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

API RECOMMENDED PRACTICE 934-A
SECOND EDITION, MAY 2008

ADDENDUM 1, FEBRUARY 2010
ADDENDUM 2, MARCH 2012

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

Downstream Segment

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Introduction

This recommended practice 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 recommended practice with additional proprietary requirements.

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

1 Scope

This recommended practice presents materials and fabrication requirements for new 2 1/4Cr and 3Cr steel heavy wall pressure vessels for high-temperature, high-pressure hydrogen service. It applies to vessels that are designed, fabricated, certified, and documented in accordance with ASME *BPVC*, Section VIII, Division 2, including Section 3.4, Supplemental Requirements for Cr-Mo Steels and ASME Code Case 2151, as applicable. This document may also be used as a resource when planning to modify an existing heavy wall pressure vessel.

A newer ASME *BPVC*, Section VIII, Division 3, is available and has higher design allowables, however it has much stricter design rules (e.g. fatigue and fracture mechanics analyses required) and material testing requirements. It is outside the scope of this document.

Materials covered by this recommended practice are conventional steels including standard 2-1/4Cr-1Mo and 3Cr-1Mo steels, and advanced steels which include 2 1/4Cr-1Mo-1/4V, 3Cr-1Mo-1/4V-Ti-B, and 3Cr-1Mo-1/4V-Nb-Ca steels. This document may be used as a reference document for the fabrication of vessels made of enhanced steels (steels with mechanical properties increased by special heat treatments) at purchaser discretion. However, no attempt has been made to cover specific requirements for the enhanced 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 stainless clad lining using a roll-bonded or explosion-bonded layer on Cr-Mo base metal may be acceptable, but is outside the scope of this document.

2 References

The following referenced documents are cited in the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

ASME[1] *Boiler and Pressure Vessel Code*, Section II—*Materials*; Part 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 1*

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

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

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

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

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

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

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

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

ASME SA-369, *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, *Specification for Pressure Vessel Plates, Alloy Steel, Quenched-and-Tempered, Chromium-Molybdenum, and Chromium-Molybdenum-Vanadium*

ASME SA-578, *Specification for Straight-Beam Ultrasonic Examination of Plain and Clad 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*

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] A4.2, *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Austenitic-Ferritic 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 342, *Stainless Steel Weld Metal: Prediction of Ferrite Content*

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

[2]American Society for Nondestructive Testing, 1711 Arlingate Lane, P.O. Box 28518, Columbus, Ohio 43228, www.anst.org.
[3]ASTM International, 100 Bar Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.
[4]American Welding Society, 550 N.W. LeJeune Road, Miami, Florida 33126, www.aws.org.
[5]Welding Research Council, 3 Park Avenue, 27th Floor, New York, New York 10016, www.forengineers.com.

3.1.2
final PWHT
The last postweld heat treatment after fabrication of the vessel and prior to placing the vessel in service.

3.1.3
hot forming
Mechanical forming of vessel components above the final PWHT temperature.

3.1.4
Larson-Miller parameter
Formula for evaluating heat treatments:

$$\mathrm{LMP} = T \times (20 + \log t)$$

where

T is the temperature in °K; and

t is time in hours.

3.1.5
manufacturer
The firm or organization receiving the purchase order to design and manufacture the pressure vessel.

3.1.6
maximum PWHT
Specified heat treatment of test specimens used to simulate all fabrication heat treatments including austenitizing and tempering, all intermediate heat treatments above 900 °F (482 °C), the final PWHT, a PWHT cycle for possible shop repairs, and a minimum of one extra PWHT for future use by the owner.

NOTE To determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller Parameter formula may be used; results to be agreed upon by purchaser and manufacturer.

3.1.7
minimum PWHT
Specified heat treatment of test specimens used to simulate the minimum heat treatment [austenitizing, tempering and one PWHT cycle, and ISR above 900 °F (482 °C)].

NOTE To determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller parameter may be used; results to be agreed upon by purchaser and manufacturer).

3.1.8
purchaser
The firm or organization that has entered into the purchase order with the manufacturer.

3.1.9
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 alloy steels in high-temperature service.

3.2 Acronyms

For the purposes of this recommended practice, the following acronyms apply:

CMTR certified material test report

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

MDMT minimum design metal temperature

MT magnetic particle testing

NDE nondestructive examination

PQR procedure qualification record

PT penetrant testing

PWHT postweld heat treatment

RT radiographic testing

UT ultrasonic testing

WPS welding procedure specification

4 Design

4.1 Design and manufacture should conform to the ASME *BPVC*, Section VIII, Division 2. The latest edition including addenda effective on the date of the purchase agreement should be used.

4.2 The manufacturers 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 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 should not take any credit for the corrosion allowance, and/or weld overlay or cladding thickness.

b) Weld seam layouts should provide that all welds are accessible for fabrication and in-service NDE such as RT, UT, MT, and PT.

c) Nozzle necks should have transition to the vessel body as shown in the ASME *BPVC*, 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 the ASME *BPVC*, Section VIII, Division 2, Table 4.2.10, Detail 3 through Detail 7, with integral reinforcement.

5 Base Metal Requirements

5.1 Material Specifications

5.1.1 Base metals should be in accordance with the applicable ASME specifications indicated in Table 1.

5.1.2 Unless approved in advance by the purchaser, different base metals should not be mixed in the same vessel (e.g. 2 1/4Cr-1Mo-1/4V nozzles should not be used with standard 2 1/4Cr-1Mo shell plates).

5.1.3 With the purchaser's approval in advance, it is acceptable for non-pressure parts attaching to pressure parts to match only the nominal chemistry of the pressure part, e.g. a 2 1/4Cr-1Mo support skirt attached to a 2 1/4Cr-1Mo-1/4V shell.

Table 1—Base Metal Specifications

Steel		Conventional		Advanced		
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	—	—	Type D, Class 4a	Type C, Class 4a, Grade 21V	Type E, Cl 4a, Grade 23V
	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	—	—	—	Grade 3V	Grade 3VCb
	SA 541	—	—	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 *BPVC*, Section VIII, Division 2, Section 3.4.
[b] Covered in ASME Code Case 2151-1.

5.2 Steel Making Practice

In addition to steel making practices outlined in the applicable material specifications, the steels should be vacuum degassed.

5.3 Chemical Composition Limits

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

$$\text{J-factor} = (\mathrm{Si} + \mathrm{Mn}) \times (\mathrm{P} + \mathrm{Sn}) \times 10^4 \leq 100$$

where

Si, Mn, P, and Sn are in wt %.

Additionally, Cu is 0.20 % maximum, and Ni is 0.30 % maximum (0.25 % maximum for advanced steels).

5.4 Heat Treatment

All product forms should be normalized and tempered or quenched and tempered to meet the required mechanical properties.

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 should be removed from the following locations.

a) Plate—from each plate transverse to the rolling direction in accordance with SA-20 at the standard test locations and at the $^1/_2T$ location. When permitted by the applicable product specification, coupons for all tests should be obtained from the $^1/_2T$ location only. If required, $^1/_2T$ specimens should be used for hot tensile and step cooling tests.

b) Forging—from each heat transverse to the major working direction in accordance with SA-182, SA-336, SA-508, or SA-541, and test specimens should be taken $^1/_2T$ of the prolongation or of a separate test block. A separate test block, if used, should 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 should be heat treated in the same furnace charge and under the same conditions as the production forgings.

   For thick and complex forgings that are contour shaped or machined to essentially the finished product configuration prior to heat treatment, the registered engineer who prepares the design report should designate the surface of the finished product subject to high tensile stress in service. Test specimens for these products should be removed from prolongations or other stock provided on the products. The coupons should be removed in accordance with ASME *BPVC*, Section VIII, Division 2, Paragraph 3.10.4.2.

c) Pipe—from each heat and lot of pipe, transverse to the major working direction in accordance with SA-530 except that test specimens should be taken from $^1/_2T$.

