



Induction bends in material Grade X80: experience from more than 15 years

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| E. Muthmann | Salzgitter Mannesmann Grobblech GmbH, Mülheim, Germany |
| W. Kaluza | Salzgitter Mannesmann Grobblech GmbH, Mülheim, Germany |
| M. Liedke | Salzgitter Mannesmann Forschung GmbH, Duisburg, Germany |
| W. Scheller | Salzgitter Mannesmann Forschung GmbH, Duisburg, Germany |

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Induction bends in material Grade X80: experience from more than 15 years

by E Muthmann¹, W Kaluza¹, M Liedtke², and W Scheller²

1 Salzgitter Mannesmann Grobblech GmbH, Mülheim a. d. Ruhr, Germany

2 Salzgitter Mannesmann Forschung GmbH, Duisburg, Germany

THIS PAPER PROVIDES an overview of the evaluation, manufacturing steps and challenges during the production of high strength induction bends made from heavy TMCP plates of grade X80 (L555M) and highlights the more than 15 years experience and competences of Salzgitter Mannesmann Grobblech (MGB) GmbH in this field of application. During this period of time, more than 2,700 induction bends in material grade X80 were manufactured in the bending plant located in Mülheim, Germany.

HIGH STRENGTH LINE PIPES of API 5L grade X80 (L555M) and higher are developed for the purpose of enhancing the transport efficiency of a pipeline by higher pressure operation and reducing pipe laying costs. This is because of reduced pipe weight and greatly reduced welding charges (reduced welding times) by use of thinner wall pipes/bends. For example, the adoption of X80 line pipes in the first Ruhrgas X80 pipeline project, realised in 1992/-93, led to a material saving of about 20,000 t, compared with X70 pipes by reduction of the wall thickness from 20.8 mm for X70 to 18.3 mm for X80. For onshore gas pipelines e. g. in densely populated areas or for topographic reasons there is always a need for bends in every pipeline (Figure 1). [1-3]



Figure 1 - X80 induction bends ready for shipment and bend in field connection

Bends with large radii and small bending angles can be generally fabricated on site by cold bending. But in case of smaller radii and larger bending angles of up to 90° hot induction bending is the common manufacturing process.

The upcoming trend to use large diameter high strength steel pipelines poses a number of ambitious and severe technological challenges for the manufacturing process and requirements of induction bends, maintaining excellent mechanical-technological properties and weldability. Consequently, to satisfy the customer's needs and specifications, the availability of intensive know-how on the manufacturer's side is essential. MGBs development

and evaluation work of X80 bends is including the research of appropriate base material compositions, bending parameters in terms of balanced temperature control during induction heating, full scale burst testing, detailed microstructure investigations, mechanical testing and field weldability assessment.

MGB is producing induction bends at the Mülheim plant since 1978. The bending machine can handle a wide range of dimensions. The manufacturing program accommodates all conceivable bending radii from extra large for optimum flow characteristics to extra small where space saving is a criterion. The range of starting pipes comprises seamless and welded steel pipe in outside diameters from 4" to 64" (114.3 to 1626 mm). Depending on the diameter, bending radius and base material, wall thicknesses from 6 mm of up to 200 mm can be bent. Besides carbon, alloyed and stainless steel pipes the bending plant can also handle pipes in special materials like nickel based or clad pipes.

X80 bend production

Since the beginning of the 1990s hot induction bends of steel grade X80, supplied by Salzgitter Mannesmann Grobblech, were applied to several pipeline projects in Europe. An overview of the total quantity delivered in this period of time is listed in Table 1 for some selected projects. In the past decade, one of the biggest orders with the largest amount of produced X80 bends was the onshore pipeline project in the UK from the LNG station Milford Haven to Tirley, with a total bend quantity of 1383 bends over a distance of approximately 320 km pipe line length. During this project the biggest challenge was the topography in the area located in Wales. A general overview of this pipeline route is given in Figure 2.

| Year | Project | Main bend geometry | Total quantity |
|--------------|-----------------------------|----------------------------|----------------|
| 1999 | UK, St. Fergus to Aberdeen | 48" x 28.0 mm/20 mm - 3D | 355 bends |
| 2000 | UK, Drinton to Sutton | 48" x 23.5 mm/20 mm - 3D | 101 bends |
| 2004 | Italy, SNAM | 48" x 25.9 mm - 7D | 46 bends |
| 2005 to 2007 | UK, Milford Haven to Tirley | 48" x 28.0 mm/19.5 mm - 3D | 1383 bends |
| 2007 | UK, Easington to Ganstead | 48" x 25.5 mm/19.5 mm - 3D | 85 bends |
| 2008 | UK, East Anglia | 48" x 25.5 mm/19.5 mm - 3D | 100 bends |

Table 1 - Extract of MGB reference list for X80 projects with corresponding main bend geometry and total quantity

