TMCP – A Decade of Progress, Where Next?

Thermo-mechanical Controlled Processing (TMCP) – The role of Niobium

10th July 2013
The Royal Society

PRODUCTION OF HELICAL TWO STEP PIPE – USE OF MICROALLOYING ELEMENTS TO IMPROVE STRENGTH FOR GRADES UP TO X70 WITH SOUR SERVICE RESISTANCE

Franz Martin Knoop
Salzgitter Mannesmann Grossrohr GmbH
Djordje Mirkovic, Volker Flaxa
Salzgitter Mannesmann Forschung GmbH
Introduction

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• History
• Development programme
• Manufacturing issues relevant for sour service resistance
  • steel production
  • hot rolling
  • pipe production
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Salzgitter's research and development activities for HSAW-pipe

- extending pipe/coil wall thickness up to 25.4 mm for grades X70 and X80
- steel grades with high strength and excellent low temperature toughness
- **sour service resistant steel and pipe**
- enhancement of collapse resistance for shallow water off-shore applications
- use of FEM for simulation of pipe forming and welding
- reducing residual stresses in pipe and weld seam
- improving the strain capacity of pipes for strain based design requirements
- reduction of geometrical tolerances on steel and pipe
THE HISTORY AND DEVELOPMENT OF A NEW SOHIC TEST METHOD

Dr. Chris Fowler¹ and J. Malcolm Gray²

¹EXOVA Group, 182 Halesowen Road, Netherton, Dudley, West Midlands DY2 9PL, UK
²Microalloyed Steel Institute, 5100 Westheimer, Houston, Texas 77056, USA

Figure 1. Failure of Spiral Welded Pipe, Courtesy Shell Canada
History

Cooking recipe for sour service material

## Development programme

**Targeted pipe properties R&D and commercial projects**

<table>
<thead>
<tr>
<th>Project</th>
<th>Quantity (t)</th>
<th>Grade / Standard</th>
<th>w.th. (mm)</th>
<th>OD (mm)</th>
<th>YS (MPa)</th>
<th>TS (MPa)</th>
<th>CVN (J/cm²)</th>
<th>DWTT (% shear area)</th>
<th>HIC (base + weld) NACE TM248</th>
<th>SSC (base+weld) (4 point bend.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SZ X60</td>
<td>200</td>
<td>X60MS API 5L/ISO3183</td>
<td>14.0</td>
<td>1067</td>
<td>≥ 420</td>
<td>≥ 520</td>
<td>≥ 250; 0°C (base)</td>
<td>85 @ at -40°C</td>
<td>≤ 5</td>
<td>-</td>
</tr>
<tr>
<td>SZ X65</td>
<td>200</td>
<td>X65MS API 5L/ISO3183</td>
<td>14.1</td>
<td>813</td>
<td>≥ 450</td>
<td>≥ 535</td>
<td>≥ 300; 0°C (base)</td>
<td>85 @ at -40°C</td>
<td>≤ 5</td>
<td>-</td>
</tr>
<tr>
<td>SZ X70</td>
<td>200</td>
<td>X70MS API 5L/ISO3183</td>
<td>16.0</td>
<td>1016</td>
<td>≥ 485</td>
<td>≥ 570</td>
<td>≥ 300; 0°C (base)</td>
<td>85 @ at -40°C</td>
<td>≤ 5</td>
<td>-</td>
</tr>
</tbody>
</table>

| Grade 241 | 1000 | GR241 CSA_Z245.1-07 | 15.9       | 762 and 914 | ≥ 241    | ≥ 414    | ≥ 50; 0°C | not required | - | ≤ 15 | ≤ 5 | ≤ 2 | 80% AYS No crack |
| Grade 448 | 800  | GR448 CSA_Z245.1-07 | 13.7       | 1372    | ≥ 448    | ≥ 531    | ≥ 50; -18°C | 60 @ at -18°C | - | ≤ 15 | ≤ 5 | ≤ 2 | not required |