5.5.1.2 Heat Treatment of Test Specimens

Test specimens should 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

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

[a]These heat treatments meet the requirements ASME *BPVC*, 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 heat treatment specified in 5.5.1.2 should meet the requirements of the applicable base metal specification. In addition, the following limits on the tensile properties should apply.

a) Tensile strength should not exceed the following limits:

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

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

b) Yield strength should 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, when required by the purchaser, should be performed at the equipment design temperature. Test specimens should be in the maximum PWHT condition. Acceptance values should be as specified by the owner/user. Typically, if required, the acceptance value is 90 % of values listed in ASME *BPVC*, 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 should not be less than 40 ft-lb (55 J) with no single value below 35 ft-lb (47 J). The percent ductile fracture and lateral expansion in mils should also be reported.

5.5.3.2 Step Cooling Tests

Step cooling tests of the base metals are not required. If the purchaser decides to impose the step cooling tests, the test procedure and the acceptance criteria should be in accordance with 6.2.3. The purchaser may opt to require that the step cooling tests be performed only on the heat with the highest J-factor.

In lieu of the step cooling tests, the purchaser may require impact testing at –80 °F (–62 °C) with results 40 ft-lb (55 J) average minimum and no single value below 35 ft-lb (47 J). The percent ductile fracture and lateral expansion in mils 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 requirements in 5.5.3.1 which are tested at higher temperature.

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, should match the nominal chemical composition of the base metal to be welded.

6.1.2 The following chemical composition limits should be controlled to minimize temper embrittlement.

$$\text{X-bar} = (10P + 5Sb + 4Sn + As)/100 \leq 15$$

where

P, *Sb*, *Sn*, and *As* are in ppm.

Additionally, Cu is 0.20 % maximum; and Ni is 0.30 % maximum.

6.1.3 Low hydrogen welding consumables, including fluxes, having a maximum of 8 ml of diffusible hydrogen for every 100 g of weld metal, H8 per AWS A4.3, should be used. They should be baked, stored, and used in accordance with consumable manufacturer's instructions (holding in electrode oven, length of time out of oven, etc).

6.2 Mechanical Properties

6.2.1 Tensile Properties

The tensile properties of the deposited weld metal should meet those of the base metal in accordance with 5.5.2.

6.2.2 Impact Properties

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

6.2.3 Step Cooling Tests

6.2.3.1 Prior to the start of fabrication, step-cooling tests should 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 lot of flux and heat of wire should be tested.

Two sets of Charpy V-notch test specimens, with a minimum of 24 specimens per set, should be prepared and 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.

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

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

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

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

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

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

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

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

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

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

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

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

13) Cool to ambient temperature in still air.

6.2.3.2 After the Charpy V-notch test specimen sets are heat treated, each set of specimens should be 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.

6.2.3.3 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 should meet the following requirement:

$$CvTr40 + 2.5\ \Delta CvTr40 \leq 50\ ^\circ F\ (10\ ^\circ C)$$

where

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

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

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 should consist of clean metal surface prepared by machining, grinding or blast cleaning.

7.1.2 All welded joints including non-pressure attachments to the vessel body should:

a) have full penetration joint design,

b) be located so that full ultrasonic examination of welds can be made after fabrication and after installation is complete (in cases where this is not practical, the manufacturer should propose alternate NDE methods to verify weld quality), and

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

7.1.3 All welding should be completed prior to final PWHT except welding of internal attachments to the austenitic stainless steel weld overlay. For these attachment welds, a PQR or mockup test should be performed to verify that this does not produce a HAZ in the base metal, unless waived by the purchaser.

7.1.4 All weld repairs to base metal, weld joints and weld overlay should be performed using a repair welding procedure qualified in accordance with 7.2, and should meet all the same requirements as the normal fabrication welds.

7.2 Welding Procedure Qualification

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

— conventional steels, ASME *BPVC*, Section IX;

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

7.2.2 Base metal for welding procedure qualification tests should be made from the same ASME Code material specification (same P-number and Group number) and nominal chemistry as specified for the vessel, but either plate or forging may be used. The welding electrodes, wire, and flux combination should be of the same type and brand as those to be used in production welding.

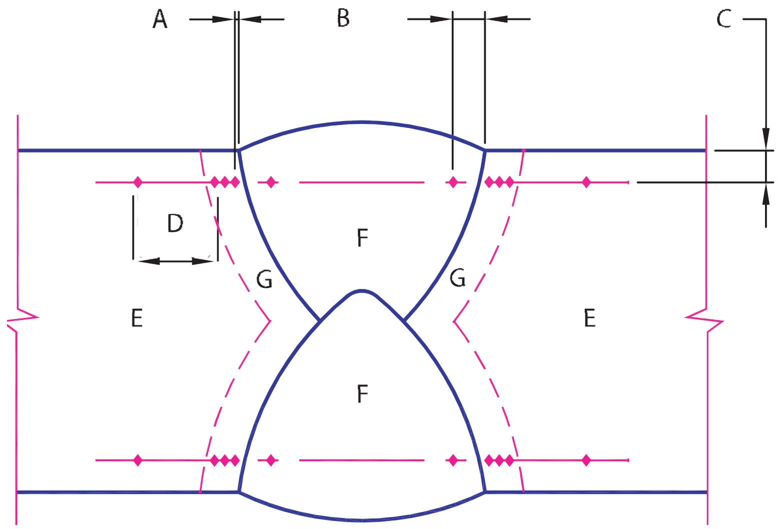
7.2.3 Charpy V-notch impact testing should be performed on weld metal and HAZ of the heat-treated test plate with specimen heat treatment in accordance with Table 2. These impact tests should be performed for each welding procedure and should meet the impact test temperature and acceptance requirements in 5.5.3.1.

7.2.4 Step cooling tests should be performed on the weld metal and HAZ for each welding procedure as specified for the weld metal in 6.2.3. Previously qualified WPSs with step cooling tests can be accepted by purchaser, based on WPSs complying with 7.2.1.

7.2.5 Two Vickers hardness traverses of the weld joint should be made on a weld sample in the minimum PWHT condition. These hardness traverses should be performed within $^{1}/_{16}$ in. (1.6 mm) from the internal and external surfaces as shown in Figure 1. The HAZ readings should include locations as close as possible [approximately 0.008 in. (0.2 mm)] to the weld fusion line. Each traverse includes ten hardness readings for a total of 20 hardness readings per weld sample. The hardness should not exceed 235 HV10 for conventional steels and 248 HV10 for advanced steels.

7.2.6 A tensile test, transverse to the weld, should be performed on a weld joint of the heat treated test plate in the PWHT condition required by Table 2, and should meet the ambient temperature properties specified for the base metal in 5.5.2.

7.2.7 All WPSs/PQRs should be approved by the purchaser prior to fabrication.



Key

A	Approx 8 mil (0.2 mm)	E	Base Metal
B	0.04 in. – 0.12 in. (1 mm – 3 mm) (TYP)	F	Weld Metal
C	1/16 in. (1.5 mm)	G	HAZ
D	0.12 in. – 0.24 in. (3 mm – 6 mm) (TYP)		

Figure 1—Location of Vickers Hardness Indentations

7.3 Preheat and Heat Treatments During Base Metal Welding

7.3.1 Preheat

All base metal should 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 welding, rolling, thermal cutting and gouging operations (except during weld overlay—see 7.5.4). During welding, the preheat temperature should be maintained until PWHT, ISR or DHT in accordance with 7.3.2. The purpose is to drive out hydrogen to minimize the risk of hydrogen cracking, and to minimize problems due to low as-welded toughness. For butt welding and attachment welding, this preheat temperature should 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

Intermediate stress relief (ISR) is required before cooling below preheat temperature prior to PWHT, unless the purchaser approves the use of dehydrogenation heat treatment (DHT). ISR should not be waived for restrained welds such as all nozzle welds for advanced grades, and nozzle welds in conventional grades with shell or head thicknesses 8 in. (200 mm) and greater.

Approval of DHT in lieu of ISR should be done only after careful consideration of the metallurgical factors and possible risks. Higher concern levels with DHT are typically applied to advanced steels, as they can have low as-welded toughness. Although a DHT will remove 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, purchaser requires test and/or experiential data. Typical information to be included in the manufacturer's request should include detailed information and data concerning hydrogen controls for procurement and handling of welding consumables, hydrogen content of weld metals after the DHT, and nondestructive examination of weld joints. The purchaser may require the manufacturer to demonstrate 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 non-restrained welds such as shell welds and shell-to-head welds.

