

# Production of Large Diameter Clad Bends using Explosion Welded Alloy 625 Clad Plates

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## 1. Abstract

The goal of this development was to manufacture an induction bent pipe from explosion clad plate to qualify the explosion welding process for induction bent pipe applications and to investigate the economic, corrosion and mechanical advantages of explosion welded material for an induction bending application.

The clad plate was welded using the explosive welding process. The backing carbon steel plate was 19 mm (3/4") thick API 5L-X70M-PSL2 and was prepared by grinding the surface to remove any mill scale and rust. The corrosion resistant alloy (CRA) plate was 4.8 mm thick Alloy 625 and was prepared in two steps. The first step was to seam weld smaller plates to achieve the full width and length needed for the pipe. The second step was to surface grind the mating surfaces prior to assembly. The plates were assembled with a calculated gap between the base plate and CRA plate. The explosives were blended to match the metal properties and loaded on top of the CRA plate. The explosives were then ignited to bond the plates together. The welded plate was then flattened and trimmed to final size and delivered to the pipe manufacturer.

Subsequently the plate was formed by press bending using the JCO-process without any prior heat treatment. After forming, the pipe was submerged arc welded from inside and outside following standard DSAW pipe production. In addition, the inner submerged arc weld seam was clad with Alloy 625 by utilizing the resistant electro-slag (RES) welding process using special strip cladding nozzles. The mother pipe of OD 508 mm (20") x WT 19+5 mm (3/4"+1/5") x L 11,278 m (37') was finished calibrated to out-of-roundness below 2 mm (< 0.4%) over the entire length using external compression.

The bends were made by the hot induction bending process. With a pipe bending machine, a narrow section of the pipe is heated by using the electric induction process and subsequently bent while controlling the radius, heating temperature, cooling rate and bending speed. Only the bent area is exposed to the induction coil.

Each bend received a specific heat treatment to restore the mechanical properties (Carbon). The bends fully comply with the latest edition of ISO 15590-1, DNV-OS F101 and ASME B16.49 specification for hot induction bends.

In this study, mechanical testing, metallographic investigations and corrosion tests show that the discussed manufacturing route provides a reliable and economic way to produce clad bends. This can be accomplished without any risk of disbonding or cracking of the CRA layer while achieving good mechanical properties of the backing steel.

## **2. Introduction**

This development evaluates an alternate manufacturing option for clad induction bends. Existing options have challenges with high manufacturing costs, variability in quality, small quantity capability and/or long lead times. The desired result is to qualify explosion clad metal as an option that provides low manufacturing costs, short manufacturing time and lower risk of technical problems. This will provide a high quality and short lead time option that provides a smooth surface finish, consistent quality and no dilution of the clad metal. The primary market focus was API pipe grades using TMCP base metal and Alloy 625 cladding. This was chosen as it is the most demanding combination to create a good quality and ductile bond while maintaining properties in the clad alloy and base metal.

This paper covers the development process from the explosion cladding through rolling and welding and induction bending. At each stage the material properties were characterized and various options were investigated. Through this development process, the starting material properties can be correlated to the material properties in the end product. Data will be presented to support that API Grade TMCP steel clad with Alloy 625 using explosion welding can be successfully processed into clad induction bends with a radius of three diameters (3D).

## **3. The Cladding Process**

The explosion clad metal was manufactured by NobelClad.

Explosion welding, also called explosion cladding (Figure 1), is the most versatile clad plate manufacturing technology. It is a cold welding technology that produces very high bond strength between two metallic materials, even between materials that cannot be combined by conventional welding techniques. This welding technology is suitable for joining virtually any combination of common engineering metals. Explosion-welded clad metal is produced as flat plates or concentric cylinders which can be further formed and fabricated as needed. The dimensional capabilities of the process are broad; cladding metal layers can range from 0.25 mm to over 50 mm; base metal thickness, width and length dimensions are primarily limited by the size capabilities of the world's plate production mills and transportation limitations. Maximum width and length is approximately 5 m and 15 m, dependent upon alloy type and thickness. Explosion welding is used to clad a very broad range of metals including steel, aluminum, titanium, nickel alloys, stainless steels and exotic or precious metals.

