Fabrication of hot induction bends from LSAW large diameter pipes manufactured from TMCP plate

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FABRICATION OF HOT INDUCTION BENDS FROM LSAW LARGE DIAMETER PIPES MANUFACTURED FROM TMCP PLATE

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Abstract

Induction bending is a largely automated, free forming process. The necessary heat for bending is induced in a narrow circumferential band by means of an induction coil, which advances continuously along the length of the pipe during bend forming operation. In order to guarantee a homogenous microstructure, heating of the pipe to be bent must be above A_{c3} transition temperature, consequently above end rolling temperature of TMCP mother plate. As a result of this requirement the analysis of the plate has to be specially designed in order to maintain mechanical-technological properties of the base material grade after induction bending.

Contents of alloying and micro-alloying elements, ensuring sufficient hardenability, are thus essential for induction bend fabrication, especially for higher material grades such as X65 through X80 and wall thickness above 20 mm. Nevertheless applicable specification limits and requirements, such as chemical composition of line pipes for low Carbon Equivalents and good weldability for field welding, have to be maintained.

Induction bending is always followed by a full body temper heat treatment or, dependent on dimensions and requirements, a full body quench & temper heat treatment. The paper presents details of hot induction bend manufacturing, including aspects of dimensional and chemical design for mother plate (TMCP) and LSAW mother pipe material, to be considered during bend fabrication.

Introduction

There is a need for bends in every pipeline. Bends with large radii and small bending angles are fabricated on site by means of cold bending. But for smaller radii and bending angles of up to 90° hot induction bending is the common manufacturing process. Longitudinal submerged arc welded (SAW) large diameter pipes manufactured from TMCP plate material are commonly used for oil and gas linepipe application. For higher efficiencies large diameters up to 56” and high strength material of grades including X80 are used in order to reduce wall thickness or to accommodate an increased design pressure. At the same time excellent weldability and toughness properties of the material must be maintained. This is realised by the TMCP process for plate production with optimised chemical composition regarding relatively low carbon equivalents and special rolling and cooling techniques. Material grades of API type X100 can be realised.

During the production of hot induction bends the mother pipe has to undergo several heat treatments. Consequently not only the geometrical aspects considering the change of wall thickness over the circumference during bending, ovality and gauging requirements must be taken into account during design stage of the mother pipe. It is a prerequisite that the chemical composition of base material and SAW seam weld is suitable for the process related heat treatments of hot induction bend fabrication. This is essential in order to maintain the specified mechanical properties.

Fabrication of Hot Bends

Induction bending is a largely automated process. The "transformation" of straight pipe to bent pipe takes place in the heated narrow annular zone which moves continuously along the length of the bend as the bending process advances (Figure 1). The heating of this zone is effected by means of an induction ring (Figure 2). An alternating current passes through the inductor and induces a potential which causes an eddy current in the material to be bent.

Figure 1: Hot induction bending of 48" line pipe at Mannemann Bending Plant

Figure 2: Detailed view on induction coil and heated zone during bending

The width of the bending area must be limited to avoid uncontrolled deformation in the bend body. The formed material is cooled by water spray immediately behind the inductor (Figure 2). During bending, the temperature of the bending zone is measured continuously and held constant at a predetermined value above A_{c3}. This results in a short-time austenitizing cycle and a quenched metallurgical structure [1]. The front end of the pipe is clamped to a pivoted arm, the bending force acts axially on the pipe, induced by a hydraulic ram, pushing the pipe through the machine. Set to the desired bending radius, the bending arm then describes a circular arc around its pivot point. As a result of the radial thrust applied to it, the pipe automatically follows this curve.

Figure 3 represents the dimensional details of a bend. The abutting pipe dimension as well as the minimum wall thickness for the bend must be specified. Radius and angle define the desired geometry of a bend. Bends can be fabricated with or without straight tangents. The tangent lengths and the center-to-end dimension must be specified in order to guarantee a proper connection between two ends of a pipeline and "make the ends meet".

