Repair welding of HP40-Nb

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Abstract
A lot of trial and error is involved when it comes to repair welding of service exposed cast material like HP40-Nb. Depending on the source a lot of different weld repair strategies are proposed and applied. With this research project, the Belgian Welding Institute wanted to make a scientific bench mark when weld repair is needed. An assessment of the mechanical properties at room and service temperature is made. Recommendations are formulated to make safe and reliable repair welds in the future.

Background
Steam Cracking furnaces manufacture ethylene and related products by the pyrolytic conversion of a feedstock mixture of hydrocarbons and steam. The feedstock is passed at low pressure (0.2-0.5 MPa) and process temperatures of 788°-843°C [1]. The radiant section of some of these cracking furnaces operate at end-of-run tube metal temperatures up to 1150°C (outlet tubes). This is the practical upper limit for most of the fabricable, heat resistant alloys. During operation, a coke layer builds up inside the hotter sections of the coils and this coke has to be burned away during a de-coke operation at intervals of 20 to 50 days [1]. The result is that steam cracking is one of the most aggressive environments to which alloys can be exposed, and coils become damaged. This has repercussions on the weldability of the alloy.

Mechanisms which are detrimental for the weldability of service exposed centrifugal casted tubes are:
- oxidation;
- ageing;
- carburization;
- nitriding.

Oxidation
Furnace gases or process gases may cause the formation of a thick oxide scale on the surface. Oxide films interfere with welding by reducing the wettability of the base material by the molten weld metal. When not removed completely, they can contribute to incomplete fusion, slag and porosity defects and seriously impair weld quality. Where local oxidation has occurred, the damaged areas should be completely removed prior to repair welding.

Ageing
In the as-cast condition there is a network of primary carbides along grain boundaries, lying in a dentritic pattern. When in service at high temperature, a distribution of fine secondary carbides is formed in an intradendritic manner, at the same time primary carbides dissolve. During ageing the lamellar aspect disappears and carbides grow. This process is called ageing. Ageing of the material results in a loss of room temperature ductility for high carbon castings.

Carburization
Carburization means carbon enrichment and carbide formation from the inner diameter of the radiant tube (process gas side) The coil metal becomes carburized by contact with the coke and the feedstock.
Carbon pick up increases the metal volume resulting in internally induced stresses due to the difference between the expansion coefficient of the matrix and the carburized layer. Any appreciable increase in base metal carbon content due to carburization destroys the weldability of these steels. The material will crack when touched with the electric arc or with the heat of the torch.
In the carburised zone the thicker \( M_{23}C_6 \) carbides will transform to \( M_7C_3 \) carbides with the release of metal noted as small spots in the carbides. The room temperature ductility is further reduced and will become very low.

![Figure 2: Transformation of carbides](image)

Diffusion of carbon in heat resistant steels can be noted during metallographic examination as a wave front, which runs concentrically to the inner surface. This line is used as reference for the carburization depth.

During carburization a massive quantity of metal carbide is formed and the austenite is chromium depleted. The matrix in the carburized zone is enriched in nickel and nickel-iron alloy, and becomes ferro-magnetic, while the unaffected matrix closer to the outside wall is nonmagnetic. Magnetic inspection with a handheld magnet can be used to locate carburized zones. Several companies offer carburization meters based on magnetic principles (permeability, eddy current, etc.).

**Nitriding**

Above 1100°C nitriding respectively internal nitride formation occurs from the outer diameter of the radiant tube (flue gas side). Nitrogen penetrates through the oxide film and reacts with chromium, or other strong nitride formers like aluminium, by precipitation of nitrides.

![Figure 3: Carburization depth](image)

The changes in materials properties which are caused by carburization and nitriding are very similar. In both cases internal brittle particles are formed and the matrix is more or less depleted of chromium.

**Summary**

The lack of weldability is caused by the low ductility of high carbon castings after exposure to high temperatures, due to the formation of brittle carbides and or nitrides. This will result in cracks in the heat affected zone due to the shrinkage stresses and (high) restraint encountered during welding.

**Weld repair - general practices**

A lot of trial and error is involved when it comes to repair welding of service exposed cast materials and depending on the source [2,3,4,5] a lot of different weld repair strategies are proposed and applied.

Four methods are generally used to enhance weldability:
- solution annealing before welding;
- buttering;
- shot peening;
- high preheat temperatures during repair welding.

