Proceedings of IPC 2006
6th International Pipeline Conference
September 25-29, 2006, Calgary, Alberta, Canada

IPC2006-10089

INDUCTION HOT BENDING AND HEAT TREATMENT OF 20" API 5L X80 PIPE

Gilmar Zacca Batista
PETROBRAS
g.zacca@petrobras.com.br

Leonardo Naschpitz
PROTUBO
leonardo.naschpitz@protubo.com.br

Eduardo Hippert Jr.
PETROBRAS
hippert@petrobras.com.br

Ivani de S. Bott
PUC-Rio
bott@dcmm.puc-rio.br

ABSTRACT

The present work discusses the effect of the induction hot bending process on the microstructure and the mechanical properties of an API 5L X80, 20" pipe produced by the UOE process. The key characteristic of the pipe was the manufacturing process of the steel plate, involving thermomechanical controlled rolling without accelerated cooling. The pipe bending was carried out applying local induction heating followed by water quenching and a further temper heat treatment which was applied to the curved section. The methodology of analysis compared the curved section with the original body pipe (tangent end), taking into account dimensional analysis, microstructural evaluation and mechanical tests which included Charpy-V impact, tensile and microhardness. A significant microstructural change and decrease, not only in the transition temperature, but also in the yield strength, occurred after induction bending. This reduction resulted in a tensile strength below the standard requirements. The subsequent tempering heat treatment applied to the curved section produced an increase in the yield strength to achieve the API 5L requirements for this class of steel.

INTRODUCTION

Gas production and consumption in Brazil are growing more and more. According to the Petrobras Strategic Plan, the growth perspective for the natural gas market is from 30,7 million m^3/day in 2003 to 77,6 million m^3/day in 2010 [1]. To attend this demand, is necessary that the new gas pipelines have larger diameters and operate with higher pressures, thus a pipe wall thickness increase or higher strength steels will be required. Increasing the strength of the steel permits the maintenance of pipe diameter while avoiding excessive wall thickness. In this way, the overall weight of the steel necessary for a given high pressure pipeline project can be reduced and economic advantages obtained.

In Brazil, the production of high strength X80 pipe grade, according to API 5L specification, is performed via the traditional controlled rolling process, as opposed to the accelerated cooling process that is used in other countries. Although already successfully produced in Brazil, the X80 pipe has not been used in onshore pipelines. For this purpose, it is necessary to evaluate the pipe behavior during the field construction, more specifically the bending and welding processes.

During pipeline construction, depending on the field profile, about 30% to 40% of the pipes are bent. The preference is cold bending, because this can be performed in the field. However, when the bend radius is small, it becomes necessary to apply a hot bending process. This process causes localized heating and fast cooling of the pipe section that is being bent, which can produce significant microstructural changes in the steel and, consequent changes in its mechanical properties.

Nowadays there is a lack of information in the open literature that shows the metallurgical details about the induction hot bending process in API 5L X80 pipe steel manufactured by controlled rolling, without accelerated cooling. In this study the influence resulting from the hot bending process and heat treatment in the microstructure and mechanical properties of the API 5L X80 pipe made in Brazil is evaluated.

This paper will be particularly useful for potential users of hot bends and present extensive and significant partial results of a thorough, ongoing program to evaluate the X80 hot bending process to facilitate its applications in pipelines.

MATERIAL AND EXPERIMENTAL PROCEDURE

A 20" x 0.75" API 5L X80 pipe, produced by the UOE process, was used for this study. The steel plate for pipe production was made by thermomechanical controlled rolling without accelerated cooling. This pipe was originally developed to be used as a straight pipe, so the wall thickness, the chemical composition and the route of production were not elaborated to anticipate the effects of the induction bending process. This situation is very common in pipeline construction in Brazil, since the amount of hot bends is very limited and doesn't justify a special batch production. Besides that, the specification and the purchase of pipes are made before the final land profile evaluation is concluded when the amount of bends that will be necessary is not still known, so the pipeline constructor has to choose the pipes available. Table 1 shows the steel's chemical composition and carbon equivalent values.

Table 1- Chemical Composition.

Elements (wt %)							
C	Mn	Si	Nb	V	Ti		
0.05	1.76	0.17	0.066	0.025	0.016		
Mo	Cr	Cu	Ceq (IIW)	Ceq (Pcm)	Nb+V+Ti		
0.20	0.15	0.02	0.42	0.17	0.11		
Elements (ppm)							
P	S	Sn	B	Ca	Ni	N	Al
160	20	20	3	30	200	57	350

Figure 1 shows the hot bending process applied. The pipe end is pushed while a rotating arm guides the pipe during the bending according to the desired bend radius, the other end remaining fixed. During the bending, the pipe passes through a high frequency coil that creates a concentrated magnetic field and induces an electric potential in the pipe creating a current flow. The pipe's resistance to the flow causes fast and localized heating that is followed by a water quenching, applied at the external pipe surface.

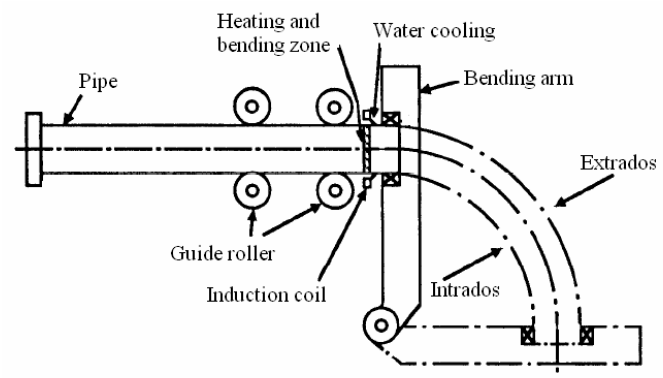

Figure 1- Schematic diagram of the bending process [2].