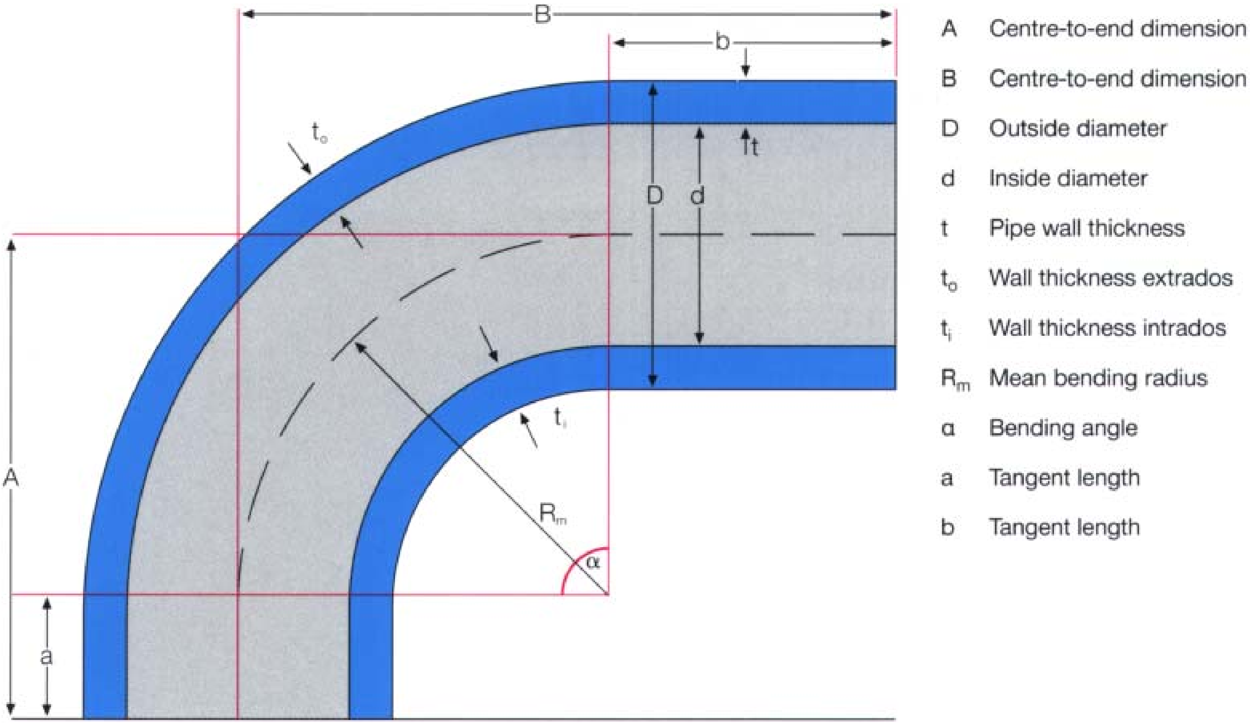
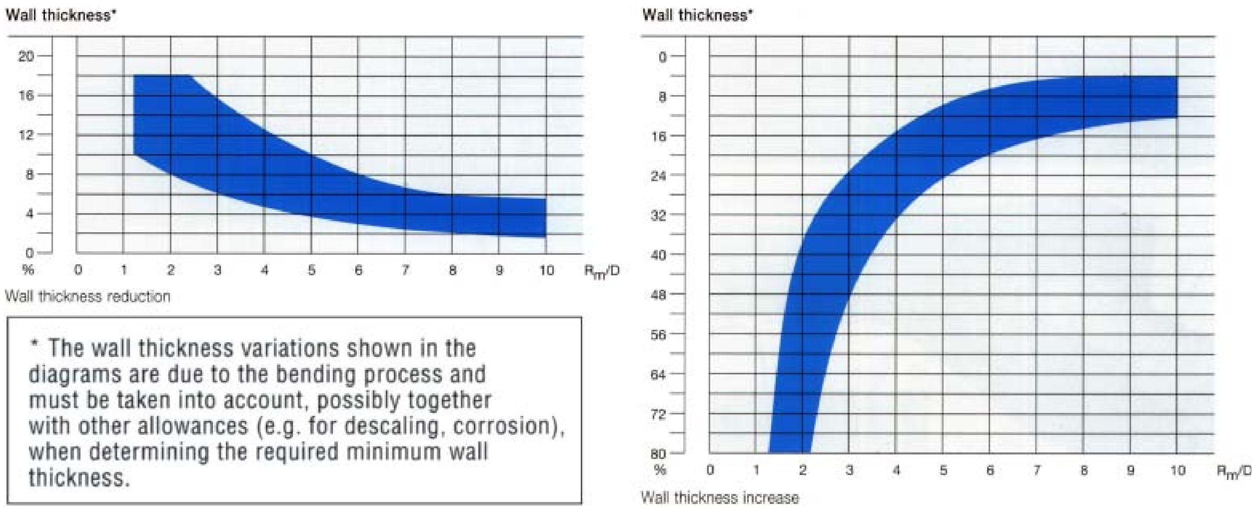


Figure 3: Geometrical details to specify a bend

During bending the material undergoes extensive plastic deformation. The bend extrados is strained, consequently the wall thickness decreases. The intrados is compressed resulting in an increased wall thickness. The percentage of thickening and thinning depends on the bend radius. Figure 4 shows the expected changes of wall thickness after bending in relation to the radius-to-diameter ratio. These changes in wall thickness must be taken into account during the geometrical design of the pre-material.



* The wall thickness variations shown in the diagrams are due to the bending process and must be taken into account, possibly together with other allowances (e.g. for descaling, corrosion), when determining the required minimum wall thickness.

Figure 4: Wall thickness change of bend extrados (wt. reduction) and intrados (wt. increase) in relation to the radius-to-diameter ratio

Figure 5 shows the distribution of material elongation respectively compression on a 5D bend, measuring 48” x 24 mm wt. in grade X65. The longitudinal seam is placed in the neutral axis of the bend, which is the area of minimum deformation over the circumference. Deformation during hot induction bending takes place in longitudinal direction only and not in circumferential direction.