7.3.2.2 Intermediate Stress Relief (ISR)

An ISR soak in a furnace should be performed at the following metal temperatures:

— 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 should 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 for duration to be agreed upon between the manufacturer and the purchaser. In no case should the duration be less than one hour for conventional steels, and four hours for advanced steels.

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 should 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 columbium content (as applicable) of the weld deposits should be within the ranges specified in ASME *BPVC*, Section II, Part C and ASME *BPVC*, Section VIII, Division 2, Table 3.2, for the specified electrodes.

7.4.2 Hardness of Weld Deposit and Adjacent Base Metal

7.4.2.1 After final PWHT (see 7.6), hardness determinations should be made for each pressure-retaining weld using a portable hardness tester.

7.4.2.2 Each hardness test result should be the average of three impressions at each test location. The test locations should 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 should not exceed:

— conventional steels, 225 HBW, or equivalent;

— advanced steels, 235 HBW, or equivalent.

7.4.2.4 Hardness tests should 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.

7.4.3 Weld Impact Tests

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

7.4.3.2 Production test plates subjected to the minimum PWHT should be impact tested before and after step cooling in accordance with the requirements of 6.2.3 unless waived by the purchaser.

7.5 Weld Overlay

7.5.1 Material Requirements

The ferrite content of austenitic stainless steel weld overlay should be between 3 FN and 10 FN, as determined in accordance with WRC Bulletin 342, prior to any PWHT except that the minimum ferrite content for Type 347 should be 5 FN (in accordance with API 582).

7.5.2 Disbonding Tests

7.5.2.1 When required by the purchaser, a method to evaluate the weld overlay for susceptibility to hydrogen disbonding should be agreed to between the manufacturer and purchaser. The purchaser should define testing requirements and acceptance criteria. The test parameters should represent or exceed the equivalent of actual maximum operating conditions (hydrogen partial pressure, temperature, and cooling rates). The test conditions are modified to be “equivalent” based on the test specimen size, geometry, and hydrogen charging as shown by the test domains in 7.5.2.3.

7.5.2.2 Results of disbonding tests should be available, prior to fabrication, for each 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 Proposed testing conditions representing or exceeding the equivalent of 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—Maximum Operation Conditions Correlated to Testing Conditions at 450 °C (842 °F)

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

Table 4—Test Conditions Domains

Domain	Testing Conditions		
	Temperature °C (°F)	**Pressure** bar (psi)	**Cooling Rate** (°C/h) (°F/h)
A[a]	450 (842)	150 (2175)	675 (1247)
B	450 (842)	150 (2175)	150 (302)
C	450 (842)	120 (1740)	150 (302)
D	450 (842)	90 (1305)	150 (302)
E	450 (842)	70 (1015)	150 (302)
F	450 (842)	50 (725)	150 (302)

[a] For Domain A, the following equivalent testing conditions may be used as an alternate:
— temperature, 842 °F (450 °C);
— pressure, 175 bar (2538 psi);
— cooling rate, 302 °F/h (150 °C/h).

7.5.2.4 For 2 $^1/_4$Cr-1Mo 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. Vanadium-modified grades are significantly less susceptible to disbonding in any domain [1, 2]. The purchaser may consider and evaluate manufacturer's existing disbonding test results, under similar conditions, for acceptability.

7.5.2.5 Test specimen should meet ASTM G146 standards and acceptable test results for such testing conditions should be Area Ranking A of same.

7.5.3 Weld Overlay Procedure Qualification

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

7.5.3.2 Procedure qualification tests should be made on base metal of the same ASME specification (same P-number and Group number) and similar chemistry as specified for the vessel, but either plate or forging may be used. Thickness of the test specimen should not be less than one-half the thicknesses of the vessel base metal or 2 in. (50 mm.), whichever is less. The welding electrode, wire, and flux used for the weld overlay procedure qualification should be the same type and brand to be used in production.

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

7.5.3.4 The chemical composition of the weld overlay should be checked by chemical analysis of samples taken at minimum specified thickness from the process side. It should meet the specified composition of the weld overlay (final layer if multiple layers). The chemical composition, determined by these samples, should be used to calculate the ferrite content in accordance with 7.5.1.

7.5.4 Preheat and Heat Treatments During Weld Overlay

Base metal should be preheated to 200 °F (94 °C) for the first layer of weld overlay. The maximum interpass temperature should be 350 °F (175 °C). Provided that subsequent still-air cooling is applied, intermediate stress relief (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 should be checked by laboratory chemical analysis of a sample taken at minimum specified thickness. This composition should meet the required chemistry of the specified overlay material (C, Cr, Ni, Nb, Mo, and V, as applicable). At least one analysis for each shell ring and head, and one for each manual welding process for nozzles, should be required.

7.5.5.2 Ferrite Content of Weld Overlay

7.5.5.2.1 A magnetic instrument calibrated to AWS A4.2 should 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 should be taken on the surface at each of the following locations:

a) at least ten locations, selected at random, should be checked 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 should meet the requirements in 7.5.1.

7.6 Final Postweld Heat Treatment (PWHT)

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 *BPVC*, Section VIII, Division 2, Paragraph 6.4.3.3.

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

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] In accordance with ASME *BPVC*, Table 6.11.
[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 *BPVC*, Section VIII, Division 2 requirements (see Table 6.11) must also be met if stricter.

7.6.2 The PWHT temperature should 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 should be insulated such that the temperature gradient is not harmful. Thermocouple arrangements should be established for each heat treatment. The skin temperature should be measured and controlled on the inside and outside of the vessel.

7.6.3 Continuous time-temperature records of all PWHT operations should be documented to meet ASME *BPVC*, Section VIII, Division 2, Paragraph 6.4.4.

8 Nondestructive Examinations (NDE)

8.1 General

All NDE personnel should be qualified in accordance with ASNT SNT-TC-1A. 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 *BPVC*, Section VIII, Division 2, Paragraph 3.3.3, all base metal plates should be ultrasonically examined with 100 % scanning in accordance with ASME SA-435 and ASME SA-578, Level C, Supplementary Requirement S1, before forming.

8.2.1.2 All forgings for shell rings, nozzles, and manways should be ultrasonically examined with 100 % scanning in accordance with ASME *BPVC*, 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 all forgings, including welding edges, should be examined by MT in accordance with ASME *BPVC*, Section VIII, Division 2, Paragraph 7.5.6, or by PT in accordance with ASME *BPVC*, Section VIII, Division 2, Paragraph 7.5.7. Examination should be after finish machining but before welding.

8.2.2.2 Entire surfaces of all formed plates to be welded for shell rings and heads, including those for weld overlay, should be examined by either MT or PT, as noted in 8.2.2.1. For formed plates to be welded for shell rings and heads, welding edges should be examined by MT or PT after forming.

8.3 NDE During Fabrication

8.3.1 MT should 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 should also be performed after any gouging or grinding operation including back gouging of root passes. MT should be in accordance with ASME *BPVC*, Section VIII, Division 2, Paragraph 7.5.6.

8.3.2 Temporary attachments should be minimized. All areas where temporary attachments have been removed should be examined by MT or PT in accordance with ASME *BPVC*, 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 All pressure-retaining butt welds and vessel to support skirt welds should be fully examined by RT in accordance with ASME *BPVC*, Section VIII, Division 2, Paragraph 7.5.3, before final PWHT.

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

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

8.4.2 Weld Overlay

Spot UT, four strips, equally spaced, approximately 3.2 in. (80 mm) wide along the full length of the vessel shell and one (1) strip approximately 3.2 in. (80 mm) wide across each head should be performed on the weld overlay. 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 All pressure-retaining base metal welds, including nozzles, should be fully examined by UT in accordance with ASME *BPVC*, Section VIII, Division 2, Paragraph 7.5.4.

8.5.1.2 All accessible welds should be examined by MT. An AC yoke method should be used to prevent arc strikes. PT may be substituted for MT whenever MT is impractical.

8.5.2 Weld Overlay

8.5.2.1 All austenitic stainless steel weld overlay, and attachments to the overlay, should be examined by PT in accordance with ASME *BPVC*, 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

Positive material identification (PMI) should be performed in accordance with the purchaser's PMI specification.