The bending temperature was around 1050ºC and a 2.54 m bend radius was produced, resulting in a 70º bend angle.

Figure 2 shows the 20" X80 bending process. Note that, just after the passage of the heating coil, the pipe is water cooled externally.

Figure 2- X80 bending process [3].

To evaluate the effect of the bending process on the pipe, mechanical tests (tensile, Charpy V and microhardness) and dimensional analysis were undertaken. The mechanical tests were carried out according to API 5L [4] and ASTM A 370 [5] standards. Tensile properties were measured using transverse round bar specimens. Impact properties were measured using transverse, full size Charpy V specimens where the long dimension was parallel to the circumferential direction. Charpy V and tensile specimens were taken from the middle of the wall thickness. In addition, a microstructural analysis was performed.

The purpose of this test methodology is not qualify a bend procedure according applicable standards but to determine the influence of the applied heating in all parts of the bend. The regions evaluated in this study are not only in agreement with ISO 15590-1 [6], DNV-OS-F101 [7] and ASME B16.49 [8] but also meet these standards requirements as can be seen in Figure 3.

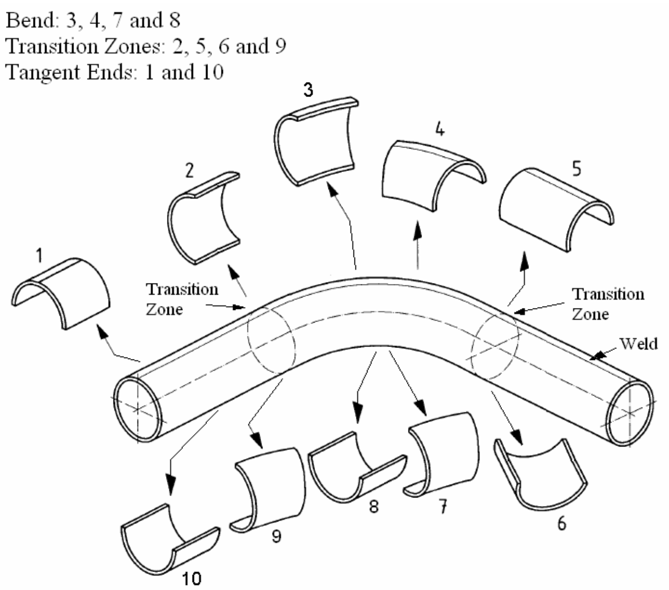

Figure 3- Location for extraction of samples for testing.

1- Tangent Weld;
2- Extrados Transition Zone;
3- Extrados;
4- Bend Weld;
5- Weld Transition Zone;
6- Neutral Axis Transition Zone;
7- Intrados;
8- Neutral Axis;
9- Intrados Transition Zone;
10- Tangent End.

RESULTS AND DISCUSSION

Dimensional Evaluation

During pipe bending, the main dimensional changes are extrados wall thickness decreasing, intrados increasing, changes in pipe diameter and ovalization.

Wall thickness measurements were performed using an ultrasonic thickness gage. These measurements were made in the intrados, extrados and tangent end regions. Pipe diameter and ovalization measurements also were performed.

The pipe diameter decreased only 0.1%. According Williams [9], this decrease is attributed to thermal expansion and contraction effects as the pipe passed through the induction coil.

The ovalization was relatively slight (only 0.5%), as calculated by the difference between the largest and smallest external diameters divided by nominal diameter. The slight amount of ovalization can be attributed to the relatively small diameter/wall thickness ratio.

The intrados wall thickness increase was 9.8% and extrados decrease was 8.4%. Pipe subjected to the hot bending process should take into account these dimensional changes. However, as mentioned before, the specification and the purchase of pipes are often performed before the final land profile evaluation is concluded, so the pipeline constructor have to choose the thicker pipes available (usually the excess pipes purchased for directional drilling).

Microstructural Evaluation

During induction hot bending the maximum temperature to which the steel is heated usually exceeds the upper critical temperature for 1 to 2 minutes; thus the microstructure of steel is transformed to austenite. Immediately after passing through the induction coil, the heated area is water quenched. After quenching, the microstructure of the steel may consist of various microconstituents, depending upon the pipe composition and cooling rate, such as ferrite, pearlite, bainite, martensite, or combinations of these transformation products. Furthermore, Williams [9] explains that different points around the pipe circumference pass beneath the induction coil at different speeds, depending on their distance from the bend axis. The outer radius would be under the induction coil for a shorter time than would the inner radius, for example.

The microstructure observed in the tangent end is shown in Figure 4.

