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

Elke Muthmann, Fabian Grimpe

Mannesmannröhren Mülheim GmbH, Wiesenstrasse 36, 45473 Mülheim, Germany

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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 the 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 the TMCP mother plate. As a result of this requirement, the composition of the plate has to be specially designed in order to maintain mechanical-technological properties of the base material grade after induction bending.

Alloying and micro-alloying element contents must be optimized, ensuring sufficient hardenability, which is 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 with low Carbon Equivalents and good weldability for field welding, must be maintained.

Induction bending is normally followed by a full body temper heat treatment or, dependent on dimensions and requirements, a full body quench & temper heat treatment. This paper presents details of hot induction bend manufacturing, including aspects of dimensional and chemical design of the mother plate (TMCP) and SAW material that must be considered during induction bend fabrication.

Introduction

There is a need for bends in every pipeline system. Bends with large radii and small bend angles are usually fabricated on site by means of cold bending. But for smaller radii and bending angles of up to 90°, hot induction bending is the most common manufacturing process. Longitudinal submerged arc welded (SAW) large diameter pipes manufactured from thermomechanical controlled processed (TMCP) plate material are commonly used for oil and gas linepipe application. For higher efficiencies, large diameters up to 56" and high strength material, grades up to and 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 realized by the TMCP process for plate production with optimised chemical composition giving relatively low carbon equivalents and special rolling and cooling techniques. Material grades of API type X100 can be realized.

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 but also, ovality and gauging requirements must be taken into account during the design stage of the mother pipe. It is a prerequisite that the chemical composition of base material and SAW seam weld are suitable for the process related heat treatments of hot induction bend fabrication. This is essential in order to maintain the specified mechanical properties of the completed bend.

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 affected 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 and therefore heat.

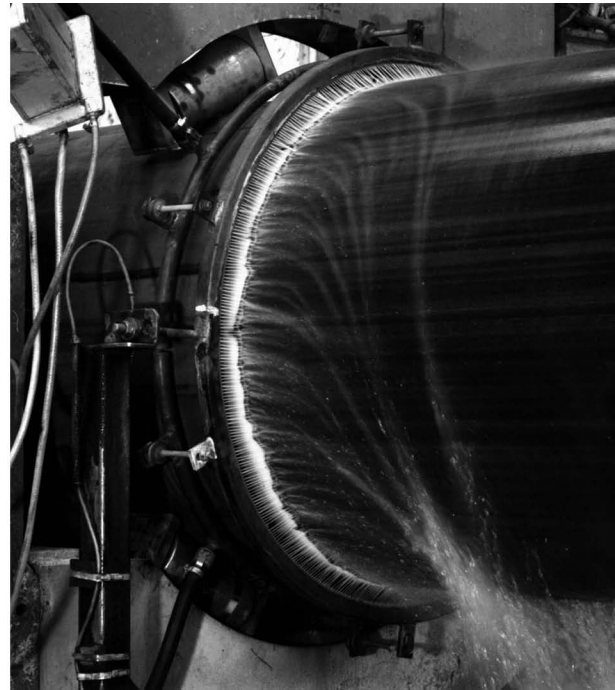Figure 1. Hot induction bending of 48" line pipe @ Mannemann Bending Plant

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" during field construction.

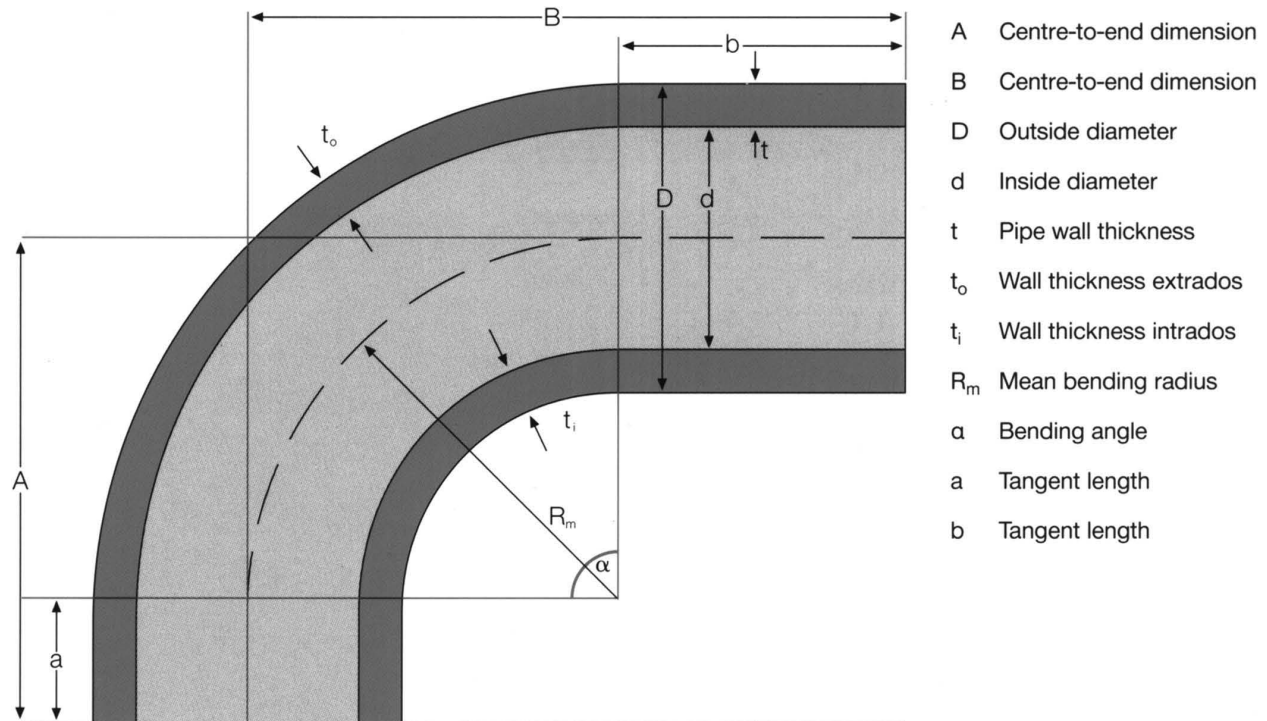|	
A	Centre-to-end dimension
B	Centre-to-end dimension
D	Outside diameter
d	Inside diameter
t	Pipe wall thickness
t_o	Wall thickness extrados
t_i	Wall thickness intrados
R_m	Mean bending radius
α	Bending angle
a	Tangent length
b	Tangent length