**Solution annealing**

For aged HP material, where the embrittlement is caused by the formation of secondary carbides, the original ductility can be restored by a high temperature solution annealing heat treatment at 1065°C during two hours [3]. With this heat treatment the secondary carbides are dissolved. After the heat treatment the component is welded at room temperature. Carburization and nitriding are metallurgically irreversible and the brittle particles formed can not be dissolved by a heat treatment.
Buttering

Buttering the face of a bevel on a low ductility casting reduces the chance of cracking in the heat affected zone, particularly when a nickel alloy filler can be used. The weld metal has higher ductility and is deposited under minimum restraint conditions. After buttering the bevel is remachined. The buttered weld layer is better able to absorb deformation when the butt weld solidifies. Closing layers should not be deposited on the base material and stay on the buttered weld metal. Buttering can be done at room or high temperature and is followed by room temperature welding.

Shot peening

Solution annealing and buttering are sometimes applied in combination with shot peening. This mechanical treatment can help where a large grain size exists. This is especially true for static casting fittings. Shot peening can be applied over bevels and adjacent areas to reduce the grain size (recrystallization). It can also be a powerful aid in reducing weld stresses. When performed it must be done after each bead while the bead is still hot. Only fill passes should be peened, never the root. The major problem with peening is that it is difficult to specify the amount of peening. A guide to an adequate force is that needed to give the weld bead a shot blast appearance [3].

High temperature welding

The last method to increase the ductility is welding at higher preheat temperatures, which also reduces the stresses during welding, by reducing the thermal shock caused by welding. This method was evaluated within this project for repair welding of HP40-Nb (GX40NiCrSiNb35-25) tubes. Hot tensile tests revealed that preheating above 600°C is necessary to restore the ductility in order to attempt crack-free repair welding [6].

Base material characterization

HP-alloys (25%Cr, 35%Ni) are fully austenitic and have replaced HK (25%Cr, 20%Ni) in many applications in petrochemical furnace tubing, due to the higher creep strength and better carburization resistance. With its higher strength, the tube wall of HP-Nb can be thinner and thermal stresses are reduced thereby helping to improve tube life.

The HP alloys contain between 0.30-0.50% carbon to form carbides which oppose metal deformation (creep) at high temperature. Creep strength depends on the distribution of fine, strong, and stable carbides. Unfortunately there is always a tendency for particles to coarsen during high temperature service. Thus there is a need to stabilize the fine dispersion of carbides. This has been achieved by modifying the HP composition by the addition of carbide-stabilizing elements such as molybdenum, tungsten or niobium with microalloys of titanium and zirconium to improve the creep strength in the high temperature range.

Within this project, HP40-Nb tubes, which have been in service in the radiant section of cracking furnaces, were delivered.

<table>
<thead>
<tr>
<th>Tube No.</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Nb</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>0.30</td>
<td>1.00</td>
<td>-</td>
<td>24.0</td>
<td>-</td>
<td>33.0</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>0.50</td>
<td>2.50</td>
<td>2.00</td>
<td>27.0</td>
<td>0.50</td>
<td>36.0</td>
<td>1.80</td>
<td></td>
</tr>
<tr>
<td>X1(X2)</td>
<td>0.35</td>
<td>1.77</td>
<td>0.98</td>
<td>23.3</td>
<td>0.22</td>
<td>34.6</td>
<td>1.09</td>
<td>0.12</td>
</tr>
<tr>
<td>XT</td>
<td>0.60</td>
<td>1.70</td>
<td>1.23</td>
<td>24.8</td>
<td>0.15</td>
<td>33.2</td>
<td>1.00</td>
<td>0.08</td>
</tr>
<tr>
<td>XB</td>
<td>0.39</td>
<td>1.53</td>
<td>1.23</td>
<td>23.8</td>
<td>0.03</td>
<td>33.7</td>
<td>0.96</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Cast high carbon austenitic stainless steel furnace tubes exhibit relatively low ductility when they are new. The minimum requirement of 8% elongation for HP40-Nb alloy is seldom exceeded by more than a few percent. After exposure to service, ductility drops drastically to values below 4% due to ageing.