9 Hydrostatic Testing

9.1 All pressure retaining welded joints should be free from any scale and other foreign material before testing. All dirt, scale, sand, and other foreign material should 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 should be at least 30 °F (17 °C) above the MDMT, or 60 °F (15 °C), whichever is warmer.

9.4 The vessel should 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 should be cleaned and dried. Heat drying and/or other evaporative means should not be used due to possible chloride contaminants.

10.2 All openings should be sealed with a steel cover and gasket, and the vessel should be filled with a minimum 5 psig (34.5 kPa) pressure of dry nitrogen gas. The nitrogen pressure should be maintained during transportation, erection and pre-commissioning. The vessel should be marked and a conspicuous warning tag should be attached at each manway stating that: 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, should be protected by applying suitable grease, rust preventative oil or coating.

11 Documentation

The following documentation for all pressure-retaining parts, including welding consumables, should be completed prior to the start of fabrication and should be available for examination by the purchaser at the time of inspection. This documentation should be submitted to the purchaser at the completion of the project:

a) CMTRs showing all chemical composition and mechanical test results;

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

c) J-factors;

d) X-bars;

e) all impact test results before and after step cooling;

f) all hot tensile test results;

g) welding procedure specifications with applicable procedure qualification records;

h) PMI report.

Annex A
(informative)

Guidance for Inspection for Transverse Reheat Cracking

A.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. The problems were determined to be reheat cracking in newly fabricated submerged arc welds (SAW). 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 ultrasonics (UT) or radiography (RT) (i.e. ASME *Code Case* 2235-9 and Section VIII, Division 2). The objective of this annex is to provide a means for detection of this cracking and to suggest appropriate evaluation/rejection criteria. Since in some welds, it may be difficult to detect all the 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 is currently being performed, and the results will be incorporated into future editions of this document. However, this document's inspection guidelines will help the industry in the interim by detecting welds with reheat cracking. 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
higher risk welds
SAW weld deposits made with heats of flux/wire that have had past cases of reheat cracking or have unknown performance as far as reheat cracking susceptibility, unless test results (e.g. Gleeble test results) indicate acceptable reheat cracking resistance.

A.2.2
lower risk welds
SAW weld deposits made with heats of flux/wire with no past cases of reheat cracking and test results that indicate negligible susceptibility to reheat cracking.

Flux/wire screening tests and recommended criteria are currently being developed as part of the research mentioned above. Until these results are available, the acceptable test methods and criteria will need to be defined by purchaser. The determination of whether welds are higher or lower risk will be a joint effort between the fabricators and purchasers, with the purchaser having the final approval.

A.3 Brief Description of the Cracking Conditions and Morphology

The "reheat cracking" which recently caused the major problems at multiple (but not all) reactor fabrication shops can be described as:

— subsurface in SAW weld deposits;

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

— may have slight branching;

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

— typically very small crack size [most are 4 mm to 10 mm (0.16 in. to 0.39 in.) in length and 2 mm to 5 mm (0.08 to 0.20 in.) in height];

— typically many cracks are 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 >620 °C (1150 °F) such as intermediate stress relief (ISR), reheating for rerolling, or postweld heat treatment (PWHT);

— does not occur after welding or dehydrogenation heat treatment (DHT); and

— has not historically occurred 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 reheat cracking in Cr-Mo welds resulted in longitudinal cracking in the coarse-grain area of weld heat affected zones (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 done in addition to ASME Code-required RT and UT examinations. The 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.4 Recommended Inspection Strategy and Timing

A.4.1 General Strategy

The techniques described in this appendix are focused on detecting transverse reheat cracks occurring in the SAW weld deposits. The default inspection mode will be from the outside diameter (OD), but 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. Reheat cracking 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 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 replaced.

A.4.2 Special Inspection Timing/Frequency

a) UT inspection (see A.5) should be performed on 100 % of “higher risk” SAW welds, before PWHT but after ISR or other >620 °C (1150 °F) reheating steps are completed.

b) On the “higher risk” 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 the welds which were originally “higher risk”, reinspection with these special TOFD procedures should be performed on the following.

- — 100 % of SAW welds which have been repaired due to reheat cracking; and
- — 10 % minimum of SAW welds which showed no reheat cracking; if reheat cracking is detected, the inspection should be increased to 100 % for this heat of flux.

d) TOFD per A.5.1 should be performed on circumferential and longitudinal seams, and pulse-echo UT per the procedures in A.5.3 should be performed on the nozzle welds. Pulse-echo UT per A.5.2 should also be used to characterize indications found by TOFD.

e) For “lower risk” 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.5.1 or A.5.2. This scanning must be performed after a heat treatment cycle >620 °C (1150 °F), 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 fabricator’s past normal 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 fabricator should develop comprehensive procedures and demonstrate the procedure capabilities and personnel competency in accordance with ASME Section V, Article 4; ASME *Code Case* 2235-9; and this annex.

A.4.3 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.5 Inspection Methods and Guidelines

A.5.1 TOFD UT

TOFD for detecting transverse reheat cracking 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 lower risk 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.

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 3 mm (0.12 in.) side drilled holes (SDH) on a 250 mm (9.8 in.) 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.

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.

An example probe setup for a 250 mm thick wall would be:

Probe Angle	Probe Diameter	Probe Frequency	Probe Center Spacing (PCS)
60 degree	6 mm	5 MHz	87 mm
45 degree	12.5 mm	2 MHz	200 mm
25 degree	12.5 mm	2 MHz	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 >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.

A.5.2 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 zones near the surface that are within the TOFD blind zones.

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 would require calibration on a SDH with a diameter which is a function of the wall thickness and would range from 6 mm to 10 mm for typical reactor wall thicknesses, this guideline requires a 3 mm SDH. This results in detection of much smaller indications.

The disadvantages of this method are that it is very operator-dependent and that 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 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 reheat cracking. There is no documented experience using phased array to detect reheat cracking, 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.

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

	Recommendation	Comments
Surface condition of welded joint	Flush Ground on both ID and OD	For higher risk welds, the grinding must be good quality and smooth enough to achieve good probe contact. For lower risk welds, grinding can be avoided if TOFD with offset probes is properly qualified per section A.5.1.
Sensitivity demonstration block	A series of 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 6mm (0.24 in.) of the near surfaces.
Probe alignment/ scanning location	B-Scan (Figure A.2) from OD. Probes centered on the weld 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 (a*s 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 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	i. Single Point Reflectors Single point reflectors should be evaluated by manual pulse-echo angle beam shear wave according to A.5.2. ii. Clusters If three indications (point reflectors) are observed in the same through- thickness plane (±2.5 mm) and separated by 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. iii. Straight Line Indications Phase reversed solid indications of 50 mm or longer noted near and above the back wall signal may be caused by small clusters of reheat cracking 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 DAC consideration. Lower angles do not adequately reflect the signal. Unless a cluster is definitely demonstrated to not be reheat cracking, it should be rejected.