## Explosion Welding Process

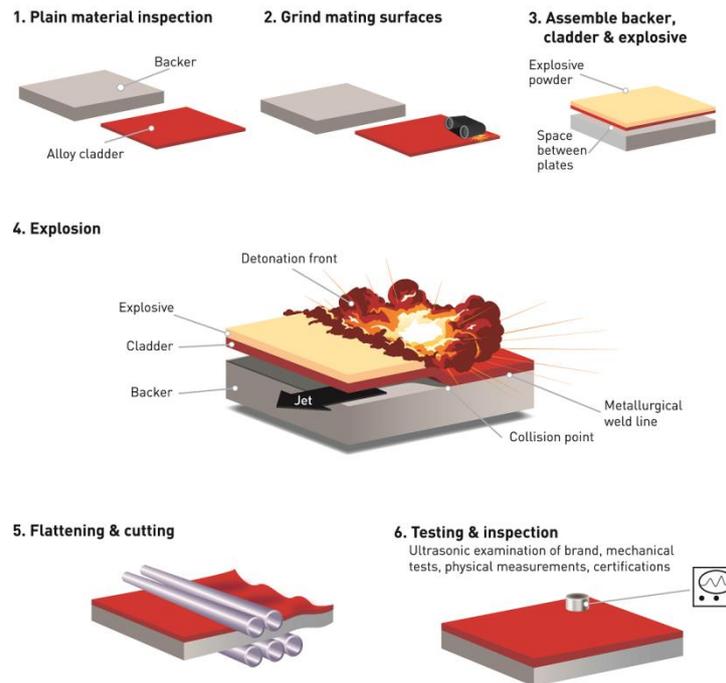


Figure 1: Schematic of the explosion welding process

Explosion welding was developed and commercialized in the 1960's. The explosion welding process produces a metallurgical weld between metal plates by harnessing the energy of an explosive detonation. The process creates a high-strength, ductile, metallurgical weld over the entire plate surface. Since the early 1960s the DETACLAD® process has provided a reliable, commercially viable solution for clad manufacture [1, 2]. Today there are well over 20 industrial producers of explosion clad plates worldwide with total annual production of approximately 300,000 tons.

### Explosion Welding: A Metallurgical Bond

Explosion welding (EXW) is accomplished by creating a high-velocity collision between two metal surfaces. The explosive detonation causes shock loading of one of the metals, the flyer plate, accelerating it downward, causing an oblique impact with the other metal, or backing plate. It is necessary that this impact has sufficient energy to cause the colliding metal surfaces to flow hydrodynamically. Upon impact, conservation of momentum results in a jetting action and hydrodynamic flow of the faying metal surfaces. The jet is ejected outward from the collision point removing oxides and impurities and forming perfect surfaces for the metallurgical bond. The residual virgin metal surfaces are then forced together under high pressure, resulting in a metallurgical weld.

The metallurgical phenomenon occurring during explosion welding has been studied for many years. The EXW interface has been characterized by using high magnification microscopes and high resolution techniques such as SEM coupling with X-ray, TEM and microhardness.

Most EXW products exhibit the characteristic wavy interface shown in Figure 2. However the morphology of an explosion weld can range from a flat interface to a highly turbulent wavy interface, depending upon the explosive detonation rate and energy. The formation of a wavy interface with limited melting is considered an indication that the bond was formed well within the acceptable process window for the given metal system.

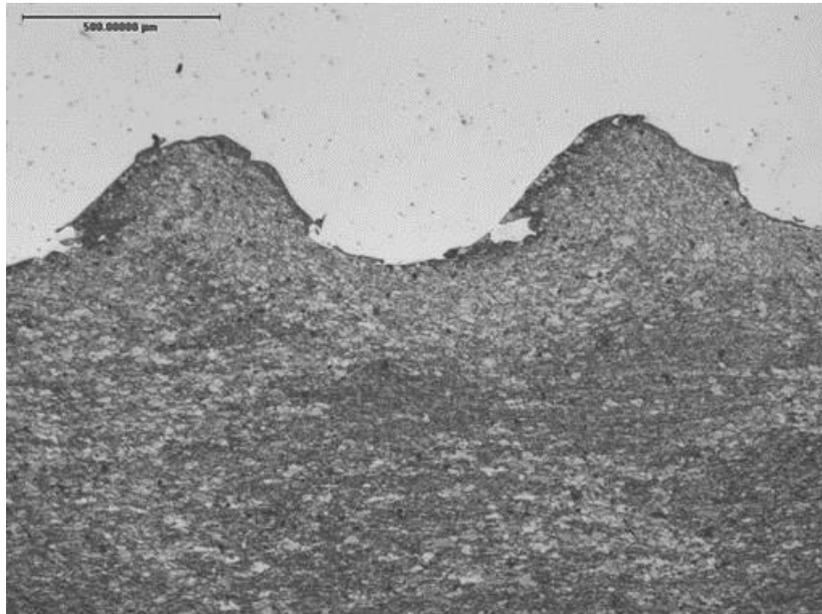


Figure 2: Typical interface achieved by the explosion welding process

TEM studies indicate that very significant heating occurs at the interface, but on a scale barely observable with optical microscopy. These TEM studies indicate the presence of a thin interface reaction layer, 20 – 200 nanometers thick. This layer appears to have been liquid at the time of formation, similar to a weld. Further, they report indications of an amorphous-like structure of the re-solidified weld metal. This finding suggests that the time at elevated temperature is extremely short and the cooling rates are extremely fast. The metals are heated to the welding conditions and returned to well below the melting point in less than 20 microseconds. The result is a metastable metallurgical condition at the interface. The deleterious phases which occur in most dissimilar metal fusion welds do not have time to form in explosion welds.

Because of the absence of heating, EXW products do not exhibit many of the metallurgical characteristics of fusion-welded, brazed or hot-rolled/forged products. Unlike those processes, in EXW:

- The component metals remain in their wrought states; continuous cast structures are not created.
- The microstructures and corrosion properties of the wrought cladding metal are not significantly altered.
- There are no bulk heat-affected zones.
- There is virtually no diffusion of alloying elements between components.
- The shear strength of explosion welded stainless and nickel alloy clad plates is 300 to 600 MPa, depending on the alloy (minimum strength required by ASTM SA 263 is 140 MPa). This interface is typically stronger than the weaker of the two parent materials.

