WHAT TO THINK ABOUT DURING WELD REPAIR

CARBON STEEL, STAINLESS STEEL AND Ni-ALLOY

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Application Specialist

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TOPICS

• What to think about during weld repair?

• Types of failures

• Understand the difference between materials

• Prior welding, during and after welding

• Applications
WHAT TO THINK ABOUT DURING WELD REPAIR

NOT INCLUDED IN THIS PRESENTATION BUT SHOULD BE CONSIDERED

• Scheduled or emergency repair
• Root cause of the failure (process, overload, fatigue, corrosion/erosion, inadequate design, wrong material)
• Planning (isolation of all connected systems, confined space, temporary structural supports, co-operation between maintenance and operation etc.)
• Spare parts
• Review of drawings
• Correct tools and equipment
WELDING – FABRICATION PROCESS

METALLURGICALLY JOINING OR CLADDING

• WELDING IS ALWAYS A LOCAL HEAT TREATMENT OF A MATERIAL THAT CHANGES THE METALLOGRAPHIC STRUCTURE
  • Dendrites, segregations
  • The weld has in many cases inferior mechanical and corrosion properties compared to the base material
WHAT TO THINK ABOUT DURING WELD REPAIR

CHECK LIST – WELD REPAIR

• Safety!
• Pressure vessel? → Third party present
• Welding procedure Specification (WPS) “Heat input; AWS or EN ISO?”
• Qualified welder
• Base material and welding consumables
• Welding technique
• Non destructive testing (NDT)
• Pre heating and/or post weld heat treatment (PWHT) needed?
• If as-welded dimensional accuracy requirement is needed → monitor welding and adjust sequencing
• Knowledge and experience!
WHAT TO THINK ABOUT DURING WELD REPAIR

POTENTIAL WELDING RELATED HAZARDS

• Eye damage
  • Arc-eye
  • Grinding

• Hearing damage
  • Grinding

• Burns
  • Welding operations
  • Hot metal

• Fumes
  • Gas inhalation
  • Dust inhalation

• Heavy equipment
  • Lifting equipment
  • Heavy plates and test pieces
  • Potential falling items (safety shoes)
WELDING QUALIFICATION

INTEGRITY OF WELDS

• How to know if a weld have the desired quality and meet the acceptance criteria?
• Welding parameters, materials and welding techniques are qualified
  • ISO (WPQR) and ASME (PQR)
• NDT testing techniques

pWPS

WPQR/PQR

WPS

(Manufacturing assessment test)
The WPS is the work instruction for the welders in manufacturing.

Important / essential parameters:
- Base material and dimension
- Filler material and dimension
- Joint preparation
- Heat-input
- Weld protection type
- Preheating
- Post Weld Heat Treatment (PWHT)
- Welding method
- Technique (weave vrs. stringers)
HEAT INPUT

EN ISO OR ASME?

EN ISO 1011-1

\[ Q = k \frac{U \cdot I}{v} \cdot 10^{-3} \text{ in kJ/mm} \]

ASME BPVC IX QW-409-1

\[ \text{Heat input [J/in. (J/mm)]} = \frac{\text{Voltage} \times \text{Amperage} \times 60}{\text{Travel Speed} \left[ \text{in/min (mm/min)} \right]} \]

Table 1 — Thermal efficiency factor \( k \) of welding processes

<table>
<thead>
<tr>
<th>Process No</th>
<th>Welding process</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Submerged arc welding</td>
<td>1,0</td>
</tr>
<tr>
<td>111</td>
<td>Manual metal-arc welding</td>
<td>0,8</td>
</tr>
<tr>
<td>131</td>
<td>MIG welding</td>
<td>0,8</td>
</tr>
<tr>
<td>135</td>
<td>MAG welding</td>
<td>0,8</td>
</tr>
<tr>
<td>114</td>
<td>Self-shielded tubular -cored arc welding</td>
<td>0,8</td>
</tr>
<tr>
<td>136</td>
<td>Tubular-cored wire metal-arc welding with active gas shield</td>
<td>0,8</td>
</tr>
<tr>
<td>137</td>
<td>Tubular-cored wire metal-arc welding with inert gas shield</td>
<td>0,8</td>
</tr>
<tr>
<td>141</td>
<td>TIG welding</td>
<td>0,6</td>
</tr>
<tr>
<td>15</td>
<td>Plasma arc welding</td>
<td>0,6</td>
</tr>
</tbody>
</table>
## SELECTING FILLER METALS