*(mechanical properties in hoop direction)*

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### Development programme

#### Chemical composition for R&D and commercial projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Purpose</th>
<th>C wt.%</th>
<th>Si wt.%</th>
<th>Mn wt.%</th>
<th>P ppmw</th>
<th>S ppmw</th>
<th>Al wt.%</th>
<th>Cu + Cr + Ni wt.%</th>
<th>Mo wt.%</th>
<th>Nb wt.%</th>
<th>CEV (IIW) wt.%</th>
<th>CEV (Pcm) wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SZ X60</td>
<td>R&amp;D</td>
<td>0.035</td>
<td>0.30</td>
<td>1.46</td>
<td>70</td>
<td>5</td>
<td>0.04</td>
<td>0.44</td>
<td>0.07</td>
<td>0.05</td>
<td>0.33</td>
<td>0.14</td>
</tr>
<tr>
<td>SZ X65</td>
<td>R&amp;D</td>
<td>0.038</td>
<td>0.28</td>
<td>1.37</td>
<td>80</td>
<td>7</td>
<td>0.04</td>
<td>0.86</td>
<td>0.04</td>
<td>0.05</td>
<td>0.36</td>
<td>0.14</td>
</tr>
<tr>
<td>SZ X70</td>
<td>R&amp;D</td>
<td>0.038</td>
<td>0.33</td>
<td>1.33</td>
<td>90</td>
<td>6</td>
<td>0.04</td>
<td>0.84</td>
<td>0.32</td>
<td>0.05</td>
<td>0.43</td>
<td>0.15</td>
</tr>
<tr>
<td>Grade 241</td>
<td>Commercial</td>
<td>0.041</td>
<td>0.23</td>
<td>1.14</td>
<td>95</td>
<td>4</td>
<td>0.04</td>
<td>0.23</td>
<td>0.004</td>
<td>0.02</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>Grade 448</td>
<td>Commercial</td>
<td>0.060</td>
<td>0.32</td>
<td>1.55</td>
<td>150</td>
<td>8</td>
<td>0.04</td>
<td>0.36</td>
<td>0.005</td>
<td>0.05</td>
<td>0.35</td>
<td>0.16</td>
</tr>
</tbody>
</table>

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Manufacturing issues relevant for sour service resistance

Production: Metallurgical process up to slab casting

1. Blast furnace
2. Hot-metal mixer
3. Desulphurization facility
4. BOF shop
5. Secondary metallurgy facilities
6. Continuous slab caster

High automatization level including close integration of steel plant control and supervision system with technical planning

slab thickness: 250 mm
Manufacturing issues relevant for sour service resistance

Steel plant: quality issues and measures

<table>
<thead>
<tr>
<th>Desired quality issues</th>
<th>Consistently applied Salzgitter’s measures to attain them</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow steel composition tolerances</td>
<td></td>
</tr>
<tr>
<td>High steel cleanliness</td>
<td></td>
</tr>
<tr>
<td>• lowering non-metal inclusions</td>
<td></td>
</tr>
<tr>
<td>( low [O] \text{total} )</td>
<td></td>
</tr>
<tr>
<td>• inclusion shape and size control</td>
<td></td>
</tr>
<tr>
<td>• low tramp element steel contents</td>
<td></td>
</tr>
<tr>
<td>( especially P and S )</td>
<td></td>
</tr>
<tr>
<td>• low H content</td>
<td></td>
</tr>
<tr>
<td>High slab centerline quality</td>
<td></td>
</tr>
<tr>
<td>• avoiding centerline segregation</td>
<td></td>
</tr>
<tr>
<td>(C, Mn, P)</td>
<td></td>
</tr>
<tr>
<td>Continuous composition control and adjustment</td>
<td></td>
</tr>
<tr>
<td>Secondary metallurgy and appropriate casting procedure</td>
<td></td>
</tr>
<tr>
<td>• gas stirring + caster with vertical section</td>
<td></td>
</tr>
<tr>
<td>• Ca – treatment for inclusion shape control</td>
<td></td>
</tr>
<tr>
<td>• vacuum degassing</td>
<td></td>
</tr>
<tr>
<td>Soft reduction at continuous slab caster</td>
<td></td>
</tr>
</tbody>
</table>
Steel cleanliness: non-metallic inclusions as HIC initiating sites