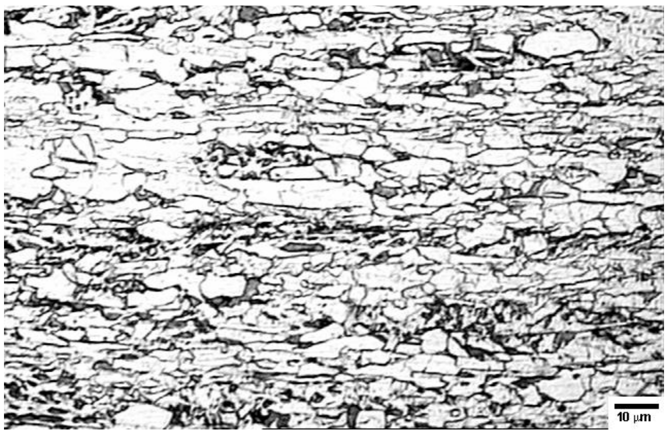

Figure 4- Original microstructure (tangent ends). Optical Microscopy. Magnification: 500X. Etch: 2% Nital.

Figure 5 shows the tangent end and bend (intrados, extrados and neutral axis) microstructures for three wall thickness areas (I- inner surface, M- mid-thickness, O- outside surface). The Vickers microhardness values (Load: 100gf) is presented at the right of the pictures.

The original pipe microstructure consisted of fine polygonal ferrite with a small amount of pearlite (Figure 4) and, scanning electron microscopy, after a two-step electrolytic etching, Ikawa's solution [10 and 11] (Figure 5a) confirmed presence of MA (martensite-austenite) in the ferrite matrix. After quenching, the microstructures of all bend regions are changed (Figure 5 b, c, d).

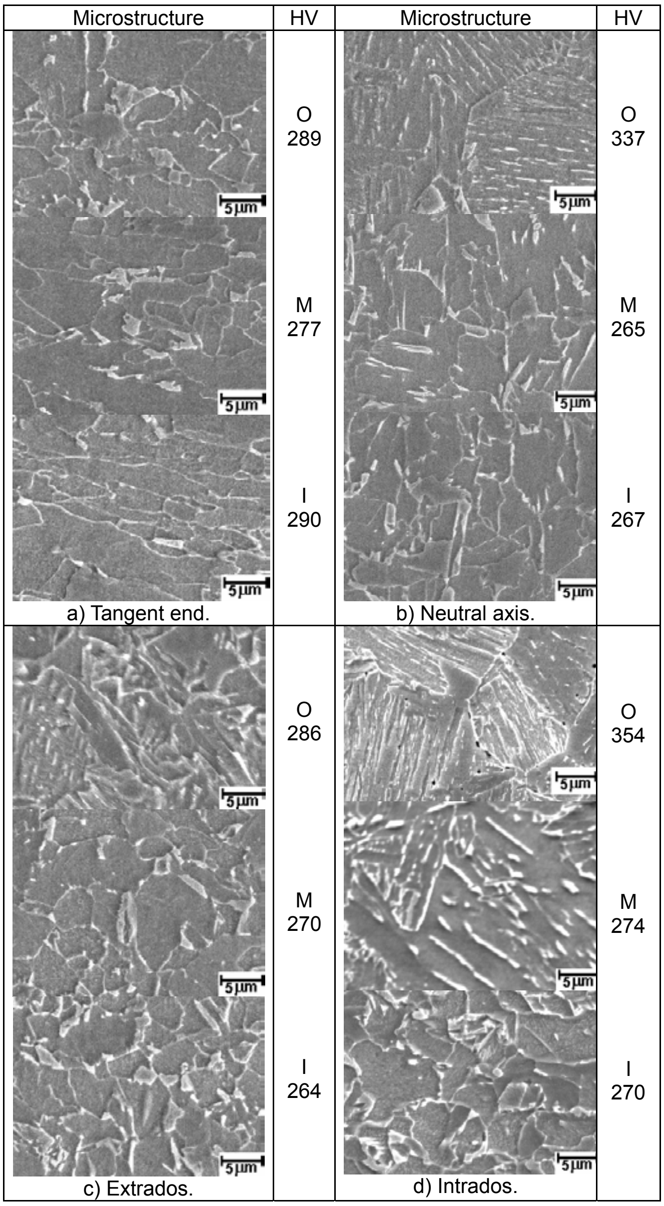

Figure 5- Tangent end and bend region microstructures. Scanning Electron Microscopy. Magnification: 2000X. Etch: Two-step electrolytic etching, using Ikawa's solution [10 and 11].

A significant microstructural change was observed across the wall thickness. The outside surface has a more acicular microstructure due to the higher cooling rate caused by outside water quenching, resulting in high hardness values. As compared to other bend areas, the intrados reached larger austenite grain sizes. This can be explained because this region had a longer exposition time at bending temperature and also because the bending strain will be higher at extrados, contributing to the grain refinement.

The transition zone's microstructures are very similar to original (tangent ends). However, due to the discontinuous bending procedures, a greater variety of grain sizes can be observed (Figure 6).