### FACTORS TO CONSIDER

<table>
<thead>
<tr>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codes</td>
</tr>
<tr>
<td>Specifications</td>
</tr>
<tr>
<td>Engineering</td>
</tr>
</tbody>
</table>

### Service Environment

<table>
<thead>
<tr>
<th>Loading Type</th>
<th>Strain Rate</th>
<th>Temperature</th>
<th>Corrosion</th>
</tr>
</thead>
</table>

### Base metal

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Chemical composition</th>
<th>Joint design</th>
</tr>
</thead>
</table>

### The process

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Position</th>
<th>Location</th>
<th>Economics</th>
<th>Usability</th>
</tr>
</thead>
</table>

[Image of filler metal coils]
SELECTING FILLER METAL

GENERAL GUIDELINES – RULES OF THUMB

• Filler metal
  • Match the chemical composition and mechanical properties (tensile and yield strength, elongation etc.) of the base metal
    • Stainless steel and Ni-alloys slightly over alloyed
  • Base metal
    • Drawings, PMI (Positive Material Identification), magnet
    • Contact the original manufacturer for weld repair advice
• Basicity and impact strength
  • Rutile slag \((\text{TiO}_2)\) – More weld metal micro oxides → Less toughness of the weld metal “Lower basicity”
  • Lime Flouride slag \((\text{CaF}_2)\) – Less weld metal micro oxides → Higher toughness of the weld metal “Higher basicity”
PRE HEATING

CARBON STEEL AND CRACK SENSITIVITY

- Decided by the code but depend on factors like
  - Chemical analysis
    - Carbon equivalent, $E_e = C + \frac{Mn}{6} + \frac{(Ni+Cu)}{15} + \frac{(Cr+Mo+V)}{5}$, suitable for welding at room temperature if $E_e$ less than 0.40. Valid for C-steel, C-Mn-steel and micro alloyed steel.
  - Heat input (welding parameters)
  - Degree of restraint of the items being joined (type of joint), firm restraint often need pre heat
  - Hydrogen content (welding method and filler material)
    - Combined thickness, $t < 10$ mm → rarely needs pre heating

- Again, specified in the WPS!
WHAT TO AVOID DURING WELD REPAIR?

CRACKING MECHANISMS

- Hot cracking
  - Solidification cracking (weld metal)
  - Liquidation cracking (segregation within the base material, heat affected zone “HAZ”)
  - Ductility dip cracking (mostly Ni-alloys)
- Cold cracking
  - Hardening crack
  - Hydrogen assisted cracking
  - Stress corrosion cracking
- Others
  - Relaxation cracking
  - Stress relief cracking
  - Typ IV cracking

Ref: Keith Packard, voestalpine, AWS Education conference, September 2017
CRACKING MECHANISMS

HOT CRACKING

• Depending on
  - Chemical analysis
  - Microstructure
  - Stress

• Countermeasure
  - Controlled heat input to slow cooling rates
    (Increase voltage, decrease speed and current)
  - Impurities as P, S, B, Nb, Ti and Si should be
    minimized
  - Clean weld joint
  - Weld bead/Joint geometry to minimize joint stress
  - Reduce level of residual and external stresses

Ref: Mechanism behind formation of a hot crack according to Arata et al.
CRACKING MECHANISMS

HOT CRACKING - IMPACT OF WELD BEAD GEOMETRY

Ref: Keith Packard, voestalpine, AWS Education conference, September 2017
CRACKING MECHANISMS

