Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering
OMAE2007
June 10-15, 2007, San Diego, California, USA

OMAE2007-29183

METALLURGICAL DESIGN OF NEWLY DEVELOPED MATERIAL FOR SEAMLESS PIPES OF X80-X 100 GRADES

Yuji Arai
Corporate Research & Development Lab's,
Sumitomo Metal Industries, Ltd.

Kunio Kondo
Corporate Research & Development Lab's,
Sumitomo Metal Industries, Ltd.

Hiroyuki Hirata
Corporate Research & development Lab's,
Sumitomo Metal Industries, Ltd.

Masahiko Hamada
Corporate Research & development Lab's,
Sumitomo Metal Industries, Ltd.

Nobuyuki Hisamune
Pipe & Tube Company
Sumitomo Metal Industries, Ltd.

Keisuke Hitoshio
Pipe & Tube Company
Sumitomo Metal Industries, Ltd.

Tsuneo Murase
Pipe & Tube Company
Sumitomo Metal Industries, Ltd.

ABSTRACT

With the increasing development of oil and gas fields in deepwater or ultra-deepwater with deep well depth, the development of high strength seamless pipe has become necessary.

This paper describes a metallurgical design of seamless pipe with high strength reaching X80-X100 grade (minimum yield strength, 552 MPa - 689 MPa) manufactured by steel containing very low carbon and with a microstructure of uniform bainite.

The effect of microstructure of quenched and tempered (QT) steel on strength and toughness is investigated in laboratory. Uniform bainitic structure without coarse martensite-austenite constituent (M-A) is obtained by lowering bainite transformation temperature during quenching process by controlling the alloying elements. Moreover the structure is very effective in obtaining good toughness for tempered steel even with the high strength X100 grade. Sufficiently low hardness and good toughness in heat affected zone (HAZ) are confirmed by welding tests.

The trial production of developed steel is conducted by applying inline QT process in medium-size seamless mill according to an alloying design obtained in laboratory tests. The seamless pipes of the trial production achieve grades X80 to X100 by changing tempering temperature. Some data of mechanical properties of the produced pipes is introduced.

1. INTRODUCTION

In recent years, explorations of oil and gas in deep water and ultra-deep water with deep well depth increasing design pressure and temperature, often defined as high pressure and high temperature (HPHT) application. In this case, flow line, steel catenary riser (SCR) and top tension riser (TTR) are affected by a HPHT environment.

Steel pipes constituting flow lines or risers installed in deepwater are exposed to a high internal fluid pressure applied to their interior due to the production pressure in deep underground regions. Therefore, steel pipes with high strength and/or heavy wall are required for deepwater and ultra deep water application. In order to ensure reliability, seamless steel pipes rather than welded steel pipes are used in such applications.

However, in general, steel pipes with higher strength tend to have low fracture toughness (either in pipe body and weld joint) and low girth weldability. Therefore, with respect to development of higher strength seamless pipes (such as yield strength of 552 MPa and more, reaching to 689 MPa), improvement of toughness and weldability are particularly important for HPHT applications.

In order to achieve high strength, good toughness and good weldability simultaneously, a new material is being developed by combining a new metallurgical design and inline heat treatment. In particular, weldable seamless pipes of the X80 grade of 40 mm wall thickness (WT) and X80 to X100 grades of 20 mm WT are being developed for HPHT application.

2. ALLOY DESIGN CONCEPT

Increasing Mn, Cr and Mo contents for high strength heavy wall seamless pipe

Contents of alloying elements such as Mn, Cr, and Mo are increased for strength of QT steel through mainly increase of hardenability at quenching process. Mn is effective in stabilizing austenite and preventing ferrite phase formed by diffusion transformation during quenching. In addition, Mo is effective in resisting temper softening.

Lowering vanadium content for excellent toughness

The strength of QT steel increases prominently by adding V which precipitates as carbides. However, precipitation hardening tends to deteriorate toughness in higher strength steel. Therefore V will be reduced to improve toughness of high strength QT steel.

Lowering carbon content to control Pcm for reliability of heat affected zone

In order to obtain good weldability, lowering carbon content and controlling carbon equivalent of the steel are most important to limit the hardness in heat affected zone (HAZ). The carbon equivalent is given by the following formula [1] for Pcm when the carbon content is less than or equal to 0.12%. Pcm should be usually regulated to 0.25% according to API specification 5L (in case of wall thickness =< 20.3 mm). High strength steel tends to have higher Pcm value because of richer alloying element, therefore, very low carbon content should be selected to control Pcm value with respect to hardness in HAZ.