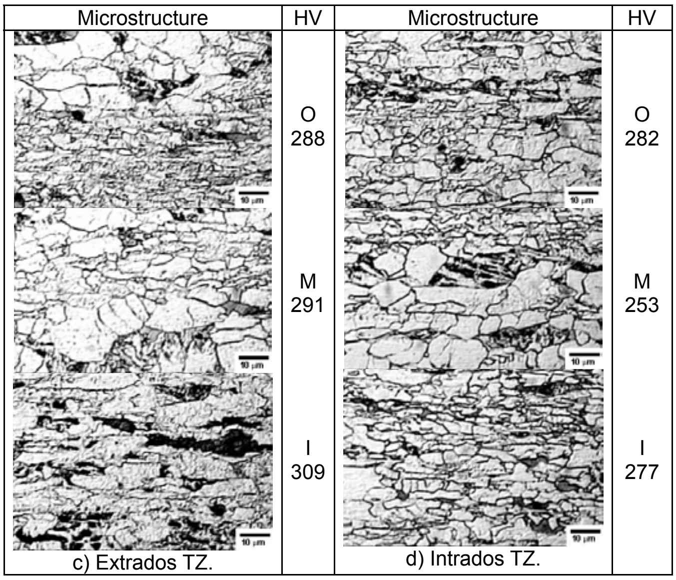

Figure 6- Transition Zones Microstructures. Optical Microscopy. Magnification: 500X. Etch: 2% Nital.

Mechanical Properties

In a bent pipe section, normally there are significant differences in mechanical properties from tangent ends to the bent region and between different locations around the pipe circumference. Figure 7 shows tangent end and bent region Charpy absorbed impact energy curves. The temperature associated with the 100J absorbed energy level in the impact tests was observed to decrease after bending. The tangent end transition temperature is about 30ºC above the intrados and about 40ºC above the extrados transition temperatures.

The behavior of transition zones is very similar to original pipe and also has higher transition temperatures than bent region.

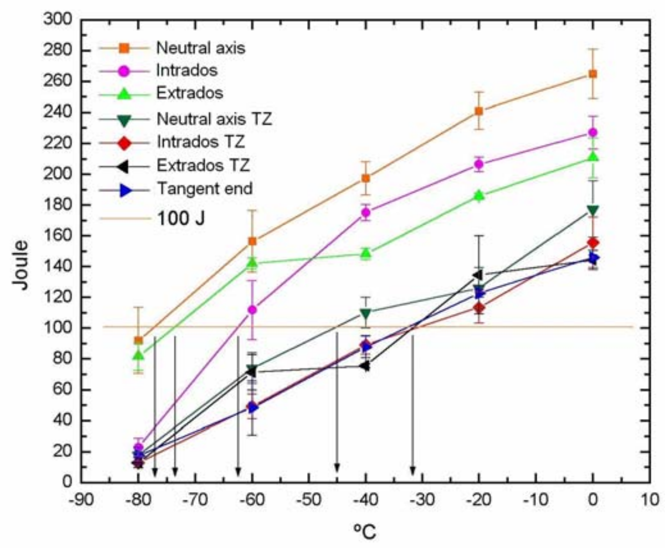

Figure 7- Charpy absorbed impact energy curves.

In general, Figure 7 shows impact toughness improvement after induction hot bending. One reason for this improvement could be associated with the presence of alloying elements such as Nb and Ti that precipitates as carbides and nitrides, during induction heating and the resulting fine precipitates suppress austenite grain growth.

Kondo et al [2] showed that although the austenite grain size of the Nb-bearing steel increases with an increase in heating temperature, because an increase in heating temperature promotes solution of Nb (C, N) in the austenite phase, it is clear that the size is much smaller than that of the Nb-free steel. Fine austenite grains lead to a fine microstructure after quenching and hence good toughness. Ti precipitates have a similar effect however with different dissolution temperature. TiN, for example, is stable at high temperatures and then is very effective in order to suppress austenite grain growth [12, 13].

Furthermore the microstructure in Figure 5 shows that the hot bending process promotes new, small ferrite grain formation as a result of refined austenite and water cooling and also reduces strain hardening which is good for the toughness [13].

In spite of high toughness, the low carbon Nb steels have low hardenability (low carbon equivalent) and for this reason, it is necessary to add other alloying elements to meet the required strength. Figure 8 shows the tangent end, bend and transition zones tensile properties.

The yield strength measured in the bend region (extrados, intrados and neutral axis) was appreciably lower than that in the original pipe and also lower than the specified minimum yield strength (SMYS). Groeneveld [14] explains that the controlled rolling process in combination with the tailoring of the chemical composition is used to produce fine grained microstructure and appropriate microconstituents in the steels to guarantee the desired yield strength. As a result of the induction hot bend process, the effects of the controlled rolling on the microstructure and properties of the steel was eliminated. DNV-OS-F101 [7] also shows that the pipes manufactured from thermomechanical control process (TMCP) plate, may not have adequate hardenability to achieve the required mechanical properties after induction bending. Kondo [2] suggests that the strength of bent pipes up to X80 grade can be controlled using CE as an indicator of hardenability and that the CE of induction bent pipe should be designed to be higher in order to increase the hardenability and minimize the yield strength loss.

For straight pipes the low CE assures good weldability but, on the other hand, does not provide the necessary hardenability to assure the high strength in bends made by the quench process. For this reason the pipe should have a CE content suitable for the hot bend process.

Previous work [15] found an optimum CE value of 0.48% for the X80 grade. This value assures good strength after bending. The steel studied in this work has a CE of only 0.42%.