Example: insufficient ladle rinsing and unsuitable degassing

consistent application of LM refining measures to remove inclusions from the steel melt, such as:
⇒ bottom stirring with N₂ and Ar
⇒ use of tap hole slide gates for minimized slag carry over
⇒ optimized Ca-treatment with Ca-wire injection; high Ca recovery
⇒ optimized ladle rinsing procedure
⇒ use of argon shielded tundish for optimized flow pattern / inclusion removal
⇒ application of caster with 2.6 m long vertical section instead of bow casters
Slab centerline quality: segregation effects

Example: casting without dynamic soft reduction

consistent slab centerline quality optimization by application of Dynamic Soft Reduction
⇒ dynamic segment regulation (soft reduction), particularly at the point of final solidification
Manufacturing issues relevant for sour service resistance

Production: layout of Salzgitter’s hot strip mill

Reheating furnaces (4)

Slab sizing press

Roughing mill

Finishing train

Run-out table: Laminar cooling unit

Crop shear descaler

Descaler

<table>
<thead>
<tr>
<th>Slab thickness</th>
<th>= 250 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip thickness</td>
<td>= 1.5 - 25 mm</td>
</tr>
<tr>
<td>Strip width</td>
<td>= 900 - 2.000 mm</td>
</tr>
<tr>
<td>Strip length</td>
<td>= 100 - 2.000 m</td>
</tr>
</tbody>
</table>

One of the world’s most modern high performance hot strip mills
Manufacturing issues relevant for sour service resistance

Hot strip mill: quality issues and measures

Desired quality issues

- Narrow strip dimension tolerances
  - lowering of residual stresses in the pipe bodies and welds
- High strip surface quality
  - prevention of surface defects e.g. slivers, roll-ins
- Homogeneous strip temperature distribution
  - prevention of $\gamma \rightarrow \alpha$ transformation during the finishing
  - strip microstructure adjustment without undesirable phases

Consistently applied Salzgitter’s measures to attain them

- Continuous control and adjustment of rolling parameters
  - highly planar strip profile
  - highly desirable acicular ferrite microstructure along the strip length and across the strip width
- Precise temperature monitoring from furnace to coiler
  - PRECISE STRIP TEMPERATURE PREDICTION AND CONTROL
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Manufacturing issues relevant for sour service resistance

Hot strip mill: strip profile and temperature distribution

Example: two-phase finish rolling / undesirable phases at strip edge area

precise temperature monitoring and control in every process phase and section
⇒ to obtain fine-grain structure across the strip width
⇒ indispensable to prevent γ→α transformation already during the finishing
⇒ to prevent undesirable phases, such as martensite

Martensite also observed

NO HIC cracks observed !
Manufacturing issues relevant for sour service resistance

Pipe production: Helical seam Two Step (HTS) technology

\[ D = \frac{B}{\pi \cdot \sin \alpha} \]

Geometric dependence of pipe diameter (D) on run in angle (\(\alpha\)) and strip width.

- \(B = 1200 - 1500\) mm
- \(\alpha = 20 - 40^\circ\)
- \(D = f (B, \alpha)\)
- \(D = 610 - 1676\) mm

First step: pipe forming with continuous tack welding

Second step: inside and outside submerged arc welding

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<table>
<thead>
<tr>
<th>Desired quality issues</th>
<th>Consistently applied SZ’ measures to attain them</th>
</tr>
</thead>
<tbody>
<tr>
<td>controlled cold working</td>
<td>Quality controls and R&amp;D</td>
</tr>
<tr>
<td>• during coil straightening and pipe forming</td>
<td>• use of FEM simulation methods</td>
</tr>
<tr>
<td>• minimized springback</td>
<td>• consistent quality controls and recording of forming parameters</td>
</tr>
<tr>
<td>• optimized pre-bending of coil edges to avoid peaking and reducing local stress which might affect sour gas resistivity at weld area (SOHIC)</td>
<td>• continuous control of pipe geometry using a patented in-situ laser diameter control</td>
</tr>
<tr>
<td>no forming stresses during welding</td>
<td>• peaking below 0.8mm</td>
</tr>
<tr>
<td>maximum hardness of 248 HV</td>
<td>separating forming and welding by using the HTS –process</td>
</tr>
</tbody>
</table>