When the tubes are carburized the ductility is further reduced. Metallographic examination revealed that the tube designated XT was only locally carburized to a limited depth, although the outer wall surface was fully magnetic. No needles due to nitride formation were observed subsurface at the outer diameter. Magnetism could be attributed to the thick oxide scale on the outer surface. The tube XB was heavily carburized with a carburization depth which extended over 50% off the wall thickness.

![Figure 5: Increase in ductility after ageing [6]](image-url)
It must be noted that carburized metal no longer makes a significant contribution to the tube strength. The tubes X1 and X2 were not carburized.

### TABLE 2: DAMAGE AND MECHANICAL PROPERTIES OF THE DELIVERED TUBES

<table>
<thead>
<tr>
<th>Tube No.</th>
<th>Damage level</th>
<th>$R_m$ (MPa)</th>
<th>$\Delta \varepsilon$ (%)</th>
<th>$K\varepsilon_{50}$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin material acc. EN10295</td>
<td></td>
<td>Min. 440</td>
<td>Min. 8</td>
<td>-</td>
</tr>
<tr>
<td>X1</td>
<td>Non carburized</td>
<td>633</td>
<td>2.9</td>
<td>1.8/1.6/1.8</td>
</tr>
<tr>
<td>X2</td>
<td>Non carburized</td>
<td>625</td>
<td>3.9</td>
<td>2.0/2.4/2.0</td>
</tr>
<tr>
<td>XT</td>
<td>Locally carburized Thick oxide layer</td>
<td>430</td>
<td>0.9</td>
<td>1.6/1.7/1.8</td>
</tr>
<tr>
<td>XB</td>
<td>Heavily carburized Rupture in screw thread</td>
<td></td>
<td></td>
<td>1.0, 2.4/2.5</td>
</tr>
</tbody>
</table>

**Repair welds – tube to tube**

**Weld procedures**

The welding processes used were GTAW and SMAW using matching filler metal.

### TABLE 3: CHEMICAL COMPOSITION UTP FILLER METALS ACCORDING DATASHEETS

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Nb</th>
<th>Ti</th>
<th>Zr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1.0</td>
<td>1.7</td>
<td>25.5</td>
<td>35.5</td>
<td>1.2</td>
<td>+</td>
<td>+</td>
<td>balance</td>
</tr>
</tbody>
</table>

**GTAW - UTPA2535Nb - Ø 2.4 mm**

**SMAW - UTP2535Nb - Ø 2.5 mm**

Two girth welds were realized in each tube and all tubes were welded in the PC position to have a joint corresponding to usual practice with similar properties in the whole girth weld. The bevel was a V-joint with an angle of 35°±5°.

The TIG joints were preheated at 300°C with gas burner. Girth welds welded with covered electrodes where preheated at min. 600 °C with thermal mats. Although put in practice by some constructors, TIG welding at this high preheat was not performed. The workload for the welders is very hard at this high preheat temperature. Disadvantages for the SMA welding process are the slag at the inside which can not be removed, and must be removed between the layers, and the limited accessibility during welding. Low preheat is recommended.

The welding parameters are summarized in the table below:

### TABLE 4: WELDING PARAMETERS

<table>
<thead>
<tr>
<th>Tube No.</th>
<th>Layers</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Heat Input (kJ/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTAW, preheating at 300°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2</td>
<td>1</td>
<td>96-103</td>
<td>11.9-12.2</td>
<td>14.6-14.7</td>
</tr>
<tr>
<td>OD118 x wt 8 mm</td>
<td>Up to 4</td>
<td>98-133</td>
<td>12.4 - 13.1</td>
<td>10.0 - 13.8</td>
</tr>
<tr>
<td>SMAW, preheating at 600°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2</td>
<td>1</td>
<td>42.0-42.3</td>
<td>22.8-23.2</td>
<td>-</td>
</tr>
<tr>
<td>OD118 x wt 8 mm</td>
<td>Up to 5-6</td>
<td>46.1-53.1</td>
<td>21.8-22.7</td>
<td>4.0-6.6</td>
</tr>
<tr>
<td>XT</td>
<td>1</td>
<td>40.0-51.0</td>
<td>21.0-23.0</td>
<td>-</td>
</tr>
<tr>
<td>OD118 x wt 10 mm</td>
<td>Up to 6</td>
<td>56.0-73.0</td>
<td>21.0-25.0</td>
<td>-</td>
</tr>
<tr>
<td>XB</td>
<td>1</td>
<td>35.0-50.0</td>
<td>21.0-24.0</td>
<td>-</td>
</tr>
<tr>
<td>OD114 x wt 7 mm</td>
<td>Up to 3</td>
<td>55.0-57.0</td>
<td>21.0-24.0</td>
<td>5.0-7.5</td>
</tr>
</tbody>
</table>

**Non-destructive examination**

Visual examination, radiographic and penetrant testing of the repair welded tubes revealed neither hot cracks in the weld metal, nor cracks in the heat affected zone. Only some minor cracks could be found near the welded joint due to arc striking.