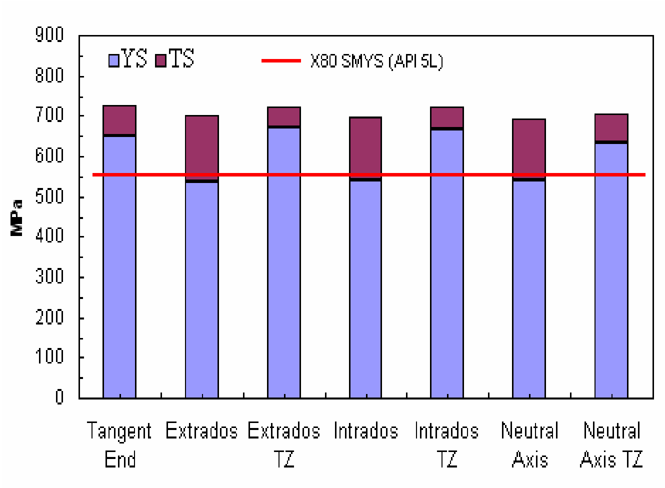

Figure 8- Yield and tensile strength.
TZ = Transition Zone.

Kondo et al [2] explain that the cooling rate is also an important parameter and strongly depends on wall thickness. Therefore, the application of a cooling method from both inside and outside for induction bending of high strength steel pipe (and/or heavy wall thickness) increases the cooling rate and is effective in reducing CE. Thus high strength could be achieved in low CE steel by cooling both sides.

Another way to improve yield strength is to perform a heat treatment after bending.

Influence of Hot Bending on Weld Seam Properties

In a bending process, the bent region and tangent end weld seams have significant differences. The tangent end weld seam is in the as-welded condition while the bent region is quenched. If a tempering heat treatment is applied, the bent region will be quenched and tempered and the tangent ends only tempered. Therefore, it is necessary a suitable alloy design to obtain sufficient properties for the both bent region and the tangent ends.

The weld metal chemical composition is given in Table 2.

Table 2- Weld metal chemical composition.

Elements (wt %)						
C	Mn	Si	Nb	V	Ti	
0.06	1.54	0.32	0.037	0.015	0.013	
Mo	Cr	Cu	Ni	P	S	Al
0.205	0.102	0.055	0.016	0.018	0.005	0.011

Kondo [2] shows that the chemical composition employed in this study can result in lower transition temperatures and therefore good toughness.

Figure 9 shows the tangent end weld seam Charpy absorbed impact energy curves. It can be seen that weld metal has the highest transition temperature and the heated affected zone (HAZ) has the lower. Previous work [16], with the same kind of pipe used in this study, attributes the HAZ's high toughness to the microstructural transformations induced by the welding thermal cycle where the high toughness is related to the MA constituent in the HAZ, which is smaller than MA in base metal, and the larger distance between the particles. Another factor that could be contributing to the high toughness values is the lack of interconnection between the particles. All these factors (morphology, size and distribution of MA) can cause the same effect as that observed in the HAZ in this study.

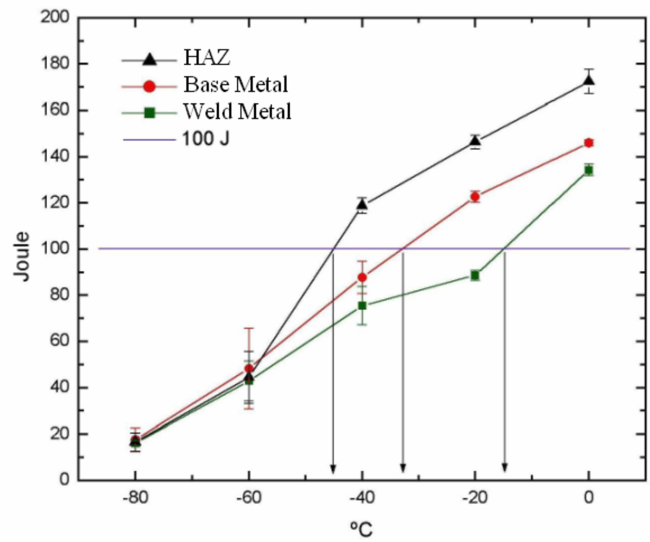

Figure 9- Charpy absorbed impact energy curves of tangent end weld seam.

The Vickers microhardness values of base metal, weld metal and HAZ are very close (Figure 10). However, it is possible to note that the HAZ has the lowest average microhardness and the weld metal the highest. Similar results were found for a 30" pipe of 0,625" wall thickness, produced by the same production route as the pipe studied here [16].

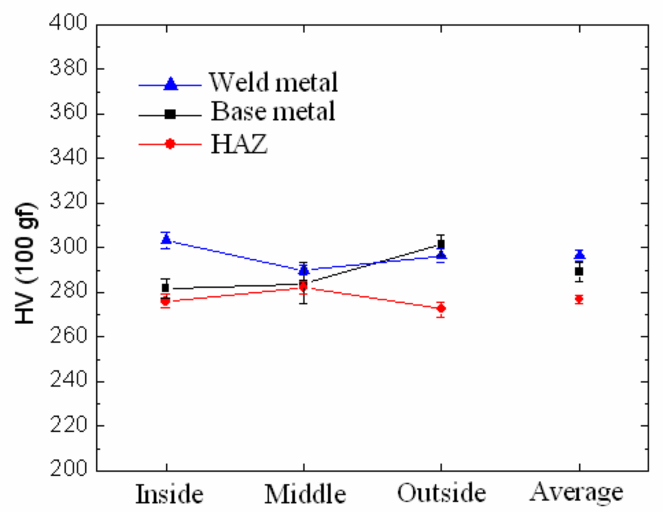

Figure 10- Tangent end weld seam microhardness.