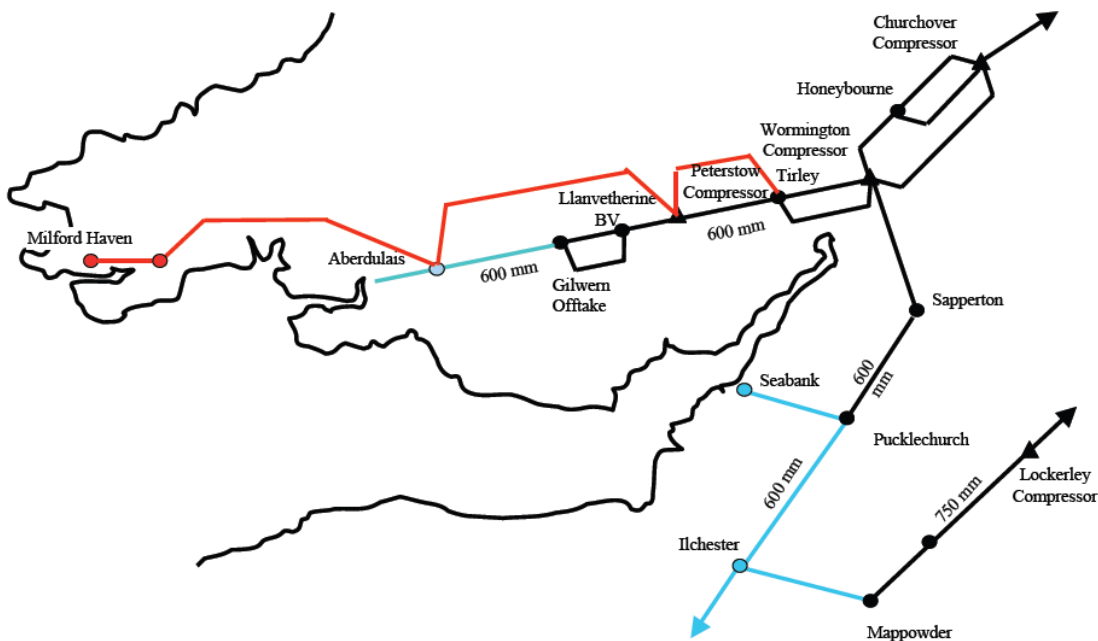


Figure 2 - Overview pipeline route (X80 OD 1220 mm, 94 bar pipeline) Milford Haven to Tirley, South Wales, UK [4]

Induction bending process

Generally, induction bending is a largely automated, free forming process. The unique construction of the computer controlled bending machine in Mülheim is endowed with two bending arms. Figure 3 shows the heavy bending arm during bending of a 48" bend. By the special design of the machine and experiences of the technical staff, a broad range of bends can be offered to customers, which is unrivalled both from the dimensional point of view and diversity.

For bending the straight length of the mother pipe is placed on the machine bed and fixed in the back. The front end of the pipe is attached to a bending arm (1) describing the pre-set bending radius. The trailing end of the pipe is pushed forward at a pre-determined rate during the bending process and pushed through an induction coil (2). The bending force acts axially on the pipe. Set to the desired bending radius, the bending arm then describes a circular arc around its pivot point (3) and as a result of the radial thrust applied to it, the pipe automatically follows this curve. [5-6]

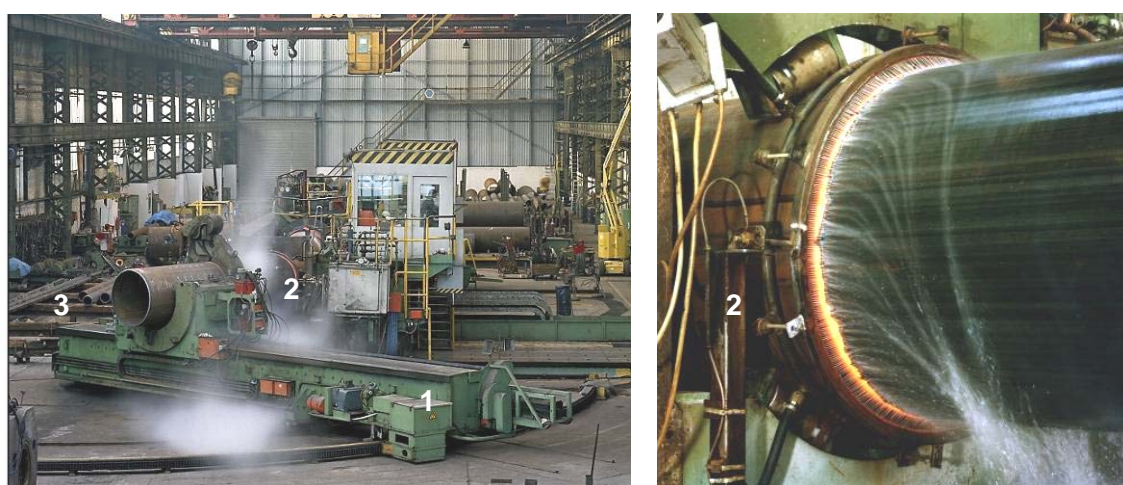


Figure 3 - Hot induction bending of 48" line pipe and induction coil with heated zone

The "transformation" of straight pipe into a bend takes place in a narrow, heated ring like zone only (detail 2 in Figure 3). The heating of this zone is achieved by a stationary induction ring, the pipe is pushed through. To avoid high ovalisation in the bend body the width of the bending area must be limited and is typically in the range of $2x$ the wall thickness of the pipe to be bent. The formed material is cooled by water spray immediately behind the induction ring (see Figure 3). The temperature of the bending zone is measured continuously by optical pyrometers during bending and held constant at pre-determined values. Depending on the wall thickness and radius to be bent, different balanced bending parameters have to be respected and controlled in narrow ranges. [5-6]

