3 Dehydrogenation Heat Treatment (DHT)

The DHT shall be performed at a minimum metal temperature of 570 °F (300 °C) for conventional steels and 660 °F (350 °C) for advanced 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 steels and four hours for advanced 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 content (as applicable) of the weld deposits shall be within the ranges specified in ASME Section II, Part C and ASME Section VIII, Division 2, Table 3.2, for the specified electrodes or wires.

7.4.2 Hardness of Weld Deposit and Adjacent Base Metal

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 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 and base metals adjacent to the fusion line on both sides. Hardness values of all three locations should be reported.

7.4.2.3 Hardness values shall not exceed:

— conventional steels, 225 HBW, or equivalent;

— advanced steels, 235 HBW, or equivalent.

Hardness tests shall be performed on each 10 ft (3 m) length of weld, or fraction thereof. This testing should be performed on the side exposed to the process environment when accessible. This requirement does not apply to weld overlays or welds that are covered with weld overlay on the side exposed to the process.

NOTE HAZ hardness tests on vessel production weldments may actually be an average of the HAZ, weld deposit, and base metal hardnesses, as the test indentation is generally larger than the HAZ width.

7.4.3 Weld Metal Production Impact Tests

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.

7.5 Weld Overlay

7.5.1 Material Requirements and Number of Layers

Material requirements and number of layers are as follows.

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 any 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.

2) Single layer overlays applied with automatic welding processes are commonly used and are acceptable as long as all the requirements herein and the requirements in API RP 582, Appendix B (except para. B.1.1) are met.

7.5.2 Disbonding Tests

7.5.2.1 When required by purchaser, hydrogen disbonding tests on the proposed overlay weld procedures shall be done per ASTM G146, at the testing conditions defined by purchaser.

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 vessel shell rings and heads. Previously qualified disbonding test results can be submitted for review by the purchaser if representative of the proposed WPS and operating conditions.

7.5.2.3 When testing is required by purchaser, the test parameters should result in hydrogen charging which meets or exceeds the hydrogen charging from operation. Since the sample size and geometry are different than the actual 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 reactor wall thickness, pressure, and temperature, are defined in Table 4.

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

Reactor 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).

7.5.2.4 Vanadium-modified grades have been shown to be very resistant to disbonding for all the domains indicated in Table 3[3,4] and purchaser can determine if testing is necessary.

7.5.2.5 For conventional 2 1/4Cr-1Mo steel reactors where the operating conditions fall into the D, E, and F domains, the risk of disbonding is very low and the purchaser can determine if testing is necessary.

7.5.2.6 The acceptance criteria for the test results shall be an Area Ranking A, per ASTM G146.

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 RP 582, Appendix B (except para. B1.1).

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 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 vessel base metal or 1 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 chemical analysis of samples taken at 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.

7.5.4 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). Provided that subsequent still-air cooling is applied, ISR may be omitted after overlay welding. No preheating is required for the second and any subsequent layers of weld overlay.

7.5.5 Production Testing of Weld Overlay

7.5.5.1 Chemical Composition of Weld Overlay

The chemical composition of the weld overlay shall be checked by laboratory chemical analysis of a sample 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 for each shell ring and head, and one for each welding process for nozzles shall be required. Use of PMI testers at the required thickness, may also be used, if approved by purchaser. 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 A4.2 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 A4.2, Appendix A7, Paragraph A7.1 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 The value of all ferrite readings at each location shall meet the requirements in 7.5.1. If readings are outside of the specification, the corrective action shall be determined to the agreement of the purchaser and the manufacturer.

7.6 Final Postweld Heat Treatment

7.6.1 The fabricated vessel should be postweld heat treated as a whole in an enclosed furnace whenever possible. When vessel size does not allow PWHT as a whole in a furnace, 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 The PWHT temperature shall be strictly controlled, measuring both the vessel skin and furnace temperatures using thermocouples, including any portion of the vessel outside of the furnace. Any section of the vessel outside the furnace shall be insulated such that the temperature gradient is not harmful. Thermocouple arrangements shall be established for each heat treatment. The skin temperature shall be measured and controlled on the inside and outside of the vessel.

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

Table 5—PWHT Holding Temperature and Time

Material	PWHT Temperature	Holding Time
Conventional Steels	1275 °F ± 25 °F (690 °C ± 14 °C)	See footnote a
Advanced Steels	1300 °F ± 25 °F (705 °C ± 14 °C)	8 hours minimum b

[a] Withholding time shall meet ASME Section VIII, Division 2, 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 requirements (Table 6.11) must also be met if stricter.

8 Nondestructive Examinations

8.1 General

NDE personnel shall be qualified in accordance with ASNT SNT-TC-1A or ASNT CP-189 or other agencies with purchaser approval. For ASME Section VIII, Division 2 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, all bare and clad base metal plates should be ultrasonically examined with 100 % scanning before forming in accordance with ASME Section V and 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 edges, 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 Entire surfaces of formed plates to be welded for shell rings and heads, including welding edges and surfaces to be weld overlayed, 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 all welds excluding stainless weld overlay. This includes pressure-retaining base metal welds, weld build-up deposits, root passes, and attachment welds. MT shall also be performed after any gouging or grinding operation, including back gouging of root passes. MT should be in accordance with ASME Section VIII, Division 2, Paragraph 7.5.6.

8.3.2 Temporary attachments should be minimized. Areas where temporary attachments have been removed shall be examined by MT or PT in accordance with 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 used 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 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 Section 8.5.1.1.

NOTE For SAW welds categorized as "non-prescreened" as defined in Annex A, the special UT is required 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, approximately 3.2 in. (80 mm) wide along the full length of the 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 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 Paragraph 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 non-overlayed 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 of attachment welds 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 the purchaser's PMI specification.

9 Hydrostatic Testing

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

9.2 Test water should not contain more than 50 ppm chlorides.

9.3 During the hydrostatic testing, the 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 Paragraph 8.2.4 of the Code states that the hydrotest temperature must be 30 °F (17 °C) above the MDMT, ASME Code Case 2718 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 vessel shall be drained and thoroughly dried immediately after testing.