As well as the base metal, the weld metal and HAZ also present a significant change in mechanical properties after hot bending. Williams [9] reports that the induction hot bend process results in the removal of the

HAZ in the bending section and appreciable homogenization and grain refinement of the weld metal. This results in a HAZ and weld metal toughness improvement, decreasing the transition temperature, as can be seen in Figure 11.

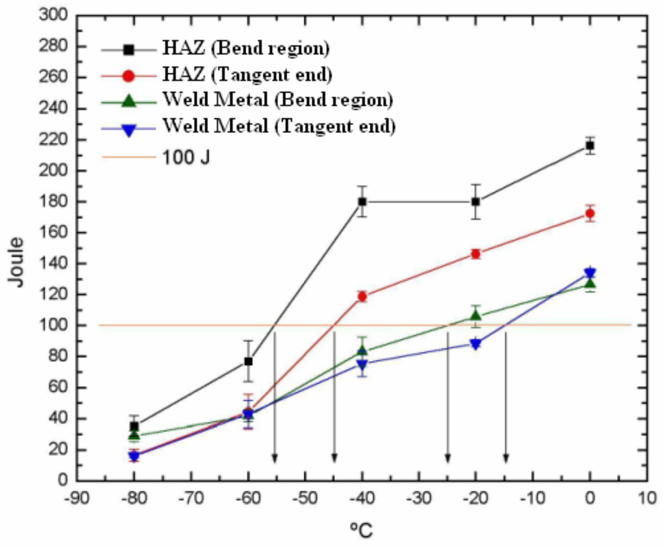

Figure 11- Effect of hot bending on HAZ and weld metal transition temperature.

Like the tangent ends, the HAZ microhardness of the bend region and transition zones is lower than that of the weld metal (Figure 12 and Figure 13). The lower HAZ hardness does not impair the weld seam strength as can be seen in Figure 14. For all regions evaluated, the weld seam strength is higher than base metal strength.

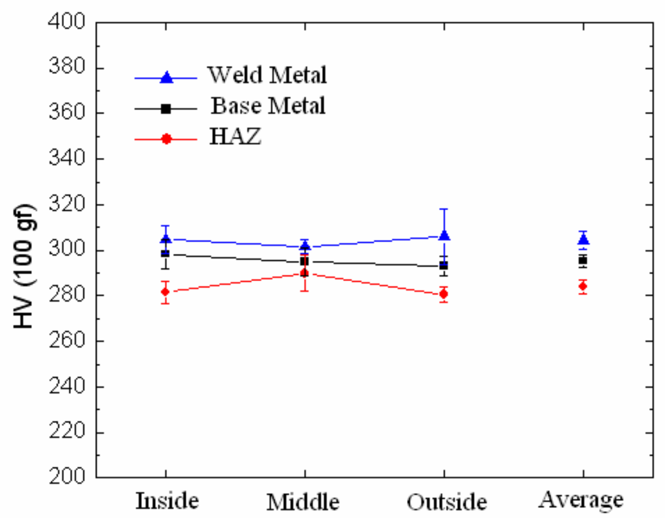

Figure 12- Microhardness of transition zone after hot bending.

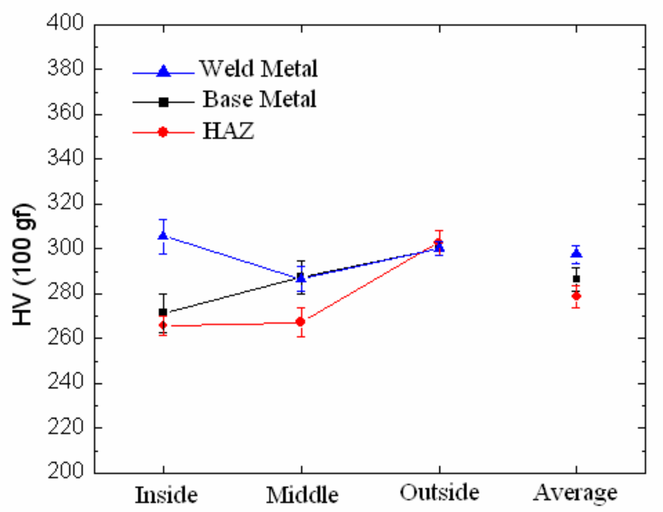

Figure 13- Microhardness of bend region after hot bending.

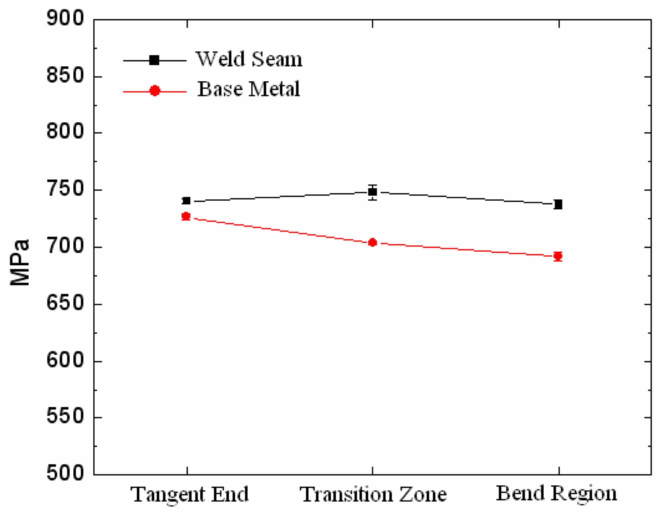

Figure 14- Weld and base metal tensile strength.