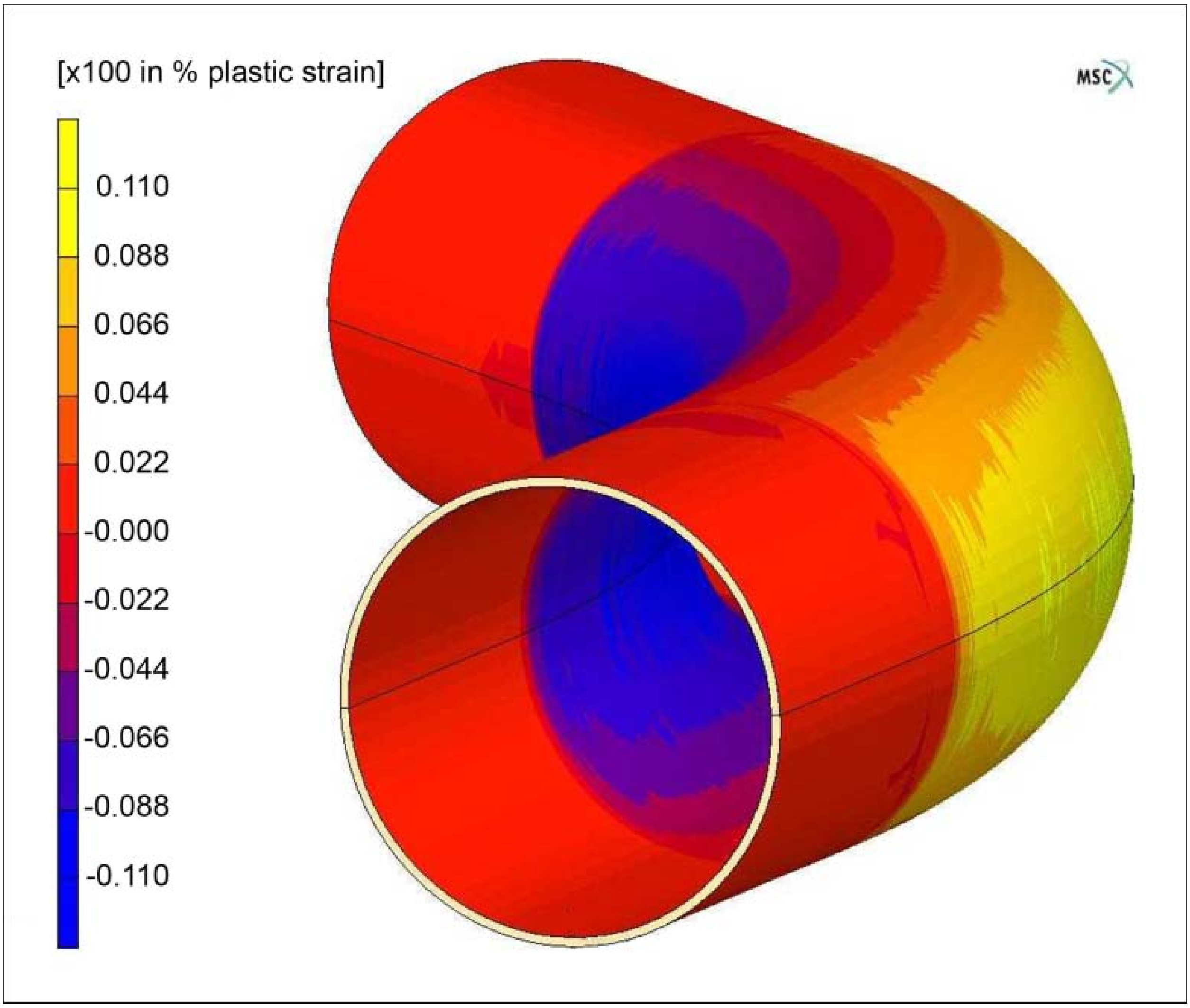


Figure 5: Distribution of elongation and compression on a 5D bend (48” x 24 mm; grade X65)

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 outside (OD) or at inside (ID) of the mother pipe. Figure 6 shows possible bend end preparation in order to match abutting line pipe and bend for girth welding.

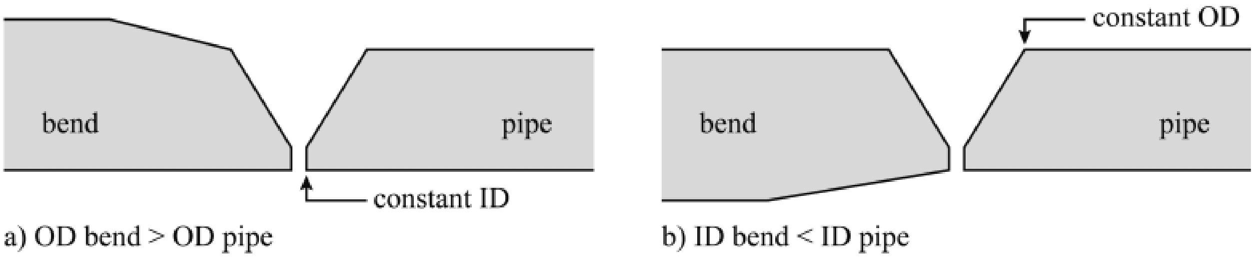


Figure 6: Typical bevel preparations for girth welding of pipe-to-bend connections

If tight gauging requirements have to be fulfilled on the finished bends, mother pipes for bends should always be ordered to constant ID (Figure 6 a).

In any case a minimum wall thickness of the mother pipe must be considered in order to avoid buckling during bending. Figure 7 gives an overview of minimum required wall thickness in combination with the desired OD and radius to be bent, possible at Mannesmann Bending Plant.

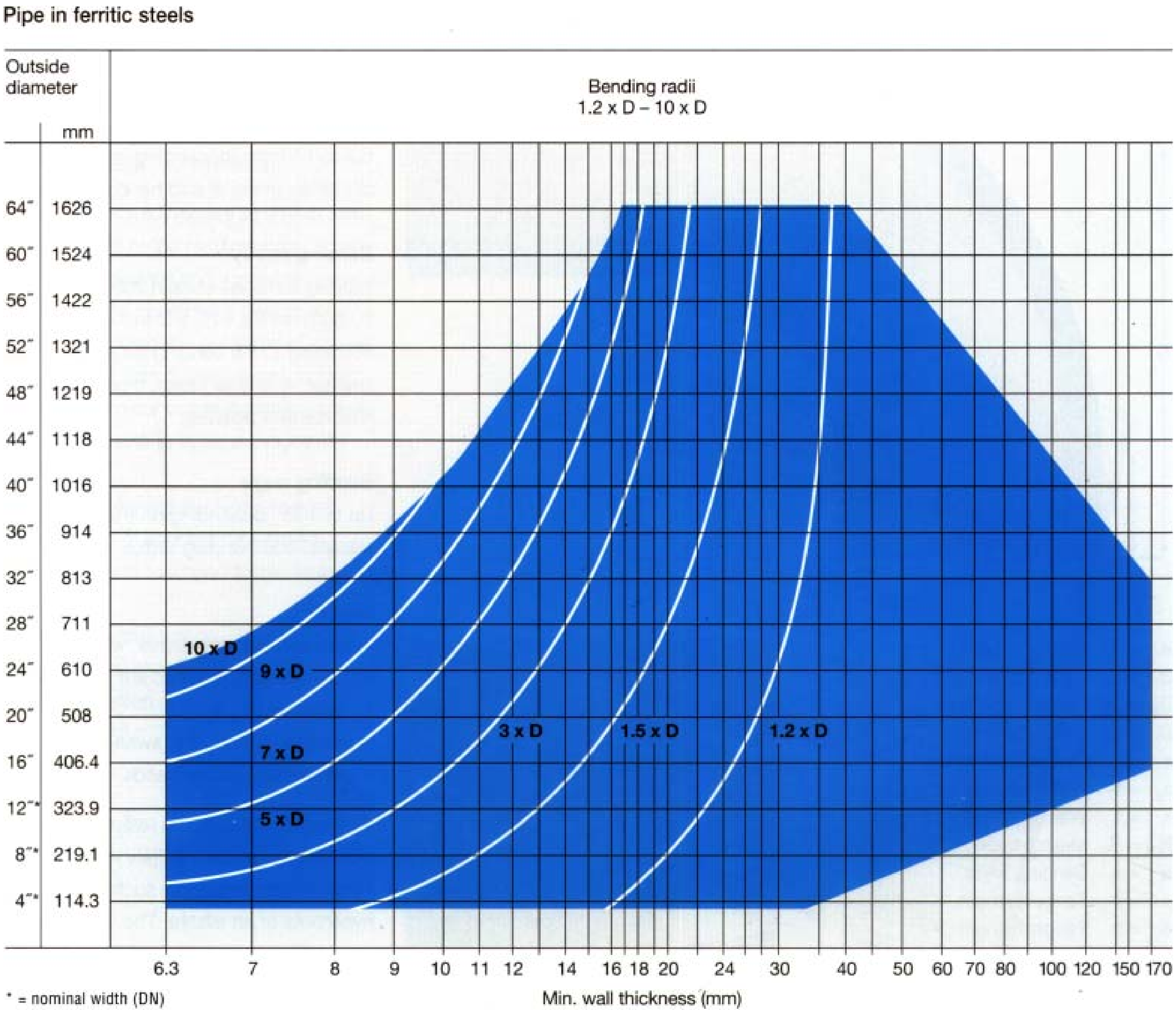
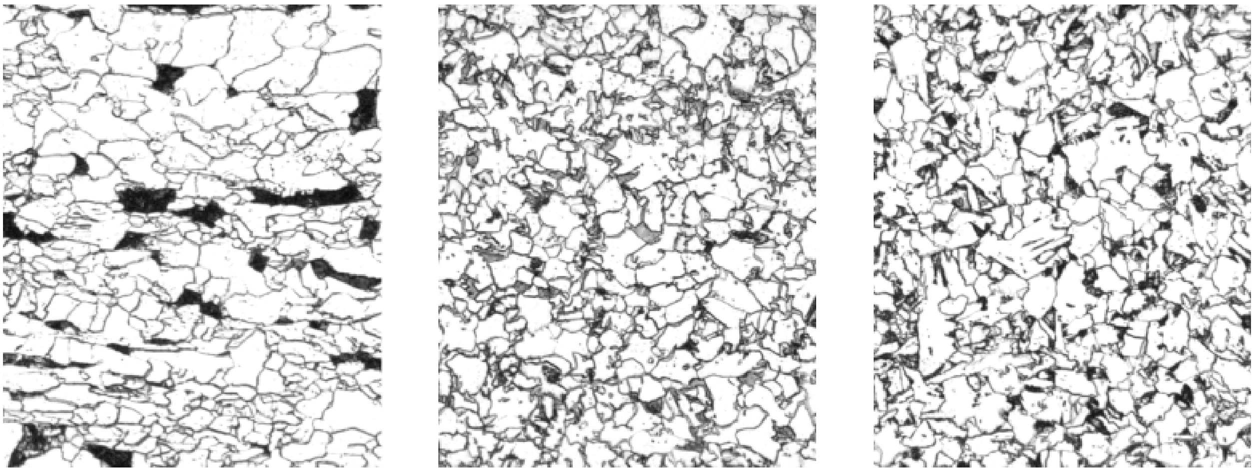