- The bond tensile strength (through thickness strength or tear strength) of explosion clad metal is consistently greater than the bond shear strength.
- Explosion clad plates pass compression, tension and side bend tests as required by international pressure vessels codes. Figure 3 shows the result of the most demanding side bend test (ADW8).



Figure 3: Typical side bend test on explosion clad plate according to ADW8

Because the EXW process depends on hydrodynamic flow produced by a collision between the dissimilar metals, there is cold work introduced, especially near the bond line. Therefore, post clad stress relief heat treatment is frequently performed to restore backer mechanical properties and ensure optimum bond toughness. With many material combinations and when the backer metal is greater than approximately 25mm thick, there is no need to perform a post clad stress relief heat treatment. For specialty metals such as Thermo-Mechanical Control Process (TMCP) materials, EXW followed by post clad heat treatment allows the steel to be purchased with optimal mechanical properties and the final product to meet the same requirements after explosion welding and stress relief heat treat.

The explosion clad plate manufactured for this test program consisted of a 19 mm (3/4") thick API 5L-X70M-PSL2 carbon steel base plate and a 4.8 mm thick Alloy 625 corrosion resistant alloy (CRA) plate. The carbon steel base plate was prepared by grinding the surface to remove mill scale and rust. The Alloy 625 plate was prepared in two steps. The first step was to seam weld smaller plates to achieve the full width and length needed for the pipe. The second step was to grind the mating surface prior to assembly. The plates were assembled with a calculated gap between the base plate and CRA plate. The explosives were blended to match the metal properties and loaded on top of the CRA plate. The explosives were then detonated to bond the plates together. The welded plate was then flattened and trimmed to final size. Typical ultrasonic bond inspection, PT inspection of the seam welds and mechanical property testing was performed prior to delivery to the pipe manufacturer.

The plate layout is shown in Figure 4. For many applications, depending on pipe and induction bend dimensions, seam welding of the cladding metal will not be required. For this test program, seam welding was intentionally added and located in the center of the bend, in order to test and qualify the seam welding process. After explosion welding there were no rejectable ultrasonic indications, however, the explosive initiation point and an additional simulated non-bond were excavated and weld repaired as shown in Figure 4. Once again, these repair areas were intentionally added in order to test and qualify the process. The GTAW seam weld was produced

using a seam weld machine equipped with shielding, backing gas, automated wire feed and weld parameter control. Welders and welding procedures were qualified in accordance with Section IX of the ASME Boiler and Pressure Vessel Code.

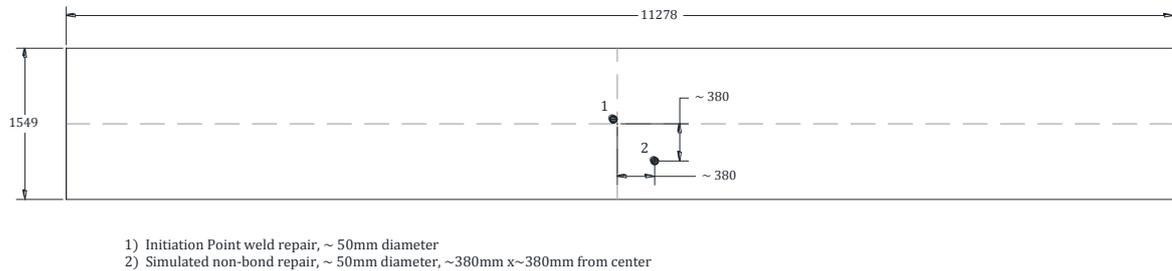


Figure 4: Layout of Initiation Point Repair and Simulated Non-bond Repair

#### 4. Pipe Manufacturing Process

The mother pipe for the bends was manufactured by Erndtebrücker Eisenwerk GmbH & Co. KG, Germany (EEW).

The manufacture of clad pipes starts with a thorough inspection of the plates. The controlled parameters are surface condition, thickness of clad layer and bonding. The clad layer thickness was measured using the magnet-inductive method (according to EN ISO 2178) along the plate edges. The bonding along the plate edges was also checked using manual UT.

Weld edge preparation of SAW clad pipes require special attention. In addition to the weld bevel preparation of the carbon backing, the clad layer was removed over a width of about 10 mm. After milling, these areas were checked at the plate ends by using copper (II) sulfate solution proving the complete removal of the clad layer (Figure 5). The copper deposits only onto the carbon steel, which is subsequently removed before forming.



Figure 5: Clad plate with weld bevel preparation

The pipe forming process starts with crimping the plate edges. At EEW, the crimping was executed stepwise (step-by-step) by means of a 33 MN crimping press. In comparison to roller-crimping, the press-crimping process is characterized by lower bearing pressure and tighter tolerances.

After crimping, the main body of the plate was formed into a circular shape using the JCO-process. This forming process is a gradual process, performed with a 43 ft. press bending machine by pressing short sections of the circumference. The pressing starts at one plate edge and progresses toward the plate center. These first strokes result in a J-shaped cross section. The second series of strokes, starting from the other edge toward the center, creates a C-shaped cross section. The last stroke, applied at the center line, closes the C into an O-shape.

