PART 2
REPAIR WELDING CONSIDERATIONS FOR Cr-Mo STEEL PRESSURE VESSELS
ARTICLE 2.15
Guide for Selection of Repair Technique

<table>
<thead>
<tr>
<th>Cr-Mo Repair</th>
<th>General wall thinning</th>
<th>Local wall thinning</th>
<th>Pitting</th>
<th>Gouges</th>
<th>Blisters</th>
<th>Laminations</th>
<th>Circumferential cracks</th>
<th>Longitudinal cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>R</td>
<td>R</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Nomenclature:
Y= Generally appropriate
S= Although it may be acceptable, is not generally used for this condition
R= May be used, but requires special caution

1. INTRODUCTION
1.1 Scope
Repair welding considerations in this article are applicable to pressure vessels for refinery, petrochemical, power generation and other services where the following requirements may be considered applicable.

1.2 Application
(a) This article describes weld repair considerations for pressure vessels made from Cr-Mo steels. The purpose of this article is to provide the reader with a high level overview of deterioration mechanisms and subsequent considerations that need to be made in developing a detailed repair, examination and testing plan required for the successful repair of Cr-Mo pressure vessels.
(b) The Cr-Mo materials listed in Table 1 of this Article are susceptible to certain types of damage in elevated temperature service (e.g., see ref. 2, 3, and 4).
(c) The repair of creep damaged Cr-Mo steels, creep enhanced ferritic steels, vanadium modified steels or stainless steel cladding or weld overlay are not included in this Article, but will be covered in a separate Article.
(d) API RP 579-1/ASME FFS-1 and API RP 571 provide further information on temper embrittlement and other aging effects on the fracture toughness of Cr-Mo steels.

1.3 Design Temperature
The maximum design temperatures of these materials are as listed in the applicable codes of construction.

1.4 Applicable Materials
Typical generic Cr-Mo materials and their ASME designations are indicated in Table 1 however, equivalent international standard materials can also be used.

<table>
<thead>
<tr>
<th>Typical Materials</th>
<th>ASME Designation</th>
<th>Plates</th>
<th>Forgings</th>
<th>Vessel Piping Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Cr-½Mo</td>
<td>SA387-12 Cl.1</td>
<td>SA182-F12</td>
<td>SA335-P12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SA387-12 Cl.2</td>
<td>SA336-F12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1⅛Cr-½Mo</td>
<td>SA387-11 Cl.1</td>
<td>SA182-F11</td>
<td>SA335-P11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SA387-11 Cl.2</td>
<td>SA336-F11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2⅛Cr-1Mo</td>
<td>SA387-22 Cl.1</td>
<td>SA182-F22 CL.1 &amp; 3</td>
<td>SA335-P21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SA387-22 Cl.2</td>
<td>SA336-F22 CL.1 &amp; 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3Cr-1Mo</td>
<td>SA387-21 Cl.1</td>
<td>SA182-F21</td>
<td>SA335-P22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SA387-21 Cl.2</td>
<td>SA336-F21 CL.1 &amp; 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5Cr-½Mo</td>
<td>SA387-5 Cl.1</td>
<td>SA182-F5</td>
<td>SA335-P5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SA387-5 Cl.2</td>
<td>SA336-F9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9Cr-1Mo</td>
<td>-</td>
<td>SA182-F9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA336-F9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2⅛Cr-1Mo.</td>
<td>SA542-B Cl.4</td>
<td>SA541-22 Cl.3</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
2. LIMITATIONS
2.1 Additional Requirements
Part 1 of this Standard contains additional requirements. This Article shall be used in conjunction with Part 1 of PCC-2.

3. DESIGN
3.1 Feasibility Study of Repair Welding
(a) The materials listed in Table 1 may be repair welded provided an investigation has been performed to determine the cause of the damage and provided appropriate weld repair procedures are used.
(b) The structural integrity of the pressure vessel should be addressed prior to repairs together with the feasibility of the repairs and suitability of the pressure vessel for the intended service after the repairs. The serviceability or Fitness for Service Assessment should be based on API RP 579-1/ASME FFS-1 as shown in Figure 1.

![Figure 1: Standard Steps In Repair Welding](image)

3.2 Evaluation of applicability of weld repair
3.2.1 Consideration of in-service degradation
(a) In-service degradation, as shown in Table 2 and Figure 2, shall be considered before developing a repair welding procedure.
(b) Typical considerations for in-service degradation for weld repair are shown in Table 3.
(c) Further information on in-service degradation is provided in API RP 571 and in WRC Bulletins 488, 489 and 490.