In order to achieve and guarantee the specified mechanical-technological properties for high strength material as X80 (L555M), all bends undergo a post bent heat treatment. For large diameter pipes this is usually limited to a full body temper heat treatment. But if necessary, bends can also be full body quenched in a large water basin, as shown in Figure 4, with subsequent temper heat treatment. For full body QT the suitable dimensions with regard to the ratio of outside diameter to wall thickness have to be respected during austenitisation to maintain the shape of the bends. [1-2]

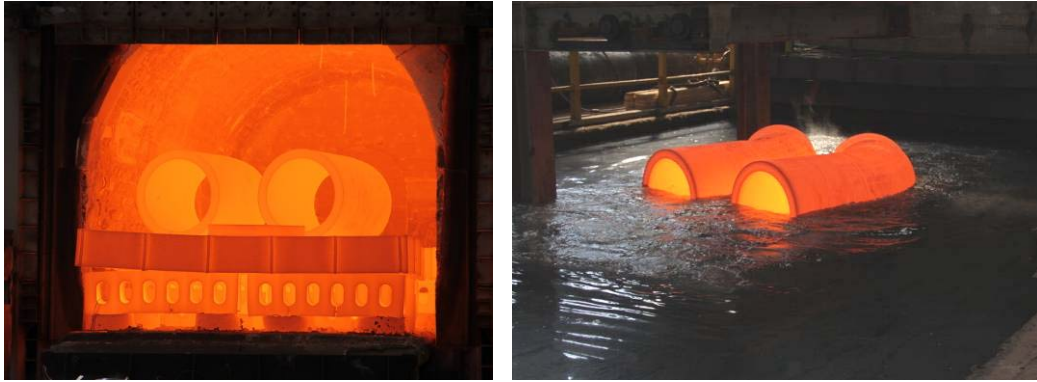


Figure 4 - Full body quenching heat treatment on bends in Mülheim plant

After heat treatment manual NDE, dimensional control and final inspection is carried out on each production bend. From additional test bends sections are cut out for the validation of the mechanical-technological properties.

Dimensional classifications of bends

Typical dimensional details to specify the geometry of a bend are shown in Figure 5. The abutting pipe dimensions as well as the minimum wall thickness for the bend need to be respected. Depending on the customer needs and requirements, bends can be fabricated with or without straight tangents. In order to guarantee a proper connection between the two ends of a pipeline in the field, the tangent lengths and the centre-to-end dimension has to be controlled to “make the ends meet” for later field welding. [5, 6]

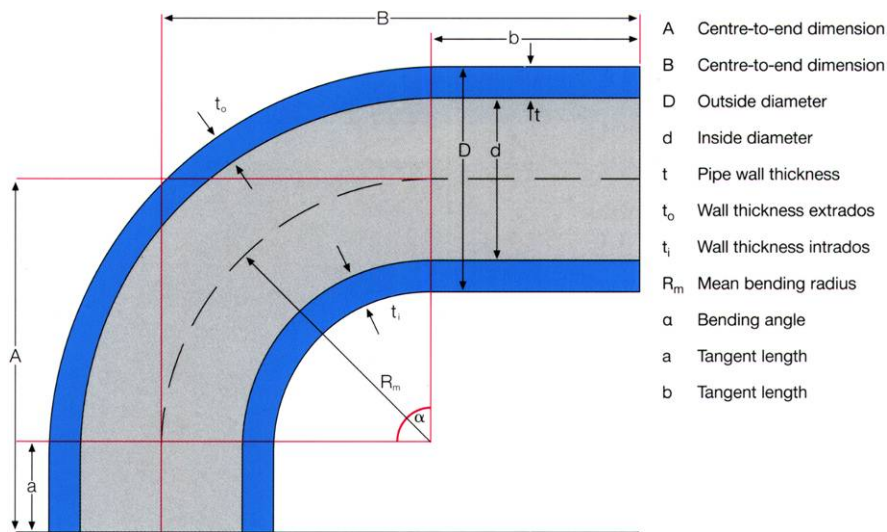


Figure 5 - Basic geometrical details to specify a bend [5]

Bending deformation transactions

During the bending process the mother pipe base material undergoes extensive plastic deformation. Generally the bend extrados is strained and the wall thickness decreases consequently. In contrast to this, the intrados is compressed, resulting in an increased wall thickness. Deformation over the circumference takes place in the longitudinal direction only, not in circumferential direction. Figure 6 shows the distribution of material elongation respectively compression on a 5D bend, measuring 48” x 25 mm.

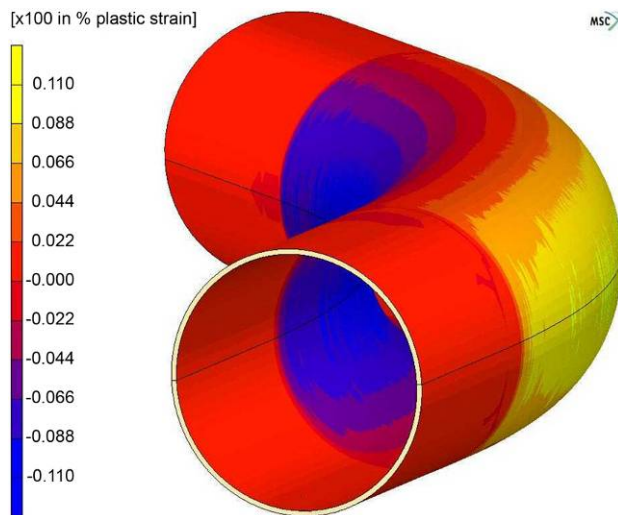


Figure 6 - Distribution of elongation and compression on a 5D bend (48" x 25 mm, X80) [6]

The material compression in longitudinal direction in the intrados is more distinct than the elongation in the extrados. This leads to a displacement of the neutral axis, as shown in Figure 7. Therefore, the longitudinal seam is placed in the neutral axis of the bend shifted approximately 10° to the extrados, which is the area of minimum deformation over the circumference. The compression in the intrados and elongation in the extrados are increasing with decreasing radius to diameter ratio.