**Figure 6: Macro/micro of girth weld in Tube No. X2**

**Macroscopic and microscopic examination**

No welding defects were found in the girth welds from the non-carburized tubes X1, X2 and the locally carburized tube XT, where both girth welds were located in non-carburized zones.
Macrographs of the heavily carburized tube XB show that the carburization depth (indicated by white arrow) of a tube can be very local, which is caused by local failure of the protective oxide scale at the inside of the tube. No welding defects were found in macro No.1.

In the second macro, an accumulation of carbon was found in the weld metal due to dilution with the carburized base material (left side). On the other side the base material was fully carburized and creep cavities were found in the heat affected zone (right side), which were enhanced by the electric arc during welding. It must be noted that the tube XB was a piece of a tube which cracked in service. This corresponds with what was found in literature, that creep damage normally starts at the inner third section of the wall thickness where thermal and hoop stresses have a combined peak [7, 8].

No sigma-phase was found after welding at preheat temperatures of 600°C. This strokes with was found in literature, i.e. that HP40-Nb does not suffer from the formation of sigma-phase [9,10]. Sigma is an intermetallic, brittle FeCr-phase which can be formed in austenitic Cr-Ni-Fe steels between 450°-850°C. It can also contain Ni, Mo, Mn and Si. If it occurs, in austenitic Cr-Ni-Fe steels, like for HK40, the sigma phase will only be formed after a very long term exposure in the sensitive temperature range. In austenitic weld metal that contains ferrite, the sigma-phase will be more easily formed. This is not the case for the matching UTP filler metal, which remains fully austenitic after welding.

**Mechanical properties at room temperature**

Tensile specimens and bend specimens, with a former corresponding to a strain of 8%, broke outside the weld metal. The impact toughness in the weld metal was low, but higher than the service exposed base material. So it can be concluded that the repairs were successful with respect to the room temperature mechanical properties.

<table>
<thead>
<tr>
<th>Tube No.</th>
<th>$R_m$ (MPa)</th>
<th>Fracture location</th>
<th>$K_{V50/5}$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>454/411</td>
<td>BM</td>
<td>6.8/6.0/6.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BM</td>
<td>2.4/2.8/2.8</td>
</tr>
<tr>
<td>X2</td>
<td>456/518</td>
<td>BM</td>
<td>4.8/4.2/4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HAZ:</td>
<td>3.4/2.6/2.4</td>
</tr>
<tr>
<td>XT</td>
<td>280/265</td>
<td>BM</td>
<td>6.2/6.9/5.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FL:</td>
<td>2.8/4.2/2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HAZ:</td>
<td>1.0/1.2/1.2</td>
</tr>
<tr>
<td>XB</td>
<td>354/314</td>
<td>BM</td>
<td>3.8/4.8/6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FL:</td>
<td>1.8/1.6/2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HAZ:</td>
<td>1.6/2.2/1.2</td>
</tr>
</tbody>
</table>
Mechanical properties at high temperature

Uniaxial stress rupture tests were performed on the service exposed base materials and welded joints at temperatures between 950°-1050°C and different stress levels i.e. 15, 30, 45 MPa. Crossweld specimens were removed from the welded joints. The following could be concluded from the stress rupture tests:

- The welded joints will show lower creep strength compared to the service exposed base materials at low stress levels experienced in service.

![Figure 11: Creep strength of filler metals](image)

- The GTA weld has substantially better stress rupture properties than those made by SMAW.

- Rupture occurred in the HAZ with secondary cracks on the opposite side of the weld metal when the GTA welding process was used. For the SMA welded joint, the rupture was located in the weaker weld metal.