HOT CRACKING SANICRO 53 (ALLOY 617, ERNiCrCoMo-1, SNi 6617)
CRACKING MECHANISMS

COLD CRACKING

• Depending on
  − Microstructure, Stress and Hydrogen
• Cracking occurs after a couple of hours or days
• Countermeasures
  − Reduce Possible hydrogen sources:
    • Low Hydrogen Welding consumables
    • Base material
    • Residual Oil, liquid, etc on surface after weld seam preparation or NDT
  − Control Humidity
  − Preheating and controlled interpass temperature to minimize Hydrogen content (Hydrogen diffusion effective at \( T > 150^\circ C \))
  − Control Internal and external stresses
  − PWHT above 740°C is necessary to avoid SCC
CRACKING MECHANISMS

STRUCTURE STABILITY DUPLEX STAINLESS STEEL (DSS)

- Structure stability decreases with increasing alloy content (Cr, Mo, W etc.)
- Sensitive temperature range
  - Austenitic, 900 – 1050°C
  - Austenitic-Ferritic (DSS), 600 – 1000°C
- DSS steels are also prone to 475°C embrittlement
- Influences welding
  - Weldment more sensitive than base metal (wrought materials)
  - Good control of the heat input and interpass temperature

<table>
<thead>
<tr>
<th>Grade</th>
<th>UNS no.</th>
<th>Heat input [kJ/mm]</th>
<th>Interpass [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAF 2205</td>
<td>S32205</td>
<td>0.5 – 2.5</td>
<td>≤ 150</td>
</tr>
<tr>
<td>SAF 2507</td>
<td>S32570</td>
<td>0.2 – 1.5</td>
<td>≤ 150</td>
</tr>
<tr>
<td>SAF 2707HD</td>
<td>S32707</td>
<td>0.2 – 1.0</td>
<td>≤ 100</td>
</tr>
<tr>
<td>SAF 3207HD</td>
<td>S33207</td>
<td>0.2 – 1.0</td>
<td>≤ 50</td>
</tr>
</tbody>
</table>
## CRACKING MECHANISMS - SUMMARY

<table>
<thead>
<tr>
<th>Crack Type</th>
<th>Mechanism</th>
<th>Countermeasure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardening Cracking</td>
<td>High internal stresses due to martensite formation</td>
<td>Control of pre-heat and interpass temperature to influence cooling rate</td>
</tr>
<tr>
<td>Hydrogen assisted cracking (HAC) / Stress Corrosion Cracking (SSC)</td>
<td>Recombinaion H atoms in sensitive microstructure (martensite / bainite) exhibiting a high level of residual stresses</td>
<td>Moisture free environment, low hydrogen welding consumables, rebaking practice for flux and electrodes, DHT, immediate PWHT, stress free storage, heating above dew point, clean weld area</td>
</tr>
<tr>
<td>Hot Cracking</td>
<td>Formation of low melting phases (e.g. Nb or B containing phases) during welding. Crack occurs as a result of shrinkage stresses</td>
<td>Low heat input, clean weld area, control of impurity level of BM and welding consumables, minimization of residual stresses during welding, optimized bead geometry (flat or convex beads)</td>
</tr>
<tr>
<td>Relaxation Cracking / Stress Relief Cracking</td>
<td>Precipitation reaction during PWHT or service at elevated temperatures. High residual stresses do not allow relaxation processes. Weak grain boundaries</td>
<td>Control of heating rate during PWHT, Control level of impurities of base material and welding consumables. Control of preheat- and interpass temperature. Minimization of residual and external stresses. Multilayer technique with thin weld beads</td>
</tr>
<tr>
<td>Type IV Cracking</td>
<td>Softer microstructure in (FG) HAZ</td>
<td>Control of temperature during welding and PWHT</td>
</tr>
</tbody>
</table>

Ref: Keith Packard, voestalpine, AWS Education conference, September 2017
# TYPES OF FAILURES