<table>
<thead>
<tr>
<th>Type of Damage</th>
<th>Applicable Operational Conditions</th>
<th>Degradation Phenomena</th>
<th>Typical Susceptible Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temper Embrittlement</td>
<td>370-580°C (700-1,080°F)</td>
<td>Toughness degradation in base metal and welds through the intergranular micro segregation of impurity elements as measured by the J factor for 2¼Cr &amp; higher Cr base metals and X bar factor for weld metals as well as 1Cr &amp; 1¼Cr base &amp; weld metals</td>
<td>1Cr-½Mo 1¼Cr-0.5Mo 2¼Cr-1Mo 3Cr-1Mo 5Cr-1Mo Embrittlement manifests at lower temperatures during start up and shutdown</td>
</tr>
<tr>
<td>Creep Embrittlement</td>
<td>Over 454°C (850 °F) and with applied load</td>
<td>Carbide precipitation and crack initiation in the coarse grain HAZ of a localized stressed area such as at a nozzle attachment weld</td>
<td>1Cr-½Mo 1¼Cr-½Mo</td>
</tr>
<tr>
<td>Hydrogen Attack</td>
<td>High temperature and high pressure hydrogen environment</td>
<td>Generation of methane bubbles, blisters and cracks See API 941</td>
<td>Low Cr materials in high hydrogen partial pressure environment</td>
</tr>
<tr>
<td>Hydrogen Embrittlement</td>
<td>High temperature, and high pressure hydrogen environment and start up and shut down conditions</td>
<td>Toughness degradation by hydrogen absorption.</td>
<td>1Cr-½Mo 1¼Cr-½Mo 2¼Cr-1Mo 3Cr-1Mo</td>
</tr>
</tbody>
</table>
3.3 Examples of Damage
(a) Figure 2 indicates some examples of damage that can occur in Cr-Mo pressure vessels with or without stainless steel cladding or weld overlay.
(b) The typical example shown is for high temperature high pressure (HTHP) pressure vessels in refining service.

![Figure 2: Examples of Damage Common to Cr-Mo Pressure Vessels](image)

<table>
<thead>
<tr>
<th>Type of Damage</th>
<th>Main Concerns</th>
<th>Repair Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temper embrittlement</td>
<td>• Low toughness at start up and shut down&lt;br&gt;• Operating temperature limits&lt;br&gt;• Weldability</td>
<td>• De-embrittled heat treatment above 600°C (1100°F) then rapid cooling&lt;br&gt;• Use welding materials with low impurity levels</td>
</tr>
<tr>
<td>Creep embrittlement</td>
<td>• Detection by NDE&lt;br&gt;• Flaw removal</td>
<td>• Elimination of stress riser and higher Cr material selection</td>
</tr>
<tr>
<td>Hydrogen attack</td>
<td>• Detection by NDE&lt;br&gt;• Flaw removal</td>
<td>• Higher Cr material selection (ref. Nelson chart, API Std 941)&lt;br&gt;Stainless steel weld overlay cladding</td>
</tr>
<tr>
<td>Hydrogen embrittlement</td>
<td>• Toughness at operating temp&lt;br&gt;• Weldability</td>
<td>• De-hydrogenation heat treatment above 300°C (570°F) 1 hr min&lt;br&gt;• Low hydrogen welding process</td>
</tr>
</tbody>
</table>

Notes: (Table includes prevention/mitigation for repair and/or replacement)

3.4 Development of Weld Repair Procedures
(a) The selection of weld repair method should be based on the reliability of the repaired area considering the future operation period as shown in Figure 3.
(b) Sleeve repair and partial patch repair methods (refer to Table 4) are normally applied temporarily and are not recommended for periods beyond the next upcoming shutdown or outage without appropriate nondestructive examination (NDE) and applicable Fitness for Service Assessment.
3.5 Applicable Repair Welding Methods

Some applicable repair welding approaches and alternates to post weld heat treatment that are outlined in ASME PCC-2 are listed in Table 4 with some additional limitations and considerations.

3.6 Welding / Preheat

When the actual aged condition of the component to be repaired cannot be sufficiently evaluated for development of a repair welding procedure, a bead-on plate test* should be used to verify the repair welding procedure.

* A bead-on plate test is a type of self-restraint weld test used to evaluate the cracking sensitivity of the base materials and arc welding consumables, See PVP 2011-57809 and 57079 References.