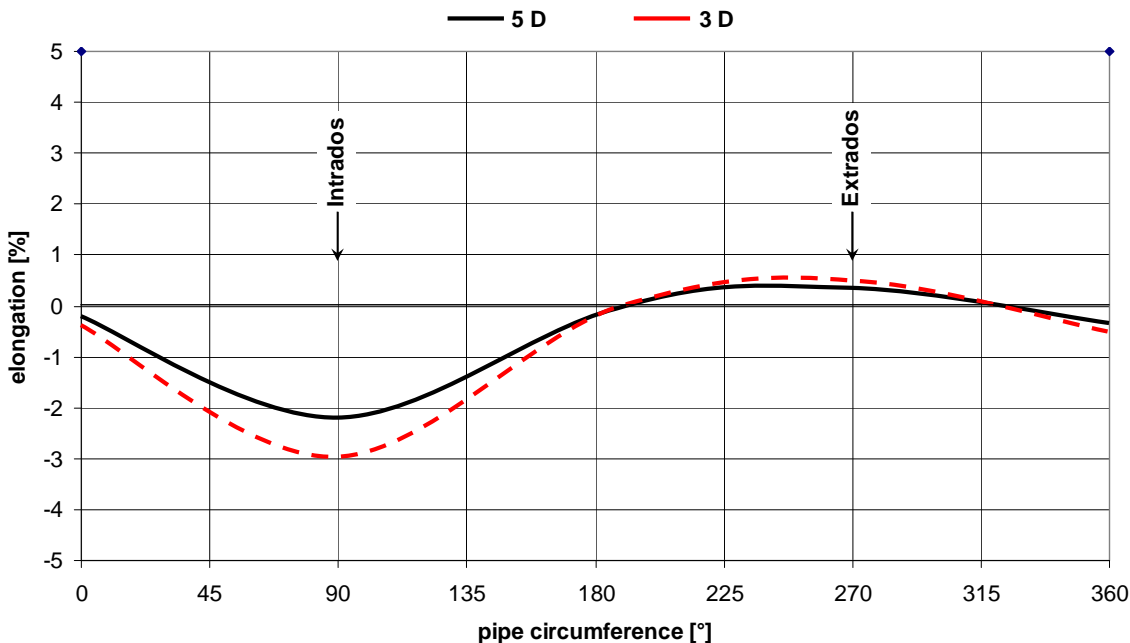


Figure 7 - General description of bend deformation transactions during bending

For hot induction bending the heated zone helps to lower the flow resistance of the material and therefore decreases the bending forces. In this zone the flow of material in circumferential direction decreases, because the heated zone is “clamped” between the cold material. This effect is more real for thinner walls. The percentage of thickening and thinning also depends on the bend radius. These changes in wall thickness must be taken into account during the geometrical design of the mother pipes. [3, 5-7]

In order to avoid buckling during bending, a minimum wall thickness of the mother pipe must be considered. Depending on the bending radii, diameter and base material, MGB can handle mother pipes with wall thicknesses in the range of 6 mm up to 200 mm. Bending angles up to 180° can be realised and bending radii are continuously variable in the range of 200 mm up to 10.000 mm. Larger radii or mathematic defined curves can be bent using a special machine set up. [1, 5, 6]

The surplus wall thickness, required on the mother pipe in order to meet with the minimum specified wall thickness on the final bend, can be located on the outside (OD) or on the inside (ID) of the mother pipe. These two different possibilities are shown in Figure 8 also in combination with possible end preparation to match with the abutting line pipe geometry for girth welding. If tight gauging requirements have to be considered, mother pipes for bends should always be ordered to constant ID (Figure 8a). [6]

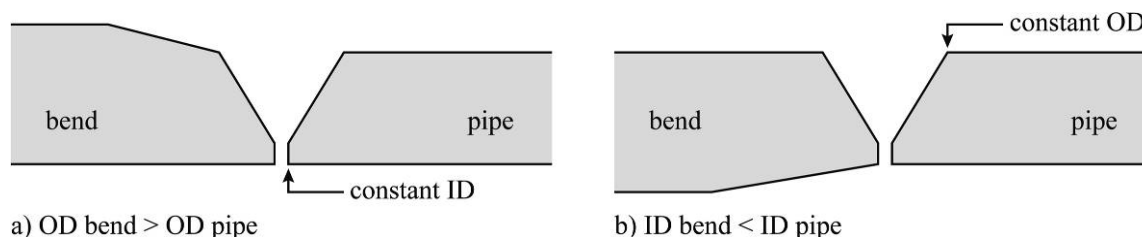


Figure 8 - Typical bevel preparations for girth welding of pipe-to-bend connections [6]

Base materials for high strength induction bends

The starting material for bends is typically made from heavy plates rolled by Thermo Mechanically Controlled Rolling Process (TMCP) and followed by three roll or UOE pipe forming. The longitudinal seam welding is realised by either two pass submerged arc or multilayer welding, depending on actual wall thickness and toughness requirements. Mother pipes for bending usually differ from line pipe regarding the chemical composition to be suitable for the induction bending process and wall thickness to guarantee the mandatory minimum wall thickness requirements after bending. [3, 5, 6]