Figure 7: Bending Program of Mannesmann Bending Plant

Bends for oil and gas application should always be heat treated after bending to fulfil the high quality level of general standards and requirements (e.g. DNV, Shell, ISO, TFE [2–5]). Possible full body heat treatments are "tempering", "quenching and tempering" or "normalizing", depending on bend dimension, material grade and chemical composition of mother pipe.

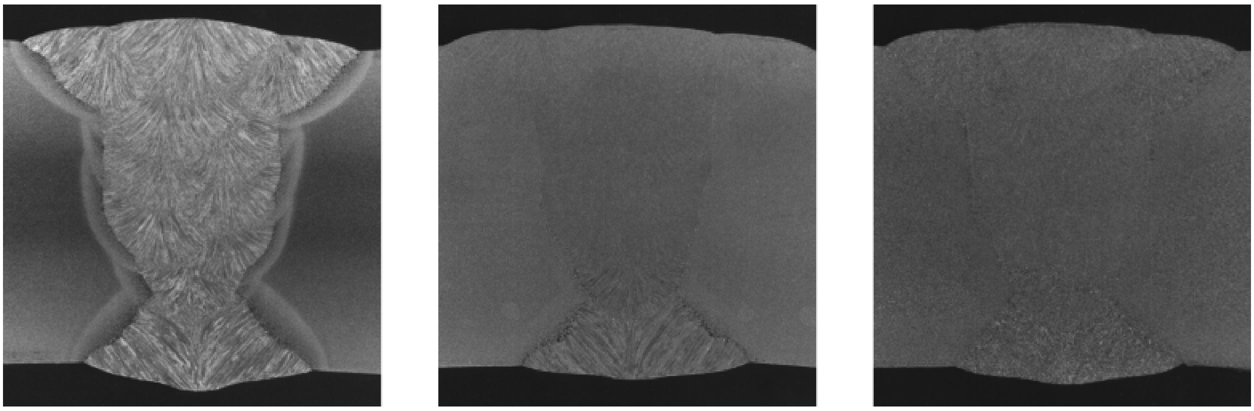


a) TMCP-plate b) as-bent c) bent & tempered

Figure 8: Microstructure at magnification x 500 in condition as-delivered/TMCP (a), as-bent (b) and bent & tempered (c)

During bending the material is heated above A_{c3} transition point into the austenitic range and cooled (quenched) by water. The fine grained TMCP microstructure present in plate (Figure 8 a) is transferred to a quenched microstructure (Figure 8 b). Generally for pipe wall thickness up to 30 mm this short-term austenitisation and quenching under the induction coil is very effective. Due thereto the typical post bend heat treatment is full body tempering on hot bent pipes with wall thickness below 30 mm (Figure 8 c).

In case of greater pipe wall thickness a certain heat gradient over the entire wall thickness can not be avoided (Figure 9 b), since cooling is normally applied to the external surface only. In order to achieve a homogenous microstructure over the complete wall thickness, a full body quench and temper heat treatment after bending is necessary (Figure 9 c).



a) as-welded b) as-bent c) full body QT

Figure 9: Macrographs from a multilayer weld of SAW bent pipe measuring 24” x 35 mm wt. in condition as-welded (a), as-bent (b) and full body QT after bending (c)

If the induction bending process is applied with inadequate controls or used to reconfigure materials that are incompletely or improperly characterised, it can produce disappointing metallurgical results and in the worst case lead to disastrous failures [1]. Therefore all important aspects must be considered prior to placement of pre-material order. Since the pre-material must be suitable for bending, the responsibility for the design and testing requirements of plates and pipes should always be with the bend supplier.