In the next production step, the open-seam pipe is tack-welded by GMAW in a tack welding press. With respect to X70 strength level and optimized impact toughness, S3NiMo1 filler metal is used and a multilayer SAW technique applied. Following the standard production route for DSAW carbon steel pipes, the clad pipe was first submerged-arc welded (SAW) on the inside, during which the process was controlled within a very small window, ensuring minimum weld reinforcement and preventing any contact of the liquid weld pool with the clad material. After inside SAW, the tack welding pass was completely removed by milling from the outside prior to the multi-pass outside SAW.

Before closing the gap of the internal clad layer in the longitudinal weld area by resistant electro-slag weld (RES) cladding, this area was carefully checked by radioscopy. Then the RES cladding was executed using a special strip cladding nozzle and Alloy 625 tape which is 30 mm wide and 0.5 mm thick (Figure 6). This process ensures good process stability as well as minimum dilution between CRA and base metal. For purposes of this investigation a single layer overlay was performed. In applications where lower dilution is desired a two layer overlay can be performed. Figure 7 shows macrograph of the finished weld joint.



Figure 6: Resistance electroslag (RES) strip cladding of longitudinal DSAW clad pipe

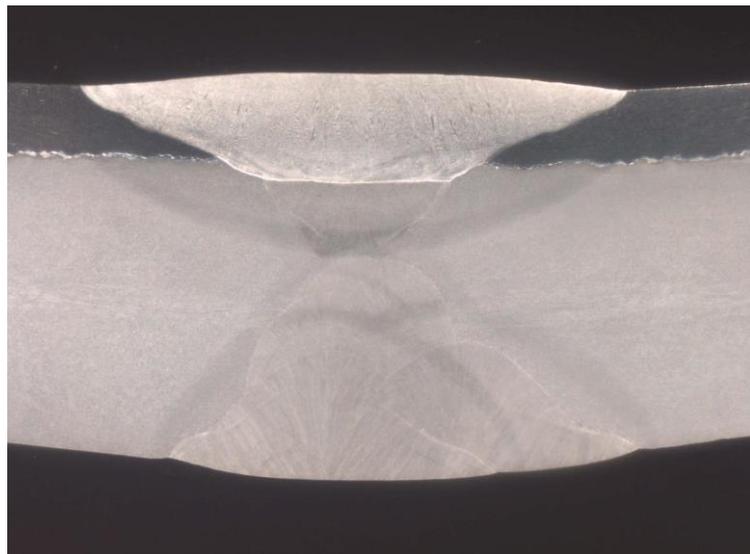


Figure 7: Longitudinal pipe weld joint

The pipe was finished using external compression to calibration it to the final dimension of 508 mm (20") outer diameter and an out-of-roundness below 2 mm (< 0.4%) over the entire length. Finally the longitudinal weld area, including a 50 mm width strip along the weld seam was ultrasonically tested. Neither weld defects nor any disbonding were detected in the pipe.

## 5. The Induction Bend Manufacturing Process

The bends were manufactured by Cofely Fabricom N.V/S.A.

Principles of hot induction bending:

A bending machine, shown conceptually in Figure 8, is composed of four basic components:

1. Frame
2. Bending arm with clamp
3. Induction heating system
4. Cooling system

The pipe is placed centrally in the machine, wherein the front side of the pipe is clamped on the radial arm. The heating system uses an induction ring to heat a narrow circumferential zone around the pipe to the desired bending temperature. When this temperature is reached, the pipe is fed through the inductor with a constant speed until the desired bending angle is achieved. The type of cooling immediately after the induction ring is dependent on the requested mechanical requirements. The cooling medium is water, compressed air or a combination of both.