With focus on the mother pipe base materials, the overall challenges for induction benders are high tensile strength combined with good toughness properties and low carbon equivalents (as close as possible to line pipe requirements). During the production of hot induction bends the mother pipe has to undergo several heat treatments. Consequently not only geometrical aspects considering the change of wall thickness over the circumference during bending, ovality and gauging requirements must be taken into account during the design of the mother pipe. Also the chemical composition of the base material and SAW seam needs to be suitable for the process related heat treatments of hot induction bend fabrication. This is essential in order to maintain the specified mechanical properties. Therefore necessary care must be taken during design of the chemical compositions of the base material and weld metal under consideration of the customer's special requirements, especially for high strength bends. The bending plant of MGB serves customers with the full service of taking responsibility for the necessary pre-material suitable for induction bending. Starting from the steel to plate and mother pipe the complete production is provided within the Salzgitter Group.

During the various fabrication steps from plate to pipe and from pipe to bend the strength properties of the TMCP material always decrease. Due to the process related heating of the material during induction bending at temperature levels above AC3, the TMCP microstructure receives a short-time austenitisation cycle followed by water quenching. The TM microstructure of the plate/pipe, consisting predominantly of a bainitic microstructure, is transformed to a QT microstructure, as can be gathered from the micrographs in Figure 9 (a, b). [5-7, 11-13]

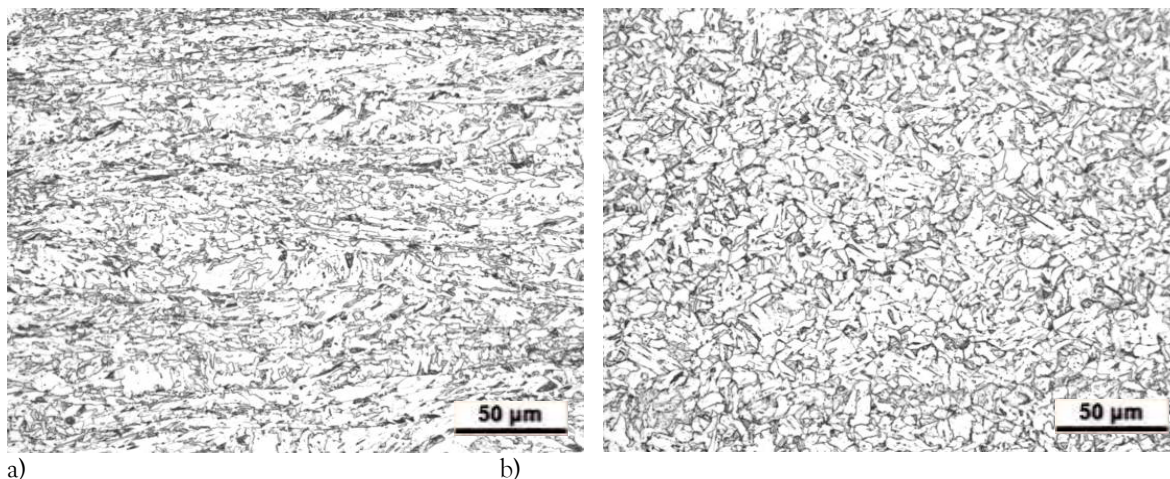


Figure 9 - Microstructure of TMCP X80 mother pipe before bending (a) and finished hot induction bend (b)

Unlike for a line pipe, where the decrease level during forming from a plate to pipe is predictable, the chemical compositions of bends are an essential variable. In order to guarantee high strength properties also after bending, the chemical composition of the mother pipe has to be designed for sufficient hardenability. Alloying elements like Cu, Cr, Ni, Mo etc. are commonly added to pipe analysis, increasing the hardenability of steel. Induction bends usually require slight higher carbon equivalents than common line pipe analyses. Therefore the carbon equivalents (CEIIW) for mother pipes suitable for induction bending are typically 0.03 to 0.04 higher compared to line pipe material of the same high strength base material grade. An example for a typical X80 alloying concept for the mother pipe base material in comparison with a usual X80 line pipe analysis is given in Table 2. [5-7, 11-14]

| Grade X80 | C | Si | Mn | P | S | others | CEIIW | Pcm |
|-------------|------|------|------|---------|----------|--------------------|-------|------|
| Mother pipe | 0.09 | 0.24 | 1.90 | < 0.015 | < 0.0015 | Cr, Ni, Mo, Nb, Ti | 0.48 | 0.22 |
| Line pipe | 0.06 | 0.03 | 1.90 | < 0.015 | < 0.0015 | Cu, Cr, Ni, Nb, Ti | 0.45 | 0.19 |

Table 2 - Example for typical alloying concept for grade X80 mother pipe in comparison with a typical line pipe analyses and the resulting carbon equivalents

Mechanical properties of X80 bends

Bend Base Material - As a matter of fact every bend has different test locations like intrados, extrados, tangent and the transition zones showing different wall thicknesses and heat treated regions. On large diameter high strength bends the bent arc receives typically a short time austenitisation and subsequent water quenching during bending since the straight tangent is only stress relieved during full body tempering. Consequently the mechanical-technological properties are differently influenced in these test locations which has to be considered choosing a balanced chemical design of the pre-material. One detailed example for the variation of the strength properties (average values - flat and round bar specimens) in different test positions of a single bend in material grade X80 is shown in Figure 10. Samples were taken from the mother pipe and the finished bend in the area of tangent, transition zone, extrados and intrados. Also the impact of the Bauschinger effect for flattened rectangular specimens has to be considered for the design of the pre-material, especially for high strength grades. [8]