## STAINLESS STEELS (SS) AND Ni-ALLOYS

<table>
<thead>
<tr>
<th>Type of defect</th>
<th>Common causes</th>
<th>Countermeasure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking</td>
<td>Dilution</td>
<td>Technique</td>
</tr>
<tr>
<td>Center of weld</td>
<td>Dilution</td>
<td>Technique</td>
</tr>
<tr>
<td>Across weld</td>
<td>Stress</td>
<td>Technique, Joint design</td>
</tr>
<tr>
<td>Along weld</td>
<td>Base metal composition</td>
<td>Chemistry, grain size</td>
</tr>
<tr>
<td><strong>Corrosion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>Alloy selection</td>
<td>Choose higher alloyed alloy</td>
</tr>
<tr>
<td>Pitting</td>
<td>Alloy selection</td>
<td>Choose higher alloyed alloy</td>
</tr>
<tr>
<td>Crevice</td>
<td>Design</td>
<td>Avoid crevices, clean-up</td>
</tr>
<tr>
<td>Stress corrosion cracking (SCC)</td>
<td>Alloy selection</td>
<td>Ferritic SS, Duplex SS</td>
</tr>
<tr>
<td>Carbide precipitation</td>
<td>Heat input (HI), alloy selection</td>
<td>Lower HI, stabilized Alloys</td>
</tr>
<tr>
<td>Galvanic</td>
<td>Design</td>
<td>Choose alloys closer in chemistry</td>
</tr>
</tbody>
</table>
MICROSTRUCTURE PHOTOS

STAINLESS STEELS AND Ni-ALLOYS

Standard 300 Series

Superaustenitics

400 Series

Duplex
**DISSIMILAR JOINING OF SS TO LOW ALLOY**

<table>
<thead>
<tr>
<th>Material</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>308</strong></td>
<td>Do not use since under alloyed, forms brittle welds due to formation of martensite → Risk of cracking!</td>
</tr>
<tr>
<td><strong>309 Type (24.13.L)</strong></td>
<td>Over alloyed to account for dilution.</td>
</tr>
<tr>
<td><strong>312 (29.9)</strong></td>
<td>Over alloyed to account for dilution. Avoid using for high temp. applications over 400°C.</td>
</tr>
<tr>
<td><strong>310 (25.20.L or C)</strong></td>
<td>Over alloyed to account for dilution. Good for high temp. applications over 400°C.</td>
</tr>
<tr>
<td><strong>Low alloy</strong></td>
<td>Do not use since forms brittle welds. High risk of cracking!</td>
</tr>
<tr>
<td><strong>Nickel</strong></td>
<td>Excellent for high temperature applications over 400°C.</td>
</tr>
</tbody>
</table>
DISSIMILAR JOINING OF SS TO Ni ALLOY

Ni alloy  Always use Ni alloy filler when joining stainless steel to Ni alloy.

Stainless steel  Do not use, forms crack sensitive welds. High risk of failure.
BEST WELDING PRACTICE – SS AND Ni ALLOYS

WELD REPAIR – WELDING HINTS

• Clean joint preps
  – Finish grind carbon arc preps to avoid carbon pickup
  – Remove all contamination
  – Beware of nitrogen in plasma cutting

• Avoid Narrow Joint Preps
  – Can cause lack of fusion

• Use Certified Materials
  – Some Stainless Steels are not weldable (machinable grades)
BEST WELDING PRACTICE – SS AND Ni ALLOYS

WELD REPAIR – REFILL OF DEFECT

• Defect to be rewelded by using GTAW (TIG), SMAW (MMA), or GMAW (MIG) methods.
• Respect recommended heat input and interpass temperature. Again, follow the WPS!
• Once refill has started, finalize without stopping for things other than interpass temperature.
• Use proper shielding gas
  – MIG avoid high CO₂ which increases carbon content. Typically Ar+2O₂ or CO₂
  – Pure Argon for TIG
  – Helium additions for alloys with poor weld puddle flow
• Use proper backing gas
  – Argon
  – Argon + Nitrogen
  – Nitrogen
BEST WELDING PRACTICE – SS AND Ni ALLOYS

