In-line Seam Heat Treatment Technology

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Abstract
The use of longitudinal seam-welded line pipe produced in continuous welding lines has increased in recent years. These pipes must apply to different standards, like API, ISO, DnV, etc. The trends are that the wall thicknesses of the pipes have increased and the materials used have set new demands on the heat treating process. Understanding the dynamics of the seam normalizing process and processes with intermediate quenching, during heating and cooling is, therefore, important in order to meet the different requirements. Process parameters like heating length/time, frequency and coil design, among others, all play a role on the final result. In the design, we use 2D finite element computations to investigate the influence of the process parameters. In addition, we have investigated the importance of positioning the heat treating coils correctly with regard to the weld seam. In our lab, we have run off-line tests on small samples following curves for heat-up, holding and cooling to simulate the heat treating process for outer and inner portions of the weld. A setup is tested with a short section of a pipe where a fixed coil is energized to simulate the heat treatment the pipe would receive passing through the different process stages. Finally we present results from a running line.

1. Introduction
During high frequency welding (HFW), the walls in the vee are heated and pressed together causing hot material and oxides to be squeezed out of the weld forming the beads. Material on the outer and inner sides of the pipe wall experiences the highest temperatures during welding that give the HAZ its characteristic hour-glass shape. The high temperatures also cause grain growth. Because the HFW process is fast, the heated zones are relatively narrow giving high cooling rate. The result is microstructures in HAZ with changed tensile properties and reduced impact strength compared with that of the base material. The purpose of the seam heat treatment is to re-establish tensile properties equal to that of the base material and to secure the required impact strength.

Modern HSLA steels have got part of their strength from small grain size - the only strength mechanism that contributes positively to both strength and toughness. Higher grades have smaller grain size than is obtainable in a normalizing heat treatment. Therefore, it can be necessary for higher grades of pipes to go to more complex heat treatment processes than the traditional normalizing-like processes. It is called normalizing-like because normalizing means heating above $A_C$ temperature and cooling in air. For in-line seam heat treatment, the colder part of the pipe acts as a heat sink. The cooling rate is, therefore, first of all a result of internal heat conduction in the pipe.

Figure 1 Picture of seam annealing process
A proper seam heat treatment must secure a heated zone with the correct normalizing temperature, with sufficient small temperature difference from outside to inside. In addition the required width at the inside must cover the entire HAZ. Cooling rate depends on the heated zone width and it influences the transformed microstructure and the required cooling length before water quenching. The heated zone must be positioned accurately. In case of unsymmetrical stretching in the forming section, the tube twists and the weld moves along a helical path away from the 12 o'clock welding position.

2. Process

For the higher strength grades, the normalizing-like process is not able to re-establish the required tensile and impact properties of the HAZ. There are two processes used that have a quenching step after the first heating to austenitisation temperature.

2.1. NQT process (Austenitisation-Quenching-Tempering)

This is the most widely used solution. The temperature set point in the first heating section is set slightly higher than in the normalizing-like process. It is high enough for austenitisation and homogenization of the outside, as well as the inside part of the pipe wall, to take place. Grain growth is the limiting factor for maximum temperature. During quenching, the material fully transforms from austenite. The high cooling rate promotes fine grain structure. The micro structure differs at different depths due to a slowed down cooling rate at an increased distance from the quenched surface. The welding zone is then, in the next step, heated again to a temperature below $A_{C1}$ temperature for tempering and finally cooled naturally. The required cooling time or distance is shorter than for the normalizing-like process since no phase transformation is involved.

2.2. NQN process (Austenitisation-Quenching-Normalisation)

This process differs from NQT in the last process step. The temperature set point in the last step is above $A_{C3}$ but somewhat lower than in step one. The outside part of the wall will be fully transformed to austenite once more and obtain grain refinement. The micro structure is ferrite/pearlite all over. Natural cooling is required as for the normalizing-like process.

3. Numerical Analysis

We use FEM based numerical modelling tools to investigate the seam annealing process. The process is represented by a 2D cross-section. Coupled electromagnetic and thermal computations are used to analyze the process. To verify the computations' results a test was done on a tube that was split along its length. A simulation on the same coil and load setup was done and the results compared. There was good conformity between computed and measured values. Further details about model and measurements can be found in [1].