Pre-material for Induction Bend Fabrication

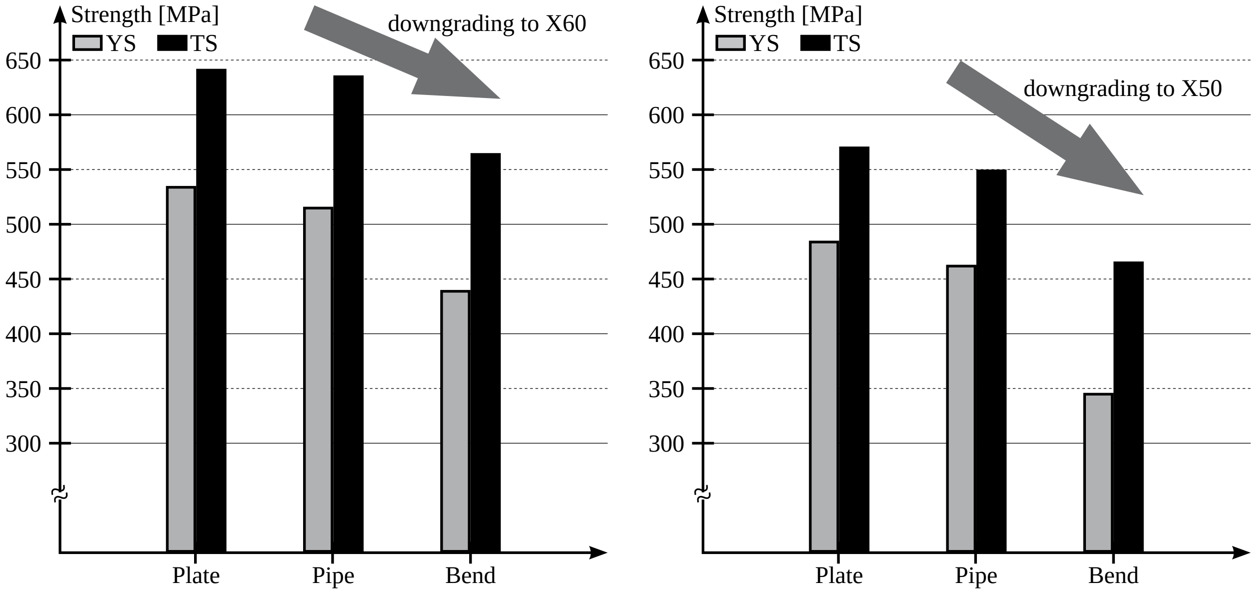
Strength Properties Considering the process related heat treatments during induction bend fabrication, plates in quenched and tempered (QT) or normalised condition seem to be most suitable as pre-material for pipes to be bent. But typically the Carbon Equivalent (CE) of such plates is higher than that of TMCP plates to obtain the same level of tensile properties [6]. Furthermore QT plates are more expensive than TMCP plates. Thus, for cost and for weldability reasons, TMCP plates are preferable for bend production where possible.

TMCP plates can be characterised by a lean chemical composition with low Carbon and Manganese contents and addition of at least one micro alloying element such as Niobium and/or Vanadium and/or Titanium. During TMCP plate production a controlled rolling schedule with different deformation ranges at specific temperature levels is followed by an accelerated cooling where necessary. This process enables production of material grades up to X100/X120 for non sour application or up to X65/X70 for sour service application [7; 8]. The latter steel grades have an even lower Carbon content than non sour grades. Hence the strength level for sour service grades is even more difficult to maintain after re-heating the material during induction bending.

In order to use “normal” TMCP pipe analysis for induction bend fabrication, the wall thickness has to be increased sufficiently in order to compensate the drop in strength properties after bending. This means, the product of specified minimum yield strength (SMYS) and specified min. design wall thickness (smwt) has to be equal or lower than the product of the actual measured yield strength (AMYS) and the actual min. wall thickness measured (amwt) on the bend [9]:

$$\text{SMYS x smwt} \leq \text{AMYS x amwt} \tag{1}$$

The expected drop in YS on the bend material must be known in advance. This in order to determine the adequate wall thickness of the mother pipe to be used. Figure 10 is showing two examples for downgrading of material during bend fabrication.



C	Si	Mn	Cu	Cr	Ni	Mo	Nb	V	Ti	CE
0.08	0.30	1.32	0.03	0.03	0.03	0.01	0.040	0.003	0.02	0.37

a) Linepipe grade X65, 44” x 25 mm

C	Si	Mn	Cu	Cr	Ni	Mo	Nb	V	Ti	CE
0.05	0.28	1.32	0.01	0.01	0.02	0.01	0.037	0.050	0.01	0.29

b) Linepipe grade X60 sour, 48” x 28 mm

Figure 10: Change of strength properties during hot induction bend fabrication for common line pipe material from TMCP plate material

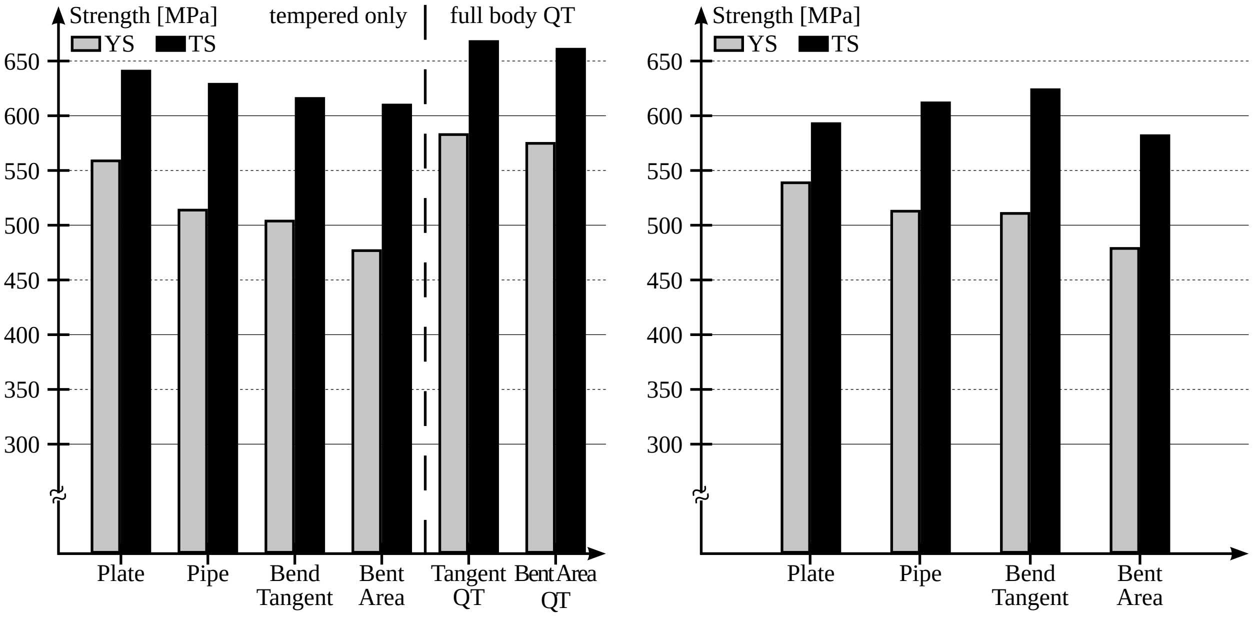
The extent of downgrading TMCP material used for bends can not be generalised. The strength level of the material to be expected in the final condition is always dependent on the actual chemical composition and the wall thickness. This effect becomes even more significant on lean alloyed material for sour gas application (Figure 10 b).