10 Preparations for Shipping

10.1 Immediately after completion of final examination of the vessel, the interior of the vessel shall be cleaned and dried. Heat drying and/or other evaporative means shall not be used due to possible chloride contaminants from the hydrotest water.

10.2 Vessel openings shall be sealed with a steel cover and gasket, and either the vessel shall be filled with dry nitrogen gas at a suggested pressure of 5 psig (34.5 kPa), or a desiccant system or a vapor phase inhibitor shall be used. If nitrogen is applied, the nitrogen pressure should be maintained during transportation, erection, and pre-commissioning. The vessel should be marked, and a conspicuous warning tag shall be attached at each manway stating, "THE VESSEL IS FILLED WITH NITROGEN—DO NOT ENTER."

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

11 Documentation

The following documentation for all pressure-retaining parts, including welding consumables, shall be completed prior to the start of fabrication and should be available for examination by the purchaser at the time of inspection (except for the results of testing done later in the fabrication). The following complete documentation should be submitted to the purchaser at the completion of the project:

a) MTRs showing chemical composition and mechanical test result;

b) J-factors;

c) X-bars;

d) impact test results before and after step cooling;

e) hot tensile test results (if required);

f) welding procedure specifications with applicable procedure qualification records;

g) PMI report;

h) hardness test results;

i) NDE reports;

j) heat treatment data showing hold time and temperature for PWHT, ISR, and DHT; and

k) production test results.

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	—	—	—	—
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	5.3.2	—	—	—	—	—	—	—
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											
Edges Prepared for Welding	—	—	—	—	—	—	—	8.2.2.1 [a] 8.2.2.2 [a]	8.2.2.1 [a] 8.2.2.2 [a]	—	—
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	—	—	—	—	—	—	—	—	—	—	—

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 Weld Overlay											
Before Overlay Welding	—	—	—	—	—	—	—	8.2.2.1 [af] 8.2.2.2 [af]	8.2.2.1 [af] 8.2.2.2 [af]	—	—
Before PWHT	—	—	8.6	7.5.5.1	7.5.5.2	—	8.4.2	—	—	—	—
After PWHT	—	—	—	—	—	—	8.5.2.2	—	8.5.2.1 [g]	—	—
Production Test Plates											
Base Metal Welds	—	7.4.3	—	—	—	—	—	—	—	—	—
Miscellaneous											
Locations of Temporary Attachments	—	—	—	—	—	—	—	8.3.2 [ah]	8.3.2 [ah]	—	—
Vessel-to-skirt Welds Prior to PWHT	—	—	—	—	—	8.4.1.1	8.4.1.2 [d]	—	—	—	—

[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 plate or forging surface to be weld overlayed; on plates, this NDE shall be after forming.

[g] All stainless steel weld overlay, and attachments to the overlay.

[h] Areas where temporary attachments have been removed.

Annex A
(informative)

Guidance for Inspection for Transverse Reheat Cracking

A.1 Foreword

This annex was issued in response to widespread fabrication problems with $2^1/_4$Cr-1Mo-V reactors 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 Code-required NDE) and to suggest appropriate evaluation/rejection criteria. Since in some welds, it may be difficult to detect *all* the reheat cracks, 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 all welds made with the same heat of welding consumables can be thoroughly evaluated.

A.2 Terms and Definitions

For the purposes of this annex, the following terms and definitions will be used and shall be assigned by purchaser.

A.2.1
non-prescreened 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).

A.2.2
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).

A.3 Referenced Industry Documents

A.3.1 American Society of Mechanical Engineers (ASME)

Boiler and Pressure Vessel Code, Section V, Article 4, *Ultrasonic Examination Methods for Welds*

Boiler and Pressure Vessel Code, Section VIII, Division 2, *Alternative Rules*

A.3.2 International Standards Organization (ISO) and European Norms (EN)

ISO 23279, *Non-destructive Testing of Welds—Ultrasonic Testing—Characterization of Discontinuities in Welds*

A.4 Brief Description of the Cracking Conditions and Morphology

The "reheat cracking" which caused the major problems at multiple (but not all) reactor 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. (10 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; and

— 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 the cracking only occurs after a heat treatment cycle 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.

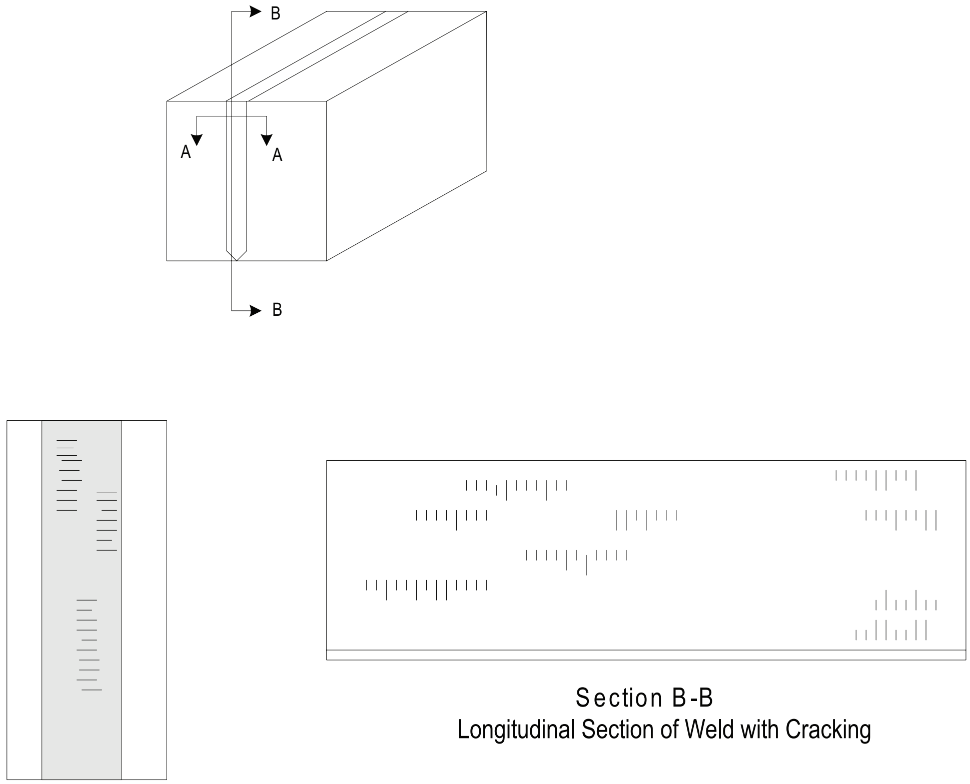
Both single and tandem wire SAW welds have experienced cracking. Cracking has not been experienced with other welding processes using flux-containing welding consumables such as SMAW or FCAW.