HAZ softening has been observed in high strength steels welded using submerged arc welding processes (tandem technique) [16]. Nagae [17] found similar results where HAZ softening did not affect the tensile strength values.

HEAT TREATMENT

In order to improve the yield strength after induction hot bending, a tempering heat treatment was applied. The parameters employed are described below:

- Free heating up to 300 ºC;
- Between 300 and 500 ºC: heating rate of 100º/h;
- Soaking temperature: 500 ºC;
- Soaking time: 1 hour;
- Cooling: Air.

The heat treatment was evaluated only at the intrados and extrados areas. The complete evaluation of the tempering effect in the bend properties is still underway but significant partial results of this study are presented.

The heat treatment applied does not reestablish the original X80 yield strength, however it increases the value to above the minimum required by API 5L standard (Figure 15).

The mechanism by which the yield strength increases and the tensile strength decreases is not yet clear. The yield strength improvement might be related to a precipitation hardening mechanism caused by the presence of alloying elements. Vanadium, for example, is in solid solution at the bending temperature and stay this way due to the high cooling rate promoted by water quenching. During the tempering heat treatment, the vanadium precipitate occurs as carbides and nitrides, inducing the yield strength increase. However, the evidence of precipitates formation is not available in this study.

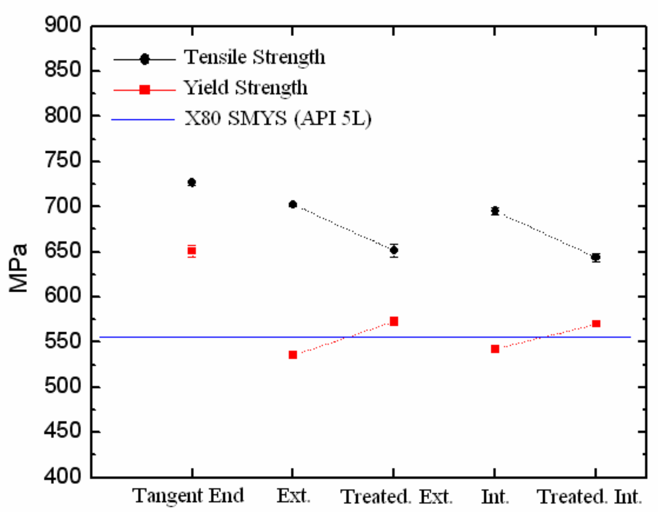

Figure 15- Yield and tensile strength before and after heat treatment. Ext = Extrados, Int = Intrados.

Figure 16 shows the extrados and intrados microstructures and Vickers microhardness values after tempering heat treatment. The microstructural differences across the wall thickness are smaller than as quenched condition. It can also be seen that the amount of MA constituent is lower.

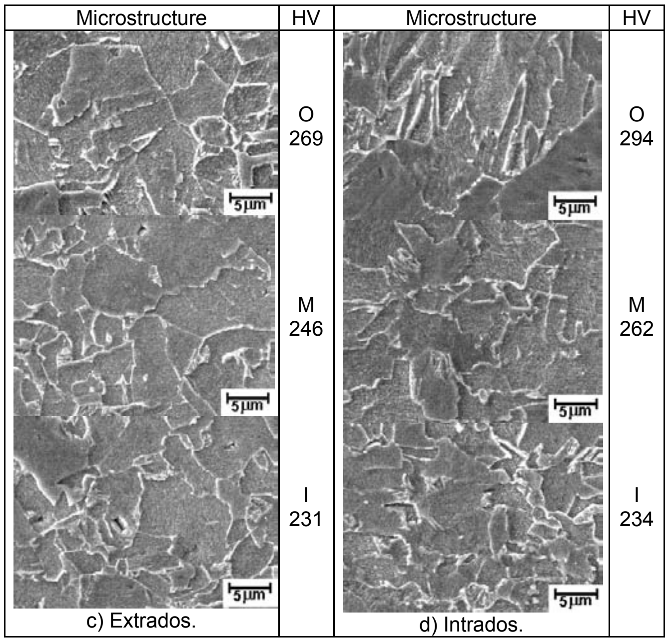

Figure 16- Microstructures after tempering. Scanning Electron Microscopy. Magnification: 2000X.
Etch: Two-step electrolytic etching, using Ikawa's solution [10 and 11].

Figure 17 shows the Vickers microhardness values for tangent end (original pipe), extrados and intrados regions. It can be seen that the tempering treatment reduces extrados and intrados hardness values.

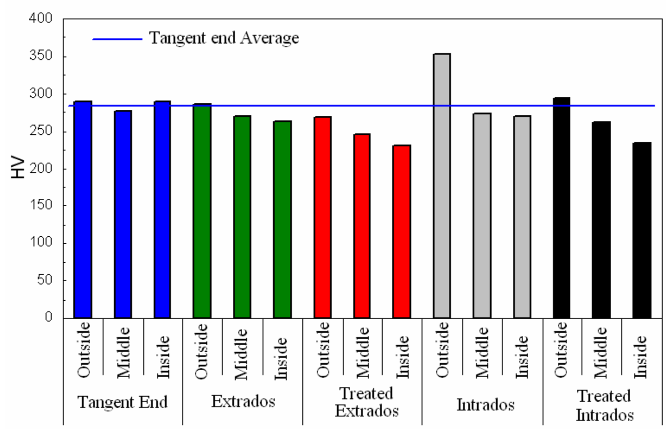

Figure 17- Vickers microhardness of the temperd pipe.

The hardness values of the tempered pipe are in agreement with the international pipe standards for non sour service application. For example, ISO 15590-1 [6] and DNV-OS-F101 [7] specify 300 HV as a maximum acceptable hardness value.

CONCLUSIONS

The induction hot bending of API 5L X80 and its effect on mechanical properties after bending and after heat treatment, as well as weld seam performance before tempering, are presented in this paper. The main conclusions are described below:

- The extrados wall thinning is about 8 %. It should be taken into account during pipe wall thickness design.

- The outside water cooling, after a region of the pipe passes through the heating coil, results in a microstructure gradient across the wall thickness. Thus the hardness values can vary from 260 HV (inner surface) to 350 HV (outer surface) before heat treatment. After tempering the hardness values range from 230 to 290 HV. These hardness values are in agreement with the pipe specifications for non sour service applications.

- After bending, a significant toughness improvement can be seen in the bend region. It is related with new, small ferrite grain formation and a reduction in work hardening. Furthermore, the alloying elements such as Nb and Ti precipitate as carbides and nitrides, during induction heating and result in fine precipitates that suppress austenite grain growth.

- The hot bending process reduces the bend region (extrados, intrados and neutral axis) X80 yield strength resulting from the prior controlled rolling process without accelerating cooling. The low CE level does not provide the necessary hardenability to assure high strength after the quench process. The application of a cooling method from both inside and outside can minimize the yield strength reduction.

- The microstructure and mechanical properties of transition zones are very similar to the original pipe. However, a greater variety of grain sizes are observed in these zones than original microstructure.

- The X80 weld metal chemical composition is suitable for the hot bending process. This process improves the weld metal, HAZ and base metal toughness. The HAZ's of tangent end, transition zone and bend region, presents the lowest transition temperature and hardness. The weld seam tensile strength was better than that of the base metal, for all regions evaluated.

- A significant extrados and intrados yield strength improvement was achieved by the tempering heat treatment applied, increasing this value to above the minimum required by the API 5L standard. This improvement might be related with a precipitation hardening mechanism caused by the presence of V. The effect of precipitation on yield strength depends on the particle size and matrix distribution and on heat treatment parameters. To improve the effect of tempering conditions on the mechanical properties it will be necessary to make tests with different parameters and evaluate the effect on the X80 mechanical properties.

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support of the CNPq and of Petrobras. The technical support of CONFAB and PROTUBO is also acknowledged.

REFERENCES

1 Petrobras 2015 Strategic Plan. Available at: <http://www.petrobras.com.br>. Access date: December 06, 2005.

2 KONDO, J. et al. The State of The Art of High Strength Induction Bent Pipe. NKK Corporation. Eighth Symposium on Line Pipe Research. PRCI. September, 1993.

3 BATISTA, G. Z. et al. Induction Hot Bending of API 5L X80 Pipe. Rio Pipeline Conference & Exposition 2005. October, 2005. (in portuguese).

4 Specification for Line Pipe, API Specification 5L. American Petroleum Institute, March. 2004.

5 Standard Test Methods and Definitions for Mechanical Testing of Steel Products. ASTM A 370. American Society for Testing and Materials. 2003.

6 Petroleum and Natural Gas Industries – Induction Bends, Fittings and Flanges for Pipeline Transportation Systems - Part 1: Induction Bends. ISO 15590-1. International Organization for Standardization. 2001.

7 Submarine Pipeline Systems. Offshore Standard. DNV-OS-F101. Det Norske Veritas, January 2000.

8 Factory-Made Wrought Steel Buttwelding Induction Bends for Transportation and Distribution Systems. ASME B16.49. American Society of Mechanical Engineers. 2000.

9 WILLIAMS, D. N. Investigation of the Properties of Induction Hot Bends. Batelle Columbus Division. Seventh Symposium on Line Pipe Research. PRCI. October, 1986.

10 IKAWA, H.; OSHIGE, H.; TANOUE, T. Effect of Martensite-Austenite Constituent on HAZ Toughness of a High Strength Steel. IIW. DOC IX – 1156-80.

11 BISS, V.; CRYDERMAN, L. Metallurgical Transactions, 2. 2267-76. August, 1971.

12 HULKA, K. Metallurgical Concept and Full-Scale Testing of High Toughness, H2S Resistant 0.03%C-0.10%Nb Steel. Niobium Technical Report. CBMM.

13 SAGE, A. M. Physical Metallurgy of High-Strength, Low-Alloy Line-Pipe and Pipe-Fitting Steels. The Metals Society, Vol. 10, p. 224-233, June 1983. London.

14 GROENEVELD, T. P. Evaluation of Modern X70 & X80 Line Pipe Steels. Report nº 201, to PRCI from Batelle. April, 1992.

15 BEHRENS, D.; HILLENBRAND, H. G. and SPETH, W. Inductive Bends in Grade GRS 550TM/V (X80). Europipe. 1994.

16 BATISTA, G. Z. et al. Submerged Arc Welding Weldability of API X80 Steel. 58º ABM Anual Congress. July, 21-24, 2003. Rio de Janeiro. (in portuguese).

17 NAGAE, M. et al. Development of X100 UOE Line Pipe, NKK Review, n. 66, p. 17-24. 1992.