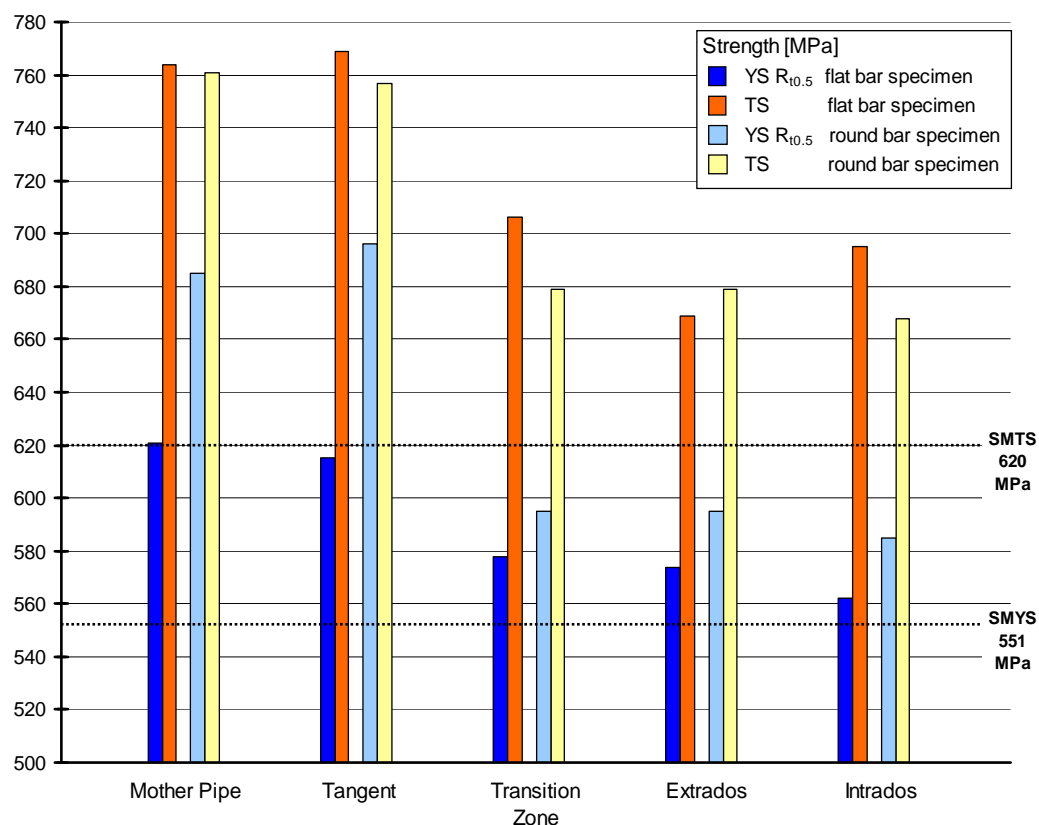


Figure 10 - Strength properties (single values, transverse/longitudinal) tested in different sections of an induction bend, grade X80

According to MGB's experience for high strength bends with wall thicknesses above 30 mm a full body QT heat treatment is recommended due to the temperature gradient during induction bending over the wall thicknesses. Full body QT heat treatment leads to a homogenisation of microstructure and mechanical-technological properties for all different test locations of bends. But this type of post bent heat treatment requires suitable dimensions regarding the ratio of diameter to wall thickness in order to maintain the shape of the bends. A comprehensive average data of 200 tested X80 bends (3D radius) for yield and tensile strength, elongation and toughness properties in the size range 48" x 19.5 mm and 28.5 mm wt. is given in Table 3, respectively. All test results are comfortably above typical specified values and fulfil customer requirements.

| | Specified values | Production results average values from 200 test bends |
|----------------------|------------------|--|
| Yield Strength | 555 - 675 MPa | 571 MPa |
| Tensile Strength | 625 MPa min | 717 MPa |
| A5-Strain | 18% min | 20.5% |
| Y/T Ratio | 0.90 max | 0.80 |
| Charpy Base Material | 55 J @ ± 0 °C | 283 J |
| Charpy Weld Metal | 55 J @ ± 0 °C | 157 J |

Table 3 - Mechanical results of X80 induction bends

Weld metal toughness properties

For production of welded large diameter mother pipes, special attention must be paid to welding consumables and welding techniques. Generally, the toughness of the longitudinal weld seam is mainly influenced by different factors like heat input, oxygen and nitrogen content in the weld metal, the later chemical composition (the dilution with the base material has also be respected) and the heat treatment which is applied on the final product. The favourable and target microstructure for SAW seams is in general acicular ferrite which exhibits sufficient strength and toughness properties at the same time.