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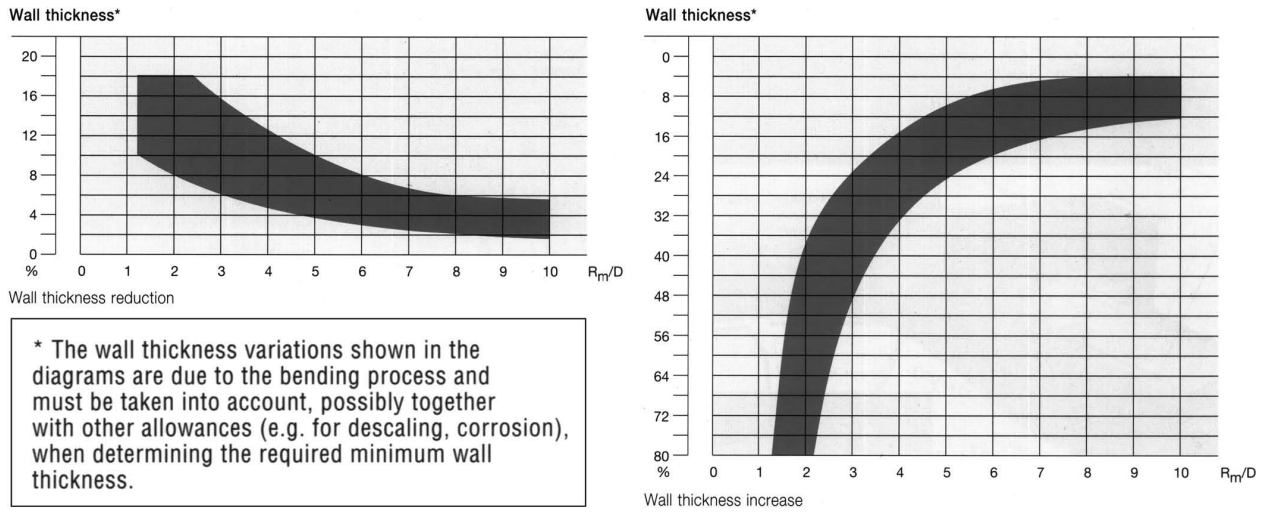
Figure 4. Wall thickness change of bend extrados (wt. reduction) and intrados (wt. increase) in relation to the radius-to-diameter ratio