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

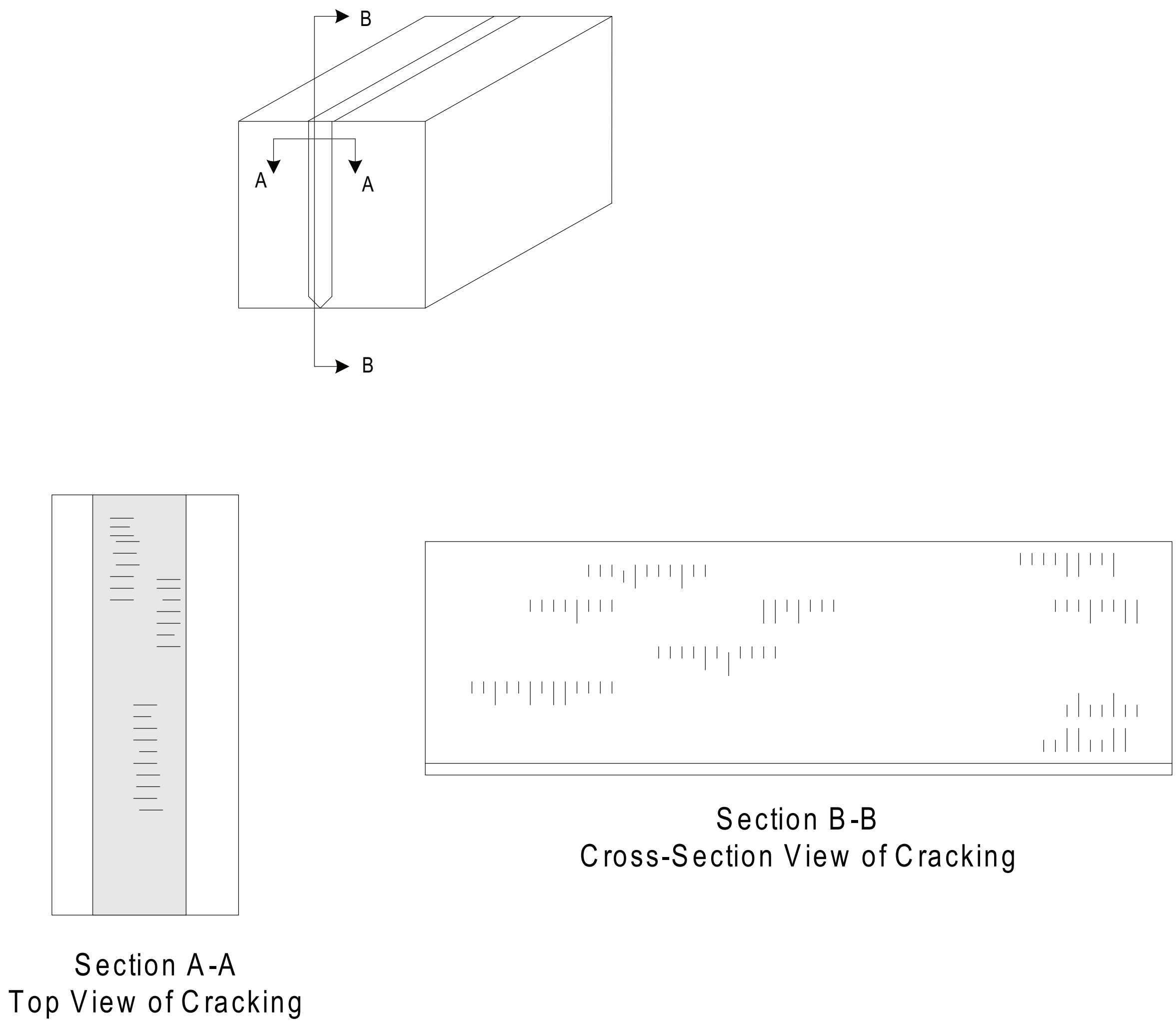
	Recommendation	Comments
Surface Condition of Welded Joint	Flush Ground	
Probe Frequency	2 to 4 MHz (focused if necessary to achieve adequate resolution at maximum depths)	Transducer frequency should be 4 MHz for near side examination and 2 MHz for depths greater than 100 mm.
Probe Angles	70 (primary detection angle), 60 and possibly 45 degrees	Multiple probes are used to “cover” the near and far zones: — 70 degrees covers about 10-100 mm, — 60 degrees covers about 50-150, and — 45 degrees covers the deeper areas.
Calibration Reference	3 mm side drilled holes (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	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 EN1713 (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 120 mm). If > 9db (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.

A.5.3 UT of Nozzle Welds

In most nozzle welds which have shown reheat cracking, the magnitude of cracking found after partial inspection has been extensive enough to justify a full repair. Nozzle welds (which require inspection for reheat cracking) 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 to 4 MHz calibrated to a 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.5.4 Other Inspection Methods