The decision whether the mother pipe should be welded using the two-pass (DSAW) technique with light basic fluxes or the multi-layer technique with fluxes exhibiting a higher index of basicity is dependent on the toughness requirements. Multilayer welding technique with low heat input leads to excellent Charpy-V-notch (CVN) toughness results even for test temperatures down to -50 °C. For test temperature ranges between -20 °C and -30 °C it depends on the actual requirements, wall thickness and type of bend (with or without tangents), whether the two-pass welding technique is still sufficient or not. Typical minimum requirements for weld metals are 30 J single / 40 J average. For two-pass welds the plate chemistries also strongly affect the weld metal properties, since the amount of weld metal dilution by the base material is in the range of 60 - 70%. For bends with straight tangents the weld metal has to fulfil the toughness requirements after tempering (tangent) and after bending and tempering (bent area). Microalloying elements in the weld metal like V, Nb and Ti are in solution in the as-welded condition. During tempering heat treatment (or stress relieving) these elements lead to precipitation hardening, e. g. by formation of carbonitrides, which influences the toughness of the weld seam [10-14].

Consequently, in two pass welds the transition temperature is shifted to higher temperatures from the as-welded to the tempered condition (tangent). In contrast to this, the toughness level of multi-layer welds is clearly on a higher level.

On the other hand, low toughness values sometimes achieved on CVN specimens with the notch located in the coarse grained zone of the fusion line (FL) are definitely improved on a bend. As can be gathered from the micrographs shown in Figure 11, the heat affected zone (HAZ) is completely transformed and refined by the heat treatment during the induction bending process.

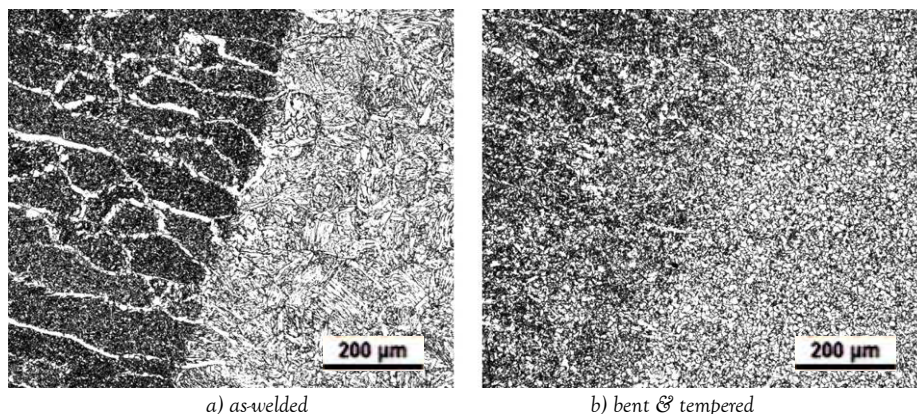


Figure 11 - HAZ and WM microstructure of a SAW two-pass weld in as-welded (a) and bent & tempered condition (b)

On the bend tangent the HAZ of the mother pipe is tempered, which already leads to an improvement of the toughness (Figure 12). In the bend area, where the HAZ is completely refined, the CVN specimens with the notch located in the fusion line (FL) show excellent test results at a level comparable to base material results. [5-7]

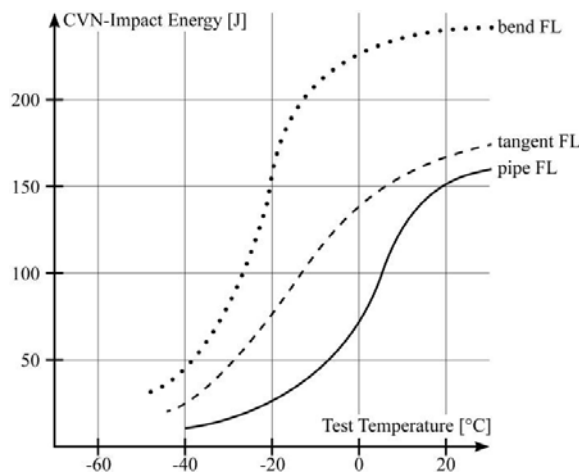


Figure 12 - Change of HAZ toughness level on a SAW two-pass weld from mother pipe to finished bend [6]

Full scale burst testing

In addition to standard destructive testing investigations, full scale burst tests were performed at Salzgitter Mannesmann Forschung GmbH on X80 bends to provide evidence that the bends burst at an adequately high pressure and maintain sufficient deformability. The results of the burst tests demonstrated that both the equivalent yield strength and burst strength calculated, based on the yield and burst pressures recorded during the burst tests, are in good agreement with the yield and tensile strength determined on tensile test specimens before. Figure 13 is showing a 3D bend in material grade X80 with 45° bending angle in dimension 48" OD x 28 mm wt. before and after the burst test. Fracture occurred in the extrados, as this is the area of minimum wall thickness and the weakest zone of a bend.



Figure 13 - Overview burst test (before and after testing) of X80 bend, measuring 48" with 28 mm min. wt. and 3D radius, performed at Salzgitter Mannesmann Forschung GmbH, Duisburg

The test results and specific details obtained during burst testing are listed in Table 4 and presented in Figure 14. The bend failed at an ultimate burst pressure of almost 340 bar. The initial design pressure was specified at 94 bar.

| | |
|--|--------------------|
| Pipe size | 48" OD x 28 mm wt. |
| Test temperature | + 15 °C |
| Ultimate burst pressure | 339.4 bar |
| Yield pressure | 294.2 bar |
| Volume (water capacity) | 9,523 litres |
| Volumetric increase | 402.6 litres |
| Volumetric increase | 4.23 % |
| Maximum circumferential permanent elongation | 3.2 % |
| Maximum circumferential permanent local elongation (grid measurements) | 28.4 %. |