A.5 Recommended Inspection Strategy and Timing

A.5.1 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 overlayed 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 which 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



Section B-B
Longitudinal Section of Weld with Cracking

Section A-A
Top View of Cracking

Not to Scale

Figure A.1—Schematic Showing Reheat Cracking Locations

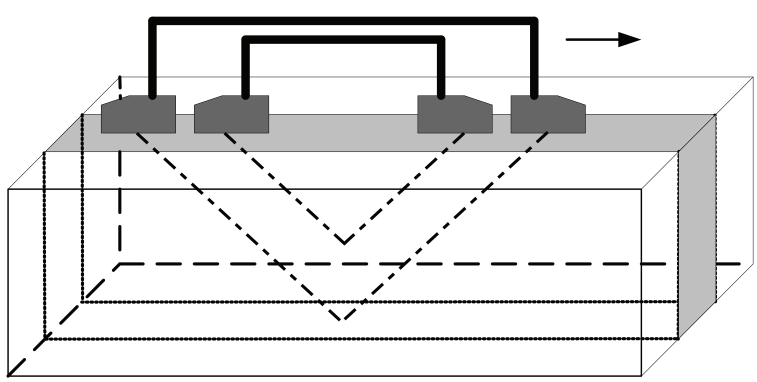


Figure A.2—B-scan for Detecting Transverse Defects with TOFD

orientation. Flaws which 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.

A.5.2 Special Inspection Timing/Frequency

a) UT inspection (see A.6) should be performed on 100 % of non-prescreened SAW welds, before PWHT but after ISR or other >1150 °F (620 °C) reheating steps are completed.

b) On the non-prescreened 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 non-prescreened welds, reinspection with these special TOFD procedures should be performed on the following:

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

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

d) TOFD per A.6.1 should be performed on circumferential and longitudinal seams, and pulse-echo UT, per the procedures in A.6.3, should be performed on the nozzle welds. Pulse-echo UT per A.6.2 should also be used to characterize indications found by TOFD.

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.6.1 or A.6.2. This scanning must be performed after a heat treatment cycle >1150 °F (620 °C), but can be done at whatever point after this or subsequent heat treatments which is optimum for the production cycle. This inspection may or may not provide scanning of the full weld thickness and/or 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.5.3 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 vessel inspection package.

A.6 Inspection Methods and Guidelines

A.6.1 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 (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 (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.