SPECIAL ALLOYS WELDING TECHNIQUES TO AVOID CRACKS

• No preheat and PWHT needed
  – If necessary reduce stresses, perform solution annealing ~1100°C followed by water quenching
• Clean joint surfaces prior welding
• Always use filler metal
• Heat input – keep low, typical max 1 kJ/mm
  – Low thermal conductivity and high thermal expansion → increased risk of distortion
  – Keep stresses low → careful planning of your welding sequence!
  – Precipitation might occur in grain boundaries closest to the fusion line. Shrinkage stresses makes the grain boundaries open up resulting in micro fissures.
• Interpass temperature normally 100°C.
BEST WELDING PRACTICE – SS AND Ni ALLOYS

SPECIAL ALLOYS WELDING TECHNIQUES TO AVOID CRACKS

- If possible, 2 passes with a smaller diameter
- Convex weld bead
- Technique – Stringers, avoid dwell time, backfill craters
  - No weaving due to less control of heat input
- Always grind end craters
- No striking marks
- PW cleaning with pickling solutions or paste to restore the Cr-oxide layer
BEST WELDING PRACTICE – SS

WELD REPAIR – POST WELD CLEANING

Oxide layer on a weld with a chromium-depleted zone.

- Crack
- Chromium depleted zone
- Parent metal
- Oxide layer

Pitting potential

1. Pickling bath or pickling paste, HNO₃ + HF
2. Grinding with different grit sizes
3. Wire brush
4. Blasting

The efficiency of different post-weld cleaning processes.
EXAMPLE - Tube91/Pipe91 (X10CrMoVNb91)

PRE HEATING AND PWHT

• Martensitic Cr-steel with optimum balance of Nitrogen (N), Manganese (Mn), Nickel (Ni), Niobium (Nb) and Vanadium (V)
• Application - Power plants
  • Superheater and reheater tubes, headers and steam piping (main and hot reheat)
  • Excellent strength and creep properties up to 580-600°C. Reduced wall thickness compared to e.g. T22.
  • Higher resistance to thermal fatigue compared to standard steels and higher heat transfer and lower thermal expansion compared to austenitic steels
EXAMPLE - _Tube91/Pipe91 (X10CrMoVNb91)_

PRE HEATING AND PWHT

- **Welding challenges**
  - Somewhat easier to weld than X20…
  - Compared to base material, welding procedure must include heat treatment to reduce hardness, maintaining impact properties
  - Multiple welding technique
    - Preheat ~ 250°C
    - Welding ~ 250°C
    - After welding ~ < 100°C
  - PWHT 750-760°C
  - Thickness
    - < 80 mm, cooled down to RT
    - > 80 mm, limited to min 80°C

Ref: Vallourec & Mannesmann Tubes, 1999
EXAMPLE - Tube91/Pipe91 (X10CrMoVNb91)

PRE HEATING AND PWHT

- Dissimilar welding
  - T/P91 ---- T/P22 –
    - Both matching consumables can be used
    - Carbon diffuses from low Cr-steel to high Cr-steel during PWHT
    - Creep rupture strength is not affected
    - Ni alloy could be used
  - T/P91 ---- Austenitic stainless steel
    - Transition joint at the shop, buttering with Ni-alloy to T/P91 on one side followed by heat treatment
    - At site, T/P91 --- T/P91 welded with matching consumable followed by heat treatment locally
    - At site, buttered Ni-alloy --- Austenitic stainless steel welded with a Ni-alloy without any heat treatment
  - Thin wall T/P91 ---- Austenitic stainless steel
    - Ni-alloy consumable + PWHT at 760°C
    - Important that the austenitic stainless steel base material is stabilized or low carbon.
  - Thick wall T/P91 ---- Austenitic stainless steel
    - Buttering with Ni-alloy + PWHT
    - Welding to the austenitic stainless steel with a Ni-alloy, use multiple welding technique with low heat input to reduce stresses
EXAMPLE – DUPLEX STAINLESS STEEL

WELD REPAIR FLUE GAS RECIRCULATION FAN

- Duplex Stainless steel, 2205 (EN 1.4462)
- Stopped due to high vibrations, no sign of corrosion
- Weld repair initiated
  - No WPS from the supplier
  - Welding method: TIG
  - Welding consumable: ER2209
  - Shielding and backing gas: 100 % Ar
  - No pre heating or PWHT
  - Heat input: ~ 0.9 kJ/mm
  - Interpass temperature: max 150°C
  - Third party present
EXAMPLE – DUPLEX STAINLESS STEEL