![Figure 12: Rupture and secondary cracks in HAZ](image)

![Figure 13: Rupture in weld metal](image)

Service exposed repair welds - tube to fitting

Owing to their sometimes large grain size, initiated during the casting process and consequent risk of cracking, it is not recommended to weld directly onto an aged cast fitting. It is preferred to leave a section of tube of at least 100 mm of old tube attached to the fitting and weld to this. The exact length is not important and will depend on the tube condition and accessibility. Care should be taken to choose an area where the tube is not unduly deformed or oval as this will present alignment problems. If this is not possible preheating above 600°C could be the solution.

High temperature welding has been successfully applied between HP-Mo tubes and cast fittings, both with large grain size, in an ethylene furnace. The filler metal used was an HP alloy modified with niobium. These repair welds have been in service. After removal, no damage was found and the repair welds still had an acceptable strength at room and high temperature.

![Figure 14: Service exposed repair welds - tube to fitting](image)

<table>
<thead>
<tr>
<th>TABLE 6: CHEMICAL COMPOSITION OF THE FITTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>0.41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 7: MECHANICAL PROPERTIES OF THE JOINT TUBE-FITTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. (°C)</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>RT</td>
</tr>
</tbody>
</table>
Residual life of repair welds

Matching filler metals are preferred above Ni-based welding consumables for repair welding of centrifugal cast tubes because of the latter’s lower creep strength.

Operating parameters (temperature, stress) and the coil replacement strategy (breakdown, fixed age) determine which nickel base filler metal can be safely applied. Best alternative to the use of matching filler metal at operating conditions in the radiant section of cracking furnaces could be alloy 617 consumable (ENiCrCoMo-1), which is developed for applications up to 1000°C. It has the highest creep strength and carburization resistance among the nickel-base alloys. This filler metal was not used within the scope of this project. The other nickel-base weld consumables ENiCrFe-2, or better ENiCrMo-3, could be an alternative in the lower temperature range, but at higher metal temperatures replacement of the repaired tube or (part of) the coil is considered necessary in the near future because of the lower creep strength of these welds.

Since the stress rupture strength of welds is lower than the casting, where practical, welds should be located in areas of lower stress and away from corners or notches.

Using nickel base filler metal also increases stresses when the repair welds are put in to service due to:
- difference in thermal expansion coefficient;
- weld defects (lack of penetration, …). At a preheat temperature of 600°C the weld pool of a nickel base filler metal is harder to control due to the low viscosity of the filler metal.

It must be remarked that accelerated creep testing of ex-service material is not suited to determine the remnant life of pyrolysis coils, because the relevant failure mechanisms can not be taken into account by a simple creep test. The two main failure mechanisms for radiant tubes [11] are the combined action of carburization and creep ductility exhaustion, and brittle failures during furnace trips. The first mechanism results in bulging, bending, ovalization of the tubes and a short longitudinal crack. The second mechanism results in large longitudinal cracks, which “ends” in a fork-like appearance.

Cracked tubes are damaged beyond repair. Severe creep deformation, causing alignment problems, may make repair welding impossible and repair is no longer recommended. A fully carburized tube can have a remnant life of 1-2 years (if no furnace trip occurs) [11]. Repair welding is not recommended when the carburization depth extends over 50% from the wall thickness or the carbon level in the inside diameter of the tube is above 1.5% [4].
Conclusions:

Repair welding of aged, casted HP40-Nb material can often add years of life if proper procedures are followed.

Two weld procedures for high temperature repair welding of aged HP40-Nb material were developed:

- Non carburized HP40-Nb tubes can be repaired using the GTA welding process and preheating at 300°C. GTAW, requires gas backing, but is preferred above SMAW because of the higher creep strength, no slag and good accessibility during welding.

- For carburized HP40-Nb tubes, preheating above 600°C, requiring SMA welding, is necessary to restore the ductility in order to be able to perform crack-free repair welding.

Magnetic inspection using a hand held magnet can be used to locate carburized zones. When the matrix becomes ferromagnetic, although not necessarily indicating that the matrix is carburized, welding problems are likely and preheating above 600°C should be applied. Preheating at 600°C is also recommended for the repair welding of thick static castings, where a large grain size may exist. In the other cases repair welding can be attempted using the TIG welding procedure.

With respect to residual service life of the repaired tubes, matching filler metal is recommended above nickel-base welding consumables.

Repair welding under high preheating conditions should be performed by experienced welders only.

Acknowledgements

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