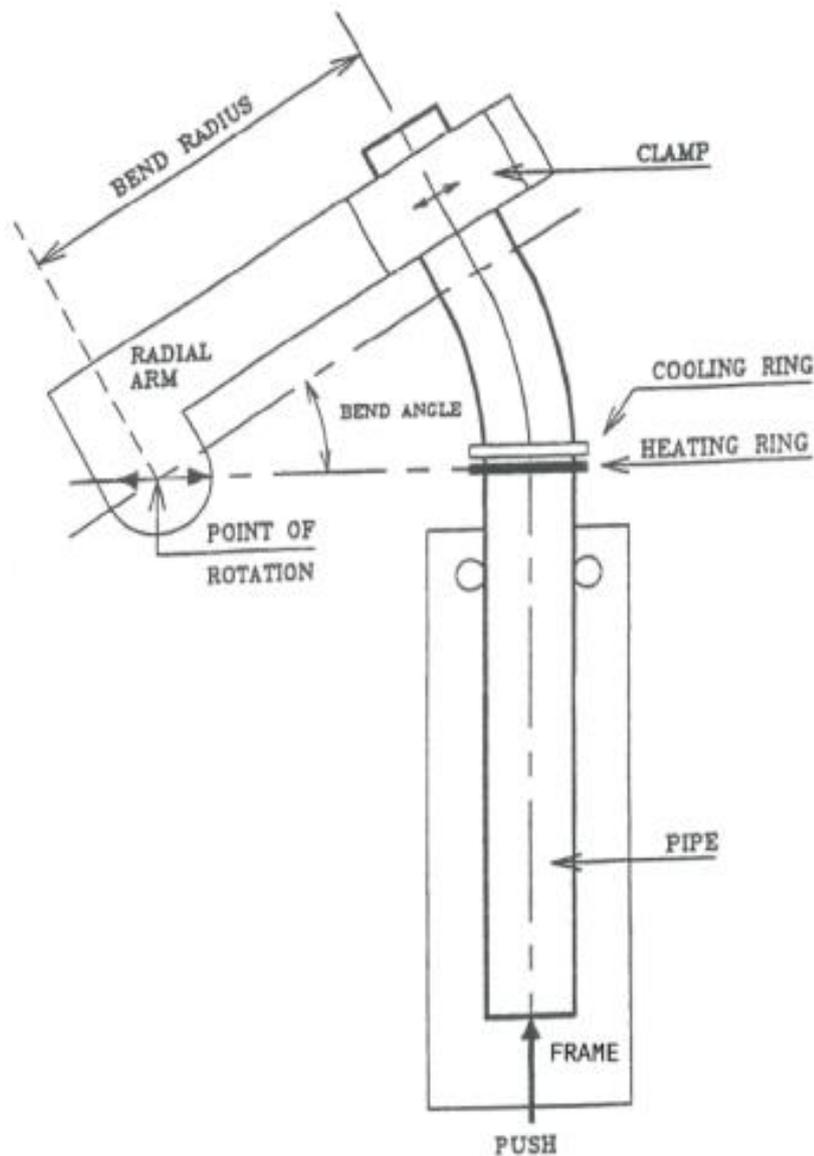


Figure 8: Induction Bending Machine

**Manufacturing steps:**

When the pipe is received, incoming inspection measures the pipe length and the exact location of the longitudinal and circumferential weld. For this testing, the circumferential weld of the clad material was purposely positioned in one of the bend areas. This is done to investigate the effect of the bending on this circumferential weld in the cladding material. Normally circumferential welds are to be avoided in bends. But, with the explosion cladding process used in long pipes, it is inevitable to have a circumferential weld in the bend area. Therefore extra care should be taken when investigating this area for defects after bending, as this will be a higher risk location for defects to occur.

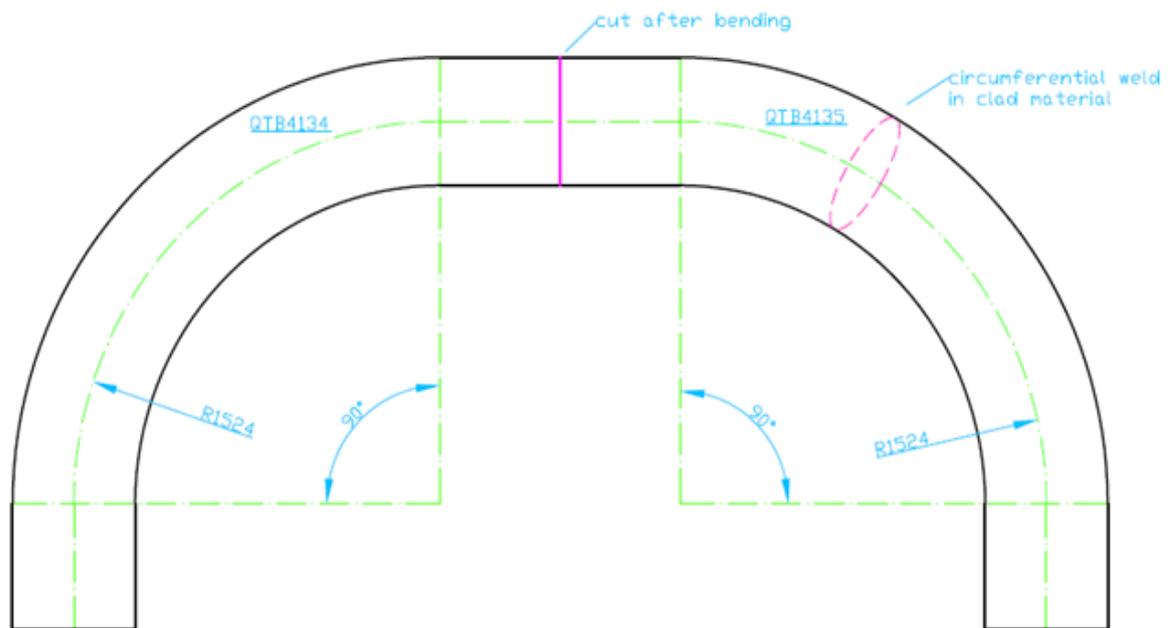


Figure 9: Layout of bending plan:

After the incoming inspection the pipe was loaded into the bending machine. From the one pipe received, two bends were made with following dimensions:

Bend No	QTB 4134	QTB 4135
Diameter	510mm	510mm
Wall thickness	23mm	23mm
Radius	1524mm (3D)	1524mm (3D)
Angle	90°	90°
Post bend heat treatment	Temper	Quench & Temper

After the hot induction bending, both bends received a different heat treatment. One bend only received a tempering treatment, while the other one received a quench and temper heat

treatment. The parameters of both the induction bending and the heat treatments were chosen in such a way to aim for API 5L X70 properties of the backing steel after bending and heat treatment. The tempering temperature of the Q&T bend was 50°C higher than the one only receiving tempering.