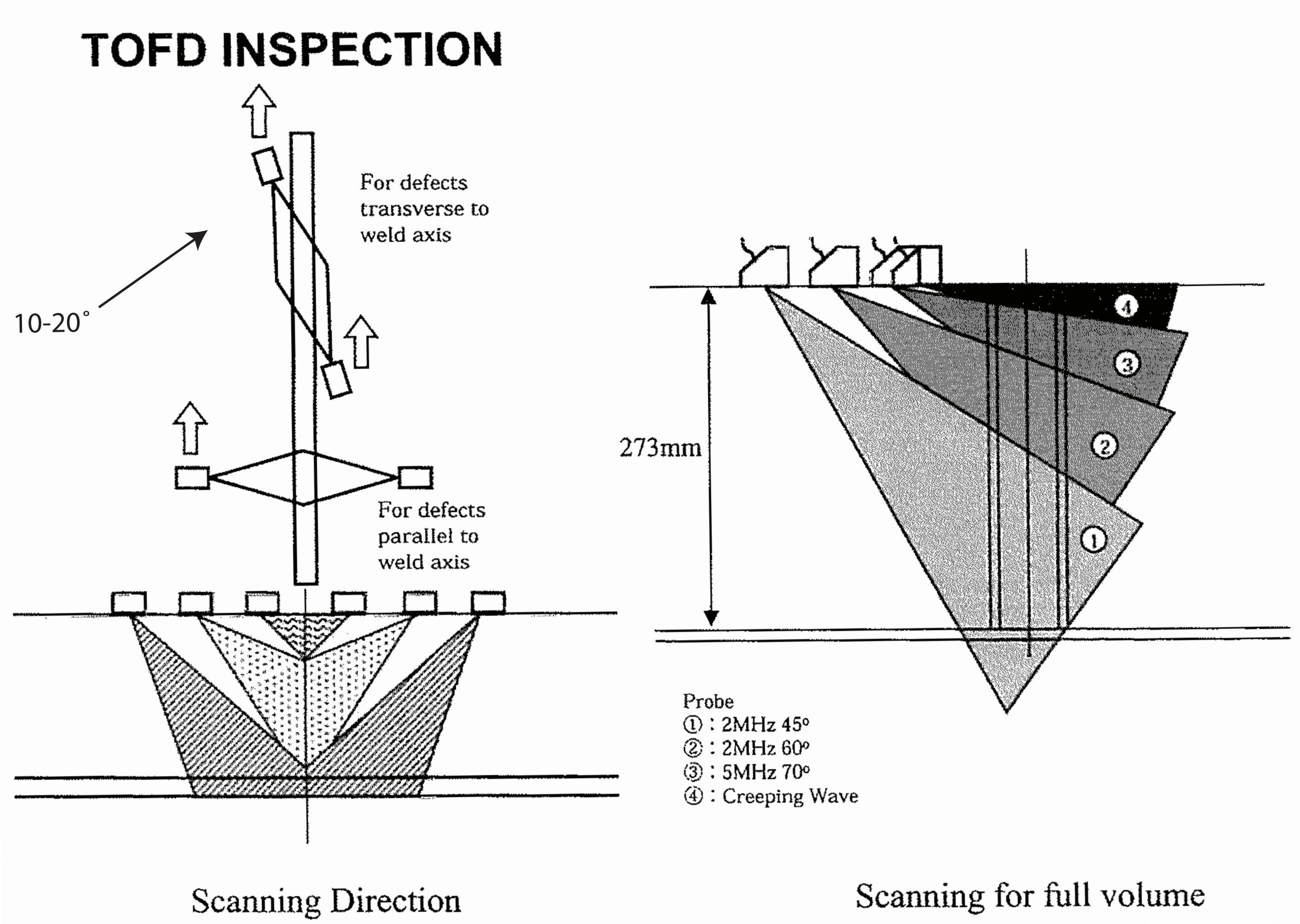


Figure A.3—Alternate Probe Setup with Offset for Detecting Transverse Defects

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 must 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, 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, 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 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

	Recommendation	Comments
Surface condition of welded joint	Flush Ground on both inside (ID) and outside (OD).	For non-prescreened welds, the grinding must 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 section A.6.1.
Sensitivity demonstration block	A series of 0.157 in. × 0.157 in. × 0.157 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 % (0.1T) 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, 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.5.2. 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 would be:

Probe Angle	Probe Diameter	Probe Frequency	Probe Center Spacing (PCS)
60 degree	$^{1}/_{4}$ in. (6 mm)	5 MHz	3.42 in. (87 mm)
45 degree	$^{1}/_{2}$ in. (12.5 mm)	2 MHz	7.87 in. (200 mm)
25 degree	$^{1}/_{2}$ 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.

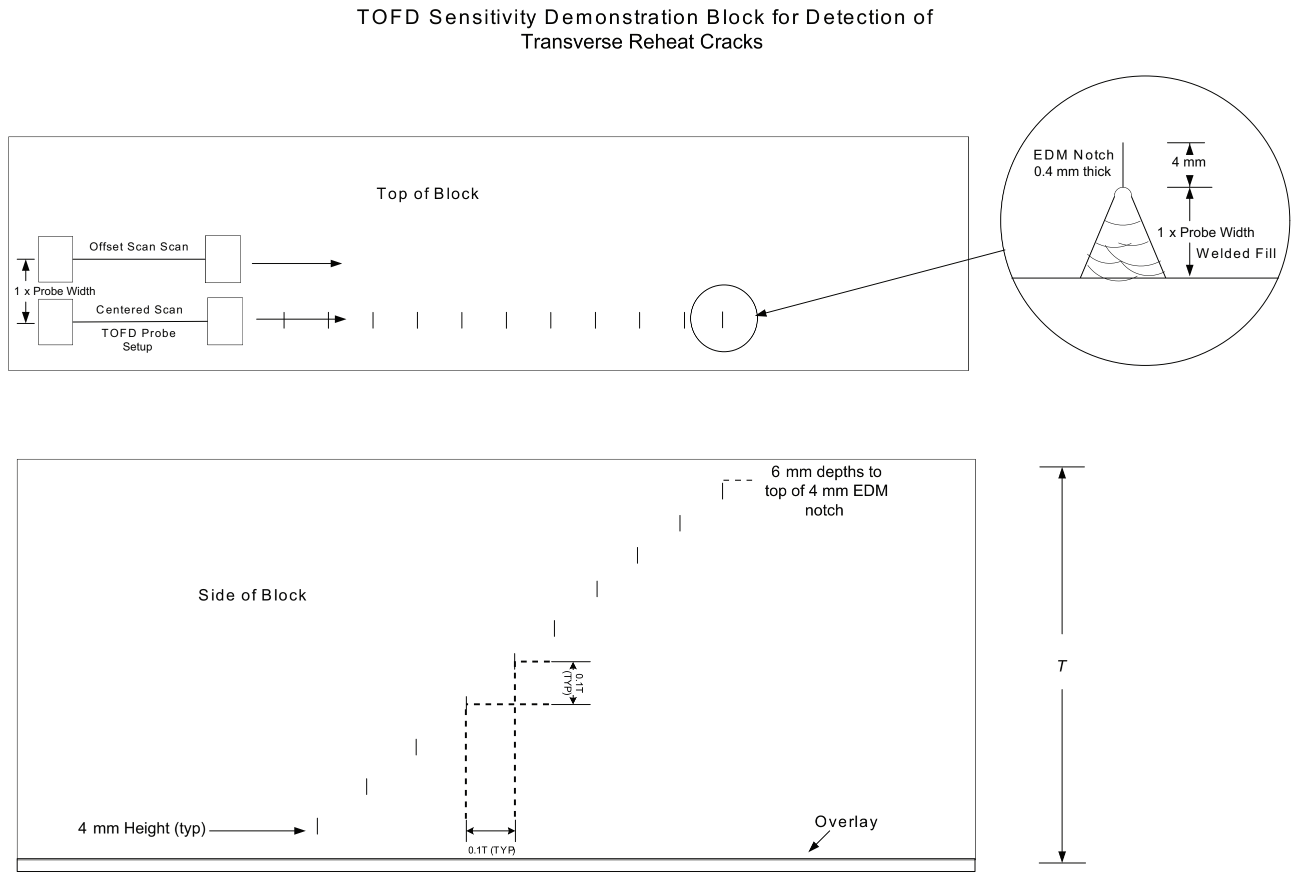


Figure A.4—TOFD Sensitivity Demonstration Block

A.6.2 Manual Pulse-echo Shear Wave UT

Table A.2 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 must be paid to areas near the surface zones that are within the TOFD blind zones.