Figure 5 shows the distribution of material elongation and 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.
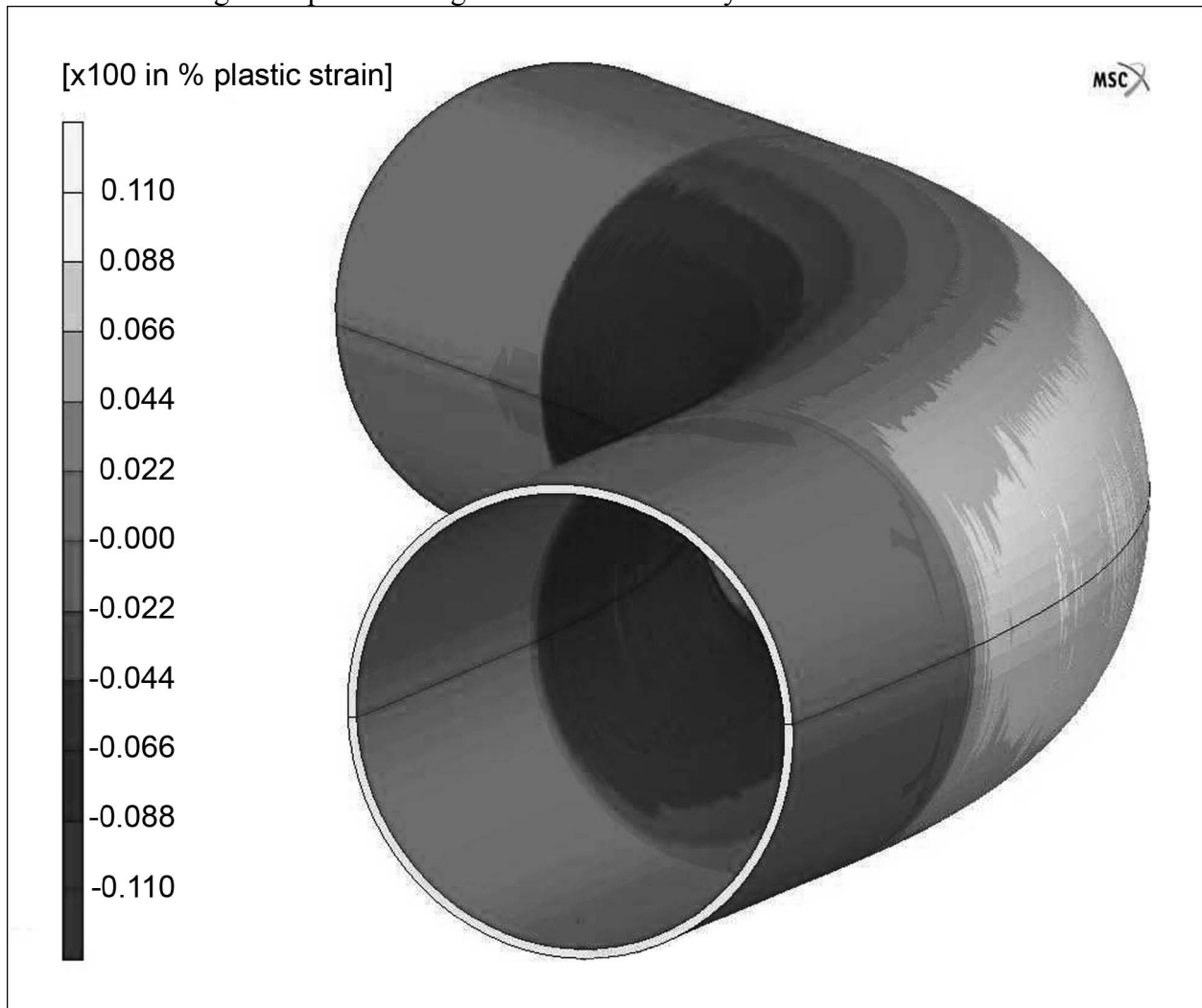

Figure 5. Distribution of elongation and compression on a 5D bend (48" x 24 mm; grade X65)

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.

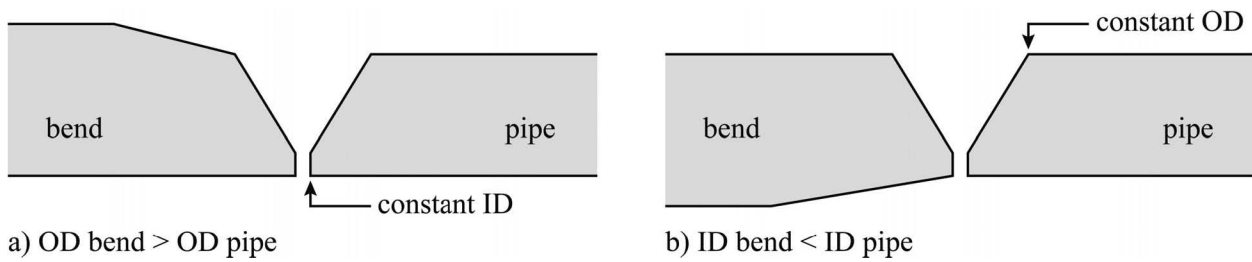a) OD bend > OD pipe   b) ID bend < ID pipe