#### Non-destructive testing (NDT):

After bending and heat treatment the bends were cleaned so they could be subjected to dimensional control and non-destructive testing. Only the outside surface of the bends was cleaned to remove any scale or oxidation formed during the bending and post bend heat treatment.

To check the carbon steel for any possible defects, the outside surface was fully inspected by wet magnetic particle inspection. This was done in both the horizontal and the vertical direction. An AC yoke was used for the magnetization of the steel. No defects were found on the outside surface of the bends.

Next, the inside clad material was investigated for surface defects by conducting a full dye-penetrant test on the inside of both bends. After application of the penetrant, cleaning of the inside with water and application of the developing agent, the inside was 100% inspected with a camera system. This system allows checking the inside of bends along the entire length and the complete circumference, providing 100% inspection of the clad surface. The dye-penetrant inspection showed no indications in the clad material of both of the test bends, including the circumferential weld in the clad area of one of the bends.

Another very important feature to check when producing hot induction bends from clad pipe is the bonding between the base material and the clad material. This is done by ultrasonic inspection with compression waves to detect any disbonding between the materials. Both bends were completely free of any disbonding. The high bond strength that is achieved with the explosion cladding process ensures good quality bond interface. Therefore the chances of disbonding are greatly reduced.

#### Destructive testing:

After NDT, samples for mechanical testing were cut from different locations in the bends. The areas tested in the bends correspond to the areas described in Figure 10.

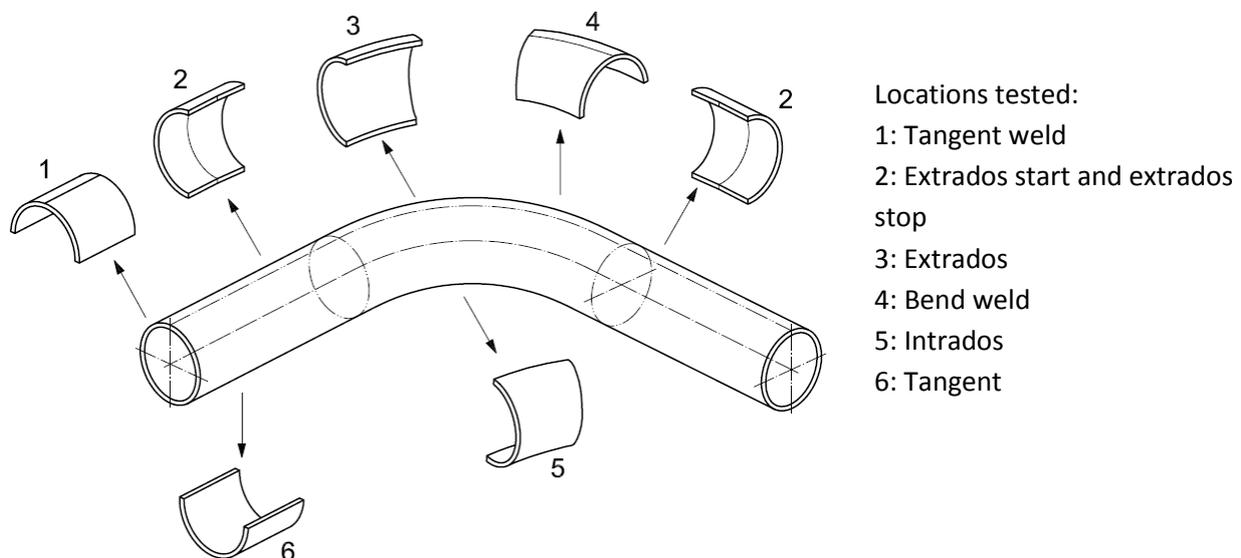


Figure 10: Clad bend test locations

## 6. Results and Discussion

Mechanical test results:

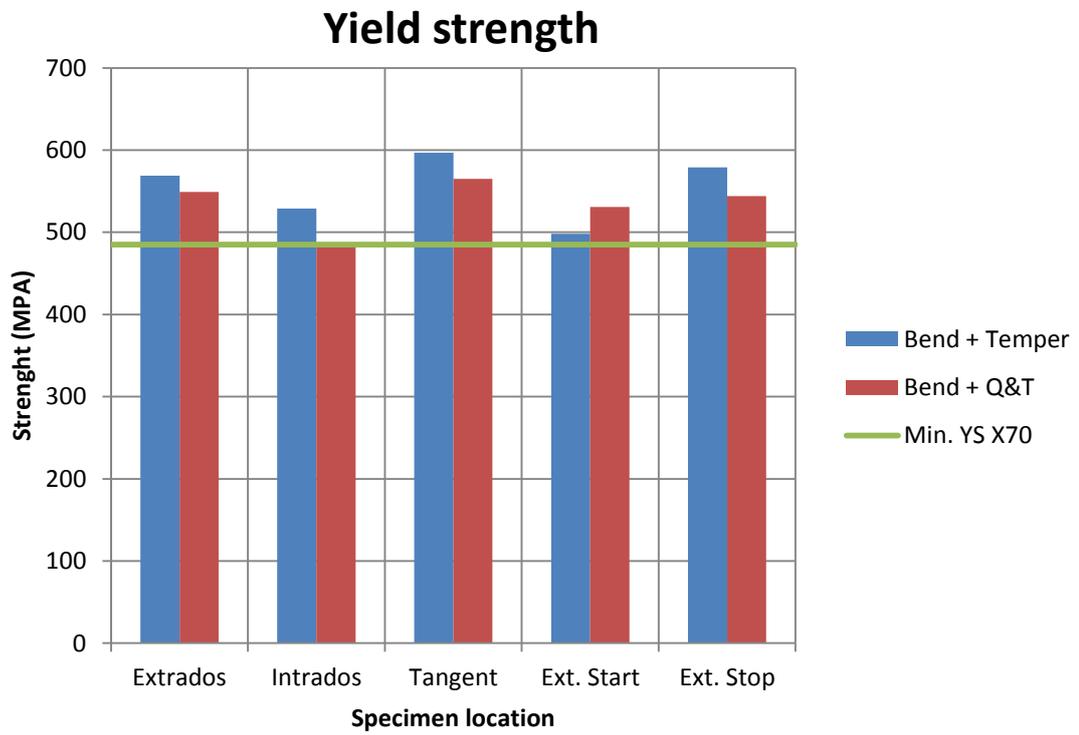


Figure 11: Material Yield Strength

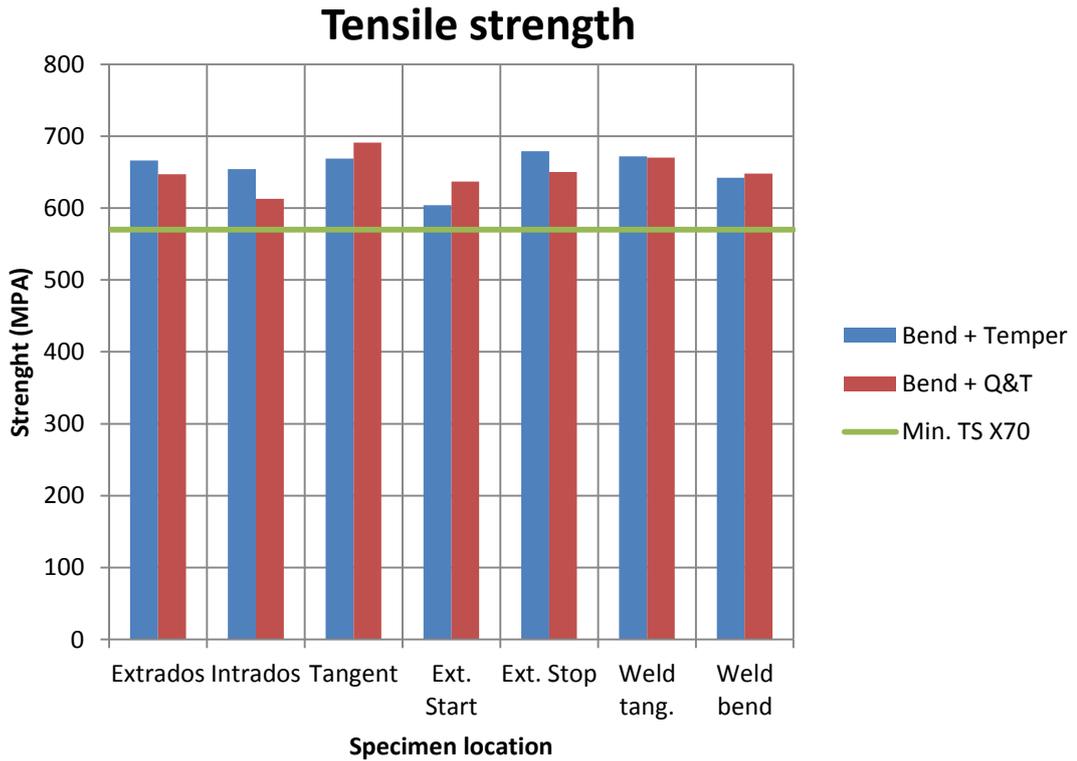


Fig. 12: Material Tensile Strength

Toughness properties:

CVN impact testing was conducted in all the locations mentioned in Figure 10. The test temperature was  $-40^{\circ}\text{C}$ . In the base material the lowest individual result was 81J, the average result was 180J. The lowest single value in the weld area was 30J, the average was 50J.