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Manufacturing issues relevant for sour service resistance

Pipe mill: reduction of residual stresses

Stress strain curves at different angles

Simulation of different forming strategies

Relative residual hoop stress as function of the curvature under load
Mechanical and corrosion test results

R&D sour service trials: SZ X65

<table>
<thead>
<tr>
<th>Coil Pipe</th>
<th>Type of samples &amp; direction</th>
<th>$R_{0.5}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>$R_{0.5}/R_m$</th>
<th>$A_{DIN}$ [%]</th>
<th>$A_{API}$ [%]</th>
<th>DWTT @ [-60°C]</th>
<th>CVN @ [-80°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip 30° [rect.]</td>
<td></td>
<td>528</td>
<td>581</td>
<td>0.91</td>
<td>24</td>
<td>39</td>
<td>93</td>
<td>382</td>
</tr>
<tr>
<td>Pipe hoop [rect.]</td>
<td></td>
<td>483</td>
<td>575</td>
<td>0.84</td>
<td>24</td>
<td>38</td>
<td>75</td>
<td>379</td>
</tr>
</tbody>
</table>

Targeted API X65 grade reached reliably; excellent low temperature toughness

**HIC**: 24 HIC specimens were tested

**Result**: mean CAR value ~0.1 %

**SSC (4-point-bending test)**: 9 specimens were tested at 85% of SMYS (383 MPa)

**Result**: no SSC cracks were observed

**Full ring test**: 72% of SMYS (323 MPa) for 720h in NACE TM0177 solution A

**Result**: No indications above threshold were found by ultrasonic examinations prior to and after the test

Very good sour gas resistivity
Targeted API X70 grade reached reliably; excellent low temperature toughness

**HIC:** 112 HIC specimens (base and weld) tested

**Result:** mean CAR value of 2.82 % (max. 13.1 %); mean average CAR value base material: 3.62%, mean CAR value for weld specimens: 1.16%

Very good sour gas resistivity, even for API X70 grade
Mechanical and corrosion test results

Commercial projects: GR448

Targeted GR448 grade reached reliably

**HIC:** 1 set for both base material and weld per heat were tested.

**Result:** mean CLR and CSR values of all samples 3.5 , 0.7 and 0.3 %, respectively

Good sour gas resistivity! (despite of relatively high C and Mn contents)

<table>
<thead>
<tr>
<th>Pipe</th>
<th>DWTT [% shear area]: average of 2 specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°C</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Excellent low temperature DWTT results
Summary and outlook

Summary

- Large diameter helical line pipe for sour service up to X70 has been successfully developed and produced.
- Critical parameters in steel production and hot rolling have been shown and their influence has been explained by means of examples.
- Well balanced microalloying and steel cleanliness has been achieved in industrial trials and commercial projects.
- All relevant process parameters during continuous casting and hot rolling were effectively controlled and adjusted to the used chemistry and microalloying.
- All necessary measures for the improvement of HIC and SSC resistance have been optimized and managed during spiral pipe forming and welding.
- Excellent mechanical properties (incl. low temperature toughness) and corrosion resistance have been achieved.
Next milestones are defined on basis of actual and future market needs

Growing interest for sour service resistant line pipe with heavy wall thickness up to 1” and grades up to X70 is expected

Technical solutions require further development
- on chemical composition of the base material,
- on welding consumables
- on further production parameters at each stage of production
- and on suitable equipment at each stage of production

Pipes with smaller diameters in the range of 26” and higher wall thickness (high cold forming degree) need further development