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

If tight gauging requirements (pigging) have to be fulfilled on the finished bends, mother pipes for bends should always be ordered to a 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 which is possible at Mannesmann Bending Plant.
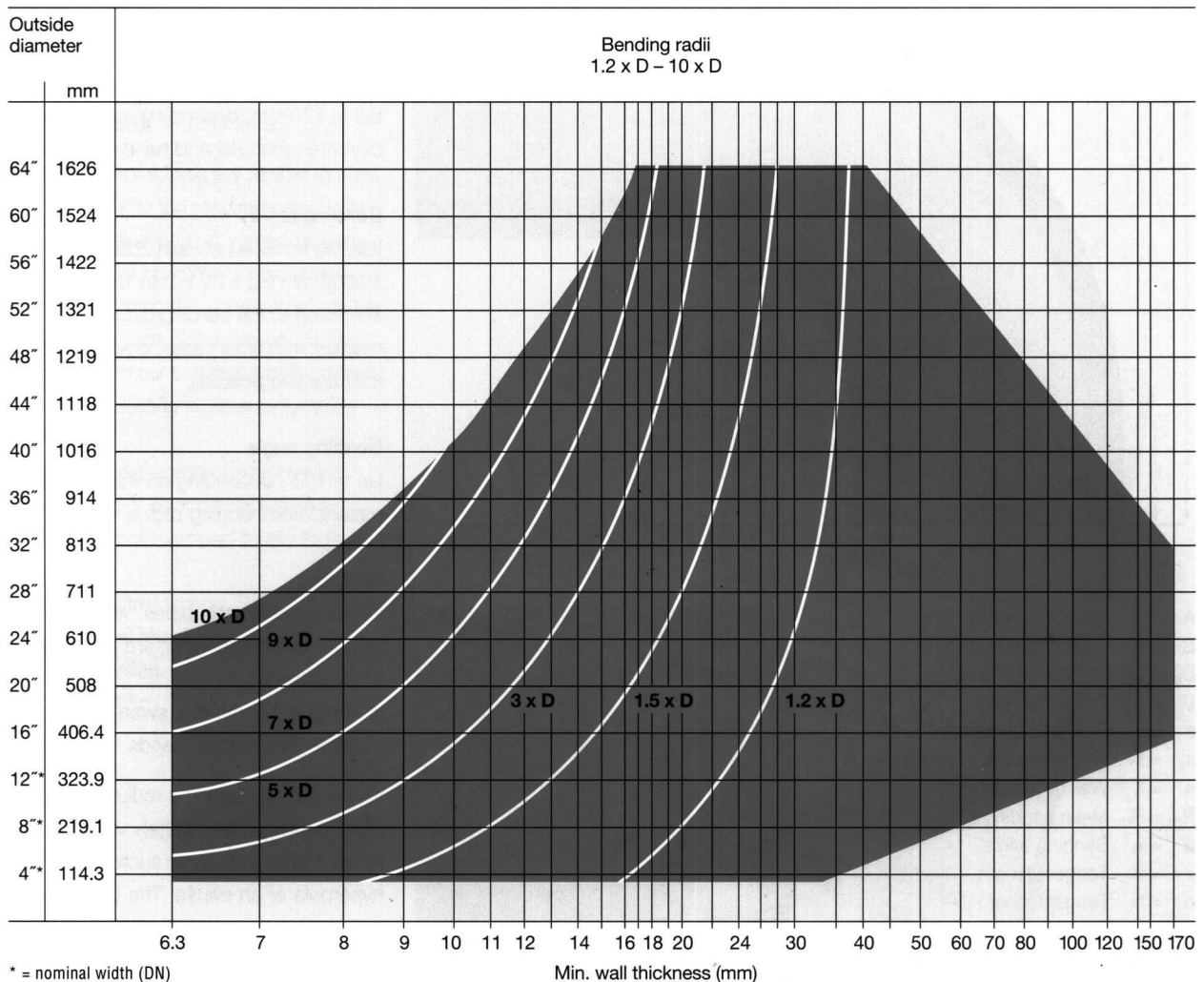
Pipe in ferritic steels

Figure 7. Bending Program of Mannesmann Bending Plant

Bends for oil and gas applications should always be heat treated after bending to fulfill the high quality level required by most codes and standards (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 the mother pipe.
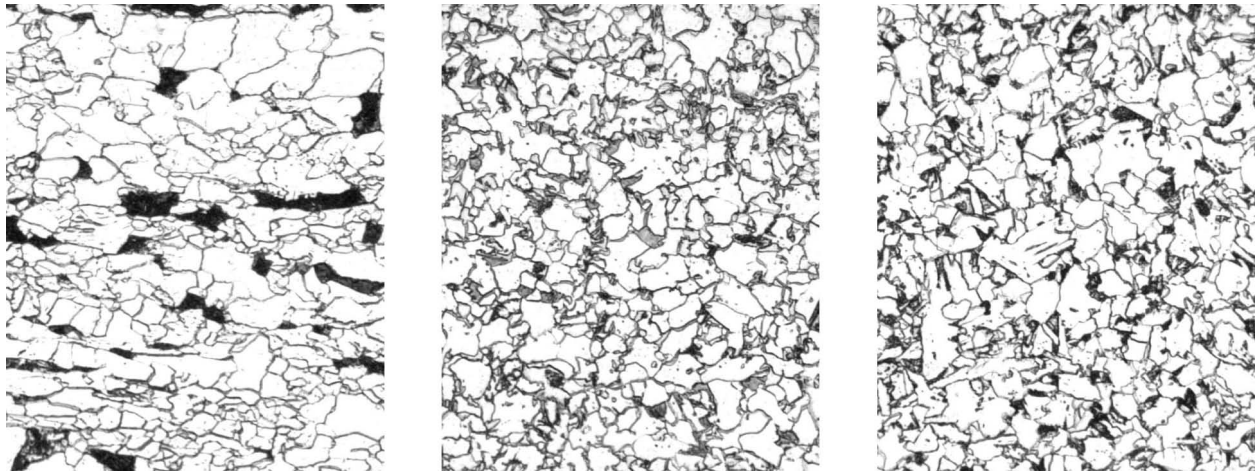

Figure 8a. TMCP-plate b) as-bent c) bent & tempered. Microstructure at magnification x 500 in condition as-delivered/TMCP (a), as-bent (b) and bent & tempered (c) During bending the material is heated above A_{c3} transition point into the austenitic range and cooled (quenched) by water. The fine grained 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. The typical post bend heat treatment is full body tempering on hot bent pipes with wall thickness below 30 mm (Figure 8 c).