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



Not to Scale

Figure A.1—Schematic Showing Reheat Cracking Locations

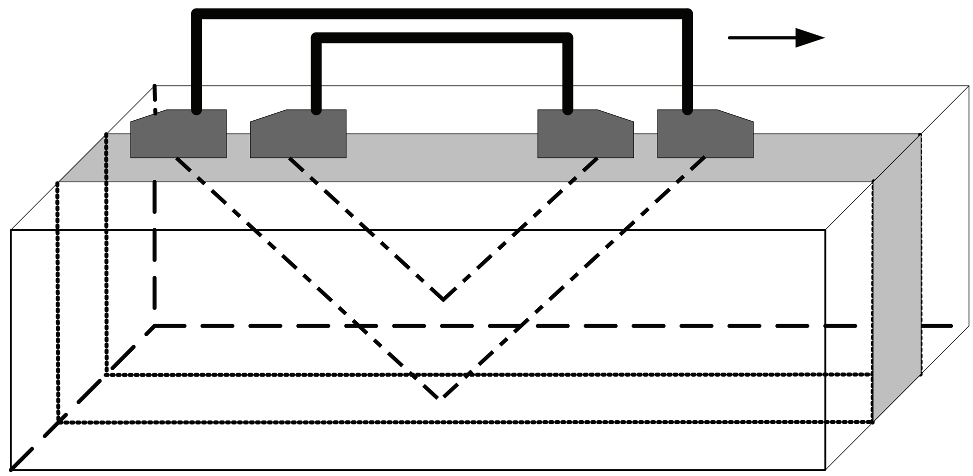


Figure A.2—B-scan for Detecting Transverse Defects with TOFD

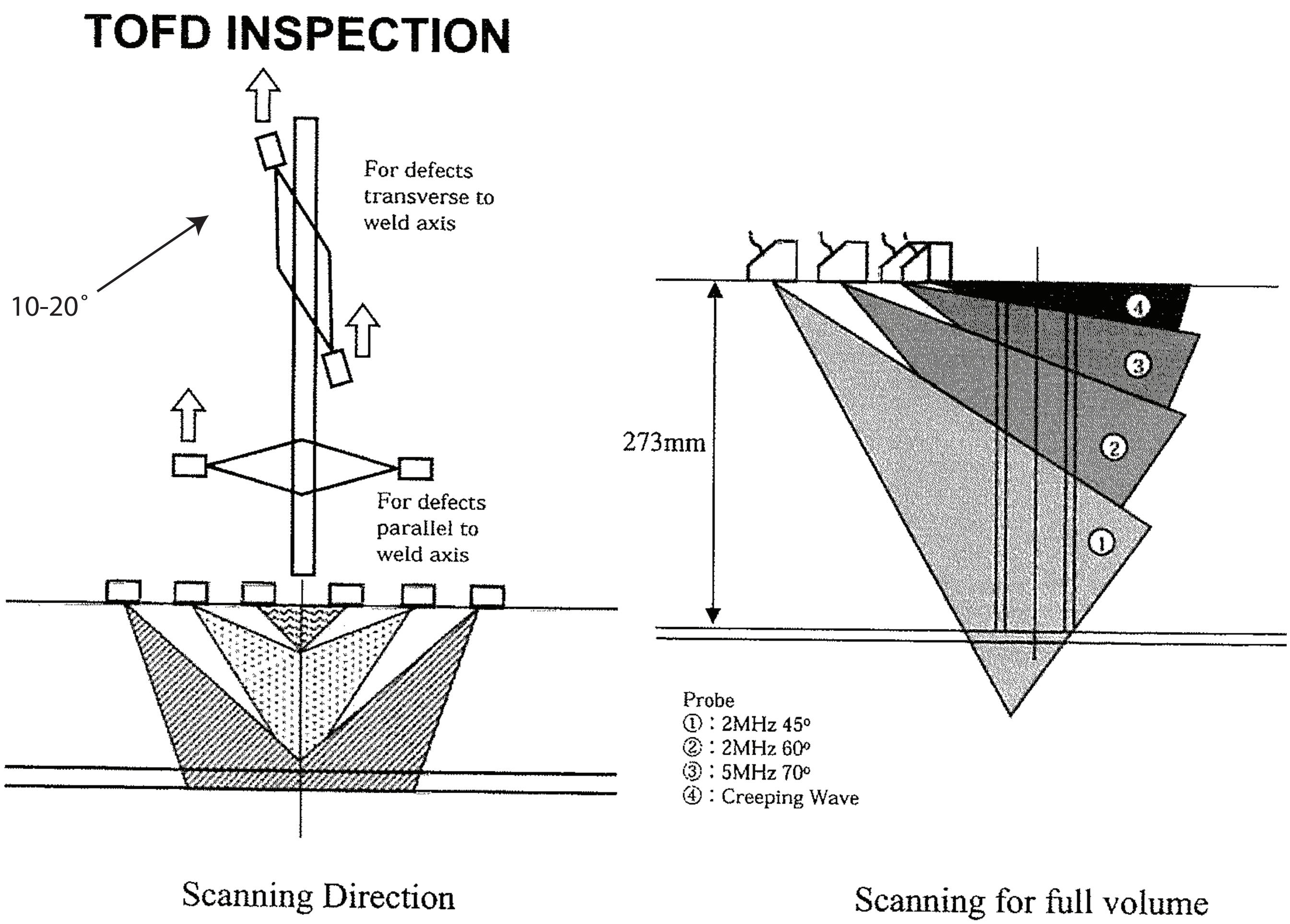


Figure A.3—Alternate Probe Setup with Offset for Detecting Transverse Defects

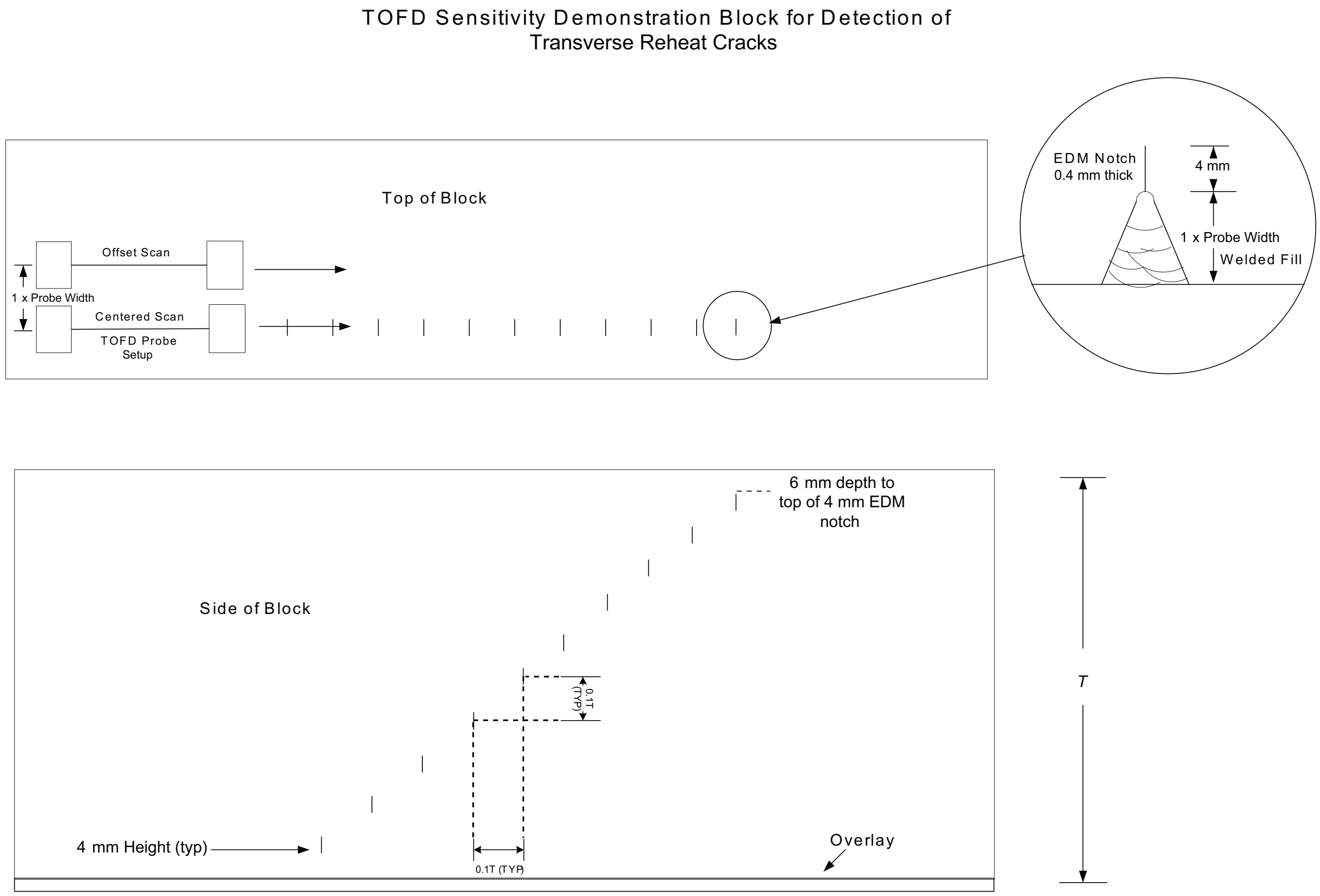


Figure A.4—TOFD Sensitivity Demonstration Block

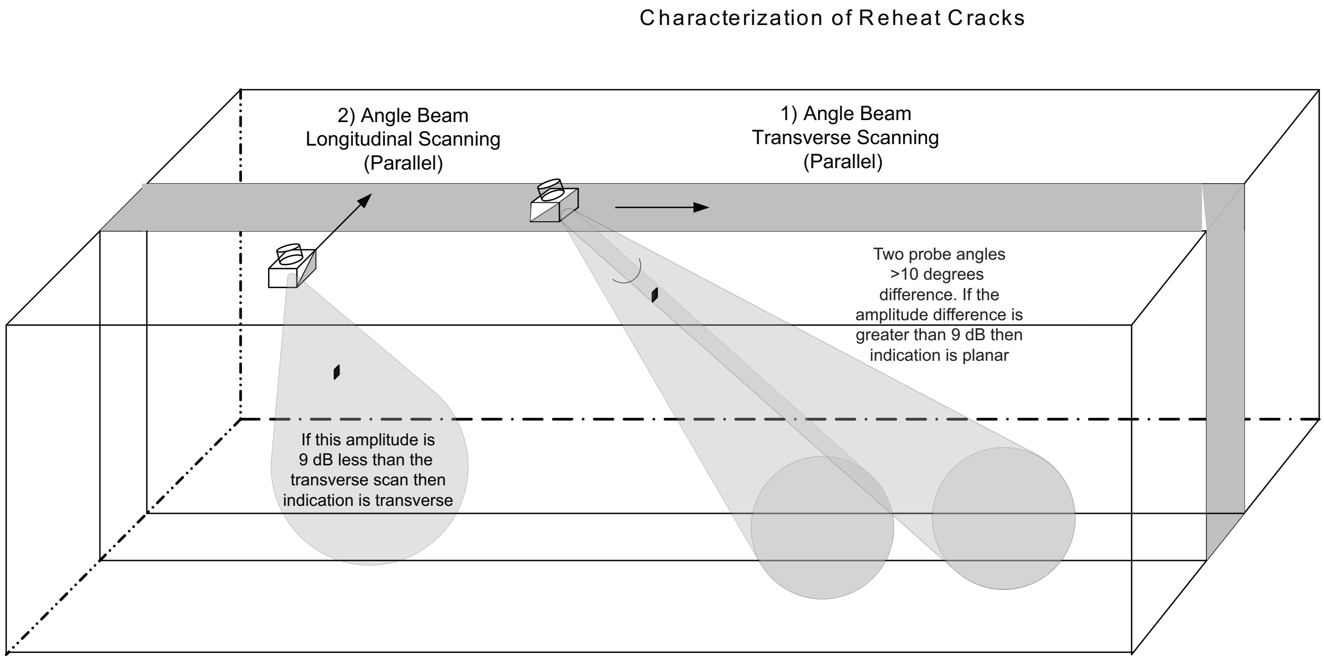


Figure A.5—Characterization of Reheat Cracks Using Pulse-echo UT

Annex B
(informative)

Weld Metal/Flux Screening Test for Reheat Cracking Susceptibility

B.1 Foreword

This annex is being issued in response to widespread fabrication problems with 2 $^1/_4$ Cr-1Mo-V reactors that occurred from January 2008 through at least August 2008 due to transverse reheat cracking (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 reheat cracking, and suggests that the extent of inspection can vary based on “higher risk” versus “lower risk” welds. It further states that the risk can be determined by a screening test of the weld metal and flux heats. Initially, the screening test being 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 Feb. 2010. The JIP sponsors included numerous oil companies, reactor fabricators, 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 reheat cracking 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 reheat cracking. The Purchaser should decide on whether the screening test and/or other reheat cracking tests are required, and the Purchaser and reactor fabricator should decide which party will coordinate the testing and 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 Reheat Cracking 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.