WELD REPAIR FLUE GAS RECIRKULATION FAN

• Joint preparation
EXAMPLE – DUPLEX STAINLESS STEEL

WELD REPAIR FLUE GAS RECIRCULATION FAN

• Welding
  • Tack welding
  • Root bead from the “back side” by intermittent welding
  • Flipping of fan wheel
  • Grinding of root
  • Visual examination
  • 2nd and 3rd bead
EXAMPLE – DUPLEX STAINLESS STEEL

WELD REPAIR FLUE GAS RECIRCULATION FAN

• Welding
  • Interpass temperature checked regularly
EXAMPLE – DUPLEX STAINLESS STEEL

WELD REPAIR FLUE GAS RECIRKULATION FAN

• Post weld treatment
  • Pickling and passivation performed after below photos
WHAT TO THINK ABOUT DURING WELD REPAIR?

CARBON STEEL AND STAINLESS STEEL - SUMMARY

• How to act to get a satisfactory result?
  − Determine the grade you are working with
  − Ensure all of the defect is removed
  − Confirm welders are using the correct heat input. Again follow the WPS!
  − Preheats – to prevent hydrogen cracking are very important
  − Post weld treatment
  − Was it corrosion failure? Does the material need to be upgraded? (SS)

• What QC actions needed? Like NDT, third party etc.
  − Impact testing may be an additional requirement
  − Corrosion testing based on alloy group (SS)

• What is specially important to think about for rotating equipment?
  − Fatigue
  − Hardness of weld and HAZ
  − TIG dressing, HFMI “High Frequency Metal Impact” or peening of the weld toe
WHAT TO THINK ABOUT DURING WELDING

SANDVIK WELDING APP

• Currently in APP Store and Google Play
  − “Sandvik Welding”
• Included
  − Datasheets, products and applications
  − Welding guide
  − Troubleshooting problems
  − Cryogenics
  − Alloy selections chart
  − Shielding gas recommendations
  − Ferrite calculator
  − Heat input calculator
WHAT TO THINK ABOUT DURING WELDING

SANDVIK WELDING APP - FERRITE CALCULATOR

**Shaefller with filler metal**

**SELECT WELDING METHOD**
- TIG/GTAW

**Chemical Analysis**

**Material 1**
- Complete

**Material 2**
- Complete

**Filler Material**
- Complete

**SHOW RESULT**

**Nickel Equivalent (Material 1)**
- 9.6%

**Chromium Equivalent (Material 1)**
- 19.1%

**Nickel Equivalent (Material 2)**
- 9.2%
WHAT TO THINK ABOUT DURING WELDING

SANDVIK WELDING APP - SHIELDING THE WELD AND GRADE SELECTION

**Shielding the weld**

- **SELECT A MATERIAL GROUP**
  - Duplex stainless steels

- **SELECT A WELDING METHOD**
  - TIG/GTAW

- **SELECT A SANDVIK GRADE**
  - Sandvik 25.10.4.L

**OUR RECOMMENDATION**

- Shielding Gas: Ar + (1-2)% N₂
- All Shielding Gas: Ar / Ar + He / Ar + 30% He / (1-2)% N₂

He addition gives higher fluidity of the weld pool. N₂ addition can improve corrosion resistance and impact toughness.

**Grade selection**

- **SELECT A FIRST BASE METAL**
  - Carbon Steel

- **SELECT A SECOND BASE METAL**
  - 253MA

**OUR RECOMMENDATION**

- First Choice: Sandvik 22.12.HT
- Over Matching: Sandvik 29.9
Welding and Materials

Started February 2016

- Welding and material discussion forum focusing on stainless steel and nickel alloys.
- Publish a subject every week
  - Application specialists
  - Technical marketing and product specialists
- Nov-17; 1850 followers and increasing
QUESTIONS