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

Toughness in HAZ is degraded by existing Martensite-Austenite constituent (M-A) formed in HAZ by welding heat. Amount and size of M-A increase with carbon content of steel and with cooling time during welding. Therefore, carbon content should be reduced for HAZ toughness.

3. MANUFACTURING PROCESS

Simple & Compact mill line

The outline of the medium-size mill and the inline heat treatment which began operation in 1997 at the Wakayama steel works of Sumitomo Metals is described below. The concept of the mill line is “Simple & Compact”. The entire process for manufacturing the seamless pipe is directly connected as illustrated in Fig. 1, and the rolling line is arranged in a compact design. Consequently reduction of production costs and shortening of delivery time were achieved. In order to mass-produce heat-treated seamless pipe with high efficiency, the facility of inline heat treatment was installed. As a result, almost all heat treated pipe, such as high grade OCTG or project line pipe that used to be heat treated in an offline process, have been treated in an inline process.

One characteristic of the inline heat treatment facility is the installation of the heating furnace which is located just after the pipe making line in order not only to guarantee the quenching temperature above Ar3 transformation temperature, but also to improve the uniformity of mechanical property by homogeneous heating. This furnace is smaller than a usual furnace installed in a conventional offline heat treatment facility as it utilizes the latent heat possessed by the rolled pipe itself.

High cooling rate quenching system

Another feature of inline heat treatment is the unique water quenching system. The schematic illustration of the newly developed quenching device is shown in Fig. 2. Uniformly heated pipe is moved quickly to the cooling zone and one end is held tight 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 poured on the outside of the pipe. This quenching facility realizes a high cooling rate and homogeneous cooling for a pipe manufacturing line. Utilizing this high performance quenching ability and the optimization of the alloy design suitable to inline heat treatment has been achieved the development of X70 40 mm wall thickness seamless flow line for sour service [2] that had proved difficult to attain by conventional heat treatment.

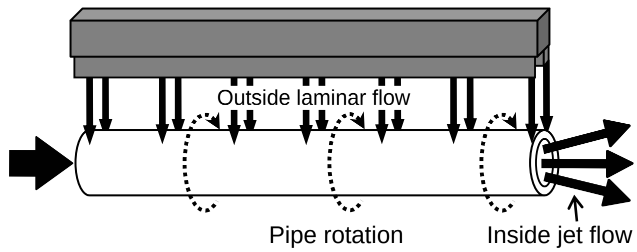


Fig. 2 Schematic illustration of the quenching device.

4. LABORATORY EXPERIMENTAL TEST

4.1 Test Procedure

As mentioned previously, the pipe manufactured in inline heat treatment has an ability to achieve higher strength, however toughness reduces in an inverse proportion, therefore, an investigation of the effect of alloying elements on strength and toughness of QT steels was conducted in laboratory to clarify a suitable alloying design for excellent combination of strength and toughness of seamless pipe produced by inline QT.

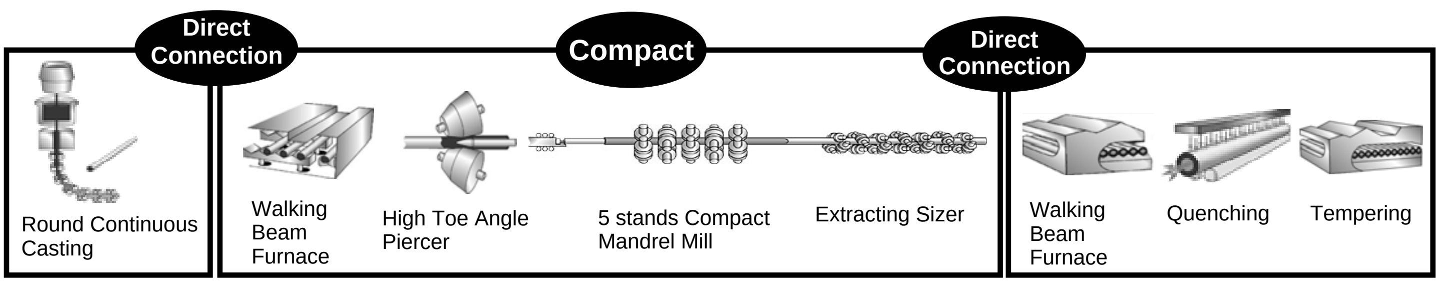


Fig. 1 Schematic illustration of the newly-constructed medium size mill and inline heat treatment facilities.

The chemical composition of materials used in this investigation was Low C-Mn steel for base composition varying C content from 0.04% to 0.07%, V content 0% and 0.05% and Pcm value from 0.15% to 0.25% by changing Mn, Cr, and Mo contents. These materials were melted in a vacuum induction furnace and the ingots were forged into blocks.

Phase transformation temperature of the steels was determined by a dilatometer which simulates cooling rate of pipe quenching, in order to investigate effect of chemical composition on hardenability.

The simulation of inline QT was carried out as follows. The blocks were heated at 1250ºC and after that were rough rolled for reduction of 20%, then were finish rolled for reduction of 50% to make steel plates with 40 mm and 20 mm thickness. The finish rolling was started at 1100ºC and the process was finished at around 950ºC. The hot-rolled plates were quenched in agitated water after the rolled plates were heated at 950ºC for 5 minutes by holding them in the furnace just after the finish rolling. The cooling rate from 800ºC to 500ºC during water quenching was 10 ºC/s and 40 ºC/s for mid portion of 40 mm thickness and 20 mm thickness plates respectively. After that the quenched plates were tempered at between 600ºC to 650 ºC for 30 minutes.

Tensile tests were conducted on longitudinal round specimens (D 8.5 mm, GL 50 mm). Transverse Charpy V-notch (CVN) specimens were used to determine the absorbed energy transition temperature (ETT).

Microstructure of the quenched steel plates was examined at the center portion of thickness. Characteristics of bainite structure were examined by transmission electron microscopy (TEM). Distribution of M-A constituent was observed by section after Le Pera's etching [3] by optical microscope (OM).

4.2 Results

Effect of Pcm on transformation temperature from gamma phase to bainite during quenching process

Fig. 3 a) and Fig. 3 b) show the effect of Pcm value of the steel on bainitic transformation temperature during continuous cooling at cooling rate of 10 ^{o}C/s and 40 ^{o}C/s respectively. Increasing Pcm value was effective in lowering the bainite start (Bs) and finish (Bf) transformation temperature even with low carbon content (from 0.05% to 0.07%) and preventing ferrite phase formed by diffusion transformation. Therefore controlling Pcm is important for achieving higher hardenability. It could be effective in preventing coarse M-A because carbon diffusion toward retained austenite phase will be delayed during transformation in lower temperature.

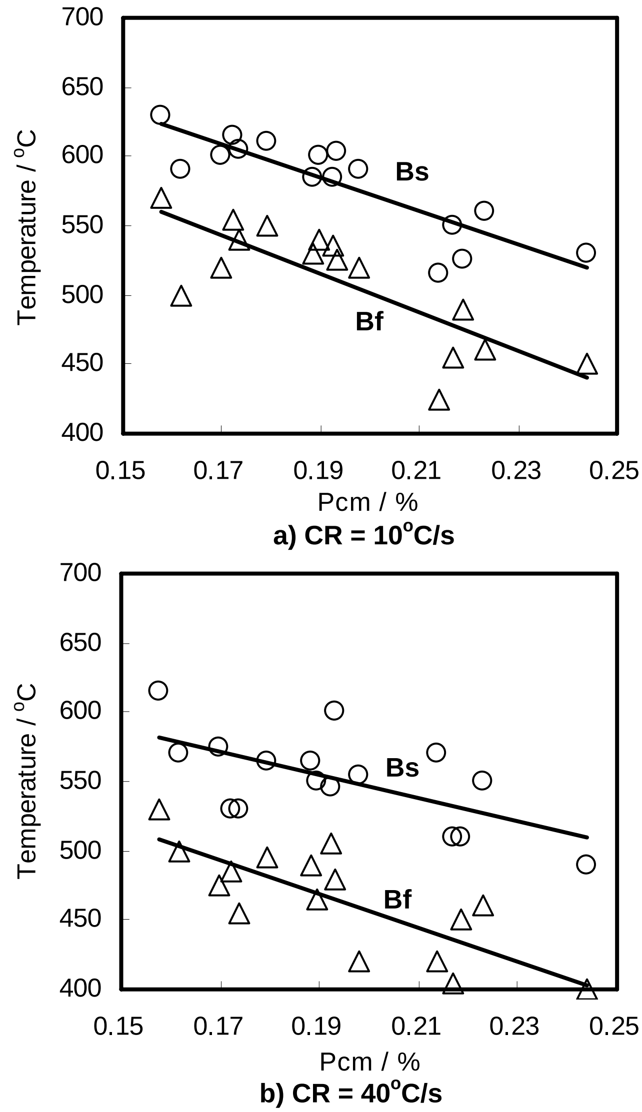


Fig. 3 Effect of Pcm on transformation temperature during continuous cooling from austenite phase (thermodilatometry test).
*CR : cooling rate from 800^{o}C to 500^{o}C

Effect of Pcm on strength and toughness

Fig. 4 a) and Fig. 4 b) show, respectively, the effect of Pcm on strength of the simulated inline QT steel plates with 40 mm thickness and 20 mm thickness. The yield strength was raised in proportion of Pcm value. X80 grade (YS>=552MPa) of 40 mm thickness was achieved by selecting the material with Pcm value of 0.21% or larger. X90 grade (YS>=621MPa) and X100 grade (YS>=689MPa) of 20 mm thickness were also achieved by Pcm value of around 0.21%. This indicates the target strength and wall thickness are achieved even with Pcm value less than 0.25% because of the applied inline heat treatment with the high cooling rate quenching facility.

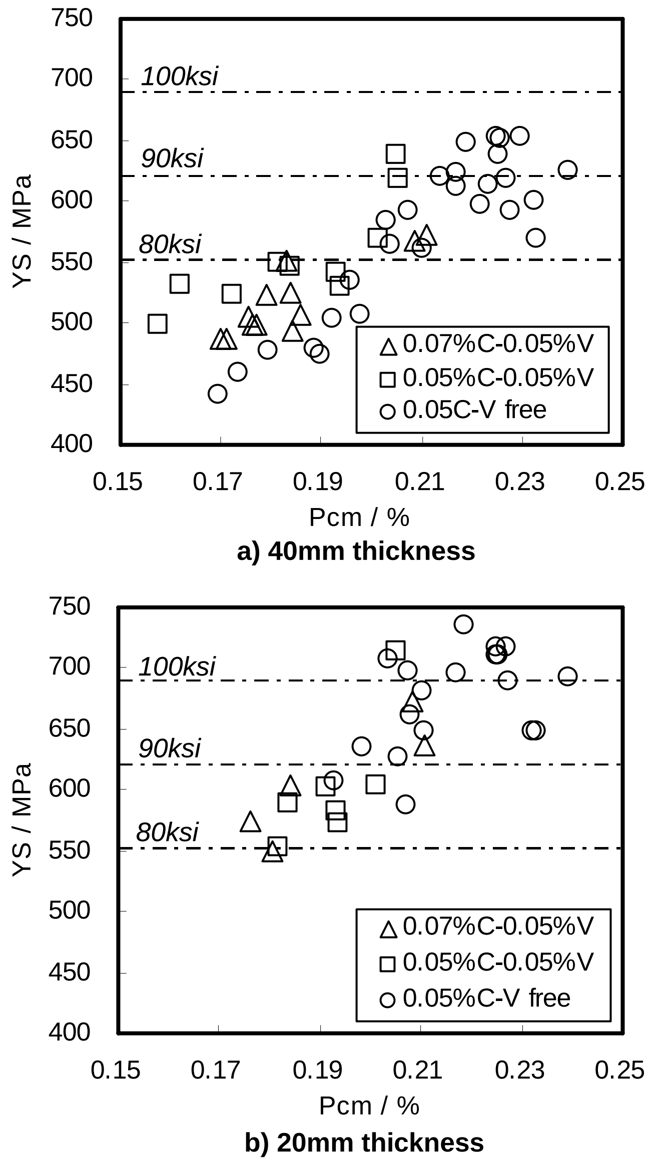


Fig. 4 Effect of Pcm on yield strength of simulated inline QT steel plate (tensile test of L-direction).

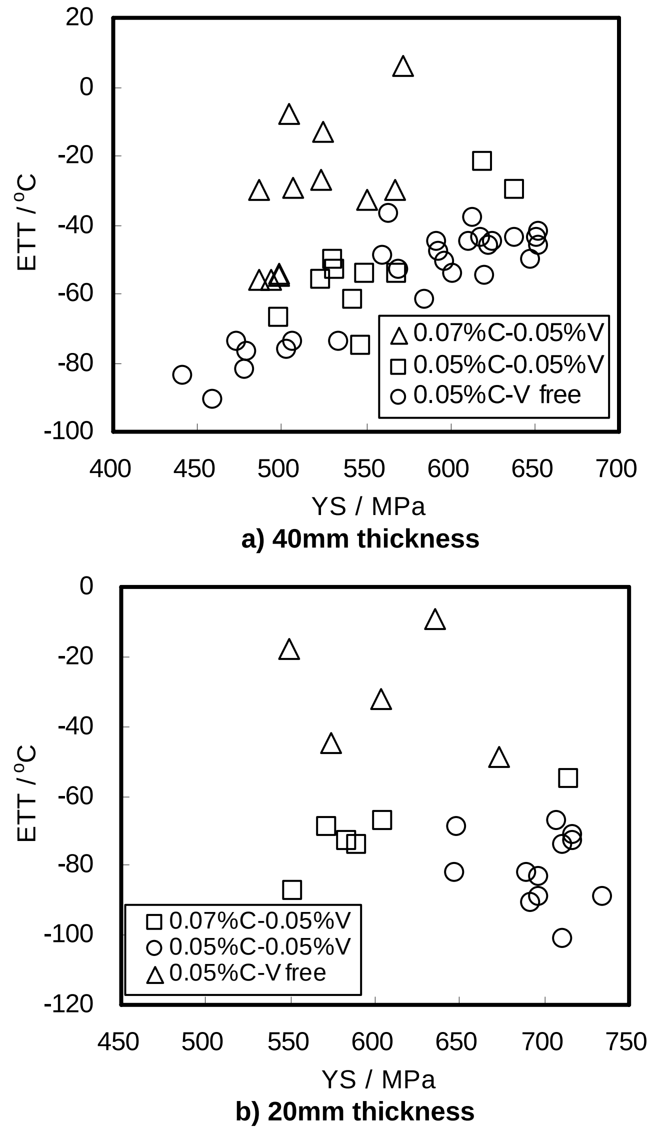


Fig. 5 Relationship between yield strength (YS) and energy transition temperature (ETT) of simulated inline QT steel plate (CVN test of T-direction).

Fig. 5a) and Fig. 5b) show, respectively, relationship between yield strength (YS) and energy transition temperature (ETT) of simulated inline QT steels plate. ETT increased with strength. But the rate of degradation of toughness was clearly different by C and V contents of the steels. In materials having 0.07%C-0.05%V, degradation of toughness was significant, on the other hand materials having 0.05%C-0.05%V did not have as much degradation of toughness, while in case of materials having 0.05%C with no V, degradation of toughness in strength was very small. It indicates that lowering C and V contents improve the toughness significantly.

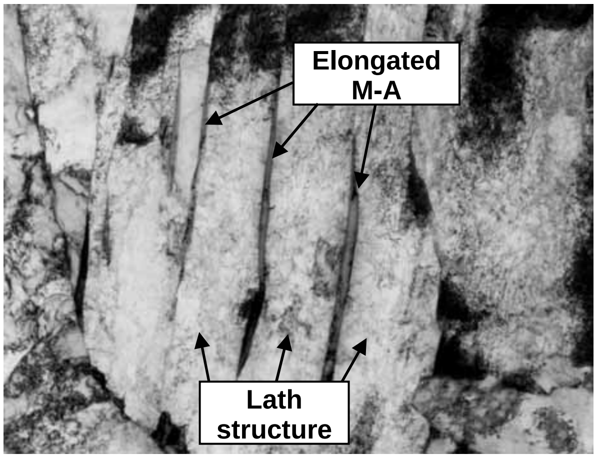
4.3 Discussion

Investigation of microstructure of quenched steel plate

In order to clarify the effect of the alloying design described above on microstructure, two types of materials each with a different chemical system which have a different Pcm value(see table 1) were observed by TEM and OM. Fig. 6 a) and Fig. 6 b) show microstructures of mid-thickness portion of the quenched steel A and steel B, respectively. In case of steel A, wide width of lath structures are observed and enlarged M-As appeared at lath boundaries. On the other hand in case of steel B, very fine lath bainitic structures were observed without large size of M-As, therefore, it is apparent that steel with increased Pcm has a potential to obtain higher strength by refining lath structure, the main reason is due to low transformation temperature (refer Table 1).

Table 1. Chemical composition used for micrographic analysis. (mass%)

Mark	C	Mn	Mo	V		Pcm	Bs(^{0}C)
A	0.07	1.4	0.2	0.05	others	0.18	605
B	0.05	2.0	0.7	tr.	others	0.22	515



a) Steel A 1μm

b) Steel B 1μm

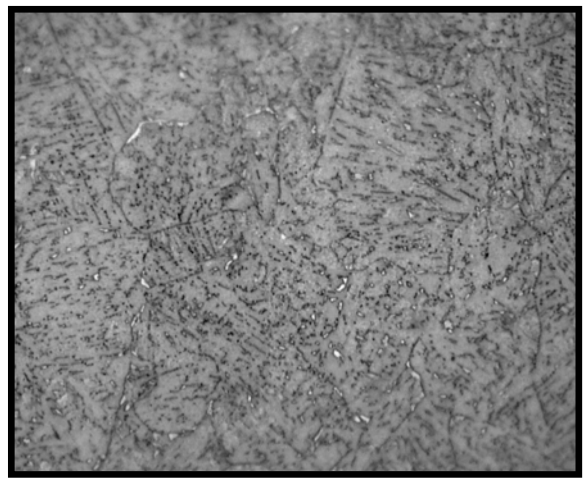
Fig. 6 TEM image of quenched steel plate (mid-thickness portion of wall thickness 40mm).

Fig. 7 a) and Fig. 7 b) show, respectively, distribution of M-A of mid-thickness portion of the quenched steel A and steel B. Large M-As appeared in large amount in steel A. Low Pcm steel, which has high transformation temperature, enhances coarse M-A because carbon diffuses quickly toward gamma phase during transformation from gamma phase to bainite in high temperature region and stabilizes retained gamma. Meanwhile, the amount of M-A in steel B was very small. It indicates that lowering carbon content and lowering transformation temperature by increasing Pcm could prevent generating M-A.

Table 2 Welding conditions used in this test.

Welding Process	Welding Position	Welding Wire	Heat input	Pre-heat	Inter pass temp.	PWHT
GMAW	1G	AWS A5.28 ER100S-G, NSSW SCH-70(1.2mm)	0.5-1.0kJ/mm	N/A	100-120^{o}C	N/A

a) Steel A 10μm



b) Steel B 10μm

Fig. 7 Optical micrograph of quenched steel plates (mid-thickness portion of wall thickness 40mm, M-As are colored white by Le Pera's etching).

From the observation above, it is suggested that the improvement in toughness by lowering C content and increasing Pcm is caused by minimizing M-A which is generated during the quenching process. In addition, it is considered that the improvement in toughness by lowering V content originates in decreasing precipitations of carbides at the tempering process.

In summary, high strength and excellent toughness are achieved by selecting material with low C content, high Pcm value (not exceeding 0.25% for weldability) and V-free. Moreover, the material could be effective in improving HAZ toughness.

5. WELDABILITY

Fundamental welding test was conducted to clarify the hardenability and the toughness in HAZ. Steel plates with a C content range between 0.03% to 0.05% and Pcm range from 0.21 to 0.24% were selected for this test according to the alloying design. The welding was conducted to simulate malti-pass welding of field girth welding. The welding conditions are listed in table 2 and steel plates with 15 mm thickness were used as the base metals in this test.

Hardness distribution in HAZ

Fig. 8 shows a typical macrostructure of the welding portion of the steel with Pcm 0.22% (steel B in table 1) and location of hardness measurement. As shown in Fig. 9, hardness along the fusion line were almost all between 240 Hv9.8 to 270 Hv9.8. Significant hardening did not occur in this test because of low carbon content and controlled Pcm. Therefore this material can be complied with hardness max. 300 Hv9.8 in DNV rule [4] for SML555 (equivalent to X80).

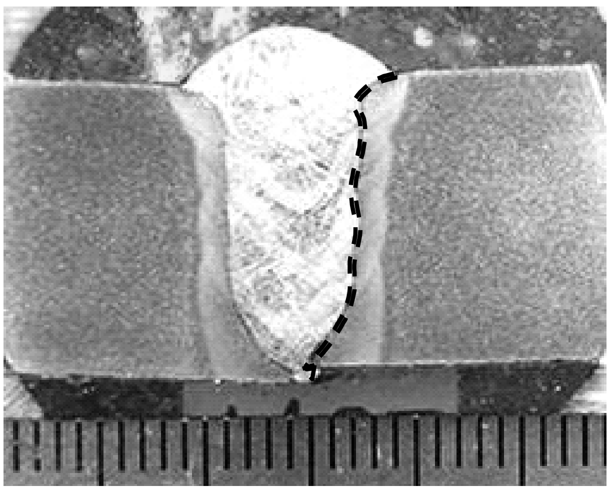


Fig. 8 Typical macrostructure of welding portion and location of hardness measurement.

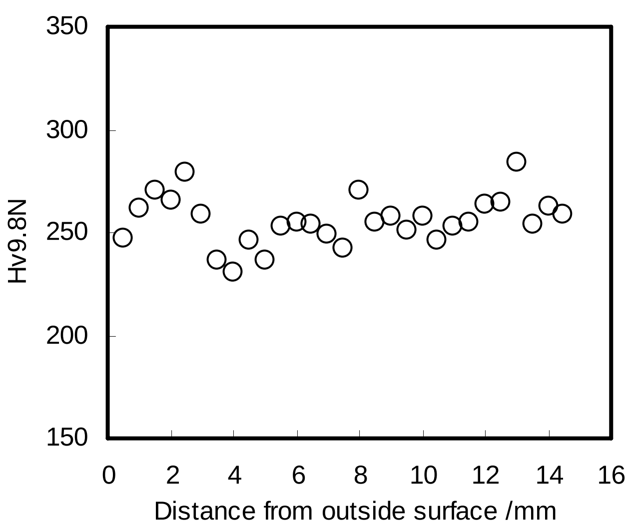


Fig. 9 Hardness distribution along fusion line of welding test.

Charpy Impact test in HAZ

Fig. 10 shows machining position of Charpy impact test specimen and V notch location. All Charpy absorbed energy at -20°C were above 60 J, therefore, these materials could have good HAZ toughness for riser application.

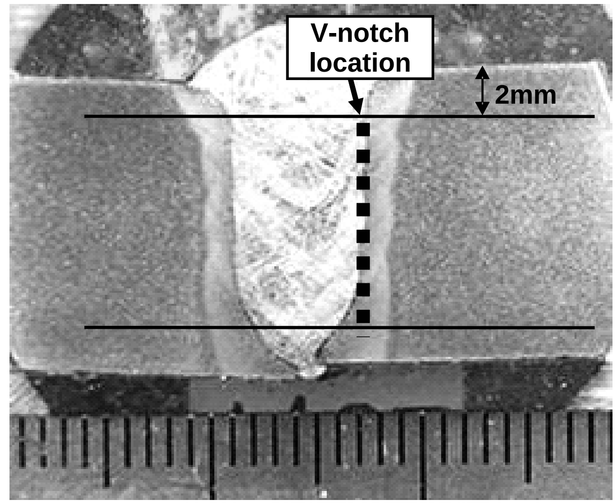


Fig. 10 Machining position of CVN specimen and V notch location.

6. TRIAL PRODUCTION

The trial production of seamless pipe using developed steel according to alloying design as mentioned above was conducted by applying inline heat treatment process in a medium-size seamless mill.

Material

Chemical composition for trial production is summarized in Table 3. This material is low C content, controlled Pcm by controlling Mn, Cr, Mo contents, with no V addition.

Table 3 Chemical composition of the steel used for the trial production of high strength seamless pips.

C	Mn	Mo	V	Ti	others	Pcm
0.04	2.1	0.7	Non-addition	0.01	Si,Cr, Al,Ca	0.22

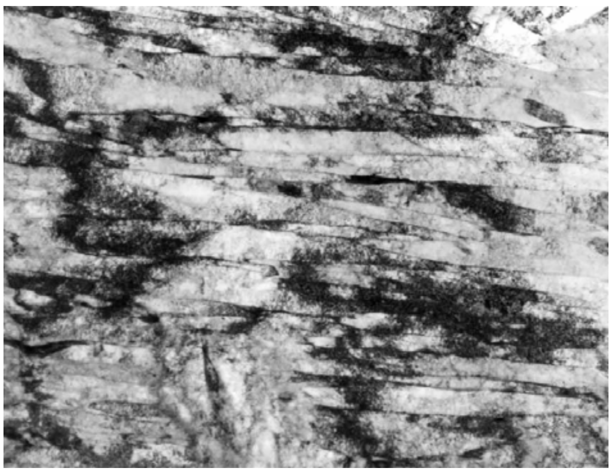
Target grades and size

323.9 mm OD and 40 mm WT was produced for X80 grade strength and 323.9 mm OD and 20 mm WT were produced for X80 to X100 grade strength. All pipes were produced by using the same material and a combination of production parameters (ex. tempering temperature).

Microstructure of Quenched pipes

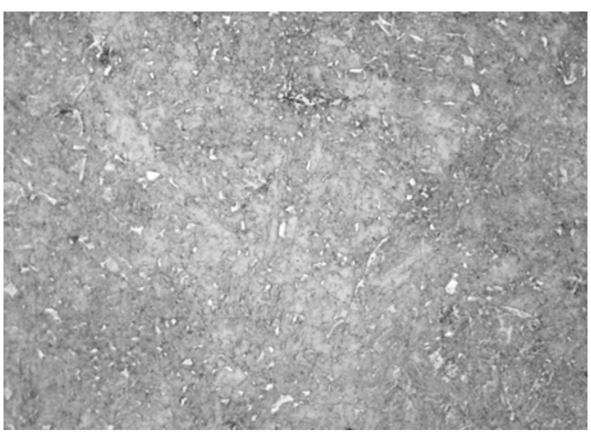
TEM images of mid-wall of the quenched pipes with 40 mm WT and 20 mm WT pipes are shown in Fig 11 a) and b) respectively. Fine lath structures were formed in both pipes. Optical micrographs mid-wall of the quenched pipes with 40 mm WT and 20 mm WT are shown in Fig 12 and Fig 13 respectively. M-A was restricted sufficiently even with 40 mm WT.

a) WT 40mm **1μm**



b) WT 20mm **1μm**

Fig.11 TEM images of mid-wall of quenched pipes.



10μm

Fig.12 Optical micrographs of mid-wall of quenched pipe with 40 mm WT (Le Pera's etching).

10μm

Fig.13 Optical micrographs of mid-wall of quenched pipes with 20mm WT (Le Pera's etching).

Tensile properties

The tensile properties of the pipes are summarized in Table 4. All of X80-X100 grades strength is able to be distributed by using one material. It is particularly worth noting that the material can control strength by changing tempering temperature. All of the pipes had sufficient low yield ratio and good elongation.

Toughness properties

The Charpy impact test was conducted to determine 50% fracture appearance transition temperature (vTrs) of the pipes corresponding to table 5 using a transverse specimen cut from the mid-wall of the pipes. The vTrs of these pipes were sufficiently low, therefore, both 40 mm WT pipe and 20 mm WT pipes have sufficient low temperature toughness for HPHT application.

Table 5 Toughness properties of trial production of high strength seamless pipes (T-direction CVN specimen).

Target grade	WT(mm)	vTrs (^{o}C)	vE-20^{o}C
X80	40	-33	251
X80	20	-60	315
X90	20	-50	258
X100	20	-35	185

Table 4 Tensile properties of trial production of high strength seamless pipes.

Grade and size of pipes			Tensile properties				
Target grade	OD(mm)	WT(mm)	Specimen	YS(MPa)	TS(MPa)	YS/TS(%)	El(%)
X80	323.9	40	Longitudinal strip	641	720	88	46
			Transverse round bar	625	705	89	24
X80	323.9	20	Longitudinal strip	618	686	90	44
			Transverse round bar	630	690	91	26
X90	323.9	20	Longitudinal strip	664	730	91	42
			Transverse round bar	664	727	91	25
X100	323.9	20	Longitudinal strip	719	822	87	40
			Transverse round bar	737	832	89	21

7. CONCLUSIONS

In order to develop high strength seamless pipes for flow line and risers with respect to HPHT applications, laboratory investigation for alloying design and trial production applied to inline heat treatment were conducted.

(1) Lowering transformation temperature by increasing Pcm value of steel contributes to refine lath bainitic structure and to minimize M-A. There were significant improvements in strength and toughness.

(2) A new alloying concept was found to improve the combination of high strength and good toughness for seamless pipes. That is, lowering C content, increasing Pcm not exceeding 0.25% and V-free material.

(3) Low hardness and good toughness at welding fusion line was confirmed by welding tests in laboratory. Sufficient weldability could be obtained by using the new material.

(4) High strength seamless pipes as X80 grade heavy-wall (40 mm) pipe and X80-X100 grades middle wall (20 mm) were produced as trial. A good combination of high strength and good toughness was confirmed.

Investigations of sour resistance and welding test by using the seamless pipes have been working.

REFERENCES

[1] Y. Ito & K. Bessyo, “Weldability Formula of High Strength Steels Related to Heat Affected Zone Cracking,” Journal of Japanese Welding Society, 1968, 37, (9), 938.

[2] Y. Arai, K. Kondo, M. Hamada, N. Hisamune, N. Murao, H. Osako, T. Murase, “DEVELOPMENT OF HIGH-STRENGTH HEAVY-WALL SOUR-SERVICE SEAMLESS LINE PIPE FOR DEEP WATER BY APPLYING INLINE HEAT TREATMENT,” Proc. of International Pipeline Conference, Calgary, Alberta, Canada, October 4 - 8, (2004), IPC04-000275.

[3] Le Pera, F. S, “Improved etching technique to emphasize martensite and bainite in high-strength dual-phase steel,” J. Met., 1980, 32(3)., 38–39.

[4] Det Norske Veritas, “Submarine Pipeline Systems,” DNV Offshore standard OS-F101, January 2000.

ACKNOWLEDGMENTS

The authors wish to thank Sumitomo Metal Industries, Ltd. for allowing publication of this study. The assistance and discussion of co-workers in the laboratories are gratefully acknowledged.