Table 4 - Burst test results of a 3D bend, 45° angle, material grade X80

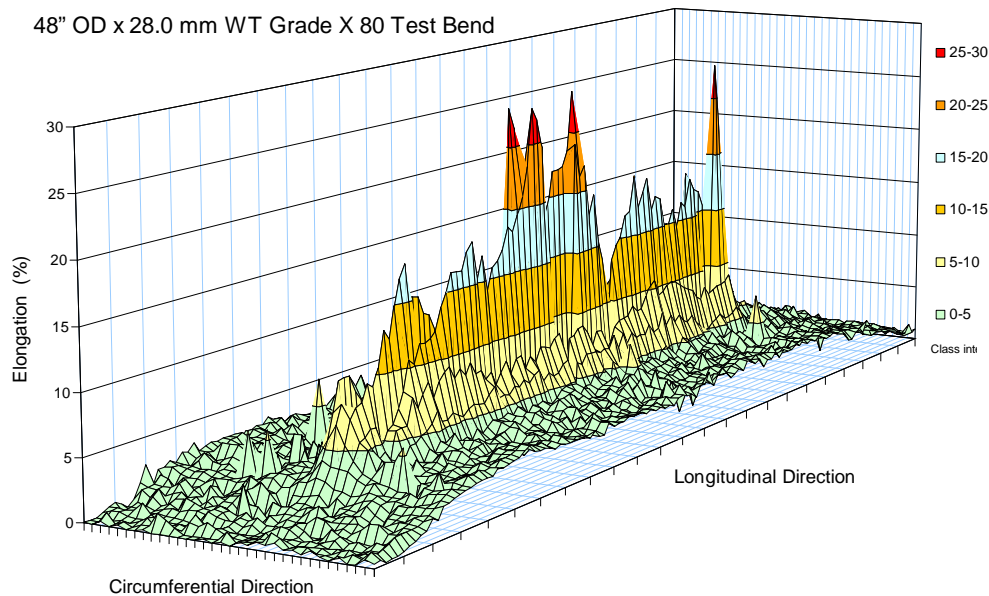


Figure 14 - Illustration of actual elongation measured on X80 full scale burst test

The high elongation values measured in the burst test proved good deformation characteristics of the bend material whilst showing high strength properties at the same time.

The fracture, as assessed from the visual appearance of the fracture surface, was entirely ductile in nature, thereby suggesting that the occurrence of brittle fracture can be excluded under service conditions [1, 7].

Weldability

In general, base material in grade X80 is more difficult to weld than lower strength materials. The micro alloy design and compositional control of TMCP steels is critical in order to achieve the desired properties, as satisfactory weld metal toughness and suitable field weldability, to avoid problems as cold cracking in the heat affected zone. Welding procedure variables such as pre-heat, interpass temperatures and overall welding parameters are much more stringent and must be carefully controlled and observed. Finally, the consumables used to weld X80 base material must meet the materials strength requirements providing good toughness properties at the same time. [15]

Since the first X80 Ruhrgas pipeline several weldability tests have been performed on bend segments (pipe to bend connection) to qualify different welding processes and consumables suitable for connection and tie-in operations used in the field as gas metal arc (GMA) and shielded metal arc (SMA) welding (Figure 15). These trials were carried out in order to investigate the mechanical-technological properties in the weld metal and in the heat affected zone of the base material. The SMA welds were performed using basic coated electrodes under simulated field conditions both in vertical-up and vertical-down position. The girth welds on the test segments were non destructive tested and evaluated by different destructive testing methods like tensile, CVN- and fracture mechanic testing according to relevant specifications.

Summarising the test results of welding trials it can be stated that this activity has confirmed a good overall weldability for X80 bends with both SMAW and GMAW techniques. Nevertheless the welders experience is still a vitally important factor for these higher strength base materials.



Figure 15 - Weldability assessment of X80 bend segments (SMAW)

Summary

In recent years, the quality and safety requirements for high-performance piping and pipeline systems increased constantly. The ability to decrease wall thicknesses by the use of higher yield strength pipe has a significant effect on fabrication costs and makes projects more economic. This upcoming trend to use large diameter high strength steel pipelines poses a number of ambitious and severe technological challenges for the manufacturing process and requirements of induction, maintaining excellent weldability and mechanical-technological properties. Therefore a vast know-how is necessary on the manufacturer side to satisfy the customer needs and specifications.

As a reflection of its innovative product strategy, Salzgitter Mannesmann Grobblech GmbH has contributed at many levels to broadening the application range for induction bends as well as to meet increasing demands in regarding material properties and dimensional tolerances. One of the world's powerful bending machines enables the process to create a multiplicity of bending radii and angles for pipes of every diameter, wall thickness and steel type.

During the past 20 years, extensive R&D work was carried out in order to produce high strength X80 induction bends and thus supported their customers to reduce weight and cost for pipeline construction. The company can reference pipeline projects with large quantities of X80 bends and has produced a total number of more than 2,700 bends, so far.

Furthermore MGB provides full product liability for its induction bent pipe regarding compliance with the specified structural dimensions and agreed material properties as well as with the relevant specifications. The comprehensive pipe manufacturing basis enables to select the optimum straight pipe for each bend. The industrial location in Mülheim / Duisburg also ensures the complete material flow from steel to plate, plate to pipe and pipe to bend.

Currently the development of hot induction bends is focused on material grade X100 which should become more important in future. Based on promising results, the bending plant is well prepared for customer requirements in terms of high strength bends in material grades up to X100.

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