Table A.2—Manual Pulse-echo Shear Wave Guideline for Identifying Transverse Reheat Cracks

	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 degrees.	Multiple probes are used to “cover” the near and far zones: — 70 degrees covers about 0.4 in. (10 mm) to 4 in. (100 mm), — 60 degrees covers about 2 in. (50 mm) to 6 in. (150 mm, and — 45 degrees 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 degree 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 (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.

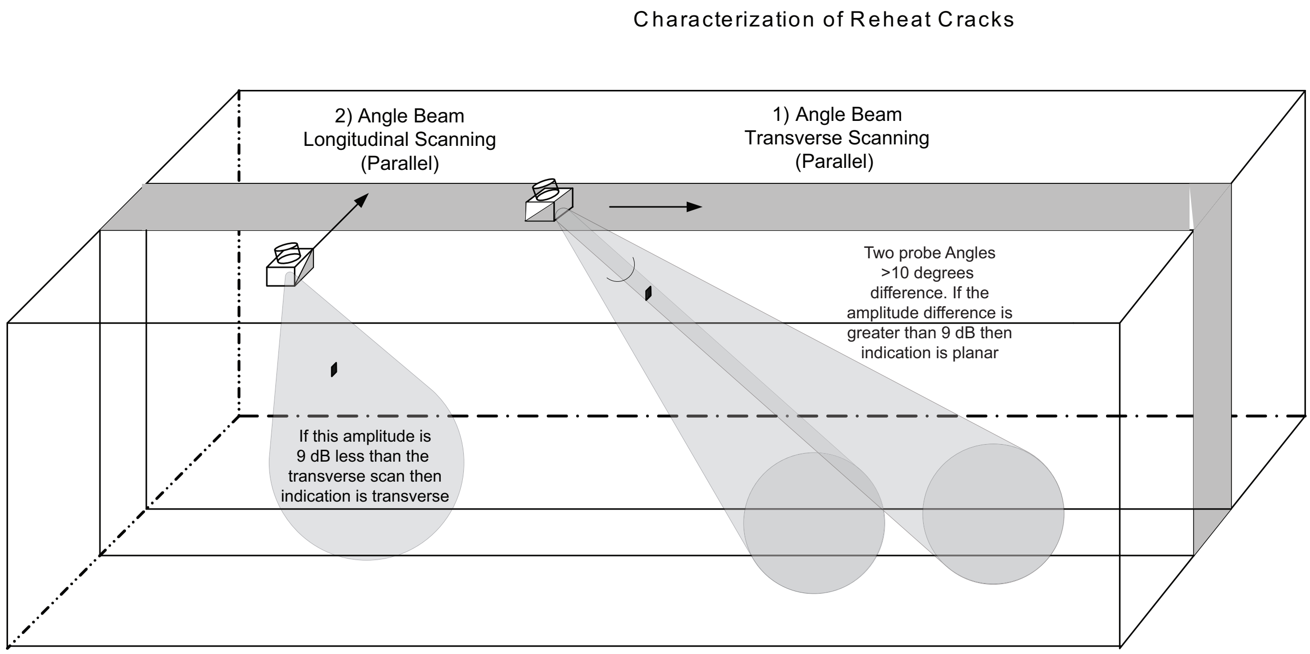


Figure A.5—Characterization of Reheat Cracks Using Pulse-echo UT

One of the primary areas where the guideline in Table A.2 exceeds ASME Code Section V, Article 4 requirements is in the calibration standard. Whereas the code requires calibration on a 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 reactor 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 non-injurious 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 an UT shear wave qualification from API (e.g. API QUTE) or an equivalent qualification approved by purchaser. Only ASNT 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.2.

A.6.3 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 (which 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 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, then the entire weld should be replaced.

A.6.4 Other Inspection Methods

Radiography has not been able to detect these cracks (as expected).

Annex B
(informative)

Alternate Probe Setup with Offset for Detecting Transverse Defects

B.1 Foreword

This annex is being issued in response to widespread fabrication problems with $2^1/_4$Cr-1Mo-V reactors that occurred from January 2008 through at least August 2008 due to transverse RHC. Additional background on the problem is given in Annex A of API 934-A. Annex A also gives guidance on inspection methods for detecting transverse RHC, and suggests that the extent of inspection can vary based on non-prescreened versus prescreened welds determined by a screening test of the weld metal and flux heats. Initially, the screening test used was the “Gleeble test,” 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 which is repeatable between multiple laboratories, a Joint Industry Sponsored Research Program (JIP) was formed in February 2010. The JIP sponsors included numerous oil companies, reactor 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 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/or other RHC tests are required, and the purchaser and reactor 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 Scope

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 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.

NOTE This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the User of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use. It is also the responsibility of the User to decide which party will coordinate the testing and to determine acceptable testing laboratories.

B.3 References

B.3.1 American Society of Testing and Materials (ASTM)

ASTM B637, *Standard Specification for Precipitation-Hardening and Cold Worked Nickel Alloy Bars, Forgings, and Forging Stock for High-Temperature Service*

ASTM E4, *Standard Practices for Force Verification of Testing Machines*

ASTM E83, *Standard Practice for Verification and Classification of Extensometer Systems*

ASTM E633, *Standard Guide for Use of Thermocouples in Creep and Stress-Rupture Testing to 1800 °F (1000 °C) in Air*

ASTM E1012, *Standard Practice for Verification of Test Frame and Specimen Alignment under Tensile and Compressive Axial Force Application*

B.3.2 International Standards Organization (ISO) and European Norms (EN)

ISO 376, *Metallic materials—Calibration of force-proving instruments used for verification of uniaxial testing machines*

ISO 9513, *Metallic materials—Calibration of extensometer systems used in uniaxial testing*

B.4 Acronyms

RHC	reheat cracking
RoA	reduction of area (%)
SAW	submerged arc welding
YS	yield strength (MPa)
UTS	ultimate tensile strength (MPa)
El %	elongation (%)

B.5 Test Apparatus

B.5.1 Testing Machine

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

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.8.5. It shall also be equipped with a means of heating and controlling the temperature to meet the requirements in B.8.3.