In the case of pipe with greater wall thickness, a certain heat gradient over the entire wall thickness cannot 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 may be necessary (Figure 9 c).
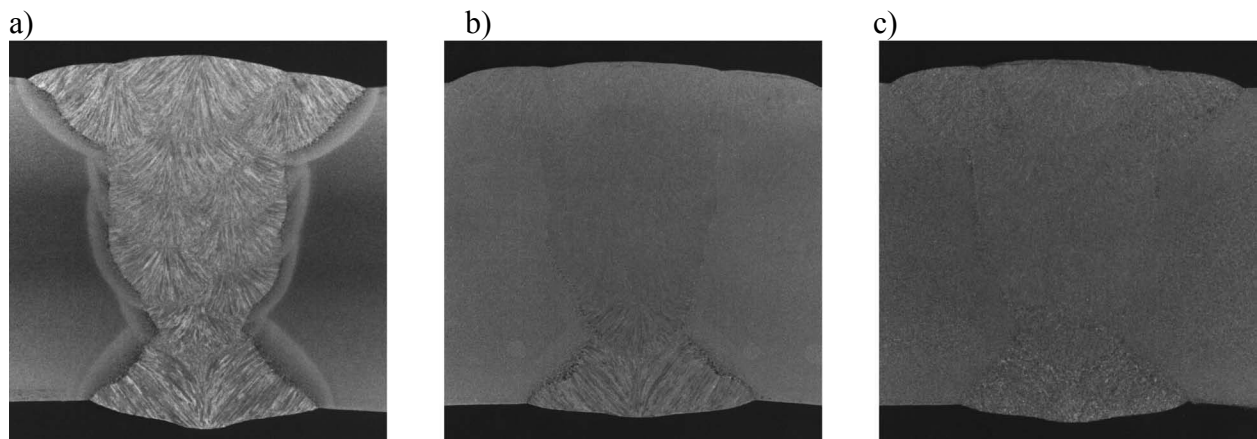

Figure 9a) as-welded b) as-bent c) full body QT.Macrographs from a multilayer weld of SAW bent pipe measuring 24" x 35 mm wt. in condition as-welded (a), as-bent (b) and full body Q&T after bending (c)

If the induction bending process is applied with inadequate controls or used to reconfigure materials that are incompletely or improperly characterised, it can produce unacceptable metallurgical

results and in the worst case lead to disastrous failures [1]. Therefore all important aspects of the finished bend must be considered prior to placement of pre-material order for the mother pipe. 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 that occur during induction the bend fabrication, plates in the quenched and tempered (QT) or normalised condition seem to be the 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 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, 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 must 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 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 minimum design wall thickness (smwt) has to be equal to or lower than the product of the actual measured yield strength (AMYS) and the actual min. wall thickness measured (amwt) on the finished bend [9]:

$$SMYS \times smwt \leq AMYS \times amwt \quad (1)$$

The expected drop in yield strength on the bend material must be known in advance. This is required in order to determine the adequate wall thickness of the mother pipe to be used. Figure 10 shows two examples of downgrading of material during bend fabrication.
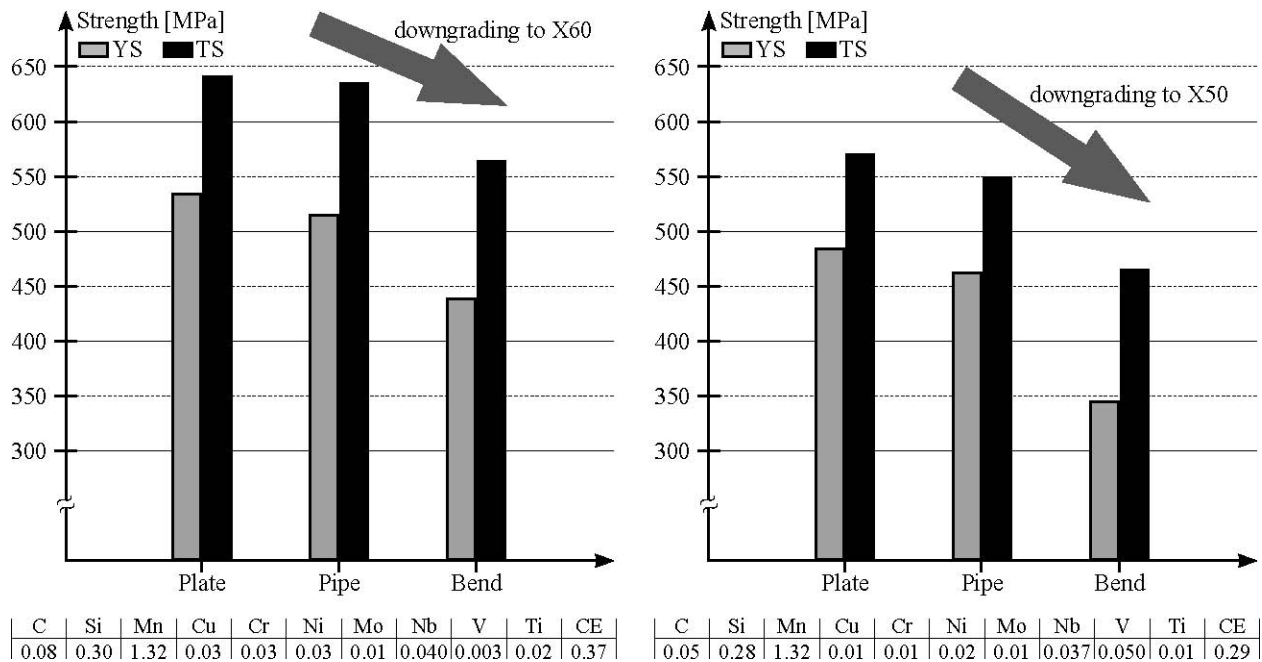
Figure 10a) Linepipe grade X65, 44" x 25 mm b) Linepipe grade X60 sour, 48" x 28 mm
Change of strength properties during hot induction bend fabrication for common line pipe
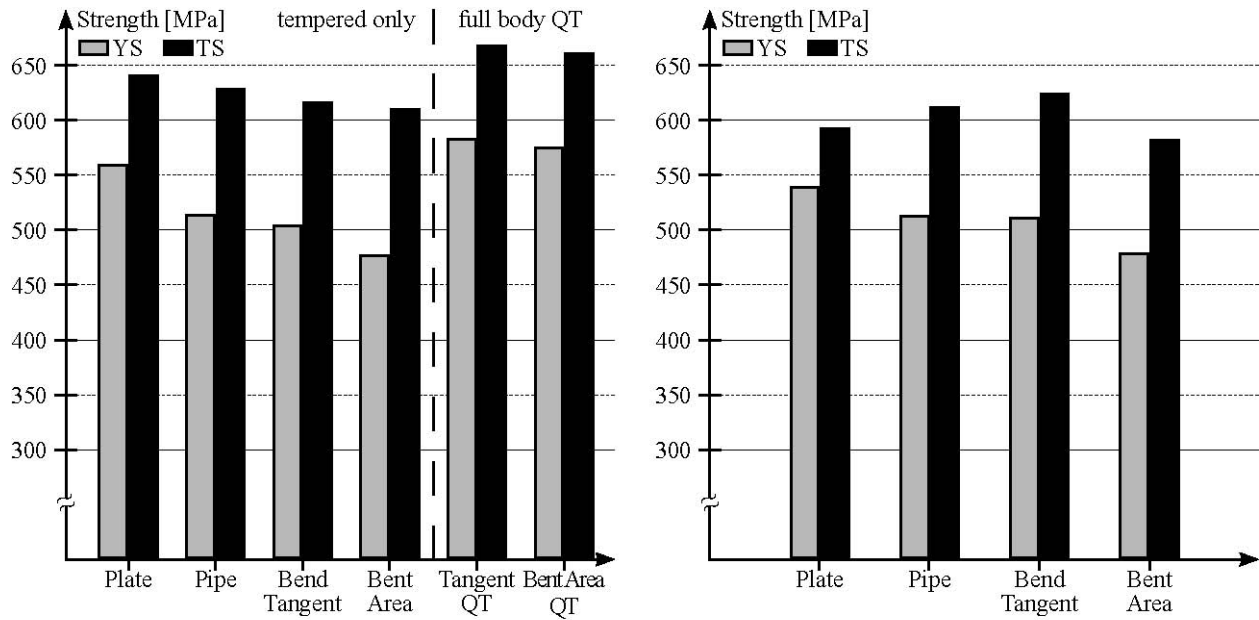material from TMCP plate material

