

Materials and Fabrication of 2¹/₄Cr-1Mo, 2¹/₄Cr-1Mo-¹/₄V, 3Cr-1Mo, and 3Cr-1Mo-¹/₄V Steel Heavy Wall Pressure Vessels for High-temperature, High-pressure Hydrogen Service

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Introduction

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

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

Materials and Fabrication of 2¹/₄Cr-1Mo, 2¹/₄Cr-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 RP covers materials and fabrication requirements for new 2¹/₄Cr and 3Cr steel heavy wall pressure vessels for high-temperature, high-pressure hydrogen service. For this RP, “heavy wall” is defined as a shell thickness of 4 in. (100 mm) or greater, and high-temperature is considered to be operating temperatures of 650 °F (345 °C) and 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 2¹/₄Cr-1Mo and 3Cr-1Mo steels, and advanced steels which include 2¹/₄Cr-1Mo-¹/₄V, 3Cr-1Mo-¹/₄V-Ti-B, and 3Cr-1Mo-¹/₄V-Nb-Ca steels. This document may be used as a reference document for the fabrication of 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 2¹/₄Cr-1Mo & 3Cr-1Mo Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service*, published December 2000. The second edition was issued in May 2008, and it was the first version referred to as “934-A.” RP 934-A, second edition, later incorporated Annex A and then Annex B, which were issued in February 2010 and March 2012 as Addendum 1 and Addendum 2, respectively.

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.

ASTM³ G146, *Standard Practice for Evaluation of Disbonding of Bimetallic Stainless Alloy/Steel Plate for Use in High-Pressure, High-Temperature Refinery Hydrogen Service*

AWS⁴ 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*

WRC⁵ 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.

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

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

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 2¹/₄Cr-1Mo nozzles should not be used with 2¹/₄Cr-1Mo-¹/₄V shell plates). Some designs use austenitic stainless steels as part of the outlet nozzle that extends to the outside of the skirt. This results in the nozzle having a dissimilar metal weld. These cases require purchaser approval (also see 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 2¹/₄Cr-1Mo to be used on 2¹/₄Cr-1Mo-¹/₄V 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 / ₄ Cr-1Mo	Standard 3Cr-1Mo	2 ¹ / ₄ Cr-1Mo- ¹ / ₄ V ^a	3Cr-1Mo- ¹ / ₄ V-Ti-B ^a	3Cr-1Mo- ¹ / ₄ V-Cb-Ca ^b
Plate	SA-387	Grade 22, Class 2	Grade 21, Class 2	—	—	—
	SA-542 ^c	—	—	Type D, Class 4a	Type C, Class 4a	Type E, Class 4a
	SA-832	—	—	Grade 22V	—	—
Forging	SA-182	Grade F22, Class 3	Grade F21	Grade F22V	Grade F3V	Grade F3VCb
	SA-336	Grade F22, Class 3	Grade F21, Class 3	Grade F22V	Grade F3V	Grade F3VCb
	SA-508 ^d	—	—	—	Grade 3V	Grade 3VCb
	SA-541 ^d	—	—	Grade 22V	Grade 3V	Grade 3VCb
Pipe	SA-335	Grade P22	Grade P21	—	—	—
Pipe (forged or bored)	SA-369	Grade FP22	Grade FP21	—	—	—

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

^b Covered in ASME Code Case 2151-1.

^c 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):

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

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

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

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:

- normalized and tempered (N&T); or
- 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/mm²);
- advanced steels: 110 ksi (760 N/mm²).

b) Yield strength shall not exceed the following limits:

- conventional steels: 90 ksi (620 N/mm²);
- advanced steels: 90 ksi (620 N/mm²).

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:

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

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

$$Ni = 0.30 \text{ wt \% max.}$$

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 2¹/₄Cr-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, $K_f = Pb + Bi + 0.03Sb$ (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.