Effect of welding on the Mechanical properties of weldments in grade 91 Creep resistant steel

International Conference on Space 2014 (ICS-2014)
12-14 November 2014
Islamabad – Pakistan

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UET Taxila,
With the name of Allah
the most HUMBLE and
BENEFICIENT
Introduction

- The creep resistant steel known as ASME/ASTM grade 91 or P91 has become a popular choice for steam plant in fossil power stations and oil refineries.

- Satisfactory performance of P91 steel is critically dependent upon obtaining the correct microstructure of tempered Martensitic steel.

- High Cr Martensitic steels have been considered as miracle steels for high temperature plant applications.

- Control of welding and PWHT parameters is critical
Current P(T)91 Usage

- Dramatic Domestic Increase of P91 usage in Last Several Years
- Use Mainly for Cogeneration
- Utility usage increasing for Repowering, Replacements & New Facilities
### Base Metal

#### Base Material Specifications

<table>
<thead>
<tr>
<th></th>
<th>P91</th>
<th>P92</th>
<th>E911</th>
<th>T23</th>
<th>T24</th>
<th>P122</th>
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<td>Cr</td>
<td>8.00-9.50</td>
<td>8.50-9.50</td>
<td>8.50-9.50</td>
<td>1.9-2.6</td>
<td>2.2-2.6</td>
<td>10.00-12.50</td>
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<td>-</td>
<td>&lt;0.50</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>Mo</td>
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<td>0.90-1.10</td>
<td>0.05-0.30</td>
<td>0.90-1.10</td>
<td>0.25-0.60</td>
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<td>W</td>
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<td>1.50-2.00</td>
<td>0.90-1.10</td>
<td>1.45-1.75</td>
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<td>Nb</td>
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<td>&lt;0.012</td>
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<td>B</td>
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<td>10-60ppm</td>
<td>-</td>
<td>5-60ppm</td>
<td>15-70ppm</td>
<td>&lt;0.005</td>
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Welding Process

Welding processes used in the fabrication of P91 steel are:

- Gas Tungsten Arc Welding (GTAW)
- Tungsten Inert Gas (TIG) welding
- Shielded Metal Arc Welding (SMAW)
- Manual Metal Arc (MMA) welding
- Submerged Arc Welding (SAW)
- Gas Metal Arc Welding (GMAW)
- Metal Inert Gas (MIG) welding

And also
- Flux Cored Arc Welding (FCAW)
Metallurgical Notch

- Consider different strengths as equivalent to different thickness.
- Change in strength equivalent to stress concentrating notch.
- Other properties such as creep strength and ductility and fatigue properties also vary.
- Position of weakest zone depends on metallurgy of weld and parent e.g. P91 type IV position is a metallurgical notch.
# Welding Consumables

<table>
<thead>
<tr>
<th>Method</th>
<th>P91</th>
<th>P92</th>
<th>E911</th>
<th>T23</th>
<th>T24</th>
<th>P122</th>
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<td>Chromet 92</td>
<td>Chromet 91W</td>
<td>Chromet 23</td>
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<td></td>
<td>E9015-B9</td>
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<td>Chromet 10MW</td>
<td>Chromet 23L</td>
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<td>9CrWV</td>
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<td>2CrMoWV</td>
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<td>ER90S-B9</td>
<td>*</td>
<td></td>
<td>*</td>
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<td><strong>FCAW</strong></td>
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<td>Supercore F92</td>
<td>Comet 10MW</td>
<td>Supercore F23</td>
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<tr>
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<td>*</td>
<td>*</td>
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<tr>
<td><strong>SAW</strong></td>
<td>Comet M91</td>
<td>9CrWV</td>
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<td>*</td>
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<tr>
<td></td>
<td>9CrMoV</td>
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<td>EB9</td>
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</table>

* No applicable National Standards.

Potential Patent Issues
Preheat & Interpass

- Preheat / interpass temperature range for P91 is 200-300°C (~390-570°F)
- Vallourec & Mannesmann Tubes recommend preheating and interpass temperatures around 250°C (480°F)
- Welding of thin wall tubes can be carried out at temperatures below 200°C (390°F)
- In Japan, interpass temperature 170-200°C to minimize risk of hot tearing
Preheat & Interpass
Preheat maintenance

Options for non-continuous welding works:

- Maintain preheat throughout
- Apply post-heat treatment if cooling partially completed
HAZ structures generated during welding of ferritic steels

Grain size variation under equilibrium conditions
After Welding (Before PWHT)

- Preheat temperature (200°C min.) is above the martensite finish temperature (Mf)
  - Martensite finish temperatures for P91 matching weld metals are in the range ~120-150°C
  - Nickel content of welding consumables is usually controlled in the range 0.4-1.0% (in Europe)
  - Work at ORNL has shown that when the %Ni is towards the upper limit, ~18% austenite is retained at 204°C (400°F)
  - AWS specification (2005): %Ni <0.8% (was <1.0%)

- After welding, it is necessary to drop the temperature in order to fully transform the retained austenite, typically down to below 80-100°C (if not cooling to ambient), before PWHT
  - P91 components up to a wall thickness of 80mm (3.15 inch) can be cooled down to room temperature
  - Heavy section forgings or castings must not be cooled below 80°C (176°F) to avoid cracking
Intermediate Heat treatment