The extent of the level of downgrading TMCP material used for bends cannot 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
for lean alloyed material for sour gas applications (Figure 10 b).

If material downgrading is not allowed or not possible, the chemical composition of the plate has
to be designed specifically for bend fabrication. Most of the tensile properties achieved by
special rolling and cooling parameters leading to excellent properties in the plate are lost during
bending (Figure 10). The tensile properties of the TMCP material always decrease during the
various fabrication stages from plate to pipe and from pipe to bend. For a UOE pipe (or a 3 roll
bent pipe) this level is predictable and related to the cold forming from plate to pipe. But for
subsequently induction bent 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. Therefore induction bends normally require slightly higher Carbon Equivalents than
normal line pipe analyses. An example taken from the DNV Offshore Standard [2] for the
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 percent 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 $_{(total)}$	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 has been considered by the DNV Offshore Standard. The differences between bend and line pipe composition are indicated in bold letters. These maximum ranges allow for the possibility to design the chemical composition of a bend according to the customers requirements without downgrading of the material in the final supplied condition.

| Strength [MPa] tempered only | full body QT |
| YS ▦ TS ■ | |

(Left chart, a)

Axis labels: Plate, Pipe, Bend Tangent, Bent Area, Tangent QT, Bent Area QT

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	0.007	0.01	0.40

a) Bend fabrication X65, 24" x 35 mm

(Right chart, b)

