DEVELOPMENT OF
CO-X SEAMLESS COEXTRUDED CLAD PIPE FOR DEEP WATER OIL & GAS PRODUCTION APPLICATIONS
The choice of the CRA is generally determined by the strength of the steel backing with a corrosion resistant alloy (CRA). Clad metallurgically bonded pipes combine the mechanical strength of the CRA clad layer with the backing steel. The extrusion method involves combining carbon steel and the CRA and extruding the hollow to longer lengths. The thick wall carbon steel is machined and the CRA tubular is inserted into the bore to produce a tight fit. The CRA interface is also within the sour service requirements of API 5L. The selection of the CRA is also influenced by the welding and clad pipe production method and optimization of the corrosion resistance. Therefore, CRA layers meet the API 5L Table 1 chemical requirements of austenitic stainless steel ASTM A240 316L, nickel base ASTM B470 alloy 825 and ASTM B436 alloy 625 are ideal candidates depending on the severity of the service environment. The INCONEL® alloy 625 is used in corrosive and sour oil and gas production environments.

The clad pipe is produced by a seamless co-extrusion method with the ability to produce pipe from 6” to 30” (152.4 – 762mm) with wall thicknesses up to 3” (76mm) and in lengths of 20 to 50 (12 -15m). The clad metallurgically bonded pipes combine the mechanical strength of the steel backing with a corrosion resistant alloy layer to offer a reliable and low cost material solution.

Subsea oil and gas production presents significant material challenges and sour conditions provide major additional challenges when combined with high chlorides at high temperatures and pressures (HTHP). These conditions are becoming increasingly more common in new field developments. Traditionally, solid pipes in stainless steel or clad pipes produced from rolling and longitudinal seam welding of hot rolled clad plates and/or carbon steel pipes with weld overlays have been utilized for risers, flowlines, manifold and other subsea piping. However, with pressure and temperature increasing with the development of new ultra deep water oil and gas projects, pipes with smaller diameters and heavier wall (i.e. low D/t) have been required to manage the well design requirements.

For these smaller diameter pipes, standard methods of clad pipe production from clad plates and/or weld overlaying small bore seamless pipe in 12 meter lengths have become increasingly challenging, which can limit these production methods in meeting the increasing demand. To meet this challenge for supply of heavy wall, small bore pipes, a seamless coextruded clad pipe technology, Co-X, has been developed to overcome these design and production issues.

The seamless coextruded clad pipe production process developed by PCC is designed to meet the mechanical and corrosion properties required by industry standards API 5L and DNV OS F101.

Clad metallurgically bonded pipes combine the mechanical strength of the steel backing with a corrosion resistant alloy inner layer to offer a reliable and low cost material solution. The choice of the CRA generally being determined by the internal service production environment. Considerations include mechanical design, general corrosion, stress cracking resistance and hydrogen embrittlement. The backing steel is typically based on an API 5L grade X80 or X65 and is protected from the external environment by using coatings and/or cathodic protection.

The choice between metallurgically clad or mechanically lined pipes options can be determined by the mechanical design for static or dynamic riser components, fabricated pipe bends and complexity in girth welding2. Use of clad pipe in subsea risers can be a good solution to reduce the risk of corrosion fatigue cracks in dynamically loaded pipe, whereby corrosion defects could initiate a failure.

### RESULTS & DISCUSSION

#### INTRODUCTION

#### MECHANICAL PROPERTIES

The grade X65 carbon base material chemistries of the pipes are shown in Table 1. The product chemistries are within the limits set by API 5L and provide sufficient hardenability for thick section pipes. Table 2, shows the mechanical properties of the backg X65 carbon steel at room temperature for three of the alloys SS316L, INCOLOY® alloy 825® and the modified INCONEL® alloy 625® (625L). The high temperature extrusion characteristics of alloy 625 are not readily compatible with the clad seamless tube technology; therefore a modified variant was developed and the properties are compared with standard production material. The CRA layer has been removed prior to performing the tensile test and generally carried out in accordance with the API GLP and DNV FS101 specifications. Tensile tests have also been carried out at temperatures up to 350°F (177°C) to demonstrate the strength of the steel for high temperature flow line applications. The results show a small drop in yield strength of 7-8 percent, however even at higher temperatures the yield properties are at or just below the X65 property requirements.