4. Parameters that influence the seam annealing process

4.1. Coil width and shape

When the coil is narrow compared with the wall thickness, the heated zone will have a shape that resembles a half-cylinder. The heat flow bends in tangential direction close to the inner surface. A narrow coil, therefore, requires longer heating time (zone length) than a wider coil, where the heat flow has a more radial direction in the required zone width at the inner surface.

Normally, one type of coil must cover a range of wall thicknesses. Coils with sufficient width to heat the largest wall thickness at minimized heating zone length create a wider zone and require more power than is necessary for the smaller wall thickness range. A wider heated zone gives better temperature homogeneity, which may also lower the maximum temperature for smaller wall thicknesses. The zone width also influences the cooling rate.
4.2. Frequency
At the start of the annealing process the temperature in the pipe is low. For normal frequencies used for this application, the current penetration depth is small compared with the wall thickness of the pipe as long as the temperatures are below the Curie temperature. This is due to the relative permeability of the steel. In the beginning, therefore, the heating of the inner side of the tube wall is by thermal conduction and the driving force is the temperature difference between the outer and inner sides. As the heating progresses, the surface passes Curie temperature and a region above this temperature gradually grows and moves towards the inner surface. Hence the penetration depth increases and heat starts to be generated closer to the inner surface. At the later stages of the process, when the over-Curie-temperature-region and the current penetration extends far into the pipe wall, there is an advantage of using a lower frequency. The large penetration depth at this stage makes it possible to get more energy into the pipe without overheating the surface. Simulation examples are shown in [1]. The ratio between over-Curie-temperature penetration depth and wall thickness influences the electric efficiency. In the frequency range used for this application, acoustic noise is a problem that has to be addressed.

4.3. Influence of increasing wall thickness.

Regardless of penetration depth, the magnetic field strength from the induction coil decreases with distance. The power density is, therefore, higher at the outside of the pipe than on the inside even at temperatures above Curie temperature. Figure 2 illustrates the power density in the tube at the beginning (below Curie temperature) and at the end of the heating process.

Figure 3 shows an illustration of how the heat is conducted in the pipe wall at a late stage of the heating process. It illustrates how the pipe acts as a heat zink for the heated zone. Phase transformation occurs at different times on the outside and inside of the wall due to the temperature difference. The energy needed for the transformation will delay the temperature equalization.

Heat losses from the inside surface of the pipe due to radiation and convection also contribute to the temperature difference between the inner and outer surfaces of the tube. This causes a stationary temperature difference that cannot be equalized by heat conduction. It starts to be significant for the higher wall thicknesses.
4.4. **Seam annealing section layout**

The result of weld seam heat treatment also depends on the layout of the seam annealing section. Often there can be limitations on available space in the line. Coil lengths and distances between the coils must be considered to get the best possible result. Necessary space needed for the pipe to cool down before the sizing section is another factor that has to be considered.

4.5. **Tracking**

It is common that the continuously welded tube twists after it is welded. Consequently, the weld seam is no longer in the 12 o'clock position when it arrives in the seam annealer and the coil has to follow its movement. This is called tracking. There are two types of tracking, horizontal and orbital.

A horizontal tracing system has a coil with a fixed minimum distance to the pipe's 12 o'clock position and can only be moved horizontally from this position. As a consequence, when the weld seam moves away from the 12 o'clock position, the coupling distance between weld seam and coil increases and its efficiency is reduced. Additionally, the coil is no longer symmetrically positioned relative to the tube.

Orbital tracking, when done correctly, keeps the coil in the same position relative to the weld seam when it moves away from the 12 o'clock position. Therefore, the heating is optimized at any position in the tracking range and no over sizing of the heated zone should be necessary.

5. **Thermal cycle simulation on samples**

For the thermal cycle simulation, test samples are taken as cut-outs perpendicular to the weld before any seam heat treatment. The sample width is small (about 10 mm) and is heated by induction from both sides so that the whole sample has relative homogenous temperature during the cycle. A thermocouple is welded to the sample near the HAZ to be used as feedback for the simulator and to record the sample's real temperature during the heat treatment. Simulations have been done for two temperature cycles that different parts of the weld experience: one sample for a position near the outer surface and another for a position near the inner surface. Treated samples can be used for microstructure examination, tensile and impact testing. Such types of off-line sample testing have some advantages and are particularly suited to the initial stage of testing:

1. Small material cost
2. Documented temperature cycle
3. Suitable for testing different heat treatment recipes and parameter studies

The shown example is material Q235 with a wall thickness of 17 mm. The following pictures show microstructure of a) untreated weld, b) cycle with a maximum temperature of 950°C to represent the portion near the outer surface and c) cycle with a maximum temperature 850°C to represent the portion near the inner surface.