If material downgrading is not allowed or not possible, the chemical composition of the plate has to be designed specially for bend fabrication. Most of the strength properties achieved by special rolling and cooling parameters leading to excellent tensile properties on the plate are lost during bending (Figure 10). The strength properties of the TMCP material always decrease during the various fabrication stages from plate to pipe and from pipe to bend. For an UOE pipe (or a 3roll bend pipe) this level is predictable and related to the cold forming from plate to pipe. But for subsequent bend fabrication the chemical composition is the essential variable. Alloying elements increasing the hardenability of the steel like Cu, Cr, Ni, Mo, Nb, V must be added. Due thereto induction bends normally require slightly higher Carbon Equivalents than normal line pipe analyses. An example taken from DNV Offshore Standard [2] for maximum restrictions of chemical composition for line pipes and bends is shown in Table I for non sour material of material grades L 450 and L 485.

Table I: Comparison of chemical composition in maximum weight% for line pipes and bends [2]

	Line Pipe	Bend	Line Pipe	Bend
	SMYS = 450 MPa		SMYS = 485 MPa	
C	0.15	***0.16***	0.16	***0.17***
Mn	1.65	***1.75***	1.75	***1.85***
Si	0.45	0.45	0.45	0.45
P	0.020	0.020	0.020	0.020
S	0.010	0.010	0.010	0.010
Cu	0.50	0.50	0.50	0.50
Ni	0.50	0.50	0.50	0.50
Mo	0.50	0.50	0.50	0.50
Cr	0.50	0.50	0.50	0.50
Al $_{\text{(total)}}$	0.06	0.06	0.06	0.06
Nb	0.05	0.05	0.05	0.05
V	0.09	0.09	0.10	0.10
Ti	0.06	0.06	0.06	0.06
N	0.010	***0.012***	0.010	***0.012***
B	0.0005	0.0005	0.0005	0.0005
CE_{IIW} |t >15	0.41	***0.45***	0.42	***0.46***
Pcm	0.24	-	0.25	-

The necessity of higher Carbon Equivalent and higher contents of single alloying elements is considered by DNV Offshore Standard. The differences between bend and line pipe composition are indicated in bold letters. These maximum ranges allow for all possibilities to design the chemical composition of a bend according to the customers requirements and without downgrading of material in the final condition.



C	Si	Mn	Cu	Cr	Ni	Mo	Nb	V	Ti	CE
0.10	0.33	1.53	0.01	0.12	0.20	0.01	0.040	0.070	0.01	0.40

a) Bend fabrication X65, 24” x 35 mm

C	Si	Mn	Cu	Cr	Ni	Mo	Nb	V	Ti	CE
0.05	0.24	1.37	0.16	0.06	0.17	0.18	0.041	0.010	0.01	0.35

b) Bend fabrication X65 sour, 42” x 25 mm

Figure 11: Change of strength properties on special designed TMCP-material, suitable for induction bend fabrication

Figure 11 shows the change in strength level during the various fabrication stages from plate to pipe to bend for specially designed material, without downgrading of the finished bend.

For bends with full body tempering, there is always a difference in strength level measured on the tangent and the bent area, since the tangent is tested in the condition "as-delivered & tempered" and the bent area in the "quenched during bending & tempered" condition. One detailed example for the variation of strength properties in different test positions of a bend in material grade L 555 MB is shown in Figure 12. Bends with full body QT heat treatment after bending show no significant difference between the measured values at different test locations (Figure 11 a). Furthermore it can be gathered from Figure 11 a, that full body QT after bending is increasing the complete level of strenght properties on the finished bend.