B.5.2 Gripping Devices

B.5.2.1 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.

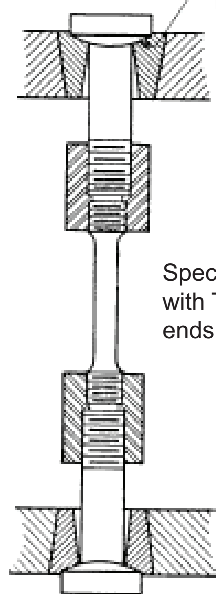


Figure B.1—Example of a Gripping Device Devoted to Threaded-end Specimens

B.5.2.2 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.5.3 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.8.7), the accuracy shall not be larger than 0.0004 in. (0.01 mm).

B.5.4 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.5.5 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.8.4.

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.10.

B.5.6 Temperature-measuring Apparatus

The method of temperature measurement must be sufficiently sensitive and reliable to ensure that the temperature of the specimen is within the limits specified in B.8.4.

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.6 Welding of Screening Test Coupons

B.6.1 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-recommended, regardless of reactor material,

— $2^1/_4$Cr-1 Mo or $2^1/_4$Cr-1 Mo-V, or

— CS with the bevel area buttered with $2^1/_4$Cr-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 (mm) [a]	3.2	4
Automatic vs Manual Welding [b]	Machine / SAW Auto.	
Heat Input (KJ/mm)	1.95 to 2.15	
Voltage (V)	30 to 32	
Amperage (A)	500 to 520	540 to 560
Travel Speed (cm/min)	50 ±2	
Polarity (AC or DC+/-)	AC	
Joint Preparation	See Figure B.2	
Welding Position	1G	
Stick-out (mm)	23	30
Use of Strongbacks to Minimize Distortion (Yes or No)	Yes - See Figure B.4 for example	
Preheating (°C)	200 minimum	
Interpass Temperature Min./Max. (°C)	200/230	
Post Heating or DHT (°C and hours)	350 °C ±10 °C for 4 hours, minimum	

[a] Either 3.2 or 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.

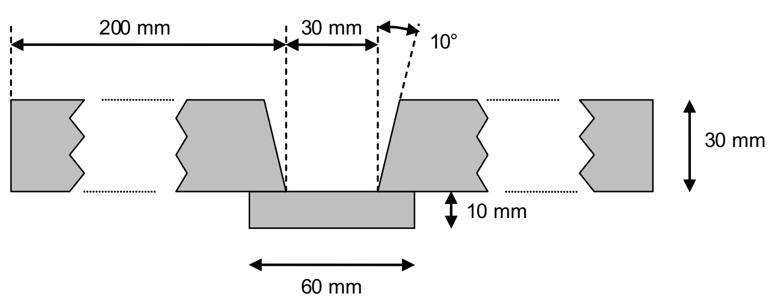


Figure B.2—Geometry of the Weld Joint to be Used for the Screening Test Coupon

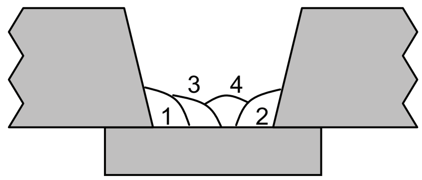
The weld coupon shall utilize a 1.2 in. (30 mm) thickness plate butt-welding joint with a 10° bevel angle and 1.2 in. (30 mm) root opening, with a backing plate and filling with 4 beads per layer (see Figures B.2 and B.3).

NOTE This test is not a weld procedure qualification test nor is it relevant to production test plates, and the test coupon must be welded with these parameters to be indicative and valid. The welding parameters are not required to reflect production welding and thicker plates shall not be used.

B.6.2 Heat Treatment of Test Coupons

Welding step shall be followed by DHT; also referred to as Post Heating) at 350 °C (±10 °C) for 4 hours minimum.

The welded coupon must not be exposed to high temperature heat treatment such as ISR or PWHT. Any deviation will lead to non-validity 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

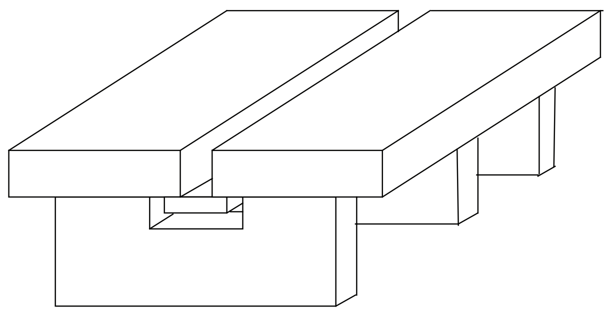


Figure B.4—Example of Strongbacks Used to Minimize Coupon Distortion

B.7 Specimens and Sampling

B.7.1 Sampling

Two parallel RHC test specimens shall be longitudinally machined from the welded joint (see Figures B.5 and 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.6.1.

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

B.7.2 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 must be coincident with the axis of the 0.47 in. (12 mm) × 0.47 in. (12 mm) × 4.75 in. (120 mm) pre-form described in B.6.1.