Axis labels: Plate, Pipe, Bend Tangent, Bent Area

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 (where the tangents are not passed through the induction coil), 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 tested 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 Q&T heat treatment after bending show no significant difference between the measured values at different test locations (Figure 11a). Furthermore it can be gathered from Figure 11 a, that full body Q&T after bending can increase the level of yield and tensile strength properties of the finished bend.
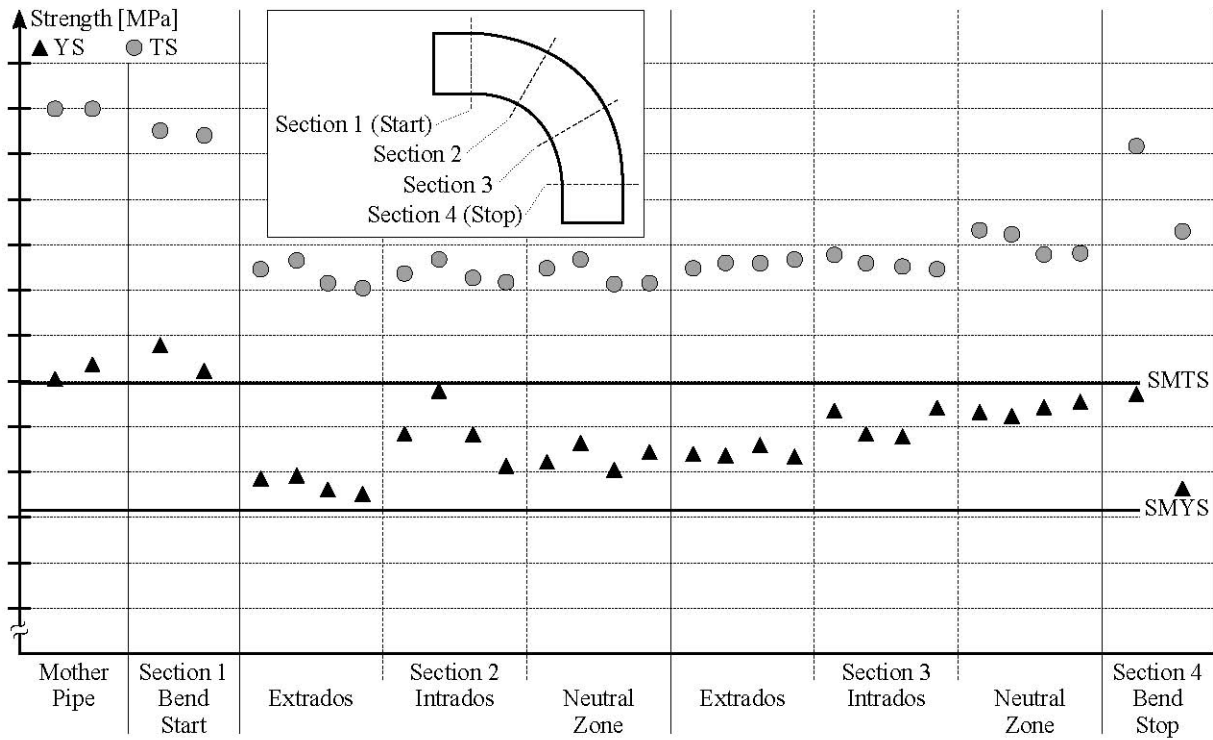
Figure 12: Strength properties (single values, flat-trensverse) tested in different sections of 7D induction bends, grade L 555 MB measuring 48" x 25.9 mm [10]

Elements that increase the hardenability generally influence the weldability as far as heat affected zone toughness properties are concerned. Therefore necessary care must be taken during the design of the chemical composition to consider the requirement of the customer for the finished material.

Toughness Properties

For mother pipe production, special attention must be paid to the welding consumables used for the SAW. 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 most favourable microstructure for SAW seam welds is acicular ferrite [12].

The seam weld has to provide 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 highly 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 chemistry strongly affects the weld metal properties, since the amount of dilution of the weld metal by the base plate is approximately 60–70% [12]. For bends with straight tangents, the weld metal has to fulfill the toughness requirements after tempering (tangent) and after bending and tempering (bent area). In the weld metal, microalloying elements such as 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 forms precipitates beginning at a tempering level of 450°C–500°C and getting to their maximum of precipitated V-carbonides between 550°C to 650°C [14]. Niobium precipitates start at 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 different post bend heat treatment (PBHT) possibilities the welding consumables and welding technique of the longitudinal seam weld of the mother pipe have to be chosen carefully.

For low temperature applications (-30°C to -50°C) a low heat input welding technique (multi-layer) using highly basic flux is the most efficient way to maintain high toughness results on finished induction bends. The excellent toughness of the mother pipe in the as-welded condition can even be improved by the subsequent 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 pipe (high heat input) is suitable up to a 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, especially the contents of micro segregating elements on dendritic grain boundaries [15].
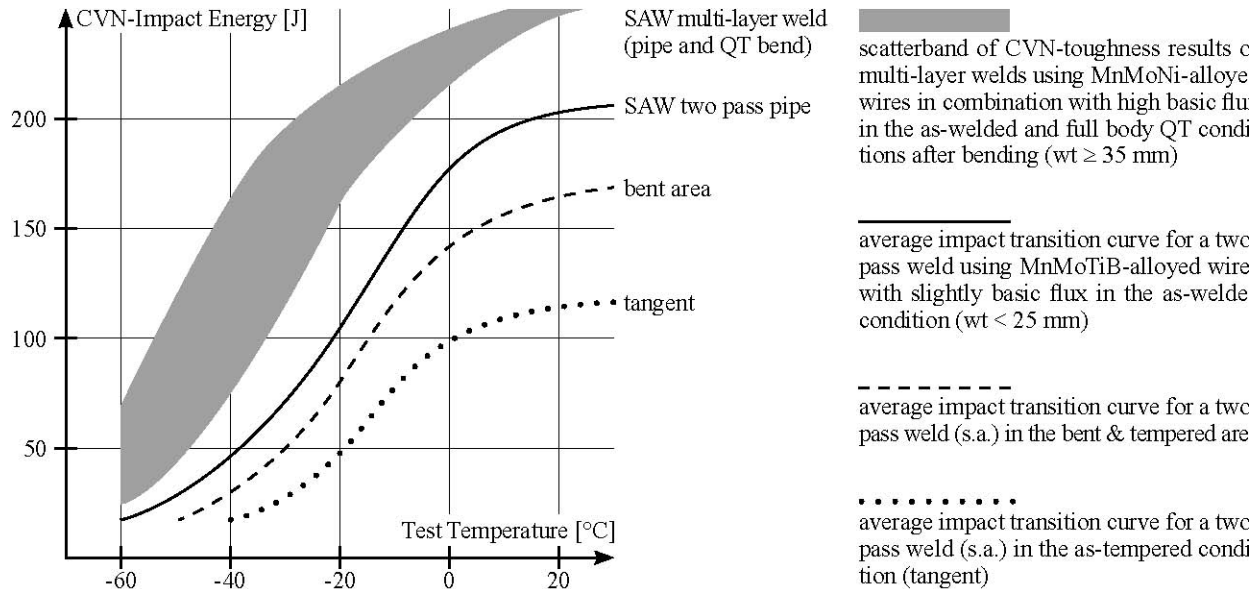