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 Referenced Industry Documents

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

ASTM B637, *Standard Specification for Precipitation-Hardening 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 extensometers used in uniaxial testing*

B.4 Terms and Definitions

RHC	Reheat Cracking
RoA	Reduction of Area (%)
SAW	Submerged Arc Welding
YS	Yield Strength (MPa)
UTS	Ultimate Tensile Strength (Mpa)
El% or 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 or 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.

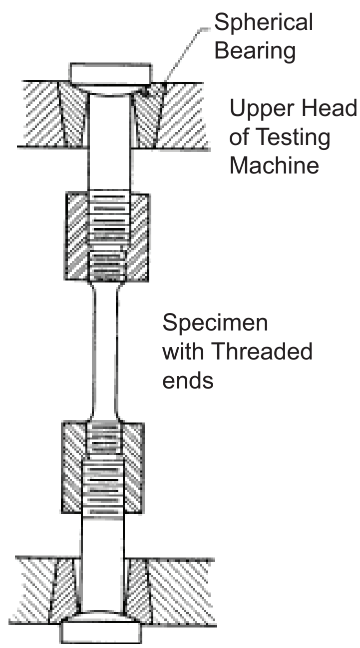


Figure B.1—Example of a Gripping Device Devoted to Threaded-end Specimens

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 to avoid yielding and 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 gauge 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 0.02 mm (per B.8.7), the accuracy shall not be larger than 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 assure 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.

Temperature 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 re-calibrated. 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 to be required 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 2 1/4 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.

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

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.

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 – 2.15	
Voltage (V)	30 – 32	
Amperage (A)	500 – 520	540 – 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 Min.	
Interpass Temperature Min./Max. (°C)	200 / 230	
Post Heating or DHT (°C and hours)	350°C+/–10°C for 4 hours min.	

[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

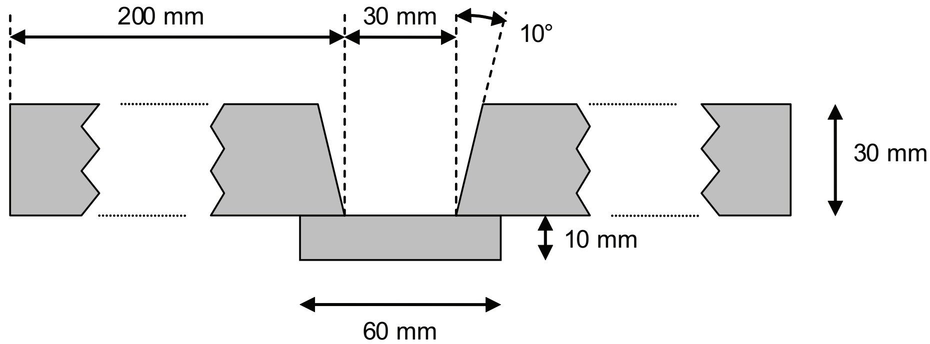
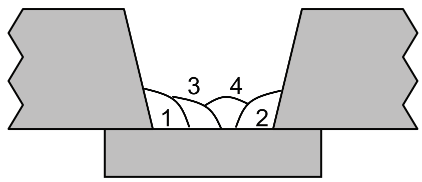


Figure B.2—Geometry of the Weld Joint to be Used for the Screening Test Coupon



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

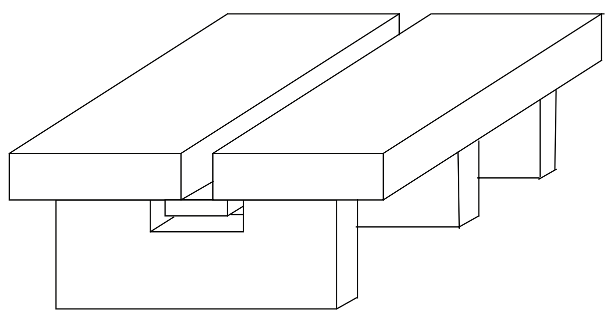


Figure B.4—Example of Strongbacks Used to Minimize Coupon Distortion

B.6.2 Heat Treatment of Test Coupons

Welding step shall be followed by Dehydrogenation Heat Treatment (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 Intermediate Stress Relieving heat treatment (ISR) or Postweld Heat Treatment (PWHT). Any deviation will lead to non-validity of the results.

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 2 mm. The length of the pre-form shall be 120 mm minimum and they shall be extracted at least 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.

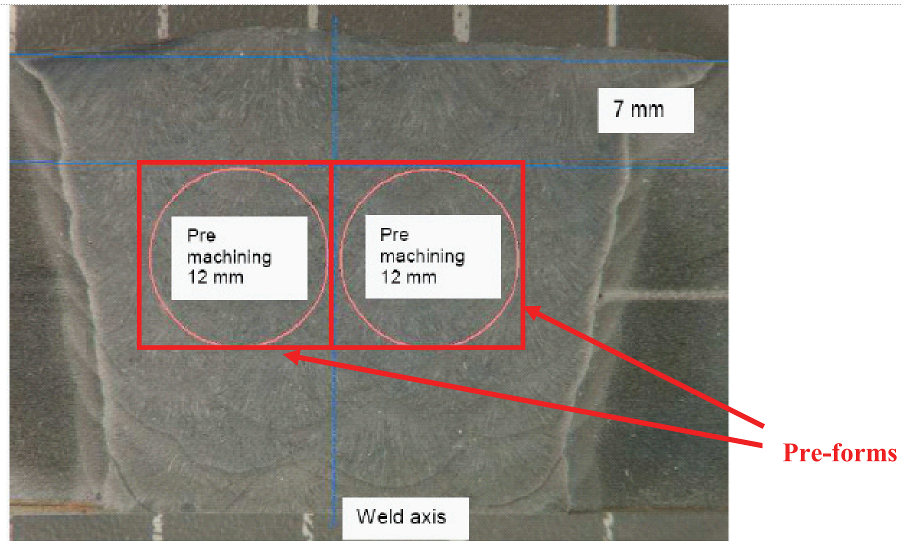


Figure B.5—Position of Pre-forms Inside the Welded Zone—Macrographic View

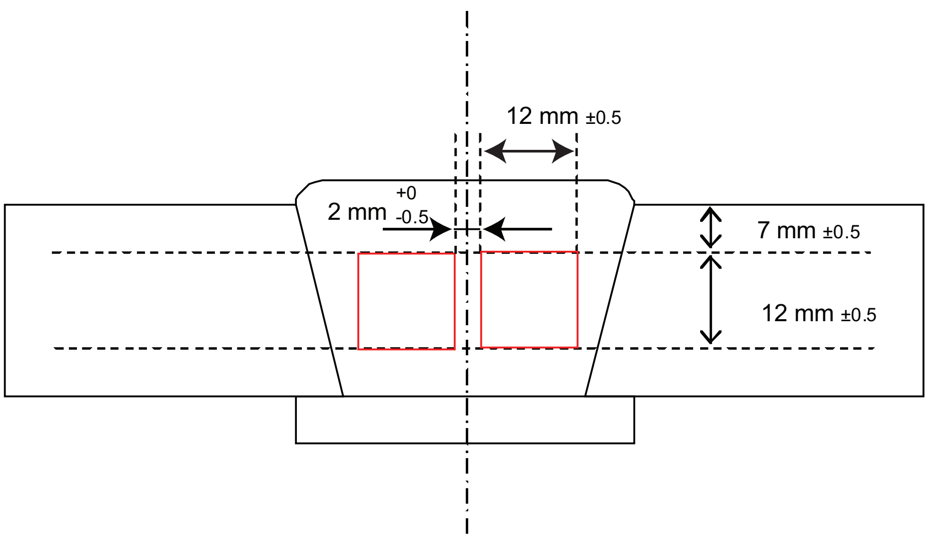


Figure B.6—Position of Pre-forms Inside the Welded Zone—Schematic View

50 mm of each ends 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 12x12x120 mm pre-form described in B.6.1.