<table>
<thead>
<tr>
<th>Types of Repair</th>
<th>Applicable Repair Methods in ASME PCC-2</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeve repair</td>
<td>Article 2.6</td>
<td>Replacement with type B sleeve at the first available opportunity is recommended</td>
</tr>
<tr>
<td>Overlay welding and or internal weld metal build up</td>
<td>Article 2.11</td>
<td>In case of corrosion metal loss, welding materials shall be selected considering cause of corrosion.</td>
</tr>
<tr>
<td>Butt-welded insert plates</td>
<td>Article 2.1</td>
<td>Thickness of insert plate shall generally not be thicker than shell or head.</td>
</tr>
<tr>
<td>Alternates To PWHT</td>
<td>Article 2.9</td>
<td>Refer to paragraph 4.7</td>
</tr>
<tr>
<td>Alternates to traditional welding preheat</td>
<td>Article 2.8</td>
<td>Welding strategies as indicated in PCC-2 Article 2.8 may provide permissible alternatives to preheat requirements</td>
</tr>
</tbody>
</table>

Table 4: Applicable Repair Methods In PCC-2

4. FABRICATION

4.1 Weld Repair Procedures

(a) Weld repair procedures may be developed as indicated in Table 5.
(b) The Welding Procedure Specification (WPS) shall be qualified in accordance with ASME BPV Code Section IX as applicable and/or the requirements imposed by the code of construction.

4.2 Preparation for welding

(a) For shielded metal arc (SMAW), drying of electrodes shall be carried out to minimize the potential for hydrogen cracking.
(b) Welding bevel surfaces shall be clean, dry and free of oil, paint or other contaminants

4.3 Welding Conditions

(a) In order to prevent hardening of welds, short length weld beads less than 2 inch (50 mm) bead length, should be avoided.
(b) Special precaution shall be taken to guard against brittle fracture due to local thermal temperature gradients
(c) For one side repair welding of piping, back shielding should be considered for 2½Cr-1Mo and higher alloy steels.
The temper bead welding method may be considered after evaluation in some cases for low alloy welds when post weld heat treatment (PWHT) will not be carried out. See paragraph 4.7.

### 4.4 Preheating and Post Heating

(a) In order to prevent hardening of welds and cold cracking, preheating, post heating and dehydrogenation heat treatment (DHT) shall be mandatory requirements unless the following paragraphs stipulate otherwise.

(b) Typical preheating and welding interpass temperatures are indicated in Table 6.

### 4.5 De-embrittlement Heat Treatment

When the materials are severely embrittled, a de-embrittlement heat treatment operation may be used to recover toughness of material as shown in Table 7.

### 4.6 Dehydrogenation Heat Treatment (DHT)

The preheat temperature should be maintained until PWHT or dehydrogenation heat treatment is performed. When the materials are required to cool to ambient temperature after repair welding, dehydrogenation heating shall be carried out at a minimum of 300°C (570°F) for a minimum of 1 hr, or for a duration to be agreed between Purchaser and Fabricator in order to prevent cold cracking.

### 4.7 Post Weld Heat Treatment

(a) PWHT should be performed when required per applicable construction code or standards.

(b) Temper bead and other welding methods as detailed in Article 2.9 Alternates To Post Weld Heat Treatment may be applicable to some low chrome steels when corresponding WPS/PQR’s are developed specifically for the welding repair considering welding position and welding circumstances.

(c) Temper bead methods are usually not appropriate for 2¼Cr-1Mo and higher chrome materials used for hydrogen service because of the high weld metal and HAZ hardnnesses generated by the welding process.

(d) In case of local PWHT, the PWHT procedure shall be developed which shall also include the arrangement of thermocouples and insulation in order to minimize the thermal stresses generated during the PWHT operation. WRC 452 and AWS D10.10 provide guidelines for developing a PWHT plan with specific band widths (soak band, heated band and gradient control band) to ensure that thermal gradients are not harmful.
<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Service Conditions</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen attack</td>
<td>All Cr-Mo steels at high temperature/pressure hydrogen services</td>
<td>Not applicable due to irreversible phenomena</td>
</tr>
<tr>
<td>Creep embrittlement</td>
<td>1Cr-½Mo, 1½Cr-½Mo at over 450°C (900 ⁰F)</td>
<td>Heating at not less than 600 ⁰C (1,120 ⁰F)</td>
</tr>
<tr>
<td>Temper embrittlement</td>
<td>2¼Cr-1Mo, 3Cr-1Mo at 370-580°C (700-1,080 ⁰F)</td>
<td>De-hydrogenation shut down operation or heat treatment at temperature not less than 300°C (570°F)</td>
</tr>
<tr>
<td>Hydrogen embrittlement</td>
<td>2¼Cr-1Mo, 3Cr-1Mo at high temperature hydrogen services</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: De-embrittlement Heat Treatment