Figure 13: Change of weld metal toughness for a typical two-pass weld during bend fabrication in comparison with the scatterband of weld metal toughness of a multi-layer weld with no significant change in toughness on the finished bend

The change in the toughness in two-pass and multi-layer welds after bending using different process related heat treatment conditions is 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.
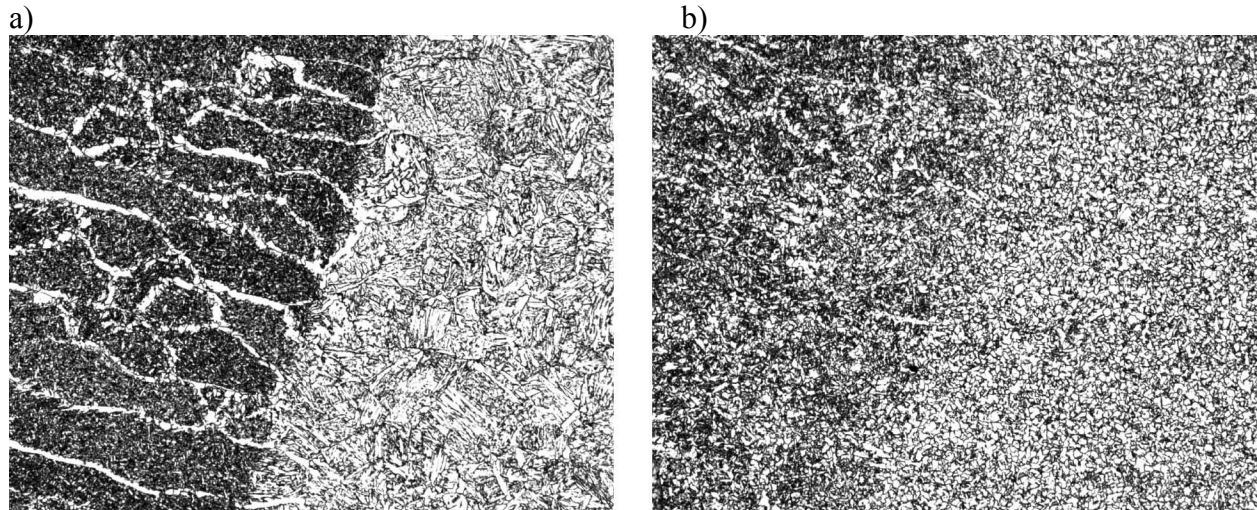
a)

b)

Figure 14 a) as-welded b) bent & tempered. 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 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 with the base material results.
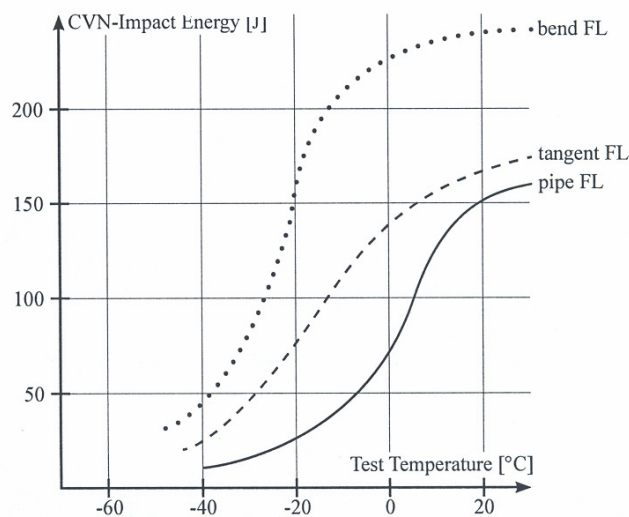

Figure 15. Change of toughness level for the HAZ on a SAW two-pass weld from mother pipe to finished bend

Summary

For hot induction bend fabrication it is not only the geometry of the mother pipe that has to be considered. The chemical compositions of base and weld metal of SAW large diameter pipes as well as the welding technique are important to fulfil the customers needs of the final product. If these aspects are taken into account when ordering pre-material, the advantages of lean alloyed TMCP heavy plate material can be utilized for induction bend fabrication. With the correct design of the chemical composition, it is possible to produce HSLA induction bends with excellent properties. For induction bends, 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 Ac3 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 toughness and strength levels of a hot induction bend depend on the design of the mother plate and pipe are the results obtained 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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