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

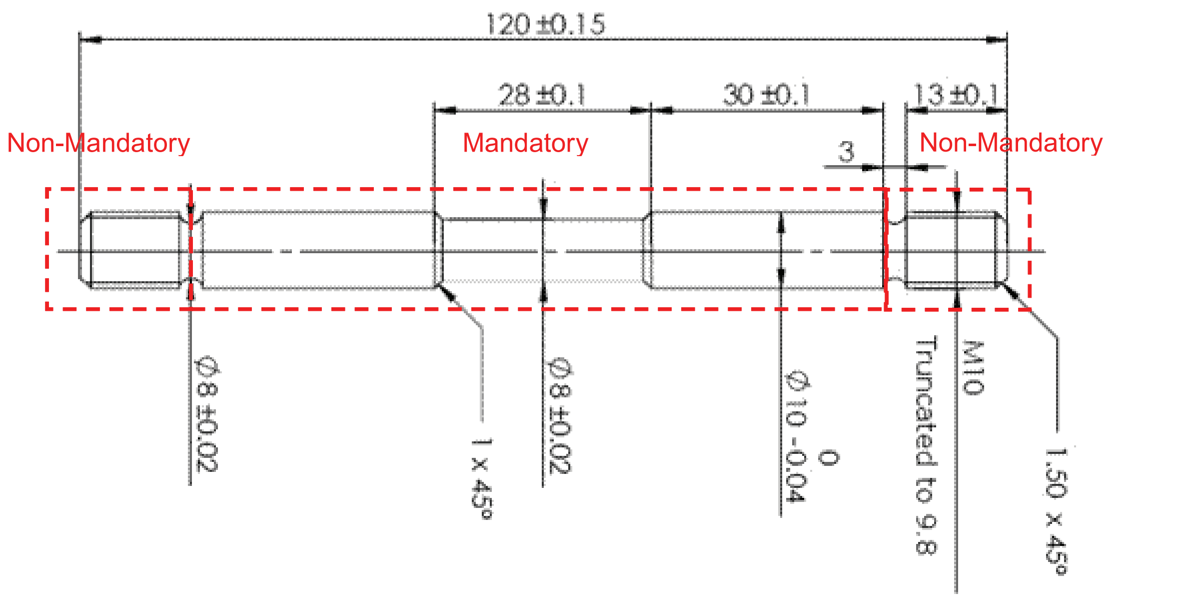


Figure B.7—Detailed Geometry of RHC Standard Specimen

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.

B.8.2 Connecting Specimen to the Machine

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

B.8.3 Testing Temperature

For the purpose of this RHC screening test procedure, testing temperature shall be equal to 650 °C +/– 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 specimen is also acceptable.

The use of three thermocouples is mandatory, one in the middle of the gauge length and one at each end of the reduced section (see Figure B.8).

The temperature difference between the three thermocouples should not exceed +/–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. 650 °C) shall not exceed +/–3 °C.

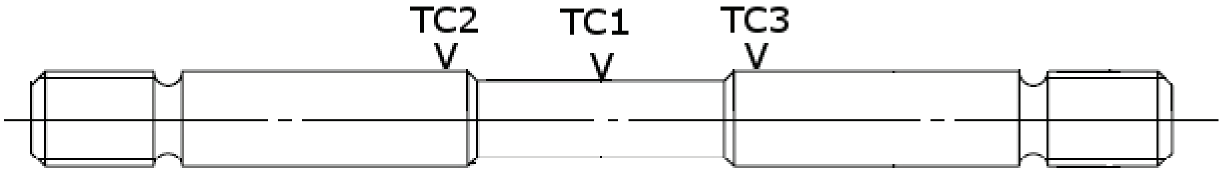


Figure B.8—Location of the Thermocouples on the RHC Standard Specimen

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 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.

NOTES:

It is highly recommended to use a spare specimen to set the parameters to obtain homogeneity and relevant conditions.

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.

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 ductility are strongly affected by the rate of deformation.

Tests must be performed at constant crosshead displacement rate of to 0.8mm/min +/–20% using the standard specimens shown in B.6.2. This 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.

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.

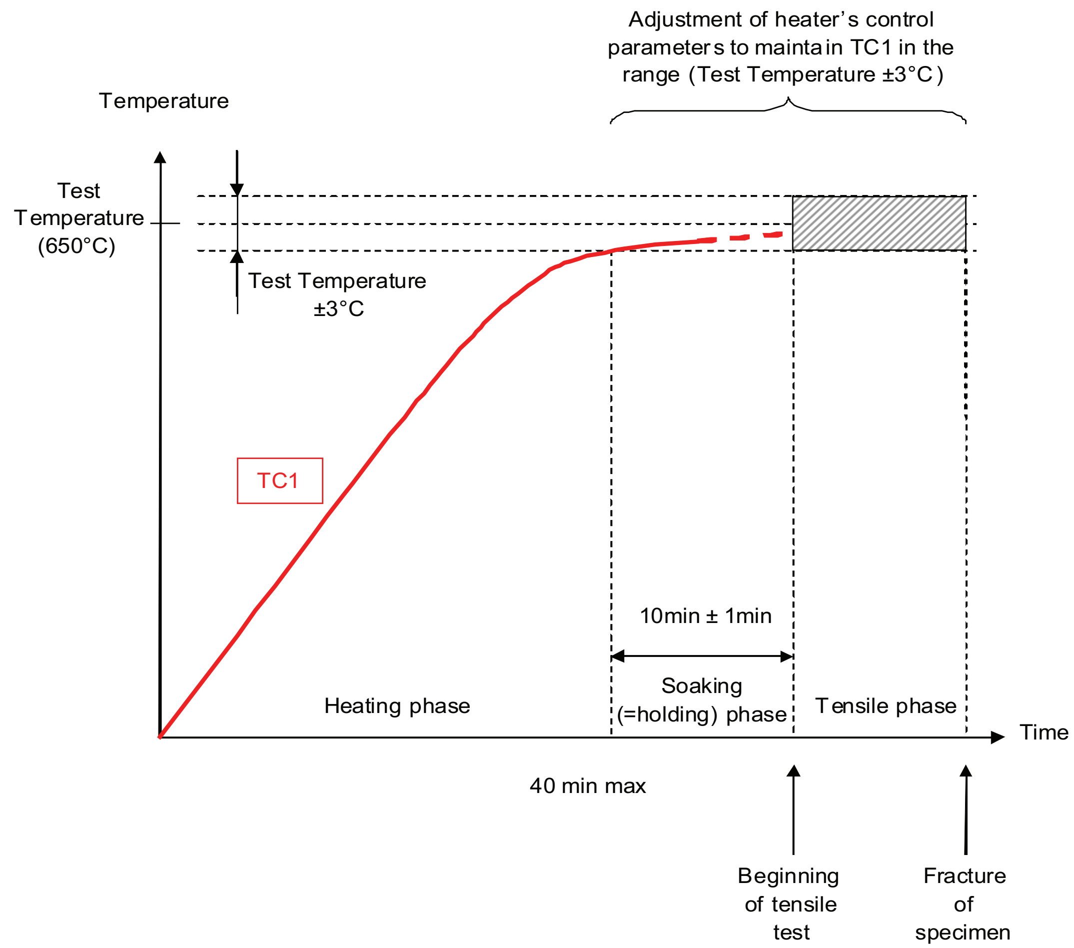


Figure B.9—Illustration of Heating Requirements on Test Specimens

The minimum diameter shall be measured to the nearest 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 gauge length (Lo) should be taken equal to 26 mm, assuming the deformation is restricted to the reduced diameter length of the specimen.

Fracture should occur in the middle of the gauge length (in the central third of the specimen gauge 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 not valid.

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 reheat cracking 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).

— Description of material tested with all specified processing information.

— Identification of the specimen(s).

— As built specimen dimensions, including cross-sectional dimensions.

— Temperature of test.

— Test atmosphere.

— Time to attain test temperature and time at temperature before testing.

— 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, amount and duration of temperature overshoot.

— 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.

— 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 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.

— Name of test technician and date of 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 Future Publication

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 Gauge Length, Gauge 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, gauge length (mm) [b]		
When required, elongation (%) [b]		
Location and description of fracture [c]		
Test Certification		
Make and capacity of testing machine		
Make and class of extensometer		
Make and size of furnace		
Type of temperature controller		
Type of thermocouples		
Name of test technician and date of test		

Notes:

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 It should be note 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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