#### Table 1. Average X65 steel chemistry of the backsting pipe

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>Carbon</th>
<th>Molybdenum</th>
<th>Silicon</th>
<th>Phosphorous</th>
<th>Potassium</th>
<th>Sulfur</th>
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</thead>
<tbody>
<tr>
<td>Yield</td>
<td>X65/316L</td>
<td>0.007</td>
<td>0.006</td>
<td>0.002</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>Tensile</td>
<td>X65/316L</td>
<td>66.4</td>
<td>87.4</td>
<td>82.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Table 2. Mechanical properties of backsting pipe

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>Temperature (°F)</th>
<th>Tension (ksi)</th>
<th>Total elongation</th>
<th>Tension (ksi)</th>
<th>Total elongation</th>
<th>Storage %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X65/316L</td>
<td>125°F (52°C)</td>
<td>35.0</td>
<td>25.4</td>
<td>28.8</td>
<td>-</td>
<td>65</td>
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<tr>
<td></td>
<td>X65/316L</td>
<td>250°F (121°C)</td>
<td>75.0</td>
<td>55.5</td>
<td>65.5</td>
<td>-</td>
<td>65</td>
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<tr>
<td></td>
<td>X65/316L</td>
<td>375°F (191°C)</td>
<td>125.0</td>
<td>85.5</td>
<td>95.5</td>
<td>-</td>
<td>65</td>
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<tr>
<td></td>
<td>X65/316L</td>
<td>475°F (246°C)</td>
<td>175.0</td>
<td>100.0</td>
<td>105.0</td>
<td>-</td>
<td>65</td>
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</tbody>
</table>

#### Table 3. Hardness traverse measurements across the wall thickness of the coextruded pipe

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>Hardness</th>
<th>Impact</th>
<th>Average Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X65/316L</td>
<td>131</td>
<td>135</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>X65/316L</td>
<td>132</td>
<td>134</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td>X65/316L</td>
<td>133</td>
<td>135</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td>X65/316L</td>
<td>134</td>
<td>136</td>
<td>135</td>
</tr>
</tbody>
</table>

#### Table 4. Sub-zero impact strength results on the backsting steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>Impact</th>
<th>Average Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X65/316L</td>
<td>13</td>
<td>13.5</td>
</tr>
<tr>
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</table>
**Microstructural Assessment of the Co-X Bond**

Figures 1 and 2 show the interface between the X65/ alloy 825 and X65 alloy 625L extrusions, respectively. The CRA layer is controlled within the required tolerance of ±0.25mm. Metallography on the test pipes show the base material exhibiting a fine grain tempered martensitic structure and the CRA cladding an equiaxed microstructure typical of annealed wrought austenitic material. No evidence of delamination at the bond interface has been found. The interface shows no signs of oxidation which could have affected the bond layer during the extrusion heating process. The diffusion of carbon into the nickel alloy CRA’s appears to be limited to approximately 50 microns (0.002”) depth with some Chromium carbide formation evident, however they have only formed as discrete and discontinuous particles along the interface.

Chemical analysis data on the X65/ alloy 625L extrusions are shown in table 5, including through thickness composition scans which demonstrates the co-extrusion process produces a CRA layer with minimal variation in composition or dilution effects through the substrate. EDS scans have also indicated a change from CRA to carbon steel composition over a distance of 50 microns, less than 2 percent of the total cladding thickness. The chemical composition of the CRA shows no evidence of dilution and has good homogeneity.

Figure 3 also shows a microhardness profile across the bond interface in the X65/ alloy 825. The hardness at the interface has been shown not to exceed about 200 Hv10. Evidence of dilution and has good homogeneity.

The Co-X bonded pipe has also been demonstrated to show excellent formability without showing and disbanding or cracking in the steel or at the CRA interface. Figure 4 shows an example of a Co-X pipe 10.75” OD x 0.984” wt in X65 steel with a 3mm thick CRA layer of austenitic stainless steel.