The heating rate and cooling rate are calculated form a simulation to reflect realistic times at temperature.

![Figure 4. Microstructure of test samples](image-url)
6. **Heat cycle simulation on short length of full pipe**

The test object is a pipe with a length longer than one coil. On top of that pipe a coil is fixed that is of the same type and with the same distance coil-to-pipe as in a real line. This single coil is programmed to heat and dwell at a cycle that simulates the heating that a pipe experiences when passing under the row of coils in the real line. These tests give realistic heating conditions for a mid section of the pipe. Since it is a full pipe section, we also achieve realistic cool-down conditions. Due to the fixed setup, the temperature can be measured with thermocouples welded on both outside and inside surfaces.

Advantages with this setup are:
1. Relative low material cost
2. Documented temperature cycle
3. Testing of off-centered tracking positions
4. Verification of simulation results

![Figure 5 Test setup](image)

7. **Results from a running line**

Most important of all is, of course, how the seam annealing system works in real life. The process has to be fine tuned to achieve the best possible results and the process parameters for different sizes, and material grades must be found by tests in the line. A well-designed line is essential to give the producer the possibility to produce the desired pipes at the speeds and quality that they intend. In figure 6 we show the macrography and micrography of pipe produced at Baosteel's plant in Baoshan, Shanghai. The sample has the following characteristics.

<table>
<thead>
<tr>
<th>Steel Grade:</th>
<th>X 70</th>
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<tbody>
<tr>
<td>NQT process.</td>
<td></td>
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<tr>
<td>Wall thickness:</td>
<td>17,5 mm</td>
</tr>
<tr>
<td>OD:</td>
<td>559 mm</td>
</tr>
<tr>
<td>Induction welded</td>
<td></td>
</tr>
<tr>
<td>Welding frequency:</td>
<td>about 110 kHz</td>
</tr>
<tr>
<td>Line speed:</td>
<td>10 m/min</td>
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</tbody>
</table>

![Figure 6. Baosteel X70 test samples](image)
Table 1: Tensile test and Impact test:

<table>
<thead>
<tr>
<th></th>
<th>Position</th>
<th>Specimen dimension [mm]</th>
<th>Rt 0.5 [MPa]</th>
<th>Rm [MPa]</th>
<th>A [%]</th>
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</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>Pipe body</td>
<td>38.4</td>
<td>584</td>
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<td>32</td>
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<tr>
<td></td>
<td>Seam</td>
<td>17.49</td>
<td>586</td>
<td>647</td>
<td>30</td>
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<tr>
<td>Impact</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dimension &amp; Temperature</td>
<td></td>
<td>1 [J]</td>
<td>2 [J]</td>
<td>3 [J]</td>
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<tr>
<td></td>
<td>Pipe body</td>
<td></td>
<td>309</td>
<td>305</td>
<td>303</td>
</tr>
<tr>
<td></td>
<td>Seam</td>
<td>10<em>10</em>55 (mm)</td>
<td>149</td>
<td>206</td>
<td>260</td>
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<tr>
<td></td>
<td>HAZ</td>
<td>(-20°C)</td>
<td>238</td>
<td>291</td>
<td>264</td>
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</tbody>
</table>

8. Conclusion
There are several factors that influence the temperature difference between outside and inside of the pipe: power distribution at high and low temperature, coil width versus wall thickness, heating time (zone length) and inside thermal losses. In the last part of the zone, low frequency is beneficial.

The heating zone width is less on the inside. Exact tracking, therefore, is required so that the entire HAZ is properly treated. An optimized layout including the cooling zone is important to have the shortest possible process length and to reduce pipe at stops that is not properly heat treated. FEM based numerical modelling is a very useful tool for optimization and for describing the process dynamics.

Successful results from Baosteel’s Baoshan factory are shown.

References