- In Europe, it was noted that as-welded hardness of P91 weld metal is typically ~400 HV
  - ~100 HV less than the as-welded hardness of the widely-used

- Therefore, the risk of cold cracking is less for P91
  - Cooling to room temperature is possible without an intermediate heat treatment

- For further assurance against H-induced cold cracking, it is advisable to soak the weldment at the welding temperature before cooling to ambient
  - 250-300°C for 2-3 hours
  - Partial cool out to eliminate untransformed austenite before post-heat
SCC of As-Welded P91 components

- If there is a delay before PWHT, the combination of high hardness (~400-420 HV) and residual stress can potentially give rise to SCC in damp conditions.
- To combat the SCC risk, B&W specifies that the maximum hold time between welding and PWHT should be 14 days.
- According to V&M Tubes the storage period should not exceed one week.
- Recommend storage of as-welded P91 components in dry indoor conditions until PWHT has been performed.
- NDE should be performed before and after PWHT to demonstrate freedom from cracking.
SCC in P91
PWHT

- PWHT is mandatory regardless of the component wall thickness in order to reduce the hardness and improve the ductility and toughness of the weld/HAZ.

- Control of correct PWHT temperature and time is Critical.
Weld Heat Treatment Cycle for P91
PWHT

- Generally 750-760°C is the best PWHT for material P91

- Lower PWHT temperature can result in larger differences in the hardness between the Type IV position and the coarse grain HAZ and weld metal which adversely affects the strain accumulation in the soft Type IV region, increasing its susceptibility to creep failure.

- Higher PWHT can result in coarser precipitates and more rapid recovery of dislocation substructure, leading to drop in hardness and creep strength.
Effect of PWHT on Hardness of P91

- PWHT at 750°C
- Reduces hardness and scatter in WM
- Reduces hardness in HAZ
- Shows clear dip in Type IV region
- Increasing time and temperature reduce hardness
PWHT

- EN 1599 specifies PWHT at 750-770°C
- PWHT 704-760°C (1300-1400°F) was allowed by ASME
- Following recent revisions, PWHT range allowed by ASME now 730-775°C (1350-1425°F)
  - For P91, P92 and other CSEF steels
  - If the weld metal composition is known, then maximum PWHT limit increased to:
    - 790°C (1450°F) for 1.0<%(Ni+Mn)<1.5, or
    - 800°C (1470°F) for %(Ni+Mn)<1.0%
- American Welding Society (AWS) PWHT at 730-760°C (1346-1400°F)
- In practice, the PWHT temperature needs to be significantly higher than 730°C for weld metal tempering to take place within a reasonable period of time
Welding Issues — Industry Experience

P91 Welding Problems

- Hot cracking – known to be an occasional problem with GTAW, SMAW and SAW
  - Generally confined to weld craters - grind and re-fill
  - Some users specify Mn:S>50 as precaution

- Hydrogen-induced cold cracking has not been a significant problem for P91 – when preheat & hydrogen controls applied
  - Reflects good weldability that was designed into the alloy
  - Examples of cracking on cooling down partially completed welds

- Before PWHT, the ductility and toughness of untempered martensitic weld metal is low...
  - Risk of brittle fracture
  - May be susceptible to Stress Corrosion Cracking... if excessive delay between welding and PWHT
Welding Issues - PWHT

- Incorrect tempering during PWHT
  - Under-tempering (hard and brittle weld/HAZ)
  - Over-tempering (soft zones at welds)
  - Inter-critical heating, i.e. overheating above Ac1

- Problems arising from:
  - Incorrect selection of PWHT temperature
  - Poor temperature control (thermocouples in wrong locations; torch heating)
  - Excessive time at temperature

- Control of correct PWHT temperature & time is critical
Welding Issues - PWHT

- PWHT requirements:
  - Accurate temperature monitoring equipment
  - Properly calibrated thermocouples
  - Thermocouples in the correct locations

- Different component thicknesses present difficulties
  - Example: tube-to-header welds
Over-tempering during PWHT

- Soft spots at field welds in P91 piping
- Original microstructure in the HAZ was over-tempered, exhibiting some degradation of the tempered martensite and coarse carbides
- After 12,000 hours service, ferrite was found along the fusion line and creep cavities were present in the HAZ
P91 weld hardness limits

- Minimum hardness limit for P91 components entering service is generally considered to be ~190 HV to 200 HV
  - Considerable debate amongst P91 users about the lower limit (190 or 195 HV); ASME committee recently selected 196 HV
- According to ASTM standards, the maximum hardness limit for P91 parent material is 265 HV
- P91 weld metal (and coarse-grained HAZ) would be expected to have hardness of ~240-260 HV following PWHT at 750/760°C for 2 hours (Ref: V&M data book)
- Weld hardness for PWHT at 730°C (minimum allowed by ASME) for 2 hours would be ~280-290 HV (Ref: V&M data book)
- The limit of acceptability for welds depends upon the difference in hardness between the weld metal/CGHAZ and the weak Type IV region
  - The relative weakness of Type IV zone is worse for PWHT 730°C
P91 weld cracks types
Conclusion

The creeps resistant steel P91 has become a popular choice for steam plant in fossil power stations.

Due to the use in high temperature plant this steel have been considered a Miracle Steel.

It is also used in the petrochemical industries for such high temperature applications as distillation, cracking and hydro-treating units.
Thanks