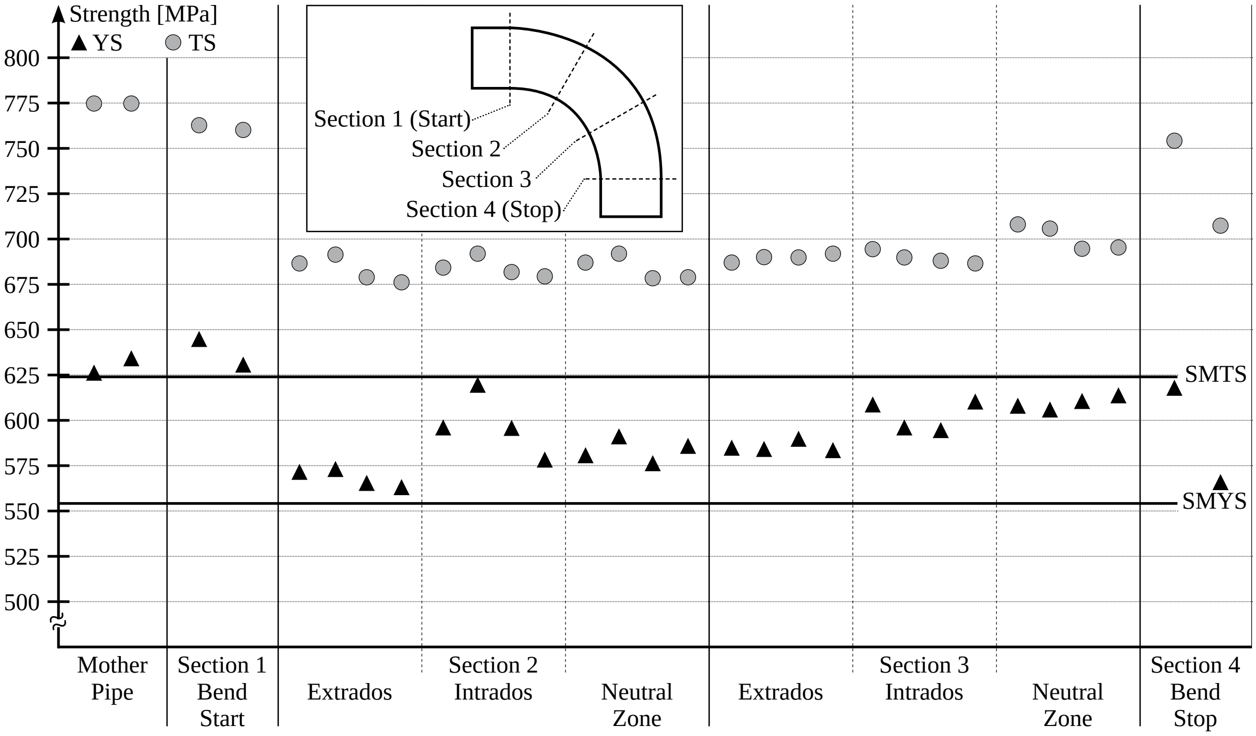


Figure 12: Strength properties (single values, flat-trensverse) tested in different sections of 7D induction bends, grade L 555 MB measuring 48" x 25.9 mm [10]

Elements that increase the hardenability generally influence the weldability as far as toughness properties are concerned. Therefore necessary care must be taken during desing of the chemical composition under consideration of the customers special requirements.

Toughness Properties For mother pipe production special attention must be paid to the welding consumables. Generally the toughness of the weld is mainly influenced by the heat input, the oxygen and nitrogen contents in the weld metal, the chemical composition of the weld metal and the heat treatment applied on the final product [11]. The favourable microstructure for SAW seams is acicular ferrite [12].

The seam weld has to show sufficient strength and toughness properties following the complete heat treatments during bend fabrication. The decision whether the mother pipe should be welded using the two-pass technique with slightly basic flux or the multi-layer technique with high basic flux is dependent on toughness requirements.

The multi-layer welding technique leads to excellent Charpy-V-Notch (CVN) toughness results for test temperatures down to -50°C. For the test temperature range 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. For two-pass welds the plate chemistries strongly affect the weld metal properties, since the amount of dilution of the weld metal by the base plate is about 60–70% [12]. For bends with straight tangents the weld metal has to fulfil the toughness requirements after tempering (tangent) and after bending and tempering (bent area). In the weld metal microalloying elements 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 which influences the toughness of the seam weld [12; 13].

Vanadium is forming precipitations starting at a tempering level of 450°C–500°C and getting to their maximum of precipitated V-carbonitids between 550°C to 650°C [14]. Niobium precipitations start on a higher temperature level, therefore the hardening effect is not that detrimental to toughness of the weld metal at the same tempering temperature level.

For the different possibilities of post bend heat treatment (PBHT) the welding consumables and welding technique of the longitudinal seam weld of mother pipes have to be chosen carefully.

For low temperature application (-30°C to -50°C) a low heat input welding technique (multi-layer) using high basic flux is the most efficient way to maintain high toughness results on finished induction bends. The excellent toughness on mother pipe in the as-welded condition can even be improved by the heat treatment of the bends [15].

For test temperatures down to -20°C and common impact energy requirements of 30 J/40 J (single/average) the use of two-pass welded pipes (high heat input) is suitable up to wall thickness of 30 mm, using a slightly basic flux and preferably TiB-alloyed wires.

For test temperatures of -10°C and higher, the normal MnMo-alloyed wires in combination with slightly basic flux using the two-pass welding technique is suitable.

Attention has to be paid to the dilution of base material into the weld metal regarding the contents of micro segregating elements on dendritic grain boundaries [15].