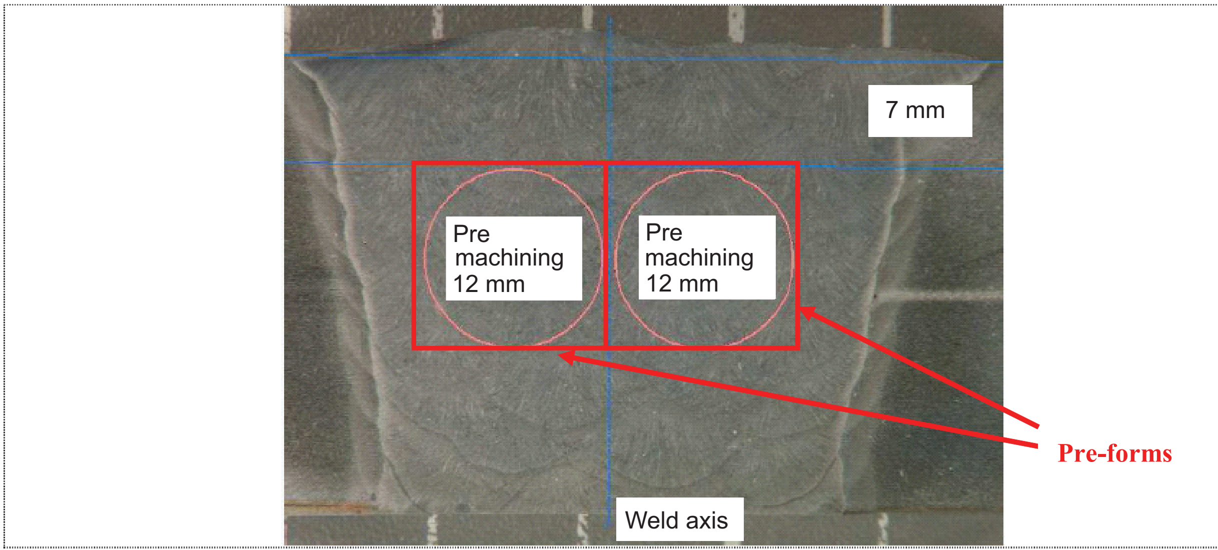


Figure B.5—Position of Pre-forms Inside the Welded Zone (Macrographic View)

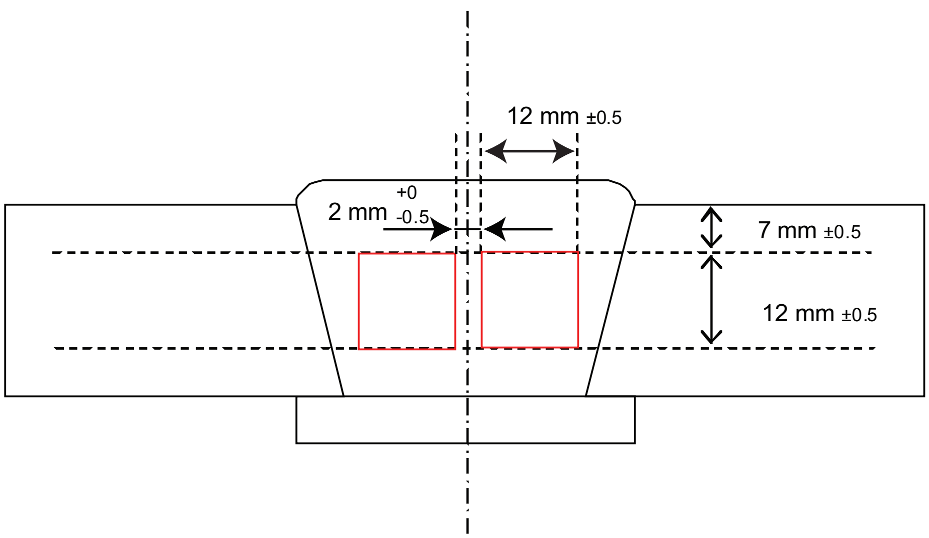


Figure B.6—Position of Pre-forms Inside the Welded Zone (Schematic View)

B.8 Test Procedures

B.8.1 Cleaning Specimen

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

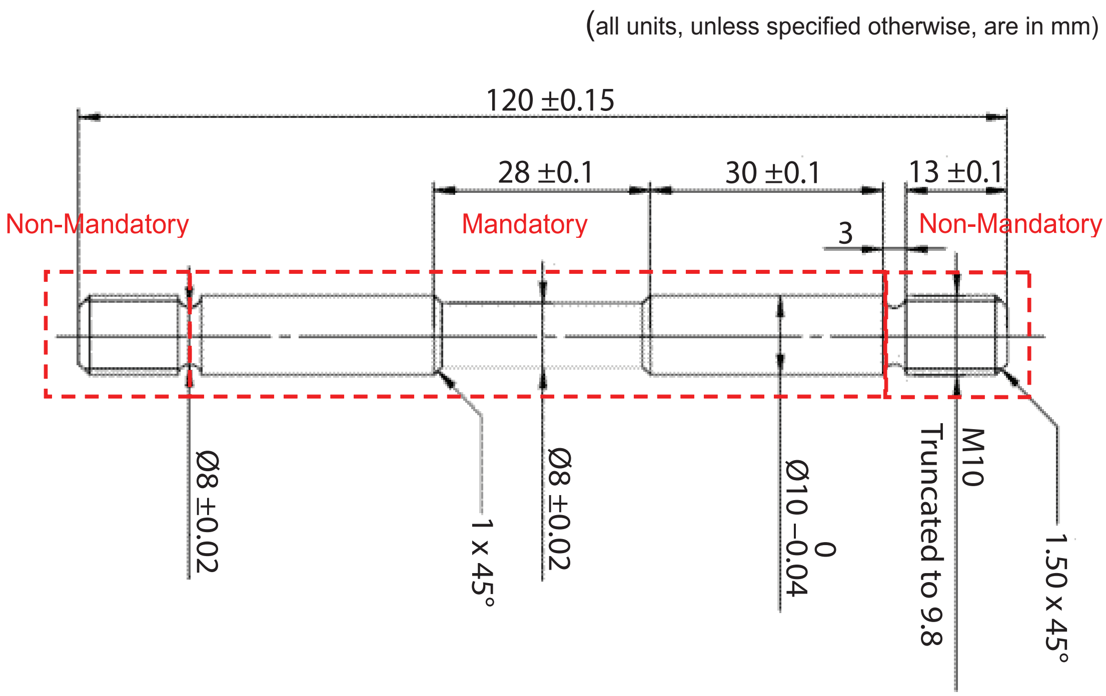


Figure B.7—Detailed Geometry of RHC Standard Specimen

B.8.2 Connecting Specimen to the Machine

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

B.8.3 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.8.4 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 must 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.8).

