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

OVERVIEW OF DEVELOPMENT AND COMMERCIALIZATION OF X120 ULTRA-HIGH STRENGTH UOE LINEPIPE

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Keywords: High Strength Steel, Line Pipe, Boron Steel, Bainite Steel,

Abstract

High-pressure operation through high strength linepipe reduces the long distance transportation cost of natural gas. In order to maximize the cost reduction, X120 UOE pipe has been developed. Low C - high Mn - Mo- Nb - Ti - B steel with a fine-grained lower bainite (LB) dominant microstructure realizes high strength, excellent low temperature toughness and good weldability. The boron-added, low carbon steel is also suitable for achieving good long seam HAZ toughness. In addition to the plate development, UOE forming technology and seam welding technology were tough challenges but successfully developed.

Suitability for use in a pipeline system was demonstrated through an extensive development program that included burst tests, fracture toughness evaluation, girth welding technology, etc. A 1.6 km demonstration line was successfully constructed.

Introduction

Natural gas is becoming an increasingly important energy source [1]. Often the major natural gas fields in the world are far from the major markets, some thousands of km apart. Improving the long distance gas transportation economics plays a critical role in deciding whether a particular remote gas filed development will be economic or not. The application of X120 high strength linepipes enables gas producers to realize significant savings in the total cost of long-distance gas transmission pipelines. These saving can be achieved from cost reductions in multiple areas including material, construction, compression, and integrated project operations [2].

Figure 1 describes rough calculation results of diameter, wall thickness and weight per unit length of high strength

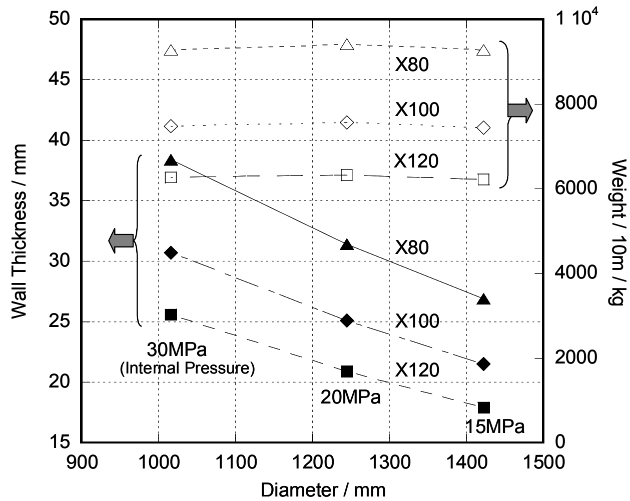


Figure 1. Change of strength and weight by pipe strength (constant transportation volume)

linepipes in the case of constant transportation volume of natural gas. Even if the material cost per unit length is the same for any grades, significant reduction of pipe weight and wall thickness by application of higher strength steel can lead to cost reduction in transportation and field welding. Furthermore, very thick pipes may be difficult to produce in a mass production process. Nippon Steel started joint development of X120 with ExxonMobil in 1996 when most linepipe produced was grade X65 or lower and very limited amount of X80 had been manufactured. Therefore, a large step in linepipe manufacturing technology was required to develop X120 from the existing technological basis. This paper describes overviews of the development and commercialization of X120 ultra-high strength UOE linepipe.

Property targets and development issues

General requirements for seam-welded linepipe are summarized in Table I. The strength of the pipe in the circumferential direction (C-direction) determines the pressure-carrying capacity of the pipeline and, therefore, is an essential requirement. For X120 pipe, a specified minimum yield strength[1)] (SMYS) in the C-direction is 827MPa (120ksi), and a specified minimum tensile strength (SMTS) is targeted to be 827MPa (135ksi)[2)]. The strength in the longitudinal direction (L-direction) of the pipe does not directly affect the pressure-carrying capacity of the pipe, and no strength targets were therefore developed for the L-direction. However, the strength and ductility in the L-direction may affect the ability to make cold bends from the pipe, and may affect the tolerance of the pipeline to axial deformation in service [3].

Table I. General requirement for seam-welded linepipe.

	Item	Required properties	Evaluation method	Test method for QA, QC
Base	Internal pressure	Base metal C-YS, C-TS	Ring expansion test	C-tensile test
		Seam weld C-TS		Trans weld tensile test
	Crack initiation	Critical crack size (typically in weld portