International Symposium on Microalloyed Steels for the Oil and Gas Industry
Edited by W.J. Fazackerley, P. Bordignon, K. Hulka, and F. Siciliano
TMS (The Minerals, Metals & Materials Society), 2007

DEVELOPMENT OF HIGH-STRENGTH HEAVY-WALL SEAMLESS LINE PIPE FOR DEEP WATER APPLICATIONS

K.Kondo[1], Y.Arai[1], M.Hamada[1], H.Hisamune[2], T.Murase[2] and I.Takeuchi[3]

[1]Corporate Research & Development Labo's, Sumitomo Metal Industries, Ltd.
1-8 Fuso-cho, Amagasaki, Hyogo, 660-0891, JAPAN
[2]Pipe & Tube Company, Sumitomo Metal Industries, Ltd.
1850 Minato, Wakayama, 640-8555, JAPAN
[3]Tokyo Head Office, Sumitomo Metal Industries, Ltd.
1-8-11 Harumi, Chuo-ku, Tokyo, 104-6111, JAPAN

Keywords: Seamless line pipe, High strength, Heavy wall, Inline heat treatment

Abstract

High-strength heavy-wall sour-service seamless line pipe suitable for deep water applications has been developed by Sumitomo Metal Industries, Ltd. This paper describes the development of these pipes applying inline heat treatment technology, installed in a newly constructed, medium-size seamless mill. Increasing hardenability through inline heat treatment achieved higher strength (X70) for heavy wall pipe (40mm) even though the carbon equivalent was lower than in a conventional Q&T process. Good toughness was obtained by the control of microalloying elements and impurities such as titanium and sulfur respectively. The pipe produced passed the hydrogen-induced cracking (HIC) test conducted according to NACE TM 0284 solution A. Controlling the microstructure and reducing maximum hardness, utilizing the uniform quenching facility during inline heat treatment, contributed to the test result. Satisfactory data on weldability for practical use were also obtained.

Introduction

Exploration of oil and gas in deep water is increasing since considerable progress has been made in offshore technology for production of oil and gas in ever deeper water. Subsea completion technology is often used for oil or gas wells in deep water, then crude oil or raw gas needs to be transported to the offshore platform using a flow line and riser system. Seamless pipe is considered to be the most suitable material for flow line and riser systems due to the range of sizes and reliability compared with ERW pipes.

Moreover, to meet the demand for developing deeper water wells, special grades for seamless flow lines are required. The typical characteristics necessary for flow lines or riser systems in deep water are described below.

<u>High strength and heavy wall thickness pipe with good weldability</u>

In order to withstand the high pressures related to transportation pressure and deep water, the development of high strength and heavy wall pipe was required. The typical strength target for that usage has been Grade X70 for strength and 40 mm as a maximum wall thickness, neither of which had been developed previously for seamless pipe.

Weldability is usually calculated by the following formulas, CE(IIW) or Pcm described below. If weldability isn't taken into account, it is easy to obtain higher strength by choosing the steel with higher CE(IIW) or Pcm. However, a rise in CE(IIW) or Pcm induces lowered welding efficiency and weldability is very important to reduce installation costs in deep sea. Consequently CE(IIW) or Pcm should be reduced according to levels which meets the users' requirement.

$$CE(IIW)=C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15 \quad (1)$$

$$Pcm = C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B \quad (2)$$

Corrosion resistance for sour service

Using the subsea completion system, it is difficult to dehydrate or desulfurize in order to reduce susceptibility to Hydrogen Induced Cracking (HIC) before the oil or gas enters the flow line. Moreover the susceptibility to HIC is considered to be increased in high strength steels. Therefore the material for the flow line should have a resistance to HIC if the crude oil or raw gas contains Hydrogen Sulfide.

Sufficient toughness at design temperature

Higher strength and heavy wall thickness usually decrease the toughness value. Therefore sufficient toughness is necessary at design temperature even in the heat affected zone (HAZ) portion.

Manufacturing Process

New Seamless Mill Line

A new medium-size seamless mill line was constructed as a result of the projection of increasing demands for seamless pipe due to the expansion of demands for fossil energy. The outline of the newly-constructed medium-size mill is described in Figure 1 [1]. This is a state-of-the-art facility, which began operation in 1997. The concept of the mill line is "Simple & Compact". The entire process for manufacturing the seamless pipe is directly connected and the rolling line was arranged in a compact design as shown in Figure 1. The continuous casting machine, pipe producing mill and heat treatment line are directly connected and synchronized with each other as if they consist of one operation. In order to mass-produce the heat-treated seamless pipes with high efficiency, the facility of inline heat treatment was installed. As a result, almost all heat-treated product, such as high grade OCTG or project line pipe that used to be heat treated in an offline process are now treated in an inline heat treatment process. Consequently the new medium-size seamless mill line reduces the production cost and shortens delivery time.

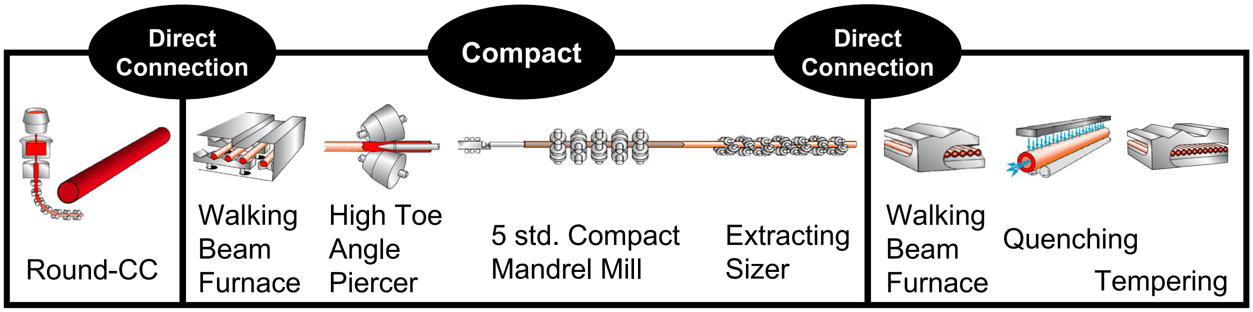

Figure 1. Schematic illustration of the newly constructed medium-size mill and inline heat treatment facilities.

As for the conventional production line shown in Figure 2 it used to consist of four independent facilities. Molten steel was cast into blooms by caster. The bloom was transported to billeting factory and heated and forged into the round billet. The billet was then transported to the pipe production mill and again heated, pierced and rolled into seamless pipe. Then it was cooled to room temperature, conveyed to the heat treatment factory, heated again and quenched and tempered.

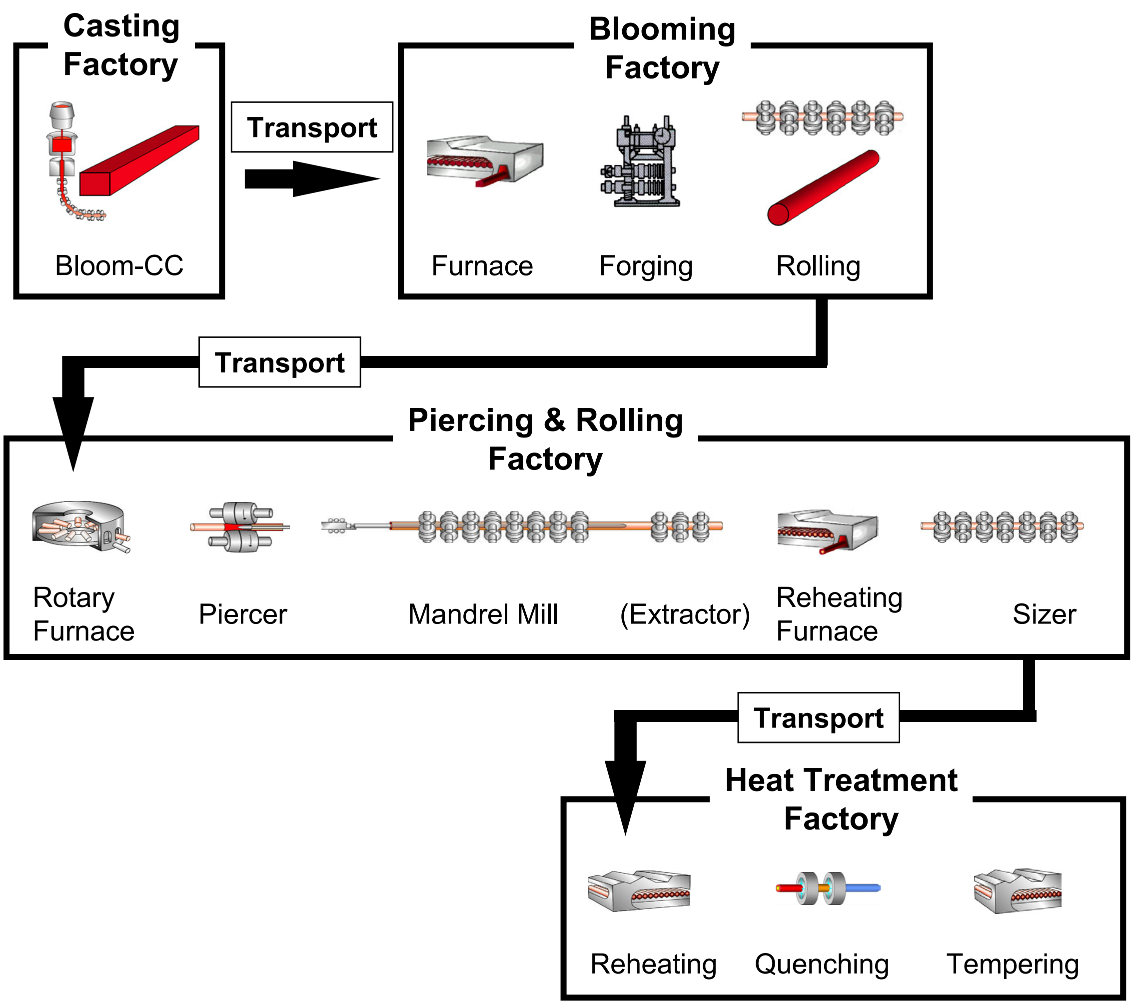

Figure 2. Schematic illustration of conventional production line for seamless pipe.

Billet Making

The pig iron is processed in a blast furnace and refined in a converter. After that the molten steel is treated in an RH (Rheinstahl Huttenwerke & Heraus) degassing process to reduce impurities and improve cleanliness, then poured into the continuous caster having a round shaped mold.

Piercing

Most of the billets are received directly from the round billet continuous caster and heated in a walking-beam type furnace, avoiding uneven heating in order to obtain minimum eccentricity in the piercing process. Then a hole is opened in the center by the high toe angle piercer to form a hollow shell [2-5].

Rolling and Sizing

The hollow shell is next rolled to the specified thickness by the 5 stand compact mandrel mill, then the pipe is extracted from the mandrel bar while being rolled to the specified outer diameter by the extracting sizer.

Inline Heat Treatment

One characteristic of the inline heat treatment facility is the installation of the heating furnace just after the pipe making line in order to guarantee the quenching temperature above Ar_3 transformation temperature but also to improve the uniformity of mechanical properties due to homogeneous heating. This furnace can be smaller than a usual furnace installed in a conventional offline heat treatment facility because it utilizes the latent heat possessed by the rolled pipe itself.

Another feature of inline heat treatment is the unique water quenching system. Austenitizing and dipping into a quenching tank or moving to a quenching tunnel, which are common quenching process in a medium size mill was not adopted because a sufficient cooling rate could not be obtained and bending could occur. The schematic illustration of the newly developed quenching device is indicated in Figure 3. Uniformly heated pipe is moved quickly to the cooling zone and one end is held tightly by a chucking device, then rotated quickly and a high-pressured jet flow is injected inside while at the same time a slit laminar flow is applied outside. This quenching facility realizes a high cooling rate and homogeneous cooling for a pipe manufacturing line. By utilizing this high performance quenching ability and optimization of the alloy design, suitable to inline heat treatment, it was possible to develop a high-strength heavy-wall line pipe for sour service that has proved difficult to attain by conventional heat treatment.

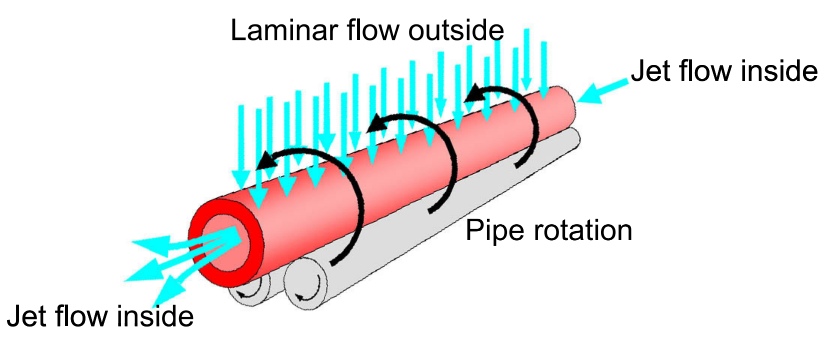

Figure 3. Schematic illustration of the inline quenching device.

Alloy Design

High Strength in Heavy Wall Pipe

Increasing CE(IIW) or Pcm contributes to an increase in strength. However in order to obtain good weldability as the line pipe, strict limitations of CE(IIW) or Pcm are required. As shown in Figure 4 when X70 Grade with a heavy wall such as 40mm thick is manufactured by conventional heat treatment, CE(IIW) must exceed 0.42 percent for example, which does not meet the users' weldability requirement. Newly developed inline heat treatment technology was applied in order to solve this problem and reduce carbon equivalent to 0.38 or less.

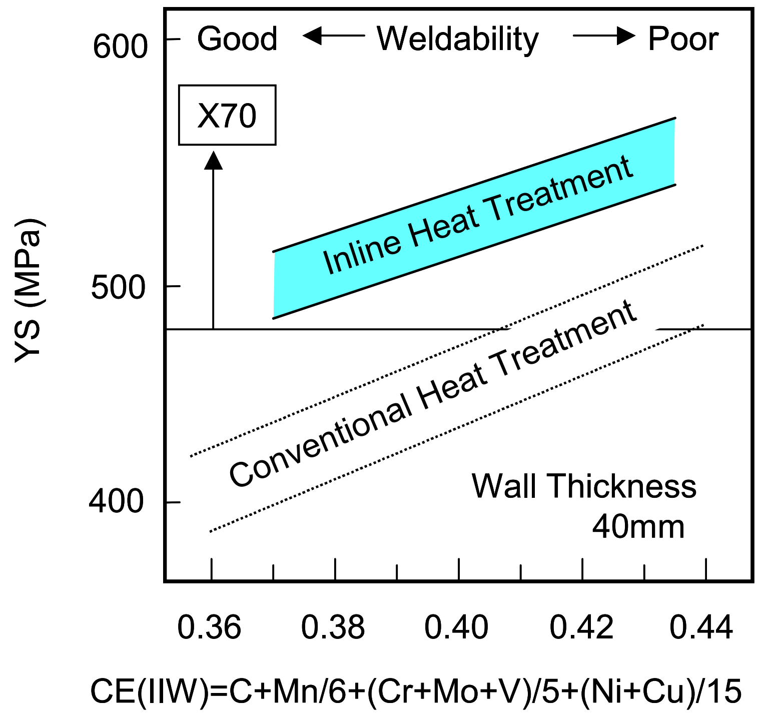

Figure 4. The difference of strength between inline and offline heat treatment

Higher strength has been achieved due not only to an increase in hardenability using inline quenching but also by a higher cooling rate obtained with the high performance quenching device. As a result higher strength has been achieved by applying inline heat treatment compared with a conventional process even if the steel pipe has the same CE(IIW). For example, in the case of CE(IIW) of <0.40 percent, it was difficult to manufacture Grade X70 with 40mm wall thickness before, however X70 grade can be manufactured by applying the new technology of inline heat treatment even in a heavy wall pipe.

Improvement in Toughness

As mentioned above, the pipe manufactured in inline heat treatment has an ability to achieve higher strength; however toughness usually reduces in inverse proportion to yield strength. Therefore an investigation to improve the toughness values of the seamless pipe produced by inline heat treatment was conducted. The chemical composition of materials used in this investigation is 0.07 percent C-1.5 percent manganese with a CE(IIW) of around 0.38 percent for base composition varying sulfur content from 7ppm to 79ppm, titanium content from 0.003 percent to 0.05 percent and nitrogen content from 19ppm to 110ppm. These materials were melted in a vacuum induction furnace and the ingots were forged into blocks. Then the simulation of inline heat treatment was carried out as follows. The blocks were heated at 1250ºC and after rough rolling for reduction of 20 percent and a finishing rolling of reduction of 30 percent to 70 percent was started at 1100ºC and the finishing temperature was 950ºC to 1000ºC. They were quenched in agitated water after the rolled plates were heated to 900ºC for 5 minutes. After that the materials were tempered at 600ºC to 650ºC for 30minutes.

Test pieces for the tensile test and the Charpy impact test were machined from the plate parallel in the transverse direction. In order to clarify the metallurgical factor to control the toughness, observation of the microstructure and observation of the fracture surface after the Charpy impact test by SEM-EDX were carried out.

It turned out that lowering sulfur and titanium contents brings about a large improvement in toughness as shown in Figure 5. The absorbed energy transition temperature (vTE) increased with sulfur and titanium content.

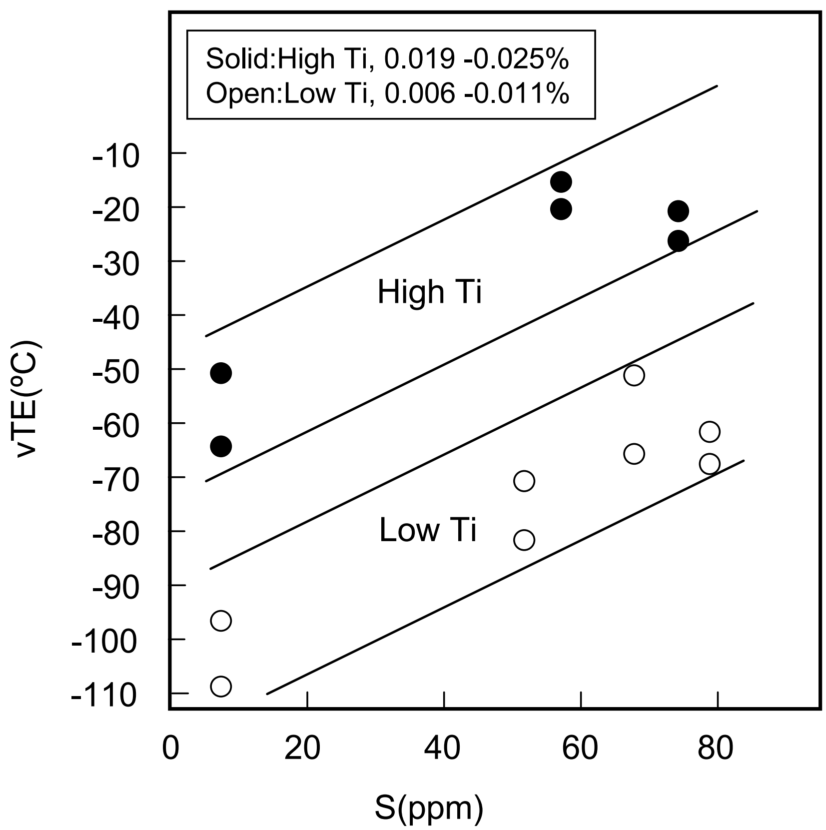

Figure 5. Influence of sulfur and titanium content in steel on toughness.

In order to understand the mechanism of improvement in toughness, observation of the fracture surface after the Charpy impact test was carried out by SEM-EDS. Figure 6 shows the fracture surface in the Charpy impact test specimen containing 72ppm sulfur. Many stripe patterns, which were not separations, were observed parallel to the direction of the propagation of the crack. Detailed observation results using EDS are shown in Figure 7. A lot of elongated MnS was observed along the stripe patterns in the specimen containing 72ppm sulfur. As for the specimen containing much high titanium, TiN was easily observed on the surface where the crack started. From that observation it is suggested that MnS and TiN act as initiators of a crack at each facet of a fracture.

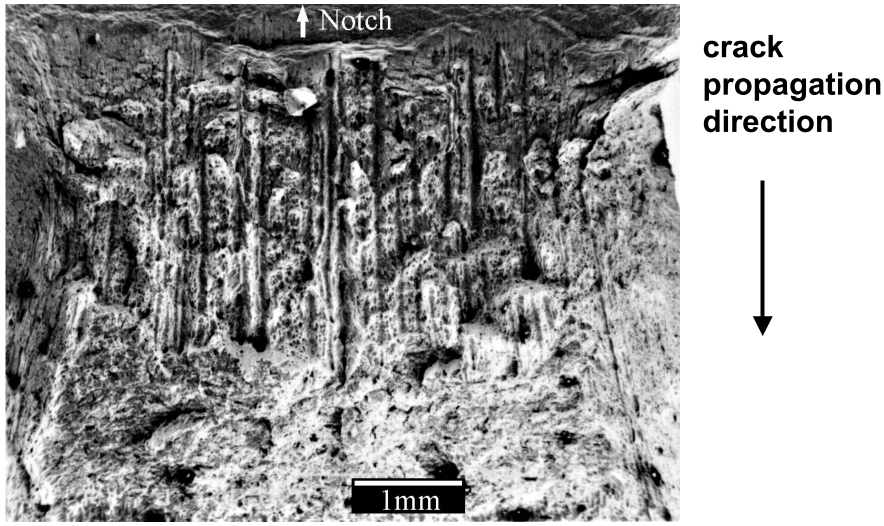

Figure 6. Observation of fractured surface of the specimen containing sulfur content of 72 ppm.

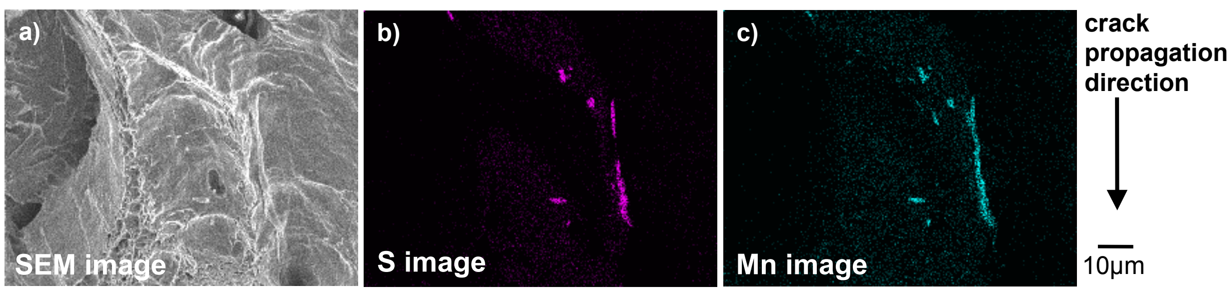

Figure 7. Observation of fractured surface of the specimen containing sulfur content of 72 ppm using EDS. a):SEM image b):sulfur image C):manganese image

Next the effect of precipitation hardening of niobium carbide on toughness was investigated. Niobium is usually utilized to inhibit coarsening of austenite grain size at austenitization temperature through pinning effect of niobium carbide in the QT process because it is insoluble in steels at normal austenitizing temperatures. Therefore, precipitation hardening by niobium carbide is not expected in the normal QT process. However it is reported that precipitation hardening by niobium carbide could be obtained when much higher temperatures were chosen for the austenitizing temperature which allow niobium carbide to go into solution [6]. Considering the inline heat treatment process soluble niobium existing during pipe-forming process at much higher temperature almost remains in solution just before quenching. Niobium precipitates as fine niobium carbide during subsequent tempering and secondary hardening can be obtained. Therefore inline heat treatment is considered to be suitable process to utilize niobium as precipitation hardening element.

Figure 8(a) describes the secondary hardening by the fine precipitation of niobium carbide after tempering. Addition of a small amount of niobium increased the yield strength markedly at the same time, however, the Charpy transition temperature, of absorbed energy, increased extremely rapidly as shown in Figure 8(b). The deterioration of transition temperature by precipitation hardening estimated in this figure proved to be 0.75ºC/MPa (5.2ºC/ksi) which is larger number than expected. From the standpoint of achieving improved toughness in high strength steel through inline heat treatment, practical use of precipitation hardening by niobium was judged to be very difficult without further modification of the overall alloying approach.

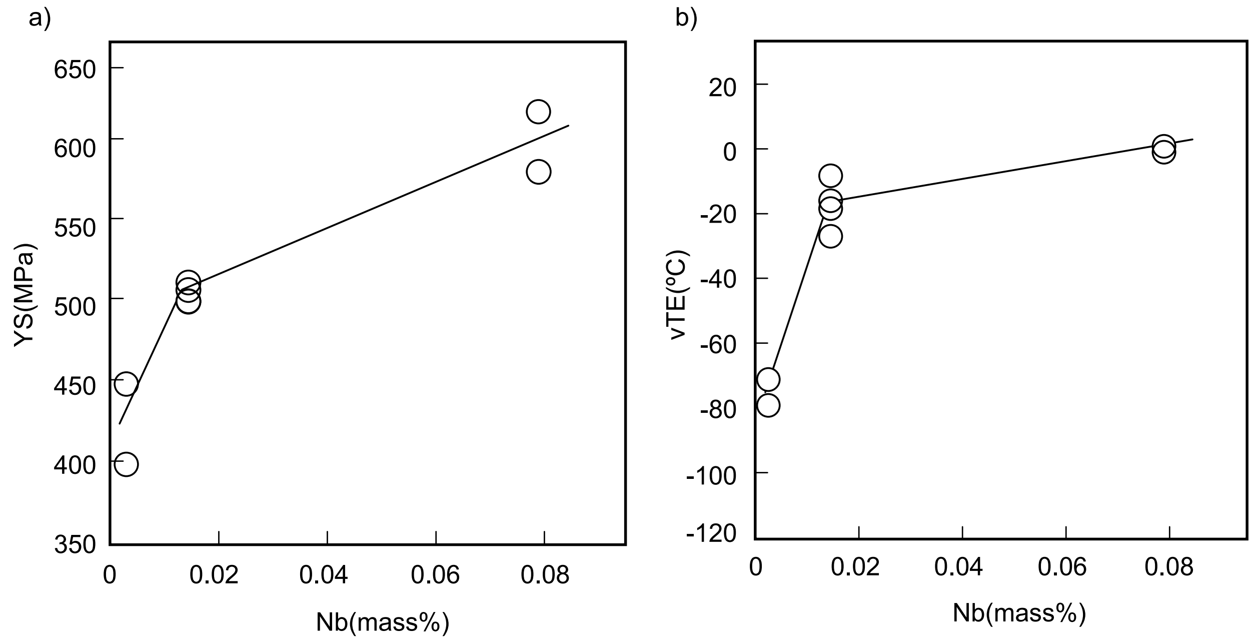

Figure 8.Effect of the niobium addition on yield strength and toughness for inline heat treatment;
a) Secondary hardening due to the fine precipitation of niobium carbide
b) Deterioration in ductility due to precipitation hardening

Improvement in Corrosion Resistance

It is well known that elongated MnS is considered to result in a crack initiation and propagation of HIC. Reducing sulfur content as the guiding principle for improving toughness was suggested but it is difficult to eliminate MnS completely. Calcium addition is also known to be useful for preventing HIC because the shape of sulfide precipitation is changed from elongated rod to spheroidized shape. Therefore reducing sulfur content and calcium addition has become the common technology for HIC resistant steel. In general, good HIC resistance is known to be achieved by maintaining the material hardness around 248 Hv or less, which has been able to be adjusted with suitable inline heat treatment and alloying elements.

Production Data for X70-Heavy Wall Pipe

Materials

Production data for API 5L-X70 heavy wall thickness pipes for sour service will be described in this section. The pipe size is 219.1mm OD x 40mm WT. Chemical composition for this material is shown in Table I. CE(IIW) was 0.42 percent and Pcm was 0.18 percent.

Table I. Chemical composition of the steel used for the production of heavy wall pipes.

C	Si	Mn	P	S	Other elements	CE(IIW)	CE(Pcm)
0.06	0.29	1.44	0.01	0.0013	Cr,Ni,Mo,V,Ti	0.42	0.1 8

Mechanical Property

Room and elevated temperature tensile tests and the Charpy impact test were carried out according to ASTM A370. Strip specimens were machined from the pipe parallel to the longitudinal direction and round bar specimens were machined parallel to the longitudinal and transverse direction for the room temperature tensile test. Round bar specimens were machined parallel to the longitudinal and transverse direction for the elevated temperature tensile test. The elevated test temperature was set at 130 degrees C. The tensile test results are shown in Tables II and III respectively. 10 x 10mm, 2mm V-notch specimens were cut in a transverse direction for the Charpy impact test. Figure 9 shows the transition curve for the Charpy impact test. Sufficient low temperature toughness was obtained for the heavy wall pipe.

Table II. Tensile test results for the production of heavy wall pipes.

Direction	Specimen	YS (MPa)	TS (MPa)	YR	El. (%)
Longitudinal	Strip	571-584	638-652	0.90-0.90	48.0- 49.6
Longitudinal	Round bar	535-544	625-631	0.85-0.87	24.9-25.2
Transverse	Round bar	538-548	629-632	0.85-0.87	23.4-24.9

Test specimen : Strip specimen (GL = 50.8mm)
Round bar specimen (GL = 50.8mm)

Table III. Tensile test results at 130 degrees C for the production of heavy wall pipes.

Direction	YS (MPa)	TS (MPa)	YR	El. (%)
Longitudinal	501	578	0.87	21.6
Transverse	497	576	0.86	19.6

Test specimen : Round bar specimen (GL = 50.8mm)

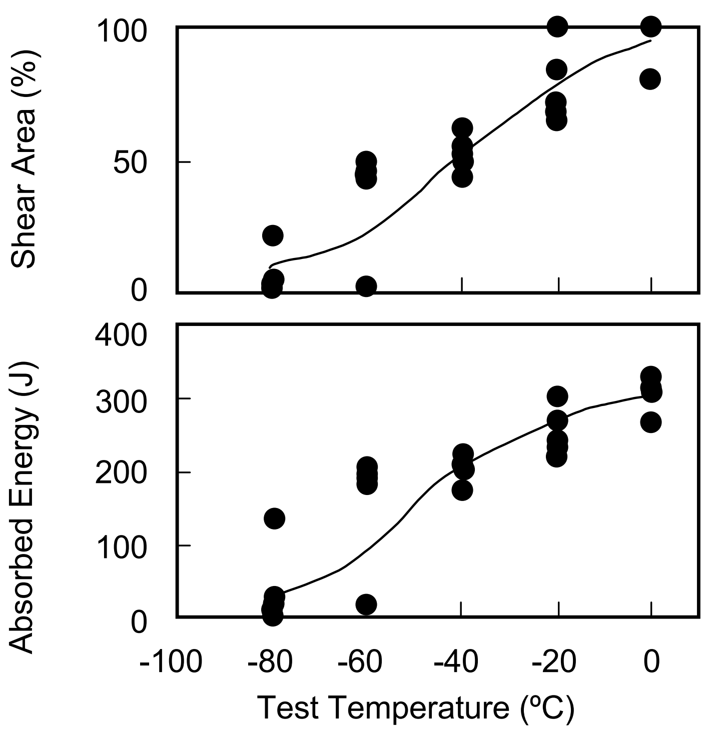

Figure 9. Charpy transition curves for base metal.

Corrosion Resistance

HIC testing was carried out according to NACE TM0284-96. Test specimens were immersed in solution A for 96 hours. No cracking was observed because of the steel composition with low sulfur content and calcium addition.

Weldability

Welded joints were prepared in a laboratory to evaluate weldability. In order to evaluate the reduction in toughness in the fusion line, L-type edge preparation was applied to match the fusion line with the crack propagation in the Charpy impact test. This L-type edge configuration is illustrated in Figure 10. The welding conditions used in this investigation are listed in Table IV.

Table IV. Welding conditions used in this test.

Welding process	Welding consumable	Welding condition	Heat input	Preheat temp.	Interpass temp.
GMAW	AWS 5.28 ER90S-G	250A-32V -32cm/min.	1.5kJ/mm	<50ºC	100ºC

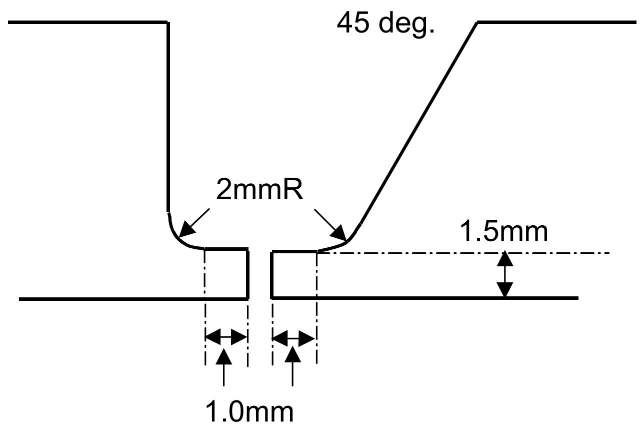

Figure 10. Schematic illustration of edge preparation for welding.

Table V. Tensile test results of weld joints.

Specimen	TS (MPa)	Fracture portion
1	626	Base metal
2	628	Base metal

Test specimen: Strip specimen

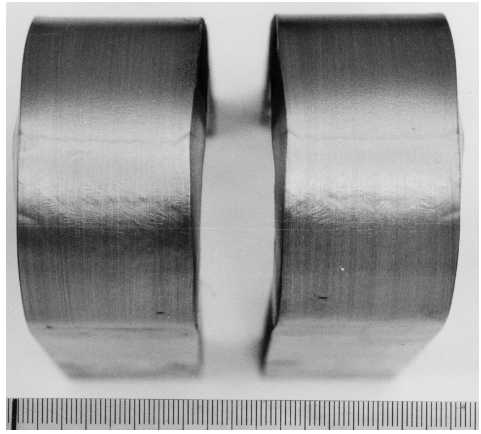

Figure 11. Side bend test results.

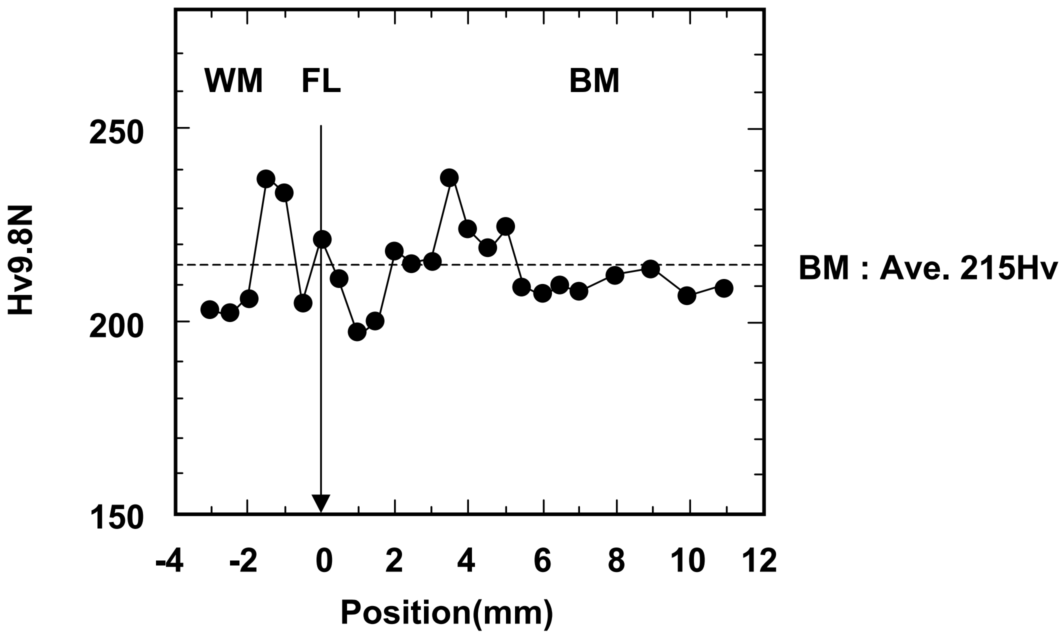

Figure 12. Typical hardness distribution of the weld joints.

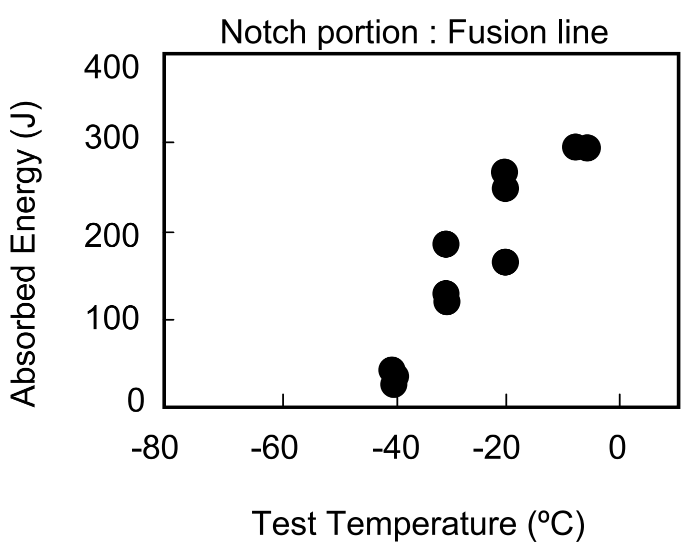

Figure 13. Charpy absorbed energy transition curve of the weld joints.

The tensile properties are shown in Table V, which indicates almost the same tensile strength as the base metal shown in Table II. This test was conducted according to API 1104 and a strip specimen was used.

The side bend test result is shown in Figure 11. This test was also conducted according to API 1104 and the bend radius was twice as long as the wall thickness. No cracking was observed in the two specimens.

Typical hardness distributions of the welded joints are shown in Figure 12. Average hardness of the base metal was 215 Hv and maximum hardness was below 240 Hv.

The Charpy absorbed energy transition curve is shown in Figure 13. In spite of the severe test for toughness in the specimen with L-type edge preparation, the deterioration of toughness is so small that this material is considered to have sufficient weldability. HIC testing of the welded joints was also carried out and no cracking was observed.

Conclusion

High-strength heavy-wall sour-service seamless line pipe suitable for deep sea applications has been successfully developed applying a new inline heat treatment process. Microalloying elements and impurities have been controlled to improve toughness and the required weldability has been achieved through limiting CE(IIW) or Pcm.

Acknowledgment

The authors would like to thank their colleague Mr. Hamagami for his assistance in carrying out this research and development. Thanks are also expressed to their former colleague Mr. Ichinose for his contribution on this paper.

References

1. H. Hori, “Medium Size Seamless Pipe Mill at Wakayama Steel Works” TUBE VERACRUZ 2003, International Tube Association Conference held in Veracruz, Mexico, October 8–10, 2003

2. C. Hayashi and T. Yamakawa, “Influences of Feed and Cross Angle on Rotary Forging Effects and Redundant Shear Deformations in Rotary Piercing Process” ISIJ International, Vol.37 (1997), No.2, 146-152

3. C. Hayashi and T. Yamakawa, “Influences of Feed and Cross Angle on Inside Bore and Lamination Defects in Rotary Piercing for Materials with Poor Hot Workability” ISIJ international, vol.37 (1997), No.2, 153-160

4. C. Hayashi, M. Akiyama, S. Tsumura, T. Yamakawa and K. Shimoda, “Influences of Expansion Ratio on Inside Bore and Lamination Defects in Expansion Piercing for Materials with Poor Hot Workability” ISIJ International, Vol.37 (1997), No.9, 892-898

5. C. Hayashi and T. Yamakawa, "Influences of Piercing Ratio, Expansion Ratio. Feed, Cross and Skew Angles on Available Piercing Size Range in Rotary Piercing Process" ISIJ International. Vol.38 (1998), No.11, 1255-1261

6. Y. Komizo, T. Kushida, K. Miyata and T. Omura, "Niobium in High Strength Steels for Oil Country Tubular Goods" Proceedings of the International Symposium Niobium 2001 held in Orlando, Florida, USA. December 2-5, 2001