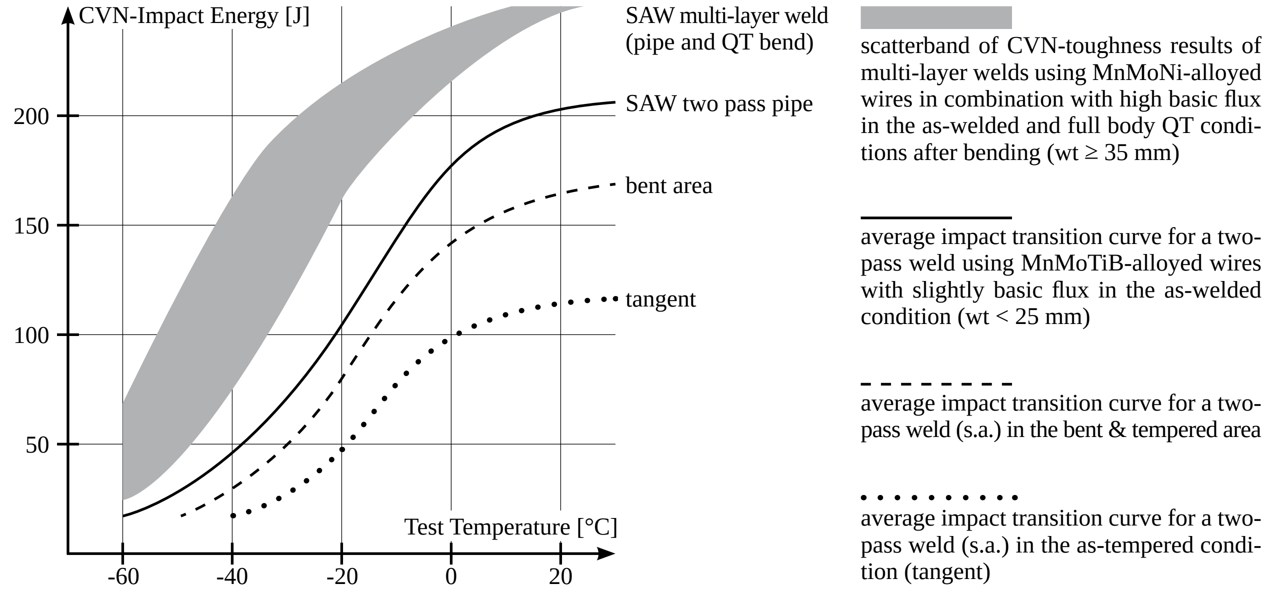
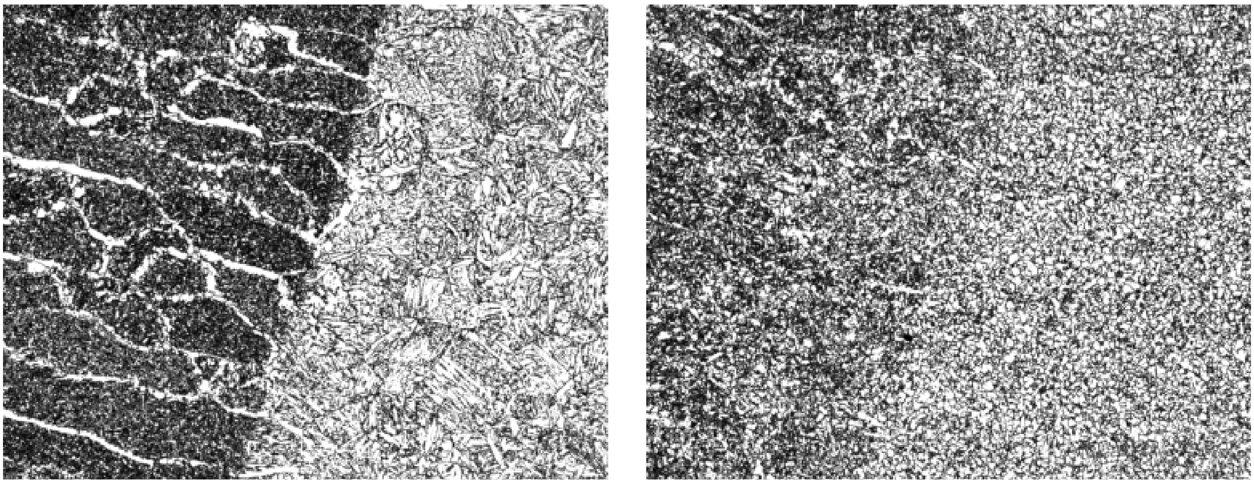


Figure 13: Change of weld metal toughness for a typical two-pass weld during bend fabrication in comparison with the scatterband of weld metal toughness of a multi-layer weld with no significant change in toughness on the finished bend

The change of the toughness level in two-pass and multi-layer welds on a bend in different process related heat treatment conditions are shown in Figure 13. In two-pass welds the transition temperature is shifted to a higher temperatures from the as-welded to the tempered condition. The toughness level for multi-layer welds in combination with the use of high basic fluxes is clearly on a higher level (Figure 13). The toughness results measured on the finished bend and in the as-welded condition of the mother pipe are in the same scatterband.

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 14, the heat affected zone (HAZ) is completely transformed by the heat treatment during the induction bending process.



a) as-welded

b) bent & tempered

Figure 14: Microstructure of the HAZ of a SAW two-pass weld in the as-welded (a) and bent & tempered condition (b) at magnification x 100

On the bend tangent the HAZ of the mother pipe is tempered which already leads to an improvement of toughness (Figure 15) and a reduction of the scatterband. In the bend area, where the HAZ is completely refined (Figure 14), the CVN-specimens with the notch located in the fusion line (FL) show excellent test results (Figure 15) and are on a comparable level like base material results.

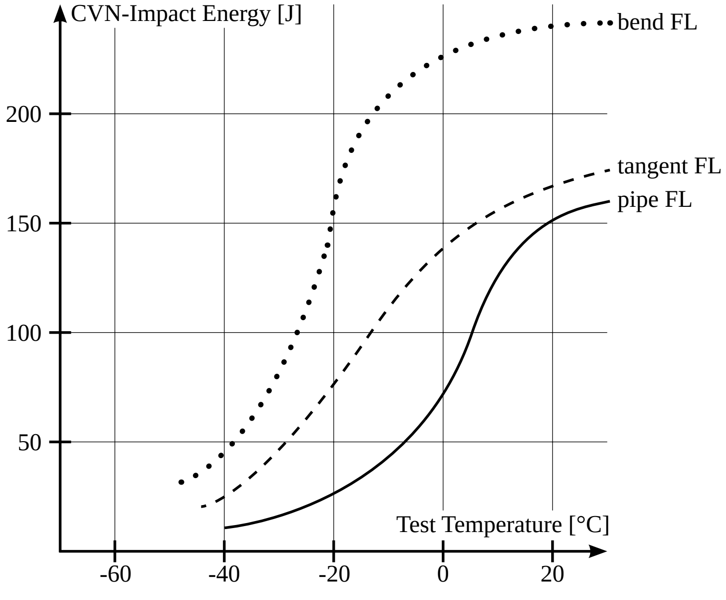


Figure 15: Change of toughness level for the HAZ on a SAW two-pass weld from mother pipe to finished bend

Summary

For hot induction bend fabrication not only the geometry of the mother pipe has to be considered. The chemical composition of base and weld metal of SAW large diameter pipes as well as the welding technique are important to fulfil the customers needs on the final product. If these aspects are taken into account from the start of ordering pre-material, the advantages of lean alloyed TMCP heavy plate material can be utilised for induction bend fabrication. With the correct design of the chemical analysis it is possible to produce HSLA induction bends. For this it must be considered that rolling effects on TMCP plate are reduced or even lost during the short-time austenitizing cycle of hot bending (above A_{c3} transition temperature). The material grade to be achieved can only be influenced by adding the necessary alloying elements to the chemical composition to guarantee adequate hardenability of the material during bending. Special attention must be paid to the longitudinal seam regarding the toughness requirements to be fulfilled. The general aspects regarding toughness and strength levels of a hot induction bend depending on the design of the mother plate and pipe are presented herein. The dynamics of the thermal cycle must be matched with the kinetics of the important metallurgical reactions to ensure that final mechanical properties and physical characteristics are suitable for the intended application.

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