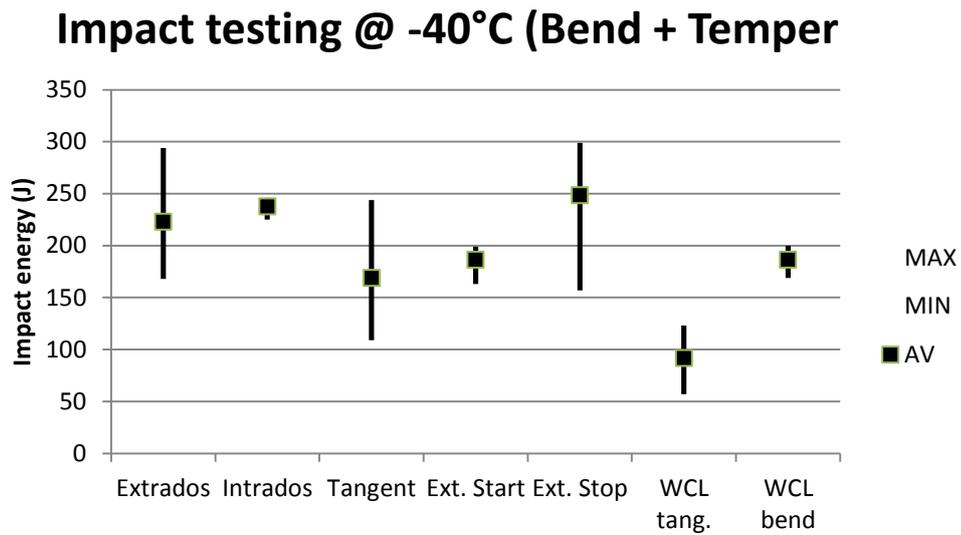


Figure 13: Bend + Temper Impact Testing

## Impact testing @ -40°C (Bend + Q&T)

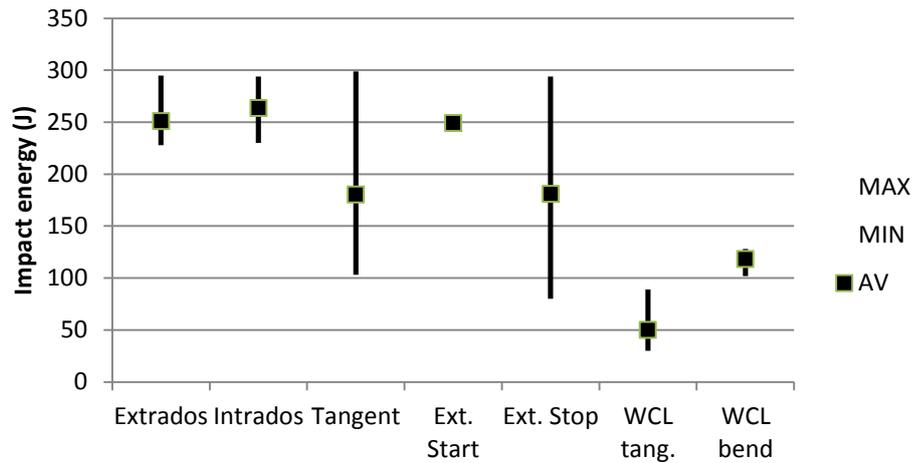


Figure 14 Bend + Q&T Impact Testing

DWTT samples were machined from the external axis of the bends. Two different test temperatures were used. At Room Temperature (+20°C) the material of both qualification bends shows more than 95% ductile fracture. At 0°C, the amount of ductile shear fracture area is between 55% and 80%. These results are typical for induction bends as the elongated structure of the plate rolling is transformed to a more granular structure during the induction heating and cooling cycle.

### Shear bond strength:

On both bends the shear strength between the clad material and the base metal was tested. Both bends show shear bond strength above 300 Mpa, which is a very high value compared to the typical requirement of 140 Mpa minimal shear bond strength.

### Corrosion test results:

A common pitting corrosion test according ASTM G48 method A test was conducted on the clad material in the extrados of both bends. No weight loss was observed after 72h at 50°C.

To examine the clad material for susceptibility to intergranular corrosion, an ASTM G28, Method A test was conducted on the cladding material. Two samples were taken from both bends. One sample was taken from the external axis and one sample was machined from the longitudinal weld of the pipe in the bend area. All samples were tested for 120h in the solution specified in the ASTM G28, Method A. The following results were obtained:

Corrosion Rate (mm/year)	Bend + Temper	Bend + Q&T	Mother Pipe PWHT
Extrados	0.38	0.74	0.11
Bend Weld	3.33	10.54	0.12

As can be seen from the results, the weld of cladding shows a high corrosion rate in the ASTM G28 test. This is due to the fact that only one layer of weld material was deposited with the RES welding.

The test results also show a difference between the two post bend heat treatment cycles test results. The Bend and Temper process shows better results in both the extrados and the weld.

## **7. Conclusions**

Induction bends manufactured using explosion welded clad pipe were investigated to determine if explosion welding was a viable technology to meet all the technical requirements and allow for reductions in lead time and manufacturing costs. The explosion welded materials easily passed all the mechanical and corrosion requirements while maintaining the TMCP steel properties. As a result, explosion welding has been qualified as a viable raw material to manufacture induction bent clad pipe. In addition, the explosion welded clad pipe was much easier to process, minimizing manufacturing costs. The flexibility of explosion welding also supports smaller quantities and custom wall thicknesses frequently needed for induction bends.