5. EXAMINATION
5.1 Nondestructive Examination
(a) NDE as indicated in Table 5 shall be considered at each step of repair welding work. The appropriate NDE procedure(s) for the applicable repair shall be selected to meet code requirements and provide the level of examination necessary for the repair.
(b) NDE procedures shall be in accordance with ASME BPV Code Section V and applicable construction code/standards
(c) NDE before repair welding of pressure boundary:
   (1) The entire area of the pressure vessel that is to be repair welded shall be examined by means of visual examination (VT) or other NDE methods as may be applicable, to ensure that the area is free of any defect harmful to the repair operation, which may include welding, PWHT and pressure testing.
   (2) The need for carrying out pressure testing after repairs as well as the pressure used in pressure testing shall be evaluated in consideration of service conditions.
(d) NDE after weld repair and after pressure test:
   (1) Complete NDE shall be performed in an area that is at least the maximum of either 2T (where T is the thickness of material) or 100 mm (4 inches) from the edge of the repair welded, preheated or post weld heat treated area in order to ensure the area is free of defects.
   (2) NDE of that area shall also be performed after any pressure test that may have been carried out.
(e) Acoustic emission testing may also be an effective means of examination following completion of repairs.
(f) Where possible, in-service NDE monitoring during operation is recommended for the repaired areas.
(g) In some instances, the use of NDE in lieu of pressure testing will be appropriate for repairs. Refer to PCC-2 Article 5.2 for Non Destructive Examination In Lieu Of Pressure Testing for Repairs and Alterations.
(h) Follow up NDE after the pressure vessel is returned to service shall be performed based on fitness-for-service assessment requirements or applicable ISI Codes.

6. PRESSURE TESTING
(a) The requirement for the applicability of a pressure test subsequent to weld repairs shall be evaluated.
(b) If a pressure test is determined to be required after the repair welding of pressure bearing parts is completed, the pressure vessel or vessel part should be pressure tested in accordance with the requirements of the applicable construction Code. In lieu of the construction code pressure test requirements, PCC-2 Article 5.1 should be followed.
(c) The pressure test, when required, shall be performed at a temperature higher than the Facture Appearance Transition Temperature (FATT) and at or above the minimum temperature specified by the code of construction in order to prevent brittle fracture during the pressure test.
(d) The toughness value of degraded materials shall be evaluated based on accumulated material database or samples obtained from vessel parts.
(e) For pressure vessels that are to be hydrotested that operate in hydrogen service, the hydrotest pressure shall be evaluated in consideration of hydrogen service conditions and shall be no higher than the vessel operating pressure.
(f) When a pressure test is to be carried out, consideration shall be given to the pressure train that the pressure vessel may be located in, the possibility of isolation of components within that train and consideration of the need for pressure testing the entire train.

7 REFERENCES
WELDING JOURNAL, April 2002, Welding Process Effects in Weldability Testing of Steels, authored by Atkins, D; Thiessen, D; Nissley, N; Adonyi, Y; Published by the AWS, Miami FL.
API RP 934 series, published by API, Washington, D.C.
   (a) 934-A, Recommended Practice for Materials and Fabrication Requirements for 2½Cr-1Mo, 2½Cr-1Mo-½V, 3Cr-1Mo & 3Cr-1Mo-¼V Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service
   (b) 934-C, Recommended Practice for Materials and Fabrication Requirements for 1¼Cr-1/2Mo Steel Heavy Wall Pressure Vessels for High Pressure Hydrogen Service Operating at or below 825ºF (441ºC)
   (c) 934-D, Technical Report on the Materials and Fabrication Issues of 1¼Cr-½Mo and 1Cr-½ Mo Steel Pressure Vessels
   (d) 934-E, Recommended Practice for Materials and Fabrication Requirements for 1¼Cr-1/2Mo Steel Pressure Vessels for Service above 825ºF (440ºC)
ASME BPV Code Section V, Non Destructive Examination, published by ASME, New York, NY.
AWS D10.10, Local Heating of Piping and Tubing, published by AWS, Miami, FL.