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).

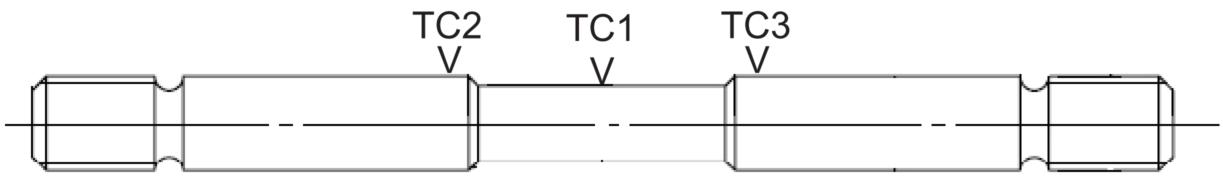


Figure B.8—Location of the Thermocouples on the RHC Standard Specimen

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 Section B.10 shall be the average of the three thermocouples.

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

The holding time at temperature prior to the start of the test shall be 10 min ± 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.10.

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.8.5 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 must be performed at constant crosshead displacement rate of 0.03 in. (0.8 mm)/min ± 20 % using the standard specimens shown in B.6.2. This displacement rate corresponds to an estimated average strain rate equal to 0.0005 s^{-1}. The displacement rate must be controlled and reported.

B.8.6 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.

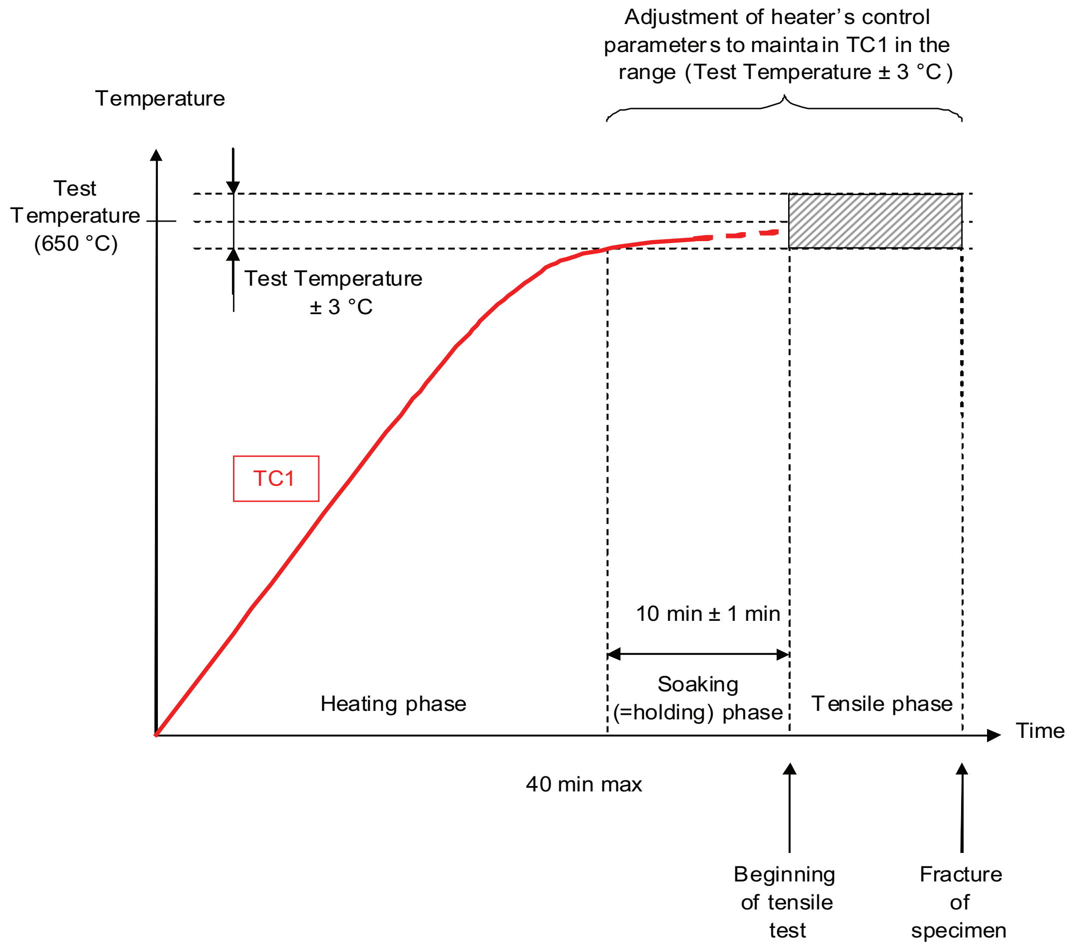


Figure B.9—Illustration of Heating Requirements on Test Specimens

B.8.7 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 must 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 (Area = $\pi*(a*b)/4$, with a = grand axis of the ellipse and b = small axis of the ellipse) instead of the disc area formula (Area = $\pi*D^2/4$, with D = average diameter).

If elongation is being reported (it is optional), the gage length (Lo) 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.8.8 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.10.

B.9 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.10 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 Table B.2. This certificate and these test results are not required to be included on—and generally will be separate from—the material mill certifications.

B.11 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 JIP was completed within its one year goal, primarily thanks to the excellent test work done by ArcelorMittal Industeel and the JIP management by Wintech Global. 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.

Table B.2—Sample Test Certificate

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]		

Table B.2—Sample Test Certificate (Continued)

Weld Metal/Flux Screening Test Results for Reheat Cracking Susceptibility Tested in accordance with API 934-A, Annex B		
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).

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