**Corrosion Testing**

Corrosion testing of the cladding alloy was performed to confirm that the pipe processing parameters and heat treatment steps maintain the corrosion resistance of the clad layer. The tests are designed to show the corrosion resistance of the CRA has been maintained and that the CRA layer is in the optimum condition. Table 5 shows the results of localized corrosion pitting tests using the ASTM G48® method. The CRA clad layer was removed from the pipe section by machining away the carbon steel prior to corrosion testing. These results also show that the alloy 825 cladding material achieves equivalent results to the solid base material in alloy 825 with the solid material and the alloy 825 clad layer having a critical pitting temperature of 30°C. The results on the alloy 625 solid and alloy 625L clad layer have critical pitting temperatures of >85°C and 80°C, respectively. The modifications to the alloy 625L and the processing having marginally influenced the localized corrosion resistance of the CRA layer compared with solid pipe material. Figure 5 shows the results comparing the CRA with the optimum corrosion acceptance properties typical of a solid pipe manufacture. Acceptance testing on a weld deposited overlay of alloy 625 on X65 steel is usually accepted with no pitting at 50°C.

Corrosion testing has also been carried out using the ferric sulphate/sulphuric acid ASTM A262 method B9 solution to examine for the materials susceptibility to intergranular corrosion. Table 6 shows the results on the alloy 825 and alloy 625L clad layer having a critical pitting temperature of >85°C and >80°C, respectively. The modifications to the alloy 625L and the processing having marginally influenced the localized corrosion resistance of the CRA layer compared with solid clad material. Figure 5 shows the results comparing the CRA with the optimum corrosion acceptance properties typical of a solid pipe manufacture. Acceptance testing on a weld deposited overlay of alloy 625 on X65 steel is usually accepted with no pitting at 50°C.
PIPE INSPECTION AND NON-DESTRUCTIVE EXAMINATION

Figure 6 shows an extruded pipe starting the pipe inspection operations. The Co-X pipes are all fully inspected using visual, dimensional and ultrasonic tests.

Figure 6. Inspection of the Co-X pipes

The pipe integrity is evaluated by ultrasonically testing 100% of the wall thickness using a shear wave with a 5 percent ID/OD notch per API 5L for defect detection. A longitudinal beam is used to assess the metallurgical bond between the base material and the cladding. No evidence of bond defects or defects in the backing steel have been detected. The CRA layer thickness is controlled within the ±0/+2mm tolerance required and the thickness has been confirmed by NDT inspection over the length of the pipe10. The NDT measurements have been confirmed by physical dimensional checks. Figure 7 shows examples of the clad pipe tested for longitudinal, transverse, delamination and disbonding defects.

Figure 7. Cross sections of the co-extruded pipe

The Co-X pipe has also been found to be capable of hot induction bending around a 3D former and maintain good control of the steel and CRA thickness. Figure 8 shows a pipe of 4.5” OD x 0.600” X65 with a 3mm 625L formed around a 3D former at 90 degrees. This capability of Co-X metallurgically bonded pipe is ideal for jumpers and gathering lines on subsea production manifolds.

Figure 8. Hot induction bond on a Co-X X65/625L pipe around a 90 degree 3D former

CONCLUSIONS

The seamless Co-X pipe is ideally suited to rapid production of heavy wall metallurgically bonded clad pipe suitable for static and dynamically loaded applications. The Wyman Gordon extrusion process can also provide an ID as well as OD dimensionally controlled pipe.

Control of the chemistry of the CRA layer optimizes the corrosion performance of the Co-X pipe.

Clad seamless pipes manufactured using the coextrusion method have been demonstrated to have good mechanical properties and toughness and meet or exceed the industry standard specifications.

The clad seamless production process has been shown to give excellent mechanical and corrosion performance.

The metallurgically bonded pipes can be fully inspected to ensure freedom from through wall defects and delamination at the CRA interface and to measure the steel and CRA thickness along the pipe length.

The clad seamless production process has been shown to give excellent mechanical and corrosion performance. Corrosion test results on the materials have demonstrated values very similar to pitting and intergranular attack corrosion resistance compared with the conventionally manufactured solid Nickel alloy.

Chemical analysis data including through thickness composition scans have shown how the co-extrusion process produces a CRA layer with minimal composition variation and negligible dilution from the substrate.

The alloy 625 has been successfully modified to make the material compatible with the X65 backing steel during the extrusion process. The corrosion resistance of the alloy 625L layer showed very high resistance to localized corrosion and intergranular attack.

REFERENCES

10. B. Chakravarti, H. White, PCC KLAD, internal report, July 2013
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The names that comprise PCC Energy Group have been on the forefront of the energy industry for decades. Backed by the strength and leadership of our Fortune 500 parent company, Precision Castparts Corp., our engineers and metallurgists work closely with the world’s most innovative energy companies to identify high-performance applications where we can help enhance operational performance.