NACE Standard MR0103-2012
Item 21305

Standard Material Requirements

Materials Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Environments

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Revised 2012-06-23
Revised 2010-10-22
Revised 2007-07-19
Revised 2005-05-23
Approved 2003-03-15
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ISBN 1-57590-168-4

Foreword

This NACE standard establishes material requirements for resistance to sulfide stress cracking (SSC) in sour refinery process environments, i.e., environments that contain wet hydrogen sulfide (H_2S). It is intended to be used by refineries, equipment manufacturers, engineering contractors, and construction contractors.

The term "wet H_2S cracking" as used in the refining industry covers a range of damage mechanisms that can occur because of the effects of hydrogen charging in wet H_2S refinery or gas plant process environments. One of the types of material damage that can occur as a result of hydrogen charging is SSC of hard weldments and microstructures, which is addressed by this standard. Other types of material damage include hydrogen blistering, hydrogen-induced cracking (HIC), and stress-oriented hydrogen-induced cracking (SOHIC), which are not addressed by this standard.

Historically many end users, industry organizations (e.g., API[(1)]), and manufacturers that have specified and supplied equipment and products such as rotating equipment and valves to the refining industry have used NACE MR0175/ISO[(2)]15156[1] to establish materials requirements to prevent SSC. However, it has always been recognized that refining environments are outside the scope of NACE MR0175/ISO 15156, which was developed specifically for the oil and gas production industry. In 2000, NACE Task Group (TG) 231 was formed to develop a refinery-specific sour service materials standard. This standard is based on the good experience gained with NACE MR0175/ISO 15156, but tailored to refinery environments and applications. Other references for this standard are NACE SP0296,[2] NACE Publication 8X194,[3] NACE Publication 8X294,[4] and the refining experience of the task group members.

The materials, heat treatments, and materials property requirements set forth in this standard represent the best judgment and experience of TG 231 and its two sponsors, Specific Technology Group (STG) 34, "Petroleum Refining and Gas Processing Industry Corrosion," and STG 60, "Corrosion Mechanisms." In many cases this judgment is based on extensive experience in the oil and gas production industry, as documented in NACE MR0175/ISO 15156, and has been deemed relevant to the refining industry by the task group.

(1) American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005-4070.
(2) International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case postale 56, CH-1211 Geneva 20, Switzerland.

Whenever possible, the recommended materials are identified by accepted generic descriptors (such as UNS(3) numbers) and/or accepted standards, such as AISI,(4) API, ASTM,(5) ASME,(6) ANSI,(7) or BSI(8) standards. This NACE standard updates and supersedes all previous editions of NACE Standard MR0103. It was originally prepared in 2003 and was revised in 2005, 2007, 2010, and 2012 by NACE TG 231, "Petroleum Refining Sulfide Stress Cracking (SSC): Review of NACE Standard MR0103." TG 231 is administered by STG 34, "Petroleum Refining and Gas Processing." It is also sponsored by STG 60, "Corrosion Mechanisms." This standard is issued by NACE International under the auspices of STG 34.

In NACE standards, the terms *shall, must, should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*. The terms *shall* and *must* are used to state a requirement, and are considered mandatory. The term *should* is used to state something good and is recommended, but is not considered mandatory. The term *may* is used to state something considered optional.

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(3) Unified Numbering System for Metals and Alloys (UNS). UNS numbers are listed in *Metals & Alloys in the Unified Numbering System*, latest revision (Warrendale, PA: SAE International and West Conshohocken, PA: ASTM International).
(4) American Iron and Steel Institute (AISI), 1140 Connecticut Ave. NW, Washington, DC 20036.
(5) ASTM International (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.
(6) ASME International (ASME), Three Park Avenue, New York, NY 10016-5990.
(7) American National Standards Institute (ANSI), 25 West 43rd St., 4th Floor, New York, NY 10036.
(8) BSI British Standards (BSI) (formerly British Standards Institution), 389 Chiswick High Road., London W4 4AL, U.K.

NACE International
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Section 1: General

1.1 Scope

1.1.1 This standard establishes material requirements for resistance to SSC in sour petroleum refining and related processing environments containing H_2S either as a gas or dissolved in an aqueous (liquid water) phase with or without the presence of hydrocarbon. This standard does not include and is not intended to include design specifications. Other forms of wet H_2S cracking, environmental cracking, corrosion, and other modes of failure, although outside the scope of this standard, should be considered in the design and operation of equipment. Severely corrosive and/or hydrogen charging conditions may lead to failures by mechanisms other than SSC and should be mitigated by methods that are outside the scope of this standard.

1.1.2 Specifically, this standard is directed at the prevention of SSC of equipment (including pressure vessels, heat exchangers, piping, valve bodies, and pump and compressor cases) and components used in the refining industry. Prevention of SSC in carbon steel materials categorized under P-No. 1 in Section IX of the ASME Boiler and Pressure Vessel Code (BPVC)[5] is addressed by requiring compliance with NACE SP0472.[6]

Note: There are a number of instances in which this standard specifically references the ASME BPVC. This reference is based on historical development of the standard, but is not intended to preclude the use of other pertinent codes and standards where they are appropriate.

1.2 Applicability

1.2.1 This standard applies to all components of equipment exposed to sour refinery environments (see Paragraph 1.3) where failure by SSC would (1) compromise the integrity of the pressure-containment system, (2) prevent the basic function of the equipment, and/or (3) prevent the equipment from being restored to an operating condition while continuing to contain pressure.

1.2.2 It is the responsibility of the user to determine the operating conditions and to specify when this standard applies.

1.2.3 It is the user's responsibility to ensure that a material will be satisfactory in the intended environment. The user may select specific materials for use on the basis of operating conditions that include pressure, temperature, corrosiveness, and fluid properties. A variety of candidate materials may be selected from this standard for any given component. Unlisted materials may also be used based on either of the following processes:

(a) If a metallurgical review based on scientific and empirical knowledge indicates that the SSC resistance will be adequate. These materials may then be proposed for inclusion into the standard using methods in Paragraph 1.6.

(b) If a risk-based analysis indicates that the occurrence of SSC is acceptable in the subject application.

1.2.4 The manufacturer is responsible for meeting metallurgical requirements.

1.3 Factors Contributing to SSC

1.3.1 SSC is defined as cracking of a metal under the combined action of tensile stress and corrosion in the presence of water and H_2S. SSC is a form of hydrogen stress cracking resulting from absorption of atomic hydrogen that is produced by the sulfide corrosion reaction on the metal surface.

1.3.2 SSC in refining equipment is affected by complex interactions of parameters including:

(a) chemical composition, strength (as indicated by hardness), heat treatment, and microstructure of the material exposed to the sour environment;

(b) total tensile stress present in the material (applied plus residual);

(c) the hydrogen flux generated in the material, which is a function of the environment (i.e., presence of an aqueous phase, H_2S concentration, pH, and other environmental parameters such as bisulfide ion concentration and presence of free cyanides);

(d) temperature; and

(e) time.

1.3.3 Material susceptibility to SSC is primarily related to material strength (as indicated by hardness), which is affected by chemical composition, heat treatment, and microstructure. Materials with high hardness generally have an increased susceptibility to SSC.

1.3.3.1 SSC has not generally been a concern for carbon steels typically used for refinery pressure vessels and piping in wet H_2S service because these steels have sufficiently low hardness levels.

1.3.3.2 Improperly heat-treated materials, weld deposits, and heat-affected zones (HAZs) may contain regions of high hardness.

1.3.4 SSC susceptibility for a given material increases with increased tensile stress.

1.3.4.1 Residual stresses contribute to the overall tensile stress level. High residual stresses associated with welds increase susceptibility to SSC.

1.3.4.2 Control of weldment hardness, with or without reduction of residual stresses, is a recognized method for preventing SSC, as outlined in NACE SP0472 for P-No. 1 carbon steels.

1.3.5 Susceptibility to SSC is also related to the hydrogen permeation flux in the steel, which is primarily associated with two environmental parameters: pH and total sulfide content of the aqueous phase. In a closed system at equilibrium condition, dissolved hydrogen sulfide (H_2S_{aq}), bisulfide ion (HS^-), and sulfide ion (S^{2-}) (sometimes called "soluble sulfide") exist in an aqueous solution in different pH ranges. The sulfide species plot exhibited in Figure A1 in Appendix A (nonmandatory) shows their relative amounts present in an aqueous solution at 25 °C (77 °F) as a function of pH. At pH less than 6, H_2S_{aq} is the dominant (> 90% of total) sulfide specie present in the aqueous phase. At pH between 8 and 11, the dominant (> 90% of total) sulfide specie present in the aqueous phase is HS^-. At pH greater than 13, the dominant (> 90% of total) sulfide specie present in the aqueous phase is S^{2-}. At pH 7, the system contains 50% H_2S_{aq}, 50% HS^-, and virtually no S^{2-}. At pH 12, the system contains 50% HS^-, 50% S^{2-}, and virtually no H_2S_{aq}. The total sulfide content therefore refers to the total amount of all three sulfide species present in the aqueous phase (i.e., the sum of H_2S_{aq}, HS^-, and S^{2-}). Typically, the hydrogen flux in steels has been found to be lowest in near-neutral pH solutions, with increasing flux at both lower and higher pH values. Corrosion at lower pH values is typically caused by H_2S_{aq}, whereas corrosion at higher pH values is typically caused by high concentrations of HS^-. In many refinery sour water environments, the presence of dissolved ammonia (NH_3) increases the pH, thereby increasing the solubility of H_2S and resulting in a high HS^- concentration. At elevated pH, the presence of free cyanides, which include dissolved hydrogen cyanide (HCN_{aq}) and cyanide ion (CN^-), can further aggravate the degree of atomic hydrogen charging into the steel. Even though SSC susceptibility is known to increase with total sulfide content of the aqueous phase, the presence of as little as 1 ppmw total sulfide in the aqueous phase can cause SSC under conditions that promote aggressive hydrogen charging.

1.3.5.1 Some environmental conditions known to cause SSC are those containing an aqueous phase and:

(a) > 50 ppmw total sulfide content in the aqueous phase; or

(b) $\geq$ 1 ppmw total sulfide content in the aqueous phase and pH < 4; or

(c) $\geq$ 1 ppmw total sulfide content and $\geq$ 20 ppmw free cyanide in the aqueous phase, and pH > 7.6; or

(d) > 0.3 kPa absolute (0.05 psia) partial pressure H_2S in the gas phase associated with the aqueous phase of a process.

1.3.5.2 The high-pH sour environments differentiate refinery sour service from the oil and gas production sour environments covered by NACE MR0175/ISO 15156, because many wet sour streams in production also contain carbon dioxide and hence exhibit a lower pH. Another major difference is that chloride ion concentrations tend to be significantly lower in refinery sour services than in oil production sour services.

1.3.6 The hydrogen charging potential increases with increasing temperature provided the aqueous phase is not eliminated by the elevated temperature. Elevated temperature promotes dissociation of H_2S (thereby producing more monatomic hydrogen), and increases the diffusion rates of monatomic hydrogen in metals, thereby promoting hydrogen charging.

However, cracking potential is maximized at near-ambient temperature. This distinction is important because metals can become charged during high-temperature exposure and subsequently crack during excursions to lower temperatures (such as during shutdowns).

1.3.7 The time to failure decreases as material strength, total tensile stress, and environmental charging potential increase. Exposure time to cause SSC can be very short if the other SSC factors favor susceptibility. Some susceptible equipment can fail even during short sour water excursions such as those encountered during equipment shutdowns.

1.3.8 The end user shall determine whether the parameters necessary to cause SSC exist in the process environment, and whether the equipment falls within the scope of this standard. The end user may rely on experience, risk-based analysis, or the above guidance (notably that related to environmental conditions provided in Paragraphs 1.3.5 and 1.3.6) to make this determination. When determining whether the equipment falls within the scope of this standard, consideration should be given to all plant operating scenarios and the likely impact on the materials of construction, i.e., normal operations, operational upsets, alternate (possible future) operations, and start-up/shutdown conditions (e.g., presulfiding of catalysts).

1.4 Materials Included in This Standard

1.4.1 Materials included in this standard are resistant to, but not necessarily immune to, SSC. Materials have been included based on their demonstrated resistance to SSC in field applications, in SSC laboratory testing, or both.

1.4.2 Listed materials do not all exhibit the same level of resistance to SSC. Standard laboratory SSC tests, such as those addressed in NACE Standard TM0177,[7] are accelerated and severe tests. Materials that successfully pass these tests are generally more resistant to cracking in sour service than materials that fail the tests. Many alloys included in this standard perform satisfactorily in sour service even though they may crack in laboratory tests.

1.4.3 Improper design, processing, installation, or handling can cause resistant materials to become susceptible to SSC.

1.4.4 No effort has been made in this standard to rank materials based on their relative resistance to SSC. Selection of the appropriate material for a given application depends on a number of factors, including mechanical properties, corrosion resistance, and relative resistance to SSC, and is beyond the scope of this standard.

1.5 Hardness Requirements

1.5.1 Hardness is related to tensile strength, a primary factor in SSC susceptibility. Because hardness testing is nondestructive and requires relatively minor component/specimen preparation compared with tensile testing, it is commonly used by manufacturers in production quality control and by users in field inspection. As such, a maximum allowable hardness is specified as a primary requirement for many of the materials in this standard.

1.5.2 Several different hardness scales are used in this standard. The most commonly used scales are Rockwell “C” (HRC), Rockwell “B” (HRBS), Brinell (HBW), and Vickers 49 N (5 kgf) or 98 N (10 kgf) (HV 5 or HV 10). Background information on these hardness scales and the logic behind the various references is provided in Appendix B (nonmandatory).

1.5.3 Hardness testing and reporting shall be performed in strict compliance with the methods described in the appropriate ASTM or ISO standards, which are listed in the References section. Appendix B also lists the appropriate standards for the various test methods.

1.5.4 The standard test parameters (indenters, loads, and major-load dwell time) shall be used for all Rockwell hardness tests. The specimen temperature for Rockwell hardness testing shall be 10 to 35 °C (50 to 95 °F). No lubricant shall be used. Because Brinell hardness tests are only indicated for steel materials in this standard, all Brinell hardness tests shall be performed using 29.4 kN (3,000 kgf) load, a 10 mm indenter, and the standard dwell time of 10 to 15 s.

1.5.5 In some cases, maximum allowable hardness values are provided in both HRC (or HRBS) and HBW. In those instances, either scale may be used.

1.5.6 When hardness requirements are stated in HBW, and testing using stationary Brinell hardness equipment is not viable, testing shall be performed using the comparison hardness test method (commonly, but incorrectly, referred to as portable Brinell hardness testing).

1.5.7 When applicable, the conversion tables in ASTM E140[8] or ISO 18265[9] shall be used for conversion of hardness values obtained by other test methods to HRC, HRBS, or HBW values. However, tables for many materials do not exist in those standards. The tables should be used only for materials that are specifically listed. Conversions may be performed based on empirical data for materials that are not covered when approved by the user. When converted hardness values are used, they shall be reported in accordance with the requirements specified in ASTM E140 or ISO 18265.

1.5.8 Sufficient hardness tests shall be made to establish the actual hardness of the material being examined. Individual hardness readings exceeding the permitted value may be considered acceptable if the average of several readings taken within close proximity does not exceed the permitted value and no individual reading exceeds the specified value by more than 2 HRC (or by more than 5% in the case of HBW or HV 10).

1.5.9 Acceptance criteria for microhardness testing using Knoop or Vickers hardness test methods (see ASTM E384[10]) are outside the scope of this standard. See Appendix B for more information.

1.5.10 The use of portable hardness testing methods to verify compliance with the requirements of this standard is prohibited unless explicitly approved by the end user. The one exception that does not require end user approval is the use of comparison hardness testing in accordance with ASTM A833[11] to evaluate weld deposits as specified in NACE SP0472. See Appendix B (nonmandatory).

1.6 Procedure for the Addition of New Materials or Processes

1.6.1 NACE's standard letter balloting process shall be used for the addition of new materials and/or processes to this standard.

1.6.2 Materials may be balloted based on field experience and/or laboratory test data.

1.6.3 Field Experience Data Requirements

1.6.3.1 Field experience data shall fully document the alloy composition(s), condition(s), and hardness level(s), the process fluid parameters that influence SSC, and the exposure history.

1.6.3.2 In certain alloy families (such as duplex stainless steels), microstructure is also a critical variable, and shall also be documented.

1.6.4 Laboratory Test Data Requirements

1.6.4.1 The laboratory testing of materials shall be performed to a level of severity in accordance with NACE Standard TM0177. If actual service conditions are outside these limits, SSC of approved materials may be possible.

1.6.4.2 The candidate material must be tested in accordance with the test procedures established in NACE Standard TM0177. The tensile bar, C-ring, bent beam, and double-cantilever beam test specimens described in NACE Standard TM0177 are accepted test specimens. Any of these test specimens may be used.

1.6.4.3 A minimum of three test specimens from each of three different commercially prepared heats must be tested in the condition balloted for inclusion. The composition of each heat and the heat treatment(s) used shall be furnished as part of the ballot. The candidate material's composition range and/or UNS number and its heat-treated condition requested for inclusion in this standard must be included with the ballot.

1.6.4.4 The hardness of each test specimen must be determined and reported as part of the ballot. The average hardness of each test specimen shall be the hardness of that test specimen. The minimum test specimen hardness obtained for a given heat/condition shall be the hardness of that heat/condition for the purpose of balloting. The maximum hardness requested for inclusion of the candidate material in this standard must be specified in the ballot and shall be supported by the data provided.

1.6.4.5 In certain alloy families (such as duplex stainless steels), microstructure is also a critical variable, and shall also be documented for each heat/condition.

1.6.4.6 For each of the tests performed, the testing details shall be reported as part of the ballot item being submitted.

1.7 New Restrictions and Deleted Materials

1.7.1 The revision/ballot process may be used to impose new restrictions on materials or to delete materials from this standard. New restrictions may include such items as imposition of a maximum hardness requirement, reduction of a maximum hardness requirement, elimination of a previously acceptable heat-treatment condition, and elimination of a previously acceptable manufacturing process.

1.7.2 Affected materials in use at the time of the change that complied with a prior edition of this standard and that have not experienced H_2S-enhanced environmental cracking in their current application are considered in compliance with this standard.

1.7.3 When affected materials (see Paragraph 1.7.2) are eventually removed from their current application, replacement materials must be selected from acceptable materials in the current edition of this standard to be in compliance with this standard, except as noted in Paragraph 1.7.4.

1.7.4 New equipment manufactured from affected materials, as well as equipment refurbished using new components manufactured from affected materials, may be qualified for use in specific applications in accordance with Paragraph 1.8.

1.8 Qualification of Unlisted Alloys, Conditions, and/or Processes for Specific Applications

1.8.1 Alloys, conditions, and processes that are not listed in this standard may be qualified for use in specific sour applications. This section provides the minimum requirements for compliance with this standard when unlisted alloys, conditions, and/or processes for specific applications are qualified.

1.8.2 The user shall be responsible for determining the suitability of an unlisted alloy, condition, and/or process for a specific application based on laboratory test data, field experience, and/or risk-based analysis.

1.8.3 If laboratory testing is used as an acceptance basis, testing should be performed in accordance with accepted standard test methods such as those documented in NACE Standard TM0177.

1.8.4 If field experience and/or risk-based analysis is used as an acceptance basis, a number of factors should be considered:

(a) The stress level, material form, forming process, heat-treatment condition, microstructure, and mechanical properties (particularly hardness) of the field experience specimen should be well documented.

(b) The environmental conditions to which the field experience specimen is exposed should be well documented.

(c) The field experience exposure time should be adequate to ensure that the unlisted alloy, condition, and/or process provides resistance to SSC.

1.8.5 The suitability of the unlisted alloy, condition, and/or process for a specific application should be determined based on an evaluation of the environmental conditions in the intended specific application compared with the environmental conditions in the laboratory tests and/or the field experience.

1.8.6 The composition, material form, forming processes, heat-treatment condition, and mechanical properties of equipment manufactured using an unlisted alloy, condition, and/or process should be controlled based on the corresponding information for the laboratory test specimens and/or field experience specimens.

1.8.7 Unlisted alloys, conditions, and/or processes qualified for specific applications based on the requirements in this section shall not become part of this standard unless they are approved through the NACE balloting process.

1.9 Standard Road Map

For ease of use, Table 1 provides general information by material/application group, as well as references to specific paragraphs that cover applicable material and fabrication requirements.

Table 1
"Road Map" for This Standard

Material Groups			
Material Group or Application	**Conditions Allowed**	**Applicable Material Requirement Paragraph(s)**	**Applicable Fabrication Requirement Paragraph(s)**
Carbon Steels	(a) Hot-rolled (b) Annealed (c) Normalized (d) Normalized and tempered (e) Normalized, austenitized, quenched, and tempered (f) Austenitized, quenched, and tempered.	2.1	2.1.8, Section 4
Alloy Steels	(a) Annealed (b) Normalized (c) Normalized and tempered (d) Normalized, austenitized, quenched, and tempered (e) Austenitized, quenched, and tempered.	2.1	2.1.8, Section 4
Ferritic Ductile Iron	Annealed	2.2.2	2.2.3
Ferritic Stainless Steels	Annealed	2.3	Section 4
Specific Low-Carbon Martensitic Stainless Steels	Quenched and double-tempered	2.4.2	2.4.3, Section 4
Austenitic Stainless Steels	Solution-annealed	2.5	Section 4
Specific Austenitic Stainless Steels	Solution-annealed or hot-rolled	2.6	Section 4
Highly Alloyed Austenitic Stainless Steels	Solution-annealed or solution-annealed and cold-worked	2.7	Section 4
Duplex Stainless Steels	Solution-annealed	2.8	2.8.2, Section 4
Precipitation-Hardenable Stainless Steels	Solution-annealed and precipitation-hardened	2.9	Section 4
Solid-Solution Nickel Alloys	Solution-annealed	3.1.1	Section 4
Precipitation-Hardenable Nickel Alloys	Various	3.1.2	Section 4
Cobalt-Nickel-Chromium-Molybdenum Alloys	Various	3.2	Section 4
Cobalt-Nickel-Chromium-Tungsten Alloys	Not specified	3.3	Section 4
Titanium Alloys	Various	3.4	Section 4
Aluminum Alloys	Not specified	3.5	Section 4
Copper Alloys	Not specified	3.6	Section 4

Material Groups			
Material Group or Application	**Conditions Allowed**	**Applicable Material Requirement Paragraph(s)**	**Applicable Fabrication Requirement Paragraph(s)**
Applications			
Material Group or Application	**Conditions Allowed**	**Applicable Material Requirement Paragraph(s)**	**Applicable Fabrication Requirement Paragraph(s)**
Fabrication	Various	Section 4	Section 4
Bolting	Various	Section 5	N/A
Platings, Coatings	Various	Section 6	N/A
Special Components	Various	Section 7	Section 4
Valves	Various	Section 8	Section 4
Compressors and Pumps	Various	Section 9	Section 4

Section 2: Ferrous Materials

2.1 Carbon and Alloy Steel Materials

2.1.1 For the purposes of this standard, the terms “carbon steel” and “alloy steel” refer to alloys that meet the corresponding definitions in ASTM A941.[12]

2.1.2 Carbon and alloy steels shall:

(a) not contain intentional additions of elements such as lead, selenium, or sulfur to improve machinability;

(b) meet the criteria of Paragraphs 2.1.7, 2.1.8, and Section 4; and

(c) be used in one of the following heat-treatment conditions:

i. hot-rolled (carbon steels only);

ii. annealed;

iii. normalized;

iv. normalized and tempered;

v. normalized, austenitized, quenched, and tempered; or

vi. austenitized, quenched, and tempered.

2.1.3 Carbon steels listed as P-No. 1 Group 1 or 2 materials in Section IX of the ASME BPVC shall meet one of the conditions listed in Paragraph 2.1.2(c). Base-metal hardness controls are not required.

2.1.3.1 Welding of P-No. 1 carbon steels shall be controlled in accordance with Paragraph 2.1.8.

2.1.3.2 Bends in P-No. 1 piping formed by heating to above the upper critical temperature (Ac3) are allowed. The material shall have met one of the conditions listed in Paragraph 2.1.2 (c) prior to forming. The hardness in the bend area shall not exceed 225 HBW.

2.1.3.3 Weld repairs in P-No. 1 castings shall be performed in accordance with the welding requirements specified in Paragraph 2.1.8.3.

2.1.4 Other carbon steels shall have a maximum hardness of 22 HRC (237 HBW).

2.1.5 Alloy steels included under the ASME BPVC Section IX P-numbers listed in Table 2 shall not exceed the indicated maximum hardness levels.

Table 2
Maximum Hardness Requirements for P-Numbered Alloy Steels

Alloy Steel	Maximum Hardness
P-No. 3	225 HBW
P-No. 4	225 HBW
P-No. 5A	235 HBW
P-No. 5B	235 HBW
P-No. 5C	235 HBW
P-No. 6	235 HBW
P-No. 7	235 HBW
P-No. 10A	225 HBW
P-No. 10B	225 HBW
P-No. 10C	225 HBW
P-No. 10F	225 HBW
P-No. 11	225 HBW
P-No. 15E	248 HBW

2.1.6 Other alloy steels shall have a maximum hardness of 22 HRC (237 HBW).

2.1.7 Cold forming of carbon and alloy steels is allowed. The material shall have met one of the conditions listed in Paragraph 2.1.2(c) prior to cold forming. Cold-formed material shall be thermally stress relieved following any cold deforming by rolling, cold forging, or another manufacturing process that results in a permanent outer fiber deformation greater than 5%. Thermal stress relief shall be performed in accordance with the applicable ASME codes, except that the minimum stress-relief temperature shall be 593 °C (1,100 °F). After stress relieving, carbon steels listed as P-No. 1 materials in Section IX of the ASME BPVC shall meet a hardness requirement of 200 HBW maximum. Other carbon and alloy steels shall meet the appropriate hardness requirements in accordance with Paragraph 2.1.4, 2.1.5, or 2.1.6.

2.1.7.1 This requirement does not apply to cold work imparted by pressure testing in accordance with the applicable code. Cold-rotary straightened pipe is allowed only when permitted in API specifications. Cold-worked line pipe fittings of ASTM A53[13] Grade B, ASTM A106[14] Grade B, API Spec 5L[15] Grade X-42, or lower-strength grades with similar chemical compositions shall contain no more than 15% cold strain, and the hardness in the strained area shall not exceed 190 HBW.

2.1.8 Welding and Overlays on Carbon Steels and Alloy Steels

2.1.8.1 Fabrication welding and weld overlays shall be performed in accordance with the general requirements listed in Section 4.

2.1.8.2 Overlays applied to carbon and alloy steels for use in sour environments shall meet the requirements listed in Paragraphs 4.2 and 4.4 and in the following subparagraphs.

2.1.8.2.1 When applied to P-No. 1 carbon steels, partial weld overlays that do not qualify as cladding in accordance with Paragraph 4.4 shall be applied in such a way that the process-contacted interface between the overlay and the base metal has a HAZ and base metal hardness within the specified limits. Methods used to control the HAZ and base metal hardness, and acceptance criteria, shall be in accordance with NACE SP0472.

2.1.8.2.2 When applied to alloy steels or to non-P-No. 1 carbon steel materials, partial weld overlays that do not qualify as cladding in accordance with Paragraph 4.4 shall be post-weld heat treated in accordance with procedures that have been shown to return the process-contacted interface between the overlay and base metal to the specified HAZ and base metal condition (i.e., hardness). Hardness acceptance criteria shall be in accordance with limits provided in Paragraphs 2.1.3 through 2.1.6, and/or 2.1.8.4, as appropriate.

2.1.8.2.3 When thermal-spray coatings are applied to P-No. 1 carbon steel materials in such a manner that any portion of the base metal exceeds the lower critical temperature (e.g., in the case of a spray and fuse coating), the procedures used shall ensure that the base metal has HAZ and base metal hardness within the specified limits. Methods used to control the HAZ and base metal hardness, and acceptance criteria, shall be in accordance with NACE SP0472.

2.1.8.2.4 When thermal-spray coatings are applied to alloy steels or to non-P-No. 1 carbon steel materials in such a manner that any portion of the base metal exceeds the lower critical temperature (e.g., in the case of a spray and fuse coating), post-weld heat treatment (PWHT) shall be performed in accordance with procedures that have been shown to return the base metal to the specified HAZ and base metal condition (i.e., hardness). Hardness acceptance criteria shall be in accordance with limits provided in Paragraphs 2.1.3 through 2.1.6 and/or 2.1.8.4 as appropriate.

2.1.8.3 Weldments in carbon steels listed as P-No. 1 materials in Section IX of the ASME BPVC shall be produced using one or more of the methods outlined in NACE SP0472 to prevent excessive weldment hardness.

2.1.8.4 Some industry codes (such as ASME B31.3[16] and ANSI/NBBVI[(9)] NB-23[17]) allow welding of P-No. 3, P-No. 4, and P-No. 5A alloy steels without PWHT in certain circumstances. Non-PWHT procedures of this type may be used provided a hardness survey in accordance with Appendix C (mandatory) has been performed on a specimen taken from the welding procedure qualification test (WPQT) coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness limits. No individual hardness reading shall exceed 248 HV 10. Other alloy steel materials shall always receive PWHT when this standard applies to ensure low hardness in the weld deposit and HAZ. When PWHT is performed, a hardness survey in accordance with Appendix C shall be performed on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the PWHT time and temperature to produce weldments that meet the specified hardness limits.

2.2 Cast Iron and Ductile Iron Materials

2.2.1 Gray, austenitic, and white cast irons shall not be used as pressure-containing members. These materials may be used in internal components related to API and other appropriate standards, provided their use has been approved by the purchaser.

2.2.2 Ferritic ductile iron in accordance with ASTM A395[18] is allowed for equipment when API, ANSI, and/or other industry standards approve its use.

2.2.3 Welding is not permitted on gray cast iron or ductile iron components.

2.3 Ferritic Stainless Steel Materials

2.3.1 Ferritic stainless steels shall be in the annealed condition and shall meet the criteria of Section 4. The hardness shall not exceed 22 HRC.

2.3.2 Weldments in ferritic stainless steels shall be produced using a weld procedure qualified by performing a hardness survey in accordance with Appendix C on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness (248 HV 10 maximum).

2.4 Martensitic Stainless Steel Materials

2.4.1 Martensitic stainless steels (UNS S41000, S42000, J91150 [CA15], and J91151 [CA15M]), either cast or wrought, shall be heat treated in accordance with Paragraph 2.4.1.1 and shall meet the criteria of Section 4. The hardness shall not exceed 22 HRC. Variations containing alloying elements such as lead, selenium, or sulfur to improve machinability shall not be used. Martensitic stainless steels that are in accordance with this standard have provided satisfactory field service in some sour environments. These materials may, however, exhibit threshold stress levels in NACE Standard TM0177 laboratory tests that are lower than the levels for other materials included in this standard.

2.4.1.1 Heat-Treatment Procedure (Three-Step Process) for UNS S41000, S42000, J91150 (CA15), and J91151 (CA15M) Martensitic Stainless Steel

2.4.1.1.1 Austenitize and quench or air cool.

2.4.1.1.2 Temper at 621 °C (1,150 °F) minimum; then air cool to ambient temperature.

2.4.1.1.3 Temper at 621 °C (1,150 °F) minimum, but lower than the first tempering temperature; then air cool to ambient temperature.

2.4.2 Low-carbon, 12Cr-4Ni-Mo martensitic stainless steels, either cast UNS J91540 (CA6NM) or wrought UNS S42400, shall be heat treated in accordance with Paragraph 2.4.2.1. The hardness shall not exceed 23 HRC.(10) Variations containing alloying elements such as lead, selenium, or sulfur to improve machinability shall not be used.

2.4.2.1 Heat-Treatment Procedure (Three Step Process)

2.4.2.1.1 Austenitize at 1,010 °C (1,850 °F) minimum and air or oil quench to ambient temperature.

2.4.2.1.2 Temper at 649 to 691 °C (1,200 to 1,275 °F) and air cool to ambient temperature.

2.4.2.1.3 Temper at 593 to 621 °C (1,100 to 1,150 °F) and air cool to ambient temperature.

2.4.3 Welding and Overlays on Martensitic Stainless Steels

2.4.3.1 Weldments in martensitic stainless steels listed in Paragraph 2.4.1 shall undergo a PWHT at 621 °C (1,150 °F) minimum. The welding procedure shall be qualified by performing a hardness survey in accordance with Appendix C on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness (248 HV 10 maximum).

2.4.3.2 Weldments in low-carbon martensitic stainless steels identified in Paragraph 2.4.2 shall undergo a double-cycle PWHT after first being cooled to ambient temperature. The double-cycle PWHT shall consist of heating at 671 to 691 °C (1,240 to 1,275 °F), cooling to ambient temperature, followed by heating at 579 to 621 °C (1,075 to 1,150 °F). The welding procedure shall be qualified by performing a hardness survey in accordance with Appendix C on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness (255 HV 10 maximum).

2.4.3.3 Welding shall only be performed on base materials listed in Paragraph 2.4.2 that have previously been austenitized, quenched, and double-tempered. Welding between martensitic stainless steels and other materials (including carbon steels, alloy steels, and austenitic stainless steels) is outside the scope of this standard.

2.4.3.4 Overlays applied to martensitic stainless steels by thermal processes such as welding, silver brazing, or thermal-spray systems are allowed for use in sour environments. In those cases in which the lower critical temperatures are exceeded, the component shall be heat treated or thermally stress relieved in accordance with procedures that have been shown to return the base metal to the specified maximum hardness level. The procedure shall be qualified by performing a hardness survey in accordance with Appendix C on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness (248 HV 10 maximum in the case of martensitic stainless steel materials identified in Paragraph 2.4.1, and 255 HV 10 maximum in the case of low-carbon martensitic stainless steel materials identified in Paragraph 2.4.2).

2.5 Austenitic Stainless Steel Materials

2.5.1 Austenitic stainless steels shall meet the chemical composition requirements specified in Paragraph 2.5.2, shall not exceed 22 HRC, shall be in the solution-annealed and quenched or solution-annealed and thermally stabilized condition, and shall be free of cold work intended to enhance their mechanical properties. Austenitic stainless steels containing lead or selenium for the purpose of improving machinability are not allowed.

2.5.2 Chemical composition requirements for the fully austenitic wrought product forms are shown in Table 3.

(10) Brinell hardness measurements obtained on duplex stainless steels cannot be converted to Rockwell C hardness values using existing tables in ASTM E140. Use of empirically derived tables for this hardness conversion is subject to the approval of the user.

Table 3
Chemical Composition Requirements for Austenitic Stainless Steels[(A)]

Element	Mass Percent
C	0.10 max
Cr	16.0 min
Ni	8.0 min
Mn	2.0 max
Si	2.0 max
P	0.045 max
S	0.04 max

[(A)] The chemical compositions of the cast "austenitic" stainless steels often vary from those of their fully austenitic wrought counterparts to optimize casting characteristics. Many of these alloys are intentionally balanced to contain some ferrite, which renders them partially magnetic.

2.5.3 Unlisted elements, such as molybdenum, nitrogen, titanium, and niobium (columbium), are allowed, provided the chemical composition requirements in Paragraph 2.5.1 are met.

2.5.4 Higher carbon contents for UNS S30900 and UNS S31000 are allowed up to the limits of their respective specifications.

2.5.5 Welding and Overlays on Austenitic Stainless Steels

Welding procedures used for welding and overlaying austenitic stainless steels do not require any hardness surveys or hardness testing to verify hardness in the HAZ.

2.6 Specific Austenitic Stainless Steel Grades

2.6.1 Austenitic stainless steel UNS S20910 shall be in the solution-annealed, hot-rolled (hot/cold-worked), or cold-worked condition. The hardness shall not exceed 35 HRC.

2.6.2 Welding procedures used for welding and overlaying UNS S20910 do not require any hardness surveys or hardness testing to verify hardness in the HAZ.

2.7 Highly Alloyed Austenitic Stainless Steels

2.7.1 Highly alloyed austenitic stainless steels shall meet the chemical composition requirements specified in Paragraph 2.7.2 and shall be in the solution-annealed condition or solution-annealed and cold-worked condition. The hardness shall not exceed 35 HRC. Free-machining highly alloyed austenitic stainless steels are not allowed.

2.7.2 The chemical composition requirements for the highly alloyed austenitic stainless steels are as follows:

$$\%Ni + (2 \times \%Mo) > 30 \text{ and } Mo > 2\%$$

or

Pitting Resistance Equivalent Number (PREN) > 40%

Where PREN is determined as shown in Equation (1):

$$PREN = \%Cr + 3.3\,(\%Mo + 0.5 \times \%W) + 16 \times \%N \qquad (1)$$

NOTE: For the purposes of this standard, PREN is used only to identify a group of alloys from a chemical composition standpoint. Use of PREN to predict relative corrosion resistance is outside the scope of this standard.

2.7.3 Welding procedures used for welding and overlaying the highly alloyed austenitic stainless steels do not require any hardness surveys or hardness testing to verify hardness in the HAZ.

2.8 Duplex Stainless Steel Materials

2.8.1 Wrought and cast duplex stainless steel products shall be in the solution-annealed and liquid-quenched condition. Tubing shall be rapidly cooled by liquid quenching, or by air or inert gas cooling to below 315 °C (600 °F). The ferrite content shall be 35 to 65 vol%. Aging heat treatments to increase strength and/or hardness are prohibited because of the formation of embrittling phases.

2.8.1.1 The hardness of grades with PREN ≤ 40% according to Equation (1) shall not exceed 28 HRC.(10)

2.8.1.2 The hardness of grades with PREN > 40% according to Equation (1) shall not exceed 32 HRC.(10)

2.8.2 Welding of Duplex Stainless Steels

2.8.2.1 Fabrication and repair welds in all wrought and cast duplex stainless steels shall be produced using a welding procedure qualified by performing the following tests on specimens taken from the WPQT coupon(s):

2.8.2.1.1 A hardness survey shall be performed in accordance with Appendix C. The average hardness shall not exceed 310 HV, and no individual reading shall exceed 320 HV.

2.8.2.1.2 Metallographic ferrite measurements shall be performed in accordance with ASTM E562.[19] The average ferrite content in the weld deposit and HAZ shall be within the range of 35 to 65%, with a relative accuracy of 10% or lower.

2.8.2.1.3 Technical considerations for qualification of welding procedures for duplex stainless steels are included in Appendix D (nonmandatory).

2.9 Precipitation-Hardenable Stainless Steel Materials

2.9.1 Austenitic precipitation-hardenable stainless steel with chemical composition in accordance with UNS S66286 shall be in either the solution-annealed and aged or solution-annealed and double-aged condition. The hardness shall not exceed 35 HRC.

2.9.2 UNS S17400 and UNS S15500 wrought martensitic precipitation-hardenable stainless steels shall be in either the H1150D condition (heat treated in accordance with Paragraph 2.9.2.2) or H1150M condition (heat treated in accordance with Paragraph 2.9.2.3). The hardness shall not exceed 33 HRC. ASTM A747[20] CB7Cu-1 and CB7Cu-2 castings shall be in the H1150 DBL condition (heat treated in accordance with Paragraph 2.9.2.2). The hardness shall not exceed 310 HBW (30 HRC). Precipitation-hardenable martensitic stainless steels that are in accordance with this standard have provided satisfactory field service in some sour environments. These materials may, however, exhibit threshold stress levels in NACE Standard TM0177 laboratory tests that are lower than those of other materials included in this standard.

2.9.2.1 The following restrictions apply to UNS S17400 and UNS S15500 when these materials are used for pressure-retaining bolting:

(a) UNS S17400 and UNS S15500 shall not be used for pressure-retaining bolting applications in the double-H1150 condition.

(b) When UNS S17400 or UNS S15500 is used for pressure-retaining bolting in the H1150M condition, the hardness shall not exceed 29 HRC.

2.9.2.2 Double-H1150 (H1150D, H1150 DBL) Heat-Treatment Procedure

(a) Solution anneal at 1,038 ± 14 °C (1,900 ± 25 °F) and air cool, or suitable liquid quench, to below 32 °C (90 °F).

(b) Harden at 621 ± 14 °C (1,150 ± 25 °F) for 4 h minimum at temperature and cool in air to below 32 °C (90 °F).

(10) Brinell hardness measurements obtained on duplex stainless steels cannot be converted to Rockwell C hardness values using existing tables in ASTM E140. Use of empirically derived tables for this hardness conversion is subject to the approval of the user.

(c) Harden at 621 ± 14 °C (1,150 ± 25 °F) for 4 h minimum at temperature and cool in air.

(d) Additional cycles at 621 ± 14 °C (1,150 ± 25 °F) may be used if required to produce the specified hardness level.

2.9.2.3 H1150M Heat-Treatment Procedure

(a) Solution anneal at 1,038 ± 14 °C (1,900 ± 25 °F) and air cool, or suitable liquid quench, to below 32 °C (90 °F).

(b) Harden at 760 ± 14 °C (1,400 ± 25 °F) for 2 h minimum at temperature and cool in air to below 32 °C (90 °F) before the second precipitation-hardening step.

(c) Precipitation harden at 621 ± 14 °C (1,150 ± 25 °F) for 4 h minimum at temperature and cool in air.

(d) Additional cycles at 621 ± 14 °C (1,150 ± 25 °F) may be used if required to produce the specified hardness level.

2.9.3 Wrought UNS S45000 martensitic precipitation-hardenable stainless steel shall be heat treated in accordance with the following two-step heat-treatment procedure. The hardness shall not exceed 31 HRC.

2.9.3.1 Two-Step Heat-Treatment Procedure

(a) Solution anneal.

(b) Precipitation harden at 621 °C (1,150 °F) for a minimum of 4 h.

2.9.4 Weldments in precipitation-hardenable stainless steels shall be produced using a weld procedure qualified by performing a hardness survey in accordance with Appendix C on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness in accordance with Table 4. Welding shall not be performed on UNS S17400 and UNS S15500 bolting.

Table 4
Maximum Hardness Requirements for
Weldments in Precipitation-Hardenable Stainless Steels

Alloy(s)	**Maximum Hardness**
UNS S66286	345 HV 10
UNS S17400, UNS S15500	327 HV 10
UNS J92200 (CB7Cu-1), UNS J92110 (CB7Cu-2)	302 HV 10 (HAZ) 327 HV 10 (weld deposit)
UNS S45000	310 HV 10

Section 3: Nonferrous Materials

3.1 Nickel Alloys

3.1.1 Solid-Solution Nickel Alloys

3.1.1.1 Wrought or cast solid-solution nickel-chromium-molybdenum alloys with compositions as specified in Paragraph 3.1.1.1.1 shall be in the solution-annealed condition.

3.1.1.1.1 The chemical composition requirements for the solid-solution nickel-chromium-molybdenum alloys are:

19.0% Cr minimum,
29.5% Ni + Co minimum, and

2.5% Mo minimum.
or
14.5% Cr minimum,
52% Ni + Co minimum, and
12% Mo minimum.

3.1.1.2 Wrought UNS N06600 shall not exceed 35 HRC.

3.1.1.3 Wrought UNS N08800 shall not exceed 35 HRC.

3.1.1.4 Only those solid-solution nickel-chromium-molybdenum alloys listed in Table 5 shall be used in the cold-worked condition. The other requirements specified in Table 5 shall also be met.

Table 5
Cold-Worked Nickel-Chromium-Molybdenum Alloys and Maximum Hardness Requirements

UNS Number	Previous Condition	Maximum Hardness
N06002	--	35 HRC
N06022	Solution-Annealed	40 HRC
N06625	--	35 HRC
N06686	Solution-Annealed	40 HRC
N06985	--	39 HRC
N08825	--	35 HRC
N10276	Solution-Annealed	35 HRC

3.1.1.5 Wrought UNS N04400 and N04405, and cast ASTM A49421 Grades M35-1, M35-2, and M30C shall not exceed 35 HRC.

3.1.1.6 Welding procedures used for welding and overlaying the solid-solution nickel alloys do not require any hardness surveys or hardness testing to verify hardness in the HAZ.

3.1.2 Precipitation-Hardenable Nickel Alloys

3.1.2.1 Only those precipitation-hardenable nickel alloys listed in Table 6 are allowed. The conditions and corresponding maximum hardness requirements listed in Table 6 shall be met.

3.1.2.2 Weldments in precipitation-hardenable nickel alloys shall be produced using a weld procedure qualified by performing a hardness survey in accordance with Appendix C on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness in accordance with Table 6.

Table 6
Precipitation-Hardenable Nickel Alloys, Conditions, and Maximum Hardness Requirements

UNS Number	Condition(s)	Maximum Hardness
N05500	Hot-worked and age-hardened or solution-annealed or solution-annealed and age-hardened	35 HRC (335 HV)
N07031	Solution-annealed	35 HRC (335 HV)
	Solution-annealed and aged at 760 to 871 °C (1,400 to 1,600 °F) for a maximum of 4 h.	40 HRC (382 HV)
N07048	Solution-annealed and aged	40 HRC (382 HV)
N07626	Hot compacted powder, solution-annealed (927 °C [1,700 °F] min) and aged (538 to 816 °C [1,000 to 1,500 °F]), max tensile strength 1,380 MPa (200 ksi)	40 HRC (382 HV)
N07716	Solution-annealed and aged	43 HRC (416 HV)
N07718	Solution-annealed or hot-worked or hot-worked and aged	35 HRC (335 HV)
	Solution-annealed and aged or cast, solution-annealed, and aged	40 HRC (397 HV)
N07725	Solution-annealed and aged	43 HRC (416 HV)
N07750	Solution-annealed or solution-annealed and aged or hot worked or hot-worked and aged	35 HRC (335 HV)
N07773	Solution-annealed and aged	40 HRC (382 HV)
N07924	Solution-annealed and aged	35 HRC (335 HV)
N09777	Solution-annealed and aged	40 HRC (382 HV)
N09925	Cold-worked or solution-annealed	35 HRC (335 HV)
	Solution-annealed and aged	38 HRC (362 HV)
	Cold-worked and aged or hot-finished and aged	40 HRC (382 HV)
	Cast, solution-annealed, and aged	35 HRC (335 HV)

3.2 Cobalt-Nickel-Chromium-Molybdenum Alloys

3.2.1 UNS R30003, UNS R30004, UNS R30035, and BS 2HR 3[22] shall not exceed 35 HRC except as otherwise noted below.

3.2.1.1 Welding requirements for UNS R30003, UNS R30004, UNS R30035, and BS 2HR 3 are outside the scope of this standard. Welding requirements shall be in accordance with the agreement between the end user (or the end user's agent) and the manufacturer.

3.2.2 UNS R30035 is allowed in the cold-reduced and high-temperature aged heat-treated condition in accordance with one of the aging treatments listed in Table 7. The hardness shall not exceed 51 HRC.

Table 7
UNS R30035 Heat Treatments

Minimum Time (h)	Temperature
4	704 °C (1,300 °F)
4	732 °C (1,350 °F)
6	774 °C (1,425 °F)
4	788 °C (1,450 °F)
2	802 °C (1,475 °F)
1	816 °C (1,500 °F)

3.2.3 Wrought UNS R31233 shall be in the solution-annealed condition. The hardness shall not exceed 33 HRC.

3.2.3.1 Welding procedures used for welding UNS R31233 do not require any hardness surveys or hardness testing to verify hardness in the HAZ.

3.3 Cobalt-Nickel-Chromium-Tungsten Alloys

UNS R30605 shall not exceed 35 HRC.

3.4 Titanium Alloys

3.4.1 Specific guidelines must be followed for successful applications of each titanium alloy specified in this standard. For example, hydrogen embrittlement of titanium alloys may occur if these alloys are galvanically coupled to certain active metals (e.g., carbon steel) in H_2S-containing aqueous media at temperatures greater than 80 °C (176 °F). Hardness has not been shown to correlate with susceptibility to SSC, but has been included for alloys with high strength to indicate the maximum testing levels at which failure has not occurred.

3.4.2 Only those titanium alloys listed in Table 8 are allowed. The conditions and corresponding maximum hardness requirements listed in Table 8 shall be met.

Table 8
Titanium Alloys, Conditions, and Maximum Hardness Requirements

UNS Number	Condition(s)	Maximum Hardness
R50400	None specified	100 HRBS
R53400	Annealed at 774 ± 14 °C (1,425 ± 25 °F) for 2 h, air cool	92 HRBS
R56260	Annealed or solution-annealed or solution-annealed and aged	45 HRC
R56323	Annealed	32 HRC
R56403	Annealed	36 HRC
R56404	Annealed	35 HRC
R58640	Annealed	42 HRC

3.4.3 Welding requirements for titanium alloys are outside the scope of this standard. Welding requirements shall be in accordance with the agreement between the end user (or the end user's agent) and the manufacturer.

3.5 Aluminum Alloys

3.5.1 Aluminum alloys are allowed because they are not susceptible to SSC. However, they can suffer corrosion when exposed outside the pH range of about 4.0 to 8.5 and also pitting corrosion if chloride ions are present.

3.5.2 Welding procedures used for welding aluminum alloys do not require any hardness surveys or hardness testing to verify hardness in the HAZ.

3.6 Copper Alloys

3.6.1 Copper alloys are allowed because they are not susceptible to SSC. However, they can suffer corrosion because of the sulfides and also stress corrosion cracking if NH_3 is present, as often noted in sour refinery environments.

3.6.2 Welding procedures used for welding copper alloys do not require any hardness surveys or hardness testing to verify hardness in the HAZ.

Section 4: General Fabrication Requirements

4.1 Materials and fabrication processes shall meet the requirements of this section.

4.2 Overlays

4.2.1 Tungsten-carbide alloys and ceramics are allowed as overlays. Following application of the overlay, the base material shall meet the hardness requirement for that base metal specified in the pertinent paragraph in Section 2 or 3.

4.2.2 Joining of dissimilar materials, such as cemented carbides to alloy steels by silver brazing, is allowed. After brazing, the base material shall meet the hardness requirement for that base metal specified in the pertinent paragraph in Section 2 or 3.

4.2.3 The base materials listed in Sections 2 and 3 are also allowed as weld overlays, provided they meet the provisions of their respective paragraphs after being applied as overlays. Following application of the overlay, the base material shall meet the hardness requirement for that base metal specified in the pertinent paragraph in Section 2 or 3.

4.2.4 Overlays of cobalt-chromium-tungsten, nickel-chromium-boron, and nickel-boron (see SAE[(11)] AMS4779[23]) hardfacing alloys are allowed. Following application of the overlay, the base material shall meet the hardness requirement for that base metal specified in the pertinent paragraph in Section 2 or 3.

4.3 Welding

4.3.1 All weldments shall meet the general requirements listed in this section (Paragraph 4.3). Specific welding requirements are provided for some materials in the pertinent material paragraphs in Section 2 or 3, in which case those requirements shall also be met. In cases in which the specific welding requirements conflict with the requirements of this section, the specific material welding requirements shall override these general requirements.

4.3.2 Welders and welding procedures shall be qualified in accordance with AWS,[(12)] API, ASME, or other appropriate industry codes.

4.3.3 Dissimilar-metal welds, such as welds produced using filler metals that are more noble than the base metal and/or welds in which the two base metals are different, shall meet the following requirements:

4.3.3.1 The weld metal shall be closely equivalent in chemistry and properties to a base material that is allowed according to this standard.

4.3.3.2 If a Vickers hardness survey is required to be performed during weld procedure qualification for either base metal, or for a base metal that is equivalent to the deposited weld metal, a Vickers hardness survey in accordance with Appendix C shall be performed on a specimen taken from the WPQT coupon(s) to demonstrate the ability of the procedure to produce weldments that meet the specified hardness. The hardness criteria for each portion of the weldment shall be as specified in the pertinent material paragraph in Section 2 or 3 for that base metal, or, in the case of deposited weld metal, for the base metal that is equivalent to the deposited weld metal.

4.4 Cladding on Carbon Steels, Alloy Steels, and Martensitic Stainless Steels

4.4.1 For the purpose of this standard, cladding is defined as a metallurgically bonded layer of a corrosion-resistant alloy material applied to the entire wetted surface of a substrate material that is relatively less corrosion-resistant.

4.4.2 Allowed fabrication methods used for cladding include hot rolling, explosion bonding, and weld overlaying.

4.4.3 Cladding materials shall be selected from Section 2 or 3 of this standard, and shall meet all requirements for the selected alloy(s) specified in the pertinent paragraph(s).

4.4.4 A number of factors influence the SSC resistance of clad components, including, but not limited to:

(a) Relative SSC resistance of the cladding material;

(b) Corrosion resistance of the clad layer in the process environment (which affects the rate of hydrogen production);

(c) Hydrogen diffusion rate in the clad layer;

(d) Soundness of the clad layer;

(e) Relative SSC resistance of the substrate material;

(f) Fabrication methods used at junctions between neighboring clad components;

(g) Fabrication methods used at junctions between clad components and neighboring unclad components; and

(11) SAE International (SAE), 400 Commonwealth Drive, Warrendale, PA 15096-0001.
(12) American Welding Society (AWS), 550 N.W. LeJeune Road, Miami, Florida 33126.

(h) Galvanic effects (if the substrate material becomes exposed or at junctions with neighboring unclad components).

4.4.5 Evaluation of these and other factors is outside the scope of this standard. Therefore, the end user shall specify whether or not the substrate material must meet the requirements of this standard.

4.5 Identification Stamping

4.5.1 Identification stamping using low-stress (dot, vibratory, and round V) stamps is allowed.

4.5.2 Conventional sharp V stamping is allowed in low-stress areas, such as the outside diameter of flanges. Sharp V stamping is not allowed in high-stress areas unless the item receives a subsequent thermal treatment to reduce the hardness to meet the maximum hardness requirement for the base metal specified in the applicable sections of this standard.

4.6 Threading

4.6.1 Machine-Cut Threads

Machine-cut threading processes are allowed.

4.6.2 Cold-Formed (Rolled) Threads

After threads have been cold formed, the threaded component shall meet the heat-treatment conditions and hardness requirements specified in either Section 2 or 3 for the parent alloy from which the threaded component was fabricated.

4.7 Cold-Deformation Processes

4.7.1 Cold-deformation processes such as burnishing that do not impart cold work exceeding that incidental to normal machining operations (such as turning or boring, rolling, threading, and drilling) are allowed.

4.7.2 Cold deformation by controlled shot peening is permitted when applied to base materials that meet the requirements of this standard, and when limited to the use of a maximum shot size of 2.0 mm (0.080 in) and a maximum of 10C Almen intensity. The process shall be controlled in accordance with SAE AMS2430.[24]

Section 5: Bolting

5.1 Materials used for bolting and fasteners that are exposed to sour environments (see Paragraph 1.3) shall meet the requirements of this section. The user shall be responsible for specifying whether bolting is exposed or unexposed in accordance with Paragraphs 5.2 and 5.3.

5.2 Exposed Bolting

5.2.1 Bolting that is exposed directly to the sour environment shall meet the requirements of Section 2 or Section 3.

5.2.1.1 External bolting and fasteners used underground, covered with insulation, equipped with flange protectors, or otherwise denied direct atmospheric exposure, and that are used on equipment that contains a sour environment, shall be considered exposed to a sour environment, and shall meet the requirements of Section 2 or Section 3.

5.2.1.2 Users and designers should be aware that it may be necessary to de-rate the strength of the joint and the pressure rating of the equipment in some cases when using bolting that meets these requirements.

5.2.1.3 Special restrictions apply to UNS S17400 and UNS S15500 when these alloys are used for pressure-retaining bolting. (See Paragraph 2.9.2.1.)

5.2.1.4 The bolting and nut materials listed in Table 9 were specifically established to meet the requirements of Section 2 or Section 3. Other materials meeting the requirements of Section 2 or Section 3 are also allowed.

5.2.1.5 Zinc or cadmium coatings should not be used on bolts, nuts, cap screws, or other fasteners in sour environments. These coatings enhance the generation of hydrogen on the surface and can contribute to hydrogen cracking.

5.3 Unexposed Bolting

5.3.1 Unexposed bolting and fasteners may be furnished to applicable standards such as ASTM A193,[25] A194,[26] and A320.[27] To be considered "unexposed," the bolting must be used externally on flanges or other parts that are not directly exposed to sour environments, and must be directly exposed to the atmosphere at all times (see Paragraph 5.2.1.1).

Table 9
Common Bolting Materials That Meet Section 2 and Section 3 Requirements

Bolting Component	Material Specification
Bolt, Stud, Cap Screw	ASTM A193 Grade B7M
	ASTM A193 Grade B8MA, Class 1A
	ASTM A320 Grade L7M
Nut	ASTM A194 Grade 2HM
	ASTM A194 Grade 7M
	ASTM A194 Grade 8MA

Section 6: Plating, Coatings, and Diffusion Processes

6.1 Metallic coatings (electroplated or electroless), conversion coatings, and plastic coatings or linings are not allowed for preventing SSC of base metals. The use of such coatings for any other purpose (such as wear resistance or corrosion resistance) is outside the scope of this standard.

6.2 Nitriding is an allowed surface diffusion treatment when performed at a temperature below the lower critical temperature of the material being treated. Its use as a means of preventing SSC is not allowed.

Section 7: Special Components

7.1 Materials for special components including instrumentation, control devices, seals, bearings, and springs shall meet the requirements of this section if they are directly exposed to sour environments during normal operation of the device. Paragraph 1.2 provides guidelines to determine the applicability of the standard to specific uses.

7.2 Bearings

7.2.1 Bearings directly exposed to sour environments shall be made from materials that meet the requirements in Section 2 or Section 3, except as noted in Paragraph 7.2.2. Bearings made from other materials must be isolated from the sour environment to function properly.

7.2.2 Nickel-chromium-molybdenum-tungsten alloy UNS N10276 is allowed for bearing pins (e.g., core roll pins) in the cold-worked condition. The hardness shall not exceed 45 HRC.

7.3 Springs

7.3.1 Springs directly exposed to the sour environment shall be made from materials that meet the requirements in Section 2 or Section 3, except as noted in Paragraphs 7.3.2, 7.3.3, and 7.3.4.

7.3.2 Cobalt-nickel-chromium-molybdenum alloy UNS R30003 is allowed for springs in the cold-worked and age-hardened condition. The hardness shall not exceed 60 HRC. UNS R30035 is allowed for springs in the cold-worked and age-hardened condition when aged for a minimum of 4 h at a temperature no lower than 649 °C (1,200 °F). The hardness shall not exceed 55 HRC.

7.3.3 Nickel-chromium alloy UNS N07750 is allowed for springs in the cold-worked and age-hardened condition. The hardness shall not exceed 50 HRC.

7.3.4 UNS N07090 is allowed for springs for compressor valves in the cold-worked and age-hardened condition. The hardness shall not exceed 50 HRC.

7.4 Instrumentation and Control Devices

7.4.1 Instrumentation and control device components directly exposed to sour environments shall be made from materials that meet the requirements in Section 2 or Section 3.

7.4.1.1 UNS S31600 austenitic stainless steel, highly alloyed austenitic stainless steel (see Paragraph 2.7), or nickel alloy (see Paragraph 3.1) materials are allowed for compression fittings, screen devices, and instrument or control tubing even though these components may not satisfy the requirements stated for those materials in Section 2 or Section 3.

7.4.2 Diaphragms, Pressure-Measuring Devices, and Pressure Seals

7.4.2.1 Diaphragms, pressure-measuring devices, and pressure seals directly exposed to a sour environment shall be made from materials that meet the requirements in Section 2 or Section 3, except as noted in Paragraphs 7.4.2.2, 7.4.2.3, and 7.4.2.4.

7.4.2.2 Cobalt-nickel-chromium-molybdenum alloys UNS R30003 and UNS R30004 are allowed for diaphragms, pressure-measuring devices, and pressure seals. The hardness shall not exceed 60 HRC.

7.4.2.3 Cobalt-nickel-chromium-molybdenum-tungsten alloy UNS R30260 is allowed for diaphragms, pressure-measuring devices, and pressure seals. The hardness shall not exceed 52 HRC.

7.4.2.4 Pressure seals shall comply with the material requirements in Section 2 or Section 3 or may be manufactured of wrought cobalt-chromium-nickel-molybdenum alloy UNS R30159 with the primary load-bearing or pressure-containing direction parallel to the longitudinal or rolling direction of wrought product. The hardness shall not exceed 53 HRC.

7.4.3 Wrought UNS N08904 is allowed for use as instrument tubing in the annealed condition. The hardness shall not exceed 180 HV 10.

7.5 Seal Rings and Gaskets

7.5.1 Seal rings directly exposed to a sour environment shall be made from materials that meet the requirements in Section 2 or Section 3.

7.5.2 Austenitic stainless steel API compression seal rings and gaskets made of wrought or centrifugally cast ASTM A351[28] Grade CF8 or CF8M chemical compositions are allowed in the as-cast or solution-annealed condition. The hardness shall not exceed 160 HBW (83 HRBS).

7.6 Snap Rings

7.6.1 Snap rings directly exposed to a sour environment shall be made from applicable materials that meet the requirements in Section 2 or Section 3, except as noted in Paragraph 7.6.2.

7.6.2 Precipitation-hardenable stainless steel alloy UNS S15700 originally in the RH950 solution-annealed and aged condition is allowed for snap rings when further heat treated in accordance with the three-step heat treatment procedure below. The hardness shall be 30 to 32 HRC.

7.6.2.1 Heat-treatment procedure (three-step process) shall be:

(a) Temper at 621 °C (1,150 °F) for 4 h, 15 min. Cool to room temperature in still air.

(b) Temper at 621 °C (1,150 °F) for 4 h, 15 min. Cool to room temperature in still air.

(c) Temper at 566 °C (1,050 °F) for 4 h, 15 min. Cool to room temperature in still air.

7.7 Special Process Parts

7.7.1 Cobalt-chromium-tungsten and nickel-chromium-boron alloys, whether cast, powder-metallurgy processed, or thermomechanically processed, are allowed.

7.7.2 Tungsten-carbide alloys, whether cast or cemented, are allowed.

Section 8: Valves

8.1 Valves shall meet the requirements of this section if they are to be exposed to sour environments (see Paragraph 1.3). A common failure mode of gate valves exposed to sour environments and not fabricated with hardness-controlled components is a dropped gate, rendering the valve inoperable.

8.2 Valves (new or reconditioned), including internal components, shall be manufactured or remanufactured from materials that meet the requirements in Section 2 or Section 3.

Section 9: Compressors and Pumps

9.1 Compressor and pump components that are to be exposed to sour environments (see Paragraph 1.3) shall be manufactured from materials that meet the requirements in Section 2 or Section 3, except as noted in Paragraphs 9.2 and 9.3.

9.2 ASTM A278[29] Class 35 or 40 gray cast iron and ASTM A395 ductile iron are allowed as compressor cylinders, liners, pistons, and valves. Aluminum alloy ASTM B26[30] A03550-T7 is allowed for pistons. Aluminum, soft carbon steel, and soft, low-carbon iron are allowed as gaskets in compressors handling sour gas.

9.3 UNS G43200 and a modified version of UNS G43200 that contains 0.28 to 0.33% carbon are allowed for compressor impellers at a maximum yield strength of 620 MPa (90 ksi) provided they have been heat treated in accordance with Paragraph 9.3.1.

9.3.1 Heat-Treatment Procedure (Three-Step Process)

9.3.1.1 Austenitize and quench.

9.3.1.2 Temper at 621 °C (1,150 °F) minimum, but below the lower critical temperature. Cool to ambient temperature before the second temper.

9.3.1.3 Temper at 621 °C (1,150 °F) minimum, but lower than the first tempering temperature. Cool to ambient temperature.

References

1. NACE MR0175/ISO 15156 (latest revision), “Petroleum and natural gas industries—Materials for use in H_2S-containing environments in oil and gas production” (Houston, TX: NACE).

2. NACE SP0296 (formerly RP0296) (latest revision), “Detection, Repair, and Mitigation of Cracking in Refinery Equipment in Wet H_2S Environments” (Houston, TX: NACE).

3. NACE Publication 8X194 (latest revision), “Materials and Fabrication Practices for New Pressure Vessels Used in Wet H_2S Refinery Service” (Houston, TX: NACE).

4. NACE Publication 8X294 (latest revision), “Review of Published Literature on Wet H_2S Cracking of Steels Through 1989” (Houston, TX: NACE).

5. ASME Boiler and Pressure Vessel Code, Section IX (latest revision), “Welding and Brazing Qualifications” (New York, NY: ASME).

6. NACE SP0472 (formerly RP0472) (latest revision), “Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments” (Houston, TX: NACE).

7. NACE Standard TM0177 (latest revision), “Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H_2S Environments” (Houston, TX: NACE).

8. ASTM E140 (latest revision), “Standard Hardness Conversion Tables for Metals—Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness” (West Conshohocken, PA: ASTM).

9. ISO 18265 (latest revision), “Metallic Materials - Conversion of Hardness Values” (Geneva, Switzerland: ISO).

10. ASTM E384 (latest revision), “Standard Test Method for Knoop and Vickers Hardness of Materials” (West Conshohocken, PA: ASTM).

11. ASTM A833 (latest revision), “Standard Practice for Indentation Hardness of Metallic Materials by Comparison Hardness Testers” (West Conshohocken, PA: ASTM).

12. ASTM A941 (latest revision), “Standard Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys” (West Conshohocken, PA: ASTM).

13. ASTM A53/A53M (latest revision), “Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless” (West Conshohocken, PA: ASTM).

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15. API Spec 5L (latest revision), “Specification for Line Pipe” (Washington, DC: API).

16. ASME B31.3 (latest edition), “Process Piping” (New York, NY: ASME).

17. ANSI/NBBPVI NB-23, “National Board Inspection Code” (Columbus, Ohio: NBBPVI).

18. ASTM A395/A395M (latest revision), “Standard Specification for Ferritic Ductile Iron Pressure-Retaining Castings for Use at Elevated Temperatures” (West Conshohocken, PA: ASTM).

19. ASTM E562 (latest revision), “Standard Test Method for Determining Volume Fraction by Systematic Manual Point Count” (West Conshohocken, PA: ASTM).

20. ASTM A747/A747M (latest revision), “Standard Specification for Steel Castings, Stainless, Precipitation Hardening” (West Conshohocken, PA: ASTM).

21. ASTM A494/A494M (latest revision), “Standard Specifications for Castings, Nickel and Nickel Alloy” (West Conshohocken, PA: ASTM).

22. BS 2HR 3 (latest revision), “Specification for Nickel-Cobalt-Chromium-Molybdenum-Aluminium-Titanium Heat-Resisting Alloy Billets, Bars, Forgings and Parts (Nickel Base, Co 20, Cr 14.8, Mo 5, Al 4.7, Ti 1.2)” (London, U.K: BSI).

23. SAE AMS4779 (latest revision), “Nickel Alloy, Brazing Filler Metal, 94Ni - 3.5Si - 1.8B, 1,800 to 1,950 °F (982 to 1,066 °C) Solidus-Liquidus Range” (Warrendale, PA: SAE).

24. SAE AMS2430 (latest revision), “Shot Peening, Automatic” (Warrendale, PA: SAE).

25. ASTM A193/A193M (latest revision), “Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications” (West Conshohocken, PA: ASTM).

26. ASTM A194/A194M (latest revision), “Standard Specification for Carbon and Alloy Steel Nuts for Bolts for High Pressure or High Temperature Service, or Both” (West Conshohocken, PA: ASTM).

27. ASTM A320/A320M (latest revision), “Standard Specification for Alloy-Steel and Stainless Steel Bolting Materials for Low-Temperature Service” (West Conshohocken, PA: ASTM).

28. ASTM A351/A351M (latest revision), “Standard Specification for Castings, Austenitic, for Pressure-Containing Parts” (West Conshohocken, PA: ASTM).

29. ASTM A278/A278M (latest revision), "Standard Specification for Gray Iron Castings for Pressure-Containing Parts for Temperatures Up to 650 °F (350 °C)" (West Conshohocken, PA: ASTM).

30. ASTM B26/B26M (latest revision), "Standard Specification for Aluminum-Alloy Sand Castings" (West Conshohocken, PA: ASTM).

31. W.M. Haynes, ed. *CRC Handbook of Chemistry and Physics*, 72nd ed. (Cleveland, OH: CRC Press, 1986).

32. ASTM E18 (latest revision), "Standard Test Methods for Rockwell Hardness of Metallic Materials" (West Conshohocken, PA: ASTM).

33. ISO 6508-1 (latest revision), "Metallic materials — Rockwell hardness test — Part 1: Test method (scales A, B, C, D, E, F, G, H, K, N, T)" (Geneva, Switzerland: ISO).

34. ASTM E10 (latest revision), "Standard Test Method for Brinell Hardness of Metallic Materials" (West Conshohocken, PA: ASTM).

35. ISO 6506-1 (latest revision), "Brinell hardness test — Part 1: Test method" (Geneva, Switzerland: ISO).

36. ASTM E92 (withdrawn), "Standard Test Method for Vickers Hardness of Metallic Materials" (West Conshohocken, PA: ASTM).

37. ISO 6507-1 (latest revision), "Vickers hardness test — Part 1: Test method" (Geneva, Switzerland: ISO).

38. ASTM A956 (latest revision), "Standard Test Method for Leeb Hardness Testing of Steel Products" (West Conshohocken, PA: ASTM).

39. ASTM A1038 (latest revision), "Standard Test Method for Portable Hardness Testing by the Ultrasonic Contact Impedance Method" (West Conshohocken, PA: ASTM

40. ASTM E110 (latest revision), "Standard Test Method for Indentation Hardness of Metallic Materials by Portable Hardness Testers" (West Conshohocken, PA: ASTM).

41. DIN(13) 50156-1 (latest revision), "Metallic materials - Leeb Hardness Test - Part 1: Test Method" (Berlin, Germany: DIN).

42. API TR 938-C (latest revision), "Use of Duplex Stainless Steels in the Oil Refining Industry" (Washington, DC: API).

43. ASTM A995/A995M (latest revision), "Standard Specification for Castings, Austenitic-Ferritic (Duplex) Stainless Steel, for Pressure-Containing Parts" (West Conshohocken, PA: ASTM).

44. ASME SFA-5.4/SFA-5.4M (latest revision), "Stainless Steel Electrodes for Shielded Metal Arc Welding" (New York, NY: ASME).

45. ASME SFA-5.9/SFA-5.9M (latest revision), "Bare Stainless Steel Welding Electrodes and Rods" (New York, NY: ASME).

46. ASTM E1245 (latest revision), "Standard Practice for Determining the Inclusion or Second-Phase Constituent Content of Metals by Automatic Image Analysis" (West Conshohocken, PA: ASTM).

47. ISO/IEC(14) 17025 (latest revision), "General requirements for the competence of testing and calibration laboratories" (Geneva, Switzerland: ISO).

48. ASTM A923 (latest revision), "Standard Test Methods for Detecting Detrimental Intermetallic Phase in Duplex Austenitic/Ferritic Stainless Steels" (West Conshohocken, PA: ASTM).

49. ASTM G48 (latest revision), "Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution" (West Conshohocken, PA: ASTM).

(13) Deutsches Institut fur Normung (DIN), Burggrafenstrasse 6, D-10787 Berlin, Germany.
(14) International Electrotechnical Commission (IEC), 3 rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland.

Appendix A
Sulfide Species Plot
(Nonmandatory)

This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

The plot in Figure A1 shows sulfide species as a function of pH. This plot was constructed based on the equilibrium constants for H_2S in Section 8-41 of *CRC Handbook of Chemistry and Physics*, 72nd Edition.[31] See Paragraph 1.3.5 for further explanation.

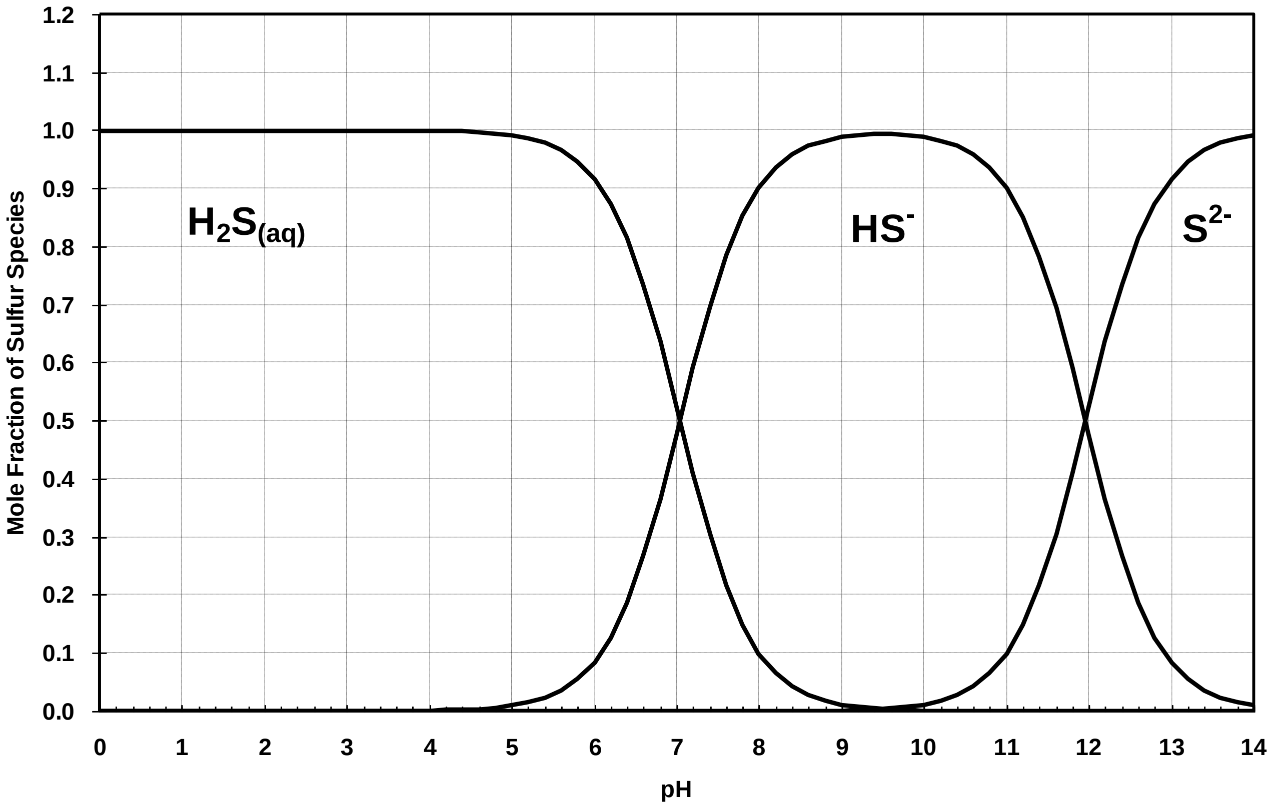


Figure A1: Sulfide Species Plot for Closed System at 25 °C (77 °F).

Appendix B
Background Information on Hardness Testing and Requirements
(Nonmandatory)

This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

B1. Accurate hardness testing requires strict compliance with the hardness test methods described in the appropriate ASTM standards.

B2. Rockwell hardness test methods, performed in accordance with ASTM Standard E18[32] or ISO 6508-1,[33] are relatively quick, direct-reading tests, and as such they are commonly used in manufacturing environments. These hardness test methods use loads ranging from 147 N (15 kgf) to 1,470 N (150 kgf). Because of the relatively small loads that are used, the hardness indentations are small, and the measurements represent the hardness in a very localized volume of material. Therefore, these hardness test methods are very sensitive, and are suited for identifying localized hard spots. Drawbacks to these test methods are the size restrictions on components that can be tested, geometrical limitations that prevent testing in certain locations, and lack of portability.

NOTE: Beginning in the 2002 revision of ASTM E18, tungsten carbide balls are allowed for “B” scale tests in addition to the hardened steel balls that were previously required. The scale designations for Rockwell “B” hardness measurements are now “HRBS” for tests performed with a steel ball, and “HRBW” for tests performed with a tungsten carbide ball. The hardness values required in this standard are all “HRBS” values, because all testing in the past used the steel ball indenter. HRBS and HRBW test results differ because of the different mechanical properties of the two ball indenters. There are currently no standardized conversion tables available for conversion of HRBS to HRBW.

B3. The Brinell hardness test method, performed in accordance with ASTM Standard E10[34] or ISO 6506-1,[35] involves creation of an indentation, optical measurement of the indentation diameter, and calculation of the hardness value. Because of the relatively large test loads used, this test method produces a hardness value that represents an “average” of the material hardness over a relatively large volume of material. The Brinell test method is often used to measure the hardness of castings and forgings. Drawbacks to this test method are the size restrictions on components that can be tested, geometrical limitations that prevent testing in certain locations, and lack of portability. ASTM E10 now requires Brinell hardness testing to be performed with a tungsten carbide ball indenter. The symbol “HBW” denotes Brinell hardness testing performed in this manner.

B4. Comparison hardness testers (commonly, but incorrectly, referred to as portable Brinell hardness testers) use a hammer blow to simultaneously indent the component being evaluated and a test bar of known hardness. The relative indentation sizes are measured and a calculation is performed to determine the hardness of the component. Comparison hardness testers are commonly used to check field weldments. Comparison hardness testing is performed in accordance with ASTM Standard A833. The hardness values obtained using comparison hardness testers correlate directly to Brinell hardness values obtained using testing parameters discussed in Paragraph B3.

B5. The macro Vickers hardness test method, performed in accordance with ASTM E384 (which has replaced ASTM E92[36]) or ISO 6507-1,[37] is similar to the Brinell hardness test method except it makes use of a diamond pyramid indenter. The advantage of the Vickers hardness test method is that it provides relatively load-independent hardness values when performed with loads ranging from 0.25 N (25 gf) to 1,180 N (120 gf). It is common practice to use 49 N (5 kgf) or 98 N (10 kgf) Vickers hardness testing for welding procedure qualifications because this produces an accurate assessment of the weldment HAZ hardness. Vickers hardness criteria have been specified for a few selected welding procedure qualifications in this standard, based on proven field experience. Further details are available in NACE SP0472. Vickers hardness is designated as HV, with the test load in kgf indicated by a suffix number (e.g., 248 HV 10 denotes a Vickers hardness of 248 determined using a 10 kgf load).

B6. Hardness requirements specified in this standard in HBW units are generally lower than the equivalent “acceptable” HRC values (which applies to both conventional Brinell hardness testing and comparison hardness testing) to compensate for inhomogeneity of some material forms and weld deposits and/or to account for normal variations in field and/or production hardness testing using the comparison hardness tester.

B7. HRC and HRBS are cited for particular materials or product forms under the following conditions:

(a) When the raw material specification lists a hardness requirement in HRC or HRBS;

(b) When the industry standard testing method for that product form is HRC or HRBS; or

(c) When the material will be tested at the component level.

B8. HBW is cited for particular materials or product forms under the following conditions:

(a) When the raw material specification lists a hardness requirement in HBW;

(b) When the industry standard testing method for that product form is HBW; or

(c) When the hardness requirement pertains to evaluation of weld metal hardness, which is most commonly performed using a portable Brinell hardness tester.

B9. A standard fixed-location hardness testing machine may not be capable of testing certain samples because of the sample size, weight, location, accessibility, or other requirements. In these circumstances, the use of a portable hardness tester may be the only option available. However, not all portable hardness testers meet the requirements of ISO or ASTM standard hardness test methods. A list of portable hardness test standards used for ferrous materials is provided in Table B1.

Table B1
Portable Hardness Testing Standards

ASTM A833	Comparison hardness
ASTM A956[38]	Leeb hardness testing
ASTM A1038[39]	Portable hardness testing by the ultrasonic contact impedance method
ASTM E110[40]	Indentation hardness of metallic materials by portable hardness testers
DIN 50156-1[41]	Leeb hardness testing

B10. Portable hardness testers that do not meet any of the standards listed in Table B1 are deemed to be nonstandard testing equipment and are outside the scope of this standard.

B11. There are two major types of portable hardness testers:

B11.1 Portable hardness testers that follow the same test principles as those defined for a standard fixed-location hardness tester using the same test method, e.g., Brinell, Rockwell, and Vickers test methods that are included in ASTM E110.

B11.2 Portable hardness testers that measure hardness by a means or procedure that is different from those defined for a standard fixed-location hardness tester, e.g., Brinell, Rockwell, and Vickers test methods that are included in ASTM A833, A956, A1038, and DIN 50156.

B12. The most common sources of error when using portable hardness testers are the alignment of the indenter to the test surface and the timing of the test forces. The user is cautioned to take all necessary measures to keep the centerline of the indenter perpendicular to the test surface and to strictly follow to the standard test method procedures.

B13. Portable hardness testers are subject to damage when they are moved from one test site to another. Therefore, the user must be aware of the test method verification requirements when the portable hardness tester is new, or when adjustments, modifications, and repairs are made that could affect the application of the test forces or depth measuring system.

B14. The standard requirements for verification should be followed. Verification should be performed with the device oriented in the same position(s) that are used in production. Verification should be repeated occasionally during testing and after testing is completed.

B15. Precision is the closeness of agreement between test results obtained under prescribed conditions. Bias is a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value. Portable hardness testers, in comparison to fixed-location hardness testers, inherently introduce larger precision variances and bias errors that influence the test results.

B16. The user must understand that not all portable hardness testing standards include precision and bias rules that may be used to establish differences in test results that would be expected between portable and fixed-location instruments.

B17. Precision rules, bias rules, and results differ not only between standard fixed location and portable hardness test methods, but also between standard portable hardness test methods. Consequently, the user is cautioned that all portable hardness testers should not be considered as equal and that the appropriate hardness testing standard(s) must be thoroughly reviewed and considered before its application is approved as meeting the hardness requirements in this standard for the equipment's intended service conditions.

B18. For example, Equations (B1) and (B2) show ASTM E110 values of R_{PB} (the typical amount of variation that can be expected between test results obtained for the same material by different operators using a different hardness tester on different days) at two different hardness levels.

Test material hardness: 201 HBW $\quad R_{PB}$ = 14 HBW (B1)

Test material hardness: 543 HBW $\quad R_{PB}$ = 39 HBW (B2)

Note: ASTM A833 is a standard practice and not a test method. Consequently, it does not contain precision and bias rules and is not capable of establishing precision variances and bias errors that may influence the test results.

B19. Hardness values obtained using portable methods shall be reported in accordance with the requirements of the corresponding specification, as follows:

(a) ASTM A833 comparison hardness test result example: 197 HBC/200, where 197 is the hardness determined, HBC indicates that the hardness was obtained using the comparison hardness test, and 200 is the Brinell hardness of the comparative test bar. The manufacturer's equipment and the diameters of the impressions in the test piece and comparative test bar must also be reported.

(b) ASTM A956 or DIN 50156-1 Leeb hardness test result example: 187 HB (HLG), where 187 HB is the Brinell hardness that was converted from the Leeb hardness number, and HLG indicates Leeb hardness obtained using a type G impact device.

(c) ASTM A1038 ultrasonic contact impedance hardness test result example: 250 HV (UCI) 10, where 250 HV is the Vickers hardness, UCI indicates that the hardness was measured using the ultrasonic contact impedance method, and 10 indicates that a force of 10 kgf was utilized.

(d) ASTM E110 portable indentation hardness test result example: 22 HRC/P, where 22 HRC is the hardness of 22 on Rockwell C scale, and /P indicates that the measurement was made using a portable Rockwell hardness tester.

B20. Conversion of hardness values from one hardness scale to another can introduce errors. ASTM E140 and ISO 18265 include warnings regarding the limitations and risks associated with conversion of hardness values, including indications that conversions are not always precise for all materials and may even be of questionable precision, bias, and uncertainty. These limitations and risks apply to hardness conversions involving the various standard fixed-location hardness test methods as well as the various portable hardness test methods.

B21. Some fixed-location and portable hardness testers perform internal conversions between hardness scales using the tables in ASTM E140 or ISO 18265. There may also be some instances in which hardness scale conversions are handled outside of the ASTM E140 or ISO 18265 tables based on proprietary data or algorithms, especially in some portable instruments where no standardized conversion tables exist. In either case, conversions may be an additional source of inaccuracy and uncertainty.

B22. Both ASTM E140 or ISO 18265 contain specific rules for reporting converted hardness numbers using their tables. Examples of reporting converted hardness numbers are as follows.

(a) ASTM E140: When converted hardness numbers are reported, the measured hardness and test scale shall be indicated in parentheses as in the following example:

353 HBW (38 HRC)

(b) ISO 18265: Conversion results shall be reported in a manner that clearly indicates which method was used to determine the original hardness value. In addition, the relevant annex to this international standard or the table used shall be given.

Example 1:

Conversion ISO 18265 - 50.5 HRC - B.2 - HV
Standard number: Conversion ISO 18265
Converted hardness value: 50.5 HRC
Table used for comparison: B.2
Original hardness test method used: HV

Example 2:

If the uncertainty of the converted value is required to be reported, it shall be reported as follows:

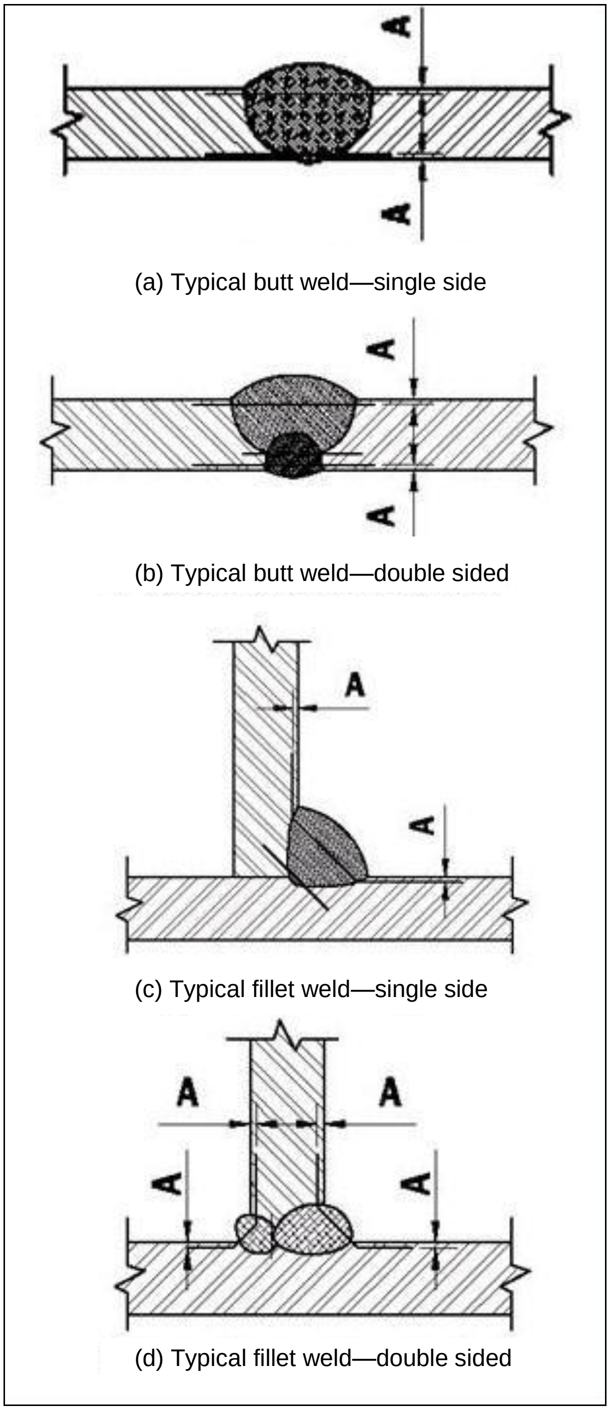
Conversion ISO 18265 - (62.0 ± 1.0) HRC - C.2 - HV
Standard number: Conversion ISO 18265
Converted hardness value, with uncertainty: (62.0 ± 1.0) HRC
Table used for comparison: C.2
Original hardness test method used: HV

B23. Microhardness evaluation, performed in accordance with ASTM E384 using either the Vickers or Knoop hardness test method, may be necessary for some components that are too small to be tested by conventional (macro) hardness test methods. Microhardness testing uses loads of 9.8 N (1 kgf) or less. Microhardness testing is more sensitive than macrohardness testing methods because of the very small indentation size. Because of this sensitivity, microscopic constituents such as second phases can cause individual hardness readings that are much higher than the bulk hardness. Thus, it is more difficult to establish general acceptance criteria based on microhardness testing. Individualized microhardness test procedures and associated acceptance criteria may need to be developed for each material/component combination being evaluated.

Appendix C
Welding Procedure Qualification Hardness Survey Layouts
(Mandatory)

C1. Hardness surveys shall be performed on a specimen taken from the WPQT coupon(s) using the Vickers hardness test method with a load of 98 N (10 kgf) or less in accordance with ASTM E384. The hardness surveys shall be performed in accordance with the layouts in Figures C1 and C2, which show hardness test locations and details, respectively, for butt welds and fillet welds.

C2. The hardness survey in accordance with Figures C1 and C2 shall be performed at a distance (A) of 1.5 ± 0.5 mm (0.06 ± 0.02 in) from the surface. If the weld interface (also sometimes called the fusion line, which is a nonstandard term) is distinct, one of the HAZ hardness measurements shall be made at a distance (B) not to exceed 0.5 mm (0.02 in) from the weld interface. If the weld interface is not distinct, a pair of indentations shall be placed 1 mm (0.04 in) apart, straddling the apparent center of the indistinct weld interface, and equidistant from the apparent center of the indistinct weld interface. The distance (L) between hardness measurements shall be 1 mm (0.04 in) in all cases.



(a) Typical butt weld—single side

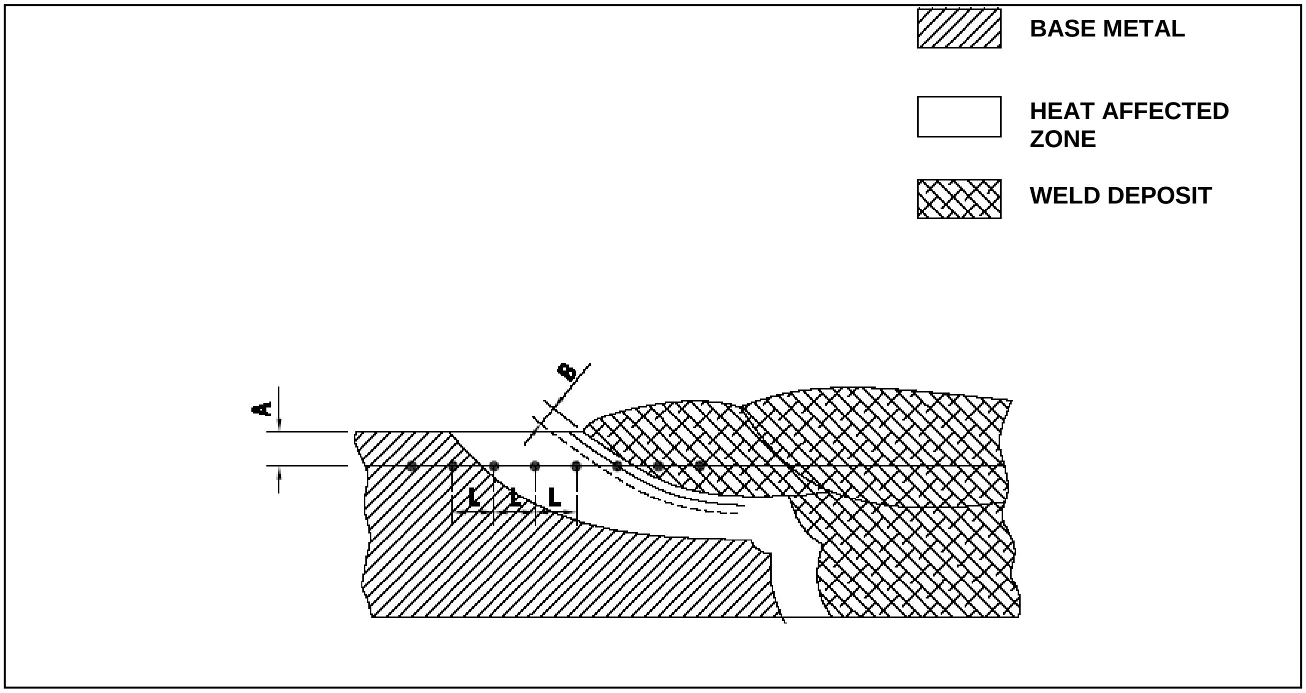
(b) Typical butt weld—double sided

(c) Typical fillet weld—single side

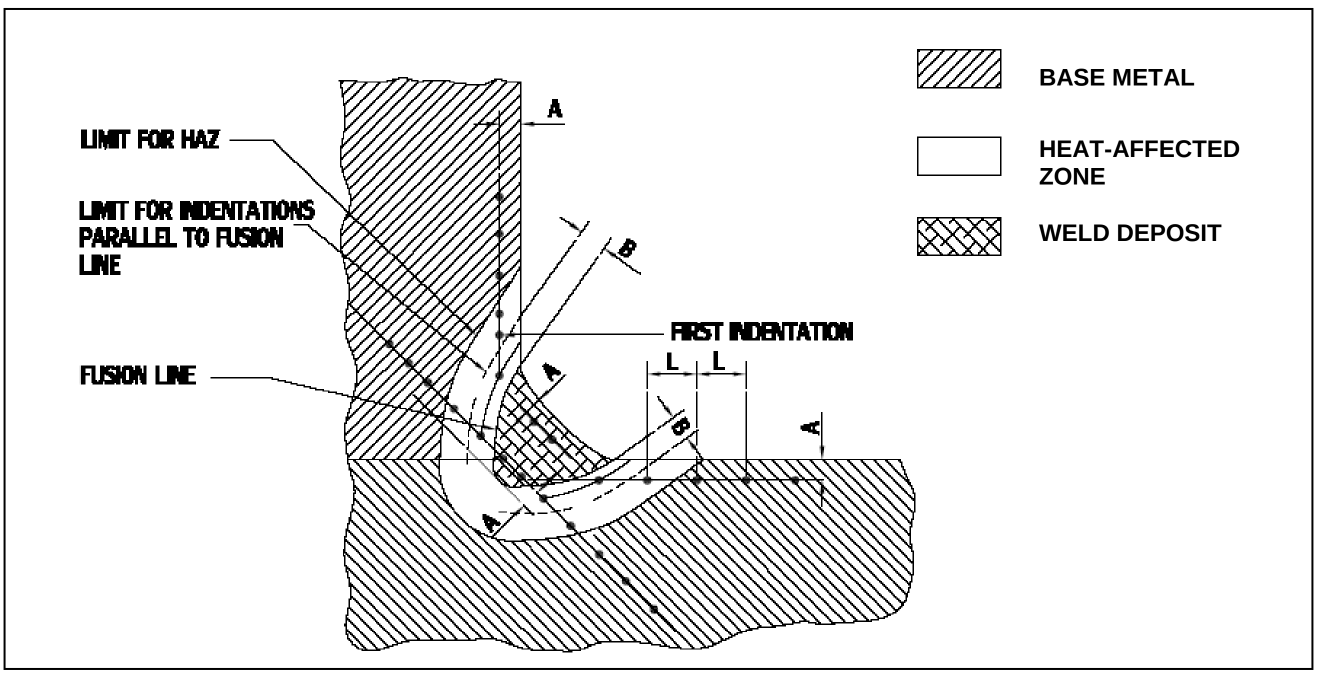
(d) Typical fillet weld—double sided

Figure C1: Hardness test locations.

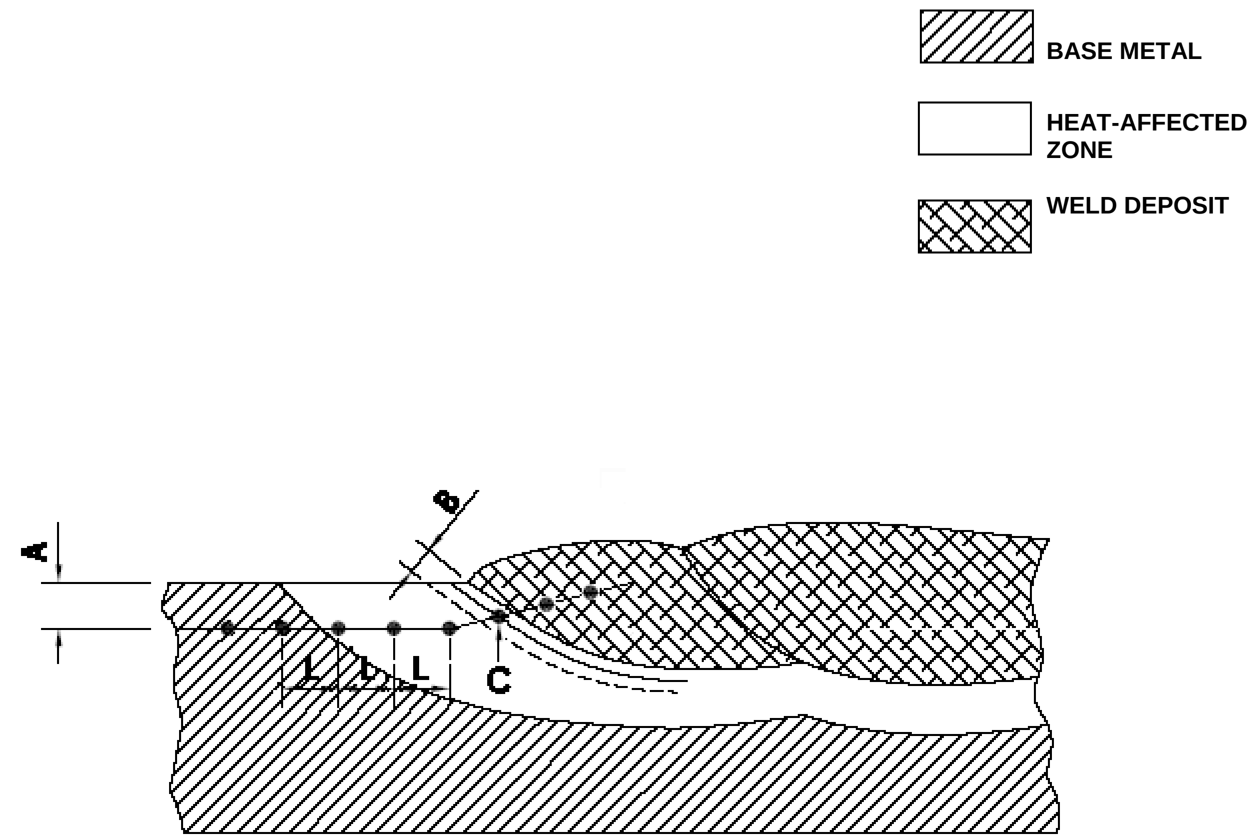
Distance A shall be 1.5 ± 0.5 mm (0.06 ± 0.02 in) from the surface.



(a) Butt weld—in any given location in Figure C1(b).



(b) Fillet weld



(c) Overlay or repair weld—if overlay terminates in exposed environment.

Figure C2: Hardness test details.

Distance A shall be 1.5 ± 0.5 mm (0.06 ± 0.02 in) from surface
Distance B shall be ≤ 0.5 mm (0.02 in) from weld interface
Indentation C shall be ≤ 0.5 mm (0.02 in) from the weld interface and shall be 1.5 ± 0.5 mm (0.06 ± 0.02 in) from the nearest surface (see Paragraph C2).
Distance L shall be 1 mm (0.04 in) between indentations

NOTE: This hardness survey shall be performed adjacent to both surfaces of the cap and root of welds.

C3. Hardness surveys performed prior to the issuance of this edition of MR0103 that used the hardness survey layouts in NACE MR0175/ISO 15156 are allowed.

C4. Microhardness testing using Knoop or Vickers tests with ≤ 4.9 N (500 gf) loads may be considered; however, the effects of surface preparation, etching, mounting procedures, appropriate criteria, and other details shall be reviewed and approved by the user before being used. Guidance on these hardness test techniques is given in ASTM E384.

C5. Individual HAZ hardness readings exceeding the value permitted by this standard shall be considered acceptable if the average of three hardness readings taken in the equivalent HAZ profile location adjacent to the hard HAZ reading (by repolishing the existing specimen taken from that WPQT coupon or taking additional specimens from that WPQT coupon) does not exceed the values permitted by this standard and no individual hardness reading is greater than 5% above the specified value.

C6. The hardness test results shall be appended to the PQR. The results shall include a sketch of the hardness test locations and corresponding results.

Appendix D
Duplex Stainless Steel Welding Considerations
(Nonmandatory)

> This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

D1. The metallurgical properties of duplex stainless steels are influenced by the microstructure. Ideally, the microstructure consists of an approximate 50/50 mix of ferrite and austenite, with no carbide or intermetallic precipitates (such as sigma phase). Too much ferrite reduces the toughness of the material and reduces its resistance to SSC. Too much austenite reduces the resistance to chloride stress corrosion cracking. Carbide and intermetallic precipitates reduce the general corrosion and pitting resistance and can adversely affect the toughness.

D2. The microstructure is strongly influenced by the cooling rate that occurs in the weld deposit and HAZ. A faster cooling rate promotes higher ferrite levels. A slower cooling rate promotes higher austenite levels, and can result in the formation of carbides and intermetallic precipitates. Achieving the desired microstructure is somewhat of a balancing act. The tendency to form second phases is a function of alloy content. The time-at-temperature to form intermetallic phases is shorter for the more highly alloyed superduplex grades than for the standard duplex grades.

D3. Cooling Rate Considerations

D3.1 A number of factors influence the cooling rate in a weldment, and those factors should be considered when creating the WPQT coupon and writing the resulting welding procedure. Major factors that influence cooling rate include base metal thickness, preheat, interpass temperature, heat input, and filler metal size.

D3.1.1 Base Metal Thickness

D3.1.1.1 In general, a thicker base metal results in a faster cooling rate. This effect is more pronounced in thin base metals. Once the base metal achieves a certain thickness, the cooling becomes three-dimensional, and further increases in thickness do not significantly affect the cooling rate.

D3.1.1.2 Many end user specifications impose special thickness constraints in addition to the qualified thickness ranges specified in Section IX of the ASME BPVC. Previous versions of MR0103 specified that the production base metal thickness qualified is the thickness of the WPQT coupon ± 20%. API TR 938-C[42] recommends that the maximum thickness qualified is 1.2 times the thickness of the WPQT coupon. API TR 938-C also recommends that impact testing be required. If impact testing is imposed, the ASME BPVC Section IX supplementary essential variables, which restrict the minimum thickness qualified, would also apply.

D3.1.1.3 Following are suggested combined requirements for qualified base metal and weld deposit thickness. These are based on API TR 938-C recommendations, but have been expanded to include special considerations for casting weld repairs, which are outside the scope of API TR 938-C.

(a) If the base metal thickness of the WPQT coupon (T) is < 38 mm (1.5 in), the minimum production base metal thickness qualified is T, and the maximum production base metal thickness qualified is 1.2T.

(b) If T is ≥ 38 mm (1.5 in) and ≤ 100 mm (4 in), the minimum production base metal thickness qualified for fabrication welds is 16 mm (0.63 in), and the maximum production base metal thickness qualified for fabrication welds is 100 mm (4 in). The maximum production base metal thickness qualified for repair welds in castings is 200 mm (8 in) provided the deposit thickness does not exceed 100 mm (4 in).

(c) If T is > 100 mm (4 in), the minimum production base metal thickness qualified for fabrication welds is 38 mm (1.5 in), and the maximum production base metal thickness qualified for fabrication welds is 1.2T. The maximum production base metal thickness qualified for repair welds to castings is unlimited, provided the deposit thickness does not exceed 1.2T.

NOTE: Although not mandatory in accordance with this standard, post-weld solution heat treatment should be considered following major weld repairs in castings. Major weld repair is defined in ASTM A995.[43]

D3.1.2 Preheat

3.1.2.1 The higher the preheat temperature (which is essentially a minimum interpass temperature for all passes, including the first pass), the slower the cooling rate.

D3.1.2.2 Duplex stainless steels are rarely preheated unless they are being welded under cold conditions, in which case they are generally preheated to room temperature.

D3.1.3 Interpass Temperature

D3.1.3.1 The higher the interpass temperature (which is the maximum temperature at which any weld pass may be started), the slower the cooling rate.

D3.1.3.2 The interpass temperature limits most commonly imposed on duplex stainless steels are 150 °C (300 °F) for the 22Cr-5Ni grades and 120 °C (250 °F) for the 25Cr-5Ni and 25Cr-7Ni grades.

D3.1.4 Heat Input

D3.1.4.1 Heat input (*HI*) in a weldment is calculated using Equation (D1) or Equation (D2):

$$\mathrm{HI} = \frac{\text{amps} \times \text{volts} \times 60}{\text{travel speed}} \tag{D1}$$

Where travel speed is expressed in mm/min or in/min.

$$\mathrm{HI} = \frac{\text{amps} \times \text{volts} \times 60}{\text{travel speed}} \tag{D2}$$

Where travel speed is expressed in mm/s or in/s.

NOTE: Both equations produce a heat input value that is expressed in joules (J) per unit length of weld (i.e., J/mm or J/in).

D3.4.1.2 The higher the heat input, the slower the cooling rate.

D3.1.4.3 Many end-user specifications impose special heat input constraints in addition to the qualified heat input ranges specified in Section IX of the ASME BPVC. Previous editions of MR0103 specified that the production heat input range qualified is the heat input used when creating the WPQT coupon ± 10%.

D3.1.4.4 Most metal producers publish recommended heat input ranges and other recommended welding parameters for their base metals, and most filler metal suppliers publish recommended amperage, voltage, and heat input ranges for their consumables. These recommendations should be considered when qualifying the welding procedure. In addition, API TR 938-C includes a heat input range recommendation for duplex stainless steels that matches the previous MR0103 requirement.

D3.1.4.5 Considering that heat input is not absolutely constant, especially in manual welding processes, following are some guidelines for establishing heat input ranges in the WPS:

(a) If the heat input is held constant while the WPQT coupon is being created, the minimum heat input qualified is 0.9 times *HI* (the heat input used to create the WPQT coupon), and the maximum heat input qualified is 1.1 times *HI*.

(b) If the heat input for a given combination of welding process and filler metal size is varied (as a result of variations in amperage, voltage, and/or travel speed during welding of the WPQT coupon), the minimum allowable heat input qualified for that combination of process and filler metal size is $0.9HI_{min}$, where HI_{min} is the minimum heat input used while creating the WPQT coupon. The maximum allowable heat input qualified is 1.1 HI_{max}, where HI_{max} is the maximum heat input used while creating the WPQT coupon.

(c) When multiple processes and/or filler metal sizes are qualified using a single WPQT coupon, the minimum and maximum allowable heat input values for each combination of process and filler metal size should be determined in this same manner and documented as such on the resulting WPS.

D3.1.5 Filler Metal Size

D3.1.5.1 For a given level of heat input, a weld deposit produced using a smaller filler metal size generally experiences a higher level of heat input per unit volume of weld deposit compared with a weld deposit created using a larger filler metal size. This can affect the ferrite level, and as such, consideration should be given to specifying filler metal size as an essential variable, thus restricting welding procedures to the same filler metal size(s) used during welding procedure qualification.

D4. Alloy Considerations

D4.1 Alloy Grouping

D4.1.1 Because the more highly alloyed superduplex grades are more prone to form intermetallic phases than the standard duplex grades, consideration should be given to specifying alloy grouping as an essential variable, thus restricting welding procedures to the same alloy grouping as the material used during welding procedure qualification. Table D1 lists the base metal alloys in each grouping.

Table D1
Duplex Stainless Steel Base Metal Groupings

Duplex Alloy Grouping	Specified Chromium Content Falling Within the Range	Specified Nickel Content Falling Within the Range
22Cr-5Ni	21–23% Cr	4.5–6.5% Ni
25Cr-5Ni	24–27% Cr	4.5–6.5% Ni
25Cr-7Ni	24–26% Cr	6.0–8.0% Ni

NOTE: Applicable construction codes or standards may not allow welding of all materials within any one of the above groupings with one welding procedure qualification.

D5. Filler Metal

D5.1 Filler metal should be selected based on the alloy being welded. Filler metals are usually over-alloyed with nickel to increase the tendency to form austenite. This is done because the weld deposit will not have the benefit of being solution annealed, which tends to reduce the ferrite content from that of the as-solidified material.

D5.2 API TR 938-C includes recommended filler metals as a function of alloy grouping. In addition to those recommendations, UNS S32760 wrought products and CD3MWCuN castings, which contain intentional additions of tungsten and copper, should be welded with ASME SFA-5.4[44] E2595 shielded metal arc welding (SMAW) filler metal, or with ASME SFA-5.9[45] ER2594 gas tungsten arc welding (GTAW)/gas metal arc welding (GMAW) filler metal with intentional additions of tungsten and copper to essentially match the E2595 composition. These filler metals are readily available.

D6. Welding Procedure Qualification Testing Requirements

D6.1 In addition to the standard ASME BPVC Section IX WPQT requirements (tensile and bend tests), MR0103 requires Vickers hardness survey testing and ferrite testing. Consideration should be given to performing additional tests to ensure that the weldment exhibits the necessary properties.

D6.2 Vickers Hardness Survey

MR0103 requires a Vickers hardness survey using a load of 98 N (10 kgf) or less. API TR 938-C specifies that a 49 N (5 kgf) load be used for the HAZ measurements. Whereas this smaller load may be able to discern a higher hardness level in a slightly narrower band adjacent to the weld fusion line, the relative size of a 49 N (5 kgf) indentation is only 30% smaller than a 98 N (10 kgf) indentation at the same hardness level. Considering the possibility of introducing errors when a hardness survey is performed using two different loads at different locations, it may be more prudent to perform all indentations using the same load, either 98 N (10 kgf) or 49 N (5 kgf).

D6.3 Ferrite Testing

D6.3.1 MR0103 requires that ferrite testing be performed in accordance with the requirements of ASTM E562. ASTM E562 is a general point count method for estimating the relative volume of a particular phase in a microstructure. ASTM E562 does not provide specific instructions regarding the etchant to be used, nor does it provide specific requirements regarding the actual magnification to be used, the number of points in the grid, the number of fields to be examined, or the percent relative accuracy that is to be achieved.

D6.3.2 Most metallographic ferrite examinations are performed after an electrolytic etch using a sodium hydroxide solution, which stains the ferrite phase.

D6.3.3 Most end-user specifications require the use of the ASTM E562 point count method rather than the ASTM E1245[46] automated image analysis method. There are concerns that the automated method cannot discern whether a darker region is actually ferrite, or if it is an inclusion or a second-phase particle.

CAUTION: A note at the beginning of ASTM E562 states, “This test method may be used to determine the volume fraction of constituents in an opaque specimen using a polished, planar cross section by the manual point count procedure. The same measurements can be achieved using image analysis per Practice E1245.” Some laboratories interpret this note to mean that they can use the ASTM E1245 method at their discretion when the customer has specified ASTM E562. That is not what the note means. It is merely informative. It may be prudent to explicitly state that the ASTM E1245 method may not be substituted.

D6.3.4 Some end-user specifications dictate specific magnifications, grid counts, and number of fields to be examined in each region of the weldment. This practice may be problematic if it is applied to a wide range of product forms and weldment sizes.

D6.3.5 According to ASTM E562 Table 2, when examining a structure with greater than 20% of the phase of interest, a 16-point grid is recommended, based upon “an optimum for efficiency for the time spent counting and for the statistical information obtained per grid placement.” To achieve 10% relative accuracy, the formula in ASTM E562 Table 3 indicates that 25 fields would need to be examined when using a 16-point grid. Magnification selection should be based on the relative size of the phases, according to the guidance in ASTM E562 Paragraph 9.3.

D6.3.6 PI TR 938-C requires one 100 point field be counted in each zone of interest. This provides a first-order approximation of the ferrite percentage at the specific location being examined, but does not provide an estimate of the ferrite percentage in the portion of the weldment of interest, nor does it provide any means for establishing the statistical certainty of the measurement.

D6.3.7 Consideration should be given to locations where ferrite testing is to be performed. API TR 938-C specifies that ferrite should be determined (a) in the parent metal, one measurement on each side of the weld at mid thickness (total of two); (b) in the HAZ on each side of the weld, in the region of the root pass (total of two); and (c) in the weld metal, three measurements near to the vertical centerline of the weld—one in the cap, one in the root, and one at mid thickness (total of three).

D6.3.8 If filler metal size is specified as an essential variable, extra weld deposit ferrite measurements should be considered if multiple filler metal sizes are qualified using a single WPQT coupon. In this case, consideration should be given to adding a ferrite measurement in the weld metal at roughly the vertical centerline of each extra group of passes performed using a different filler metal size than was used for the locations where the standard measurements are taken.

D6.3.9 In addition, if the procedure will ever be used to weld on the inside of a component (such as a casting weld repair), consideration should be given to measuring the ferrite in the HAZ adjacent to the cap layer, because it will be exposed to the process.

D6.3.10 API TR 938-C includes a statement indicating that ferrite testing is a complicated test, and should only be performed by an experienced laboratory. This is prudent advice. Mathematical errors, improper selection of magnification, and bias (selecting areas for point counts based on how they look rather than randomly) are common errors made by laboratories not very experienced in performing this testing. Consideration should be given to using a laboratory that is not only experienced with this type of testing, but which is also accredited specifically for ASTM E562 testing in accordance with ISO/IEC 17025.[47]

D6.4 Charpy Impact Testing

Charpy impact testing is commonly specified for the base metal as well as for the weld deposit and HAZ during weld procedure qualification. This testing usually is not imposed to verify whether the metal and the welding procedure will provide adequate toughness at the test temperature, but rather as an indirect assessment of the metallurgical structure. Typically, the tests are required to be performed at a temperature somewhere within the range of –40 to –51 °C (–40 to –60 °F), with acceptance criteria somewhere within the range of approximately 35 to 50 J (26 to 37 ft-lbf). These results are achievable with proper welding controls. ASTM A923[48] covers Charpy testing requirements in Method B, but most users either specify their own requirements or supplement the ASTM A923 requirements with their own.

D6.5 Corrosion Testing

Some end users specify ASTM G48[49] Method A (10% ferric chloride) testing on duplex stainless steels, and often incorporate it into the WPQT requirements. When imposed for weld procedure qualification, the specimen taken from the WPQT coupon is required to include weld deposit, HAZ, and base metal. The specified exposure time is typically 24 h, and the specified test temperature is typically 25 °C (77 °F) for the 22Cr grades and 40 °C (104 °F) for the 25Cr grades. Typically, there are two acceptance criteria: (1) no pitting shall be visible at 20X, and (2) mass loss of no more than 4 g/m^2. This test is imposed to verify that the weld deposit and HAZ do not contain excessive amounts of carbide or intermetallic phases. ASTM A923 Method C covers ferric chloride corrosion testing requirements, but most users either specify their own requirements based on ASTM G48 Method A or supplement the ASTM A923 requirements with their own.

D6.6 Metallographic Examination

Some end users specify a metallographic examination to examine for carbides and other second phases, and often incorporate it into WPQT requirements. These requirements often restrict carbides, sigma phase, and other intermetallic phases to 1% or less. Many laboratories refuse to state compliance with these requirements unless absolutely no second phase is observed, because measurement of constituent percentages this low is very difficult. Some end users feel that the ASTM G48 Method A corrosion testing is a better way to ensure that the microstructure is adequate.

D7. Production Testing of Welds

D7.1 Ferrite Testing of Production Welds

Some end users specify ferrite testing of production welds with a magnetic induction instrument to verify that the base metal and weld deposits exhibit ferrite levels within the required ranges. The ability to determine the ferrite level in the HAZ using this method is questionable, because of the narrow width of the HAZ.

ISBN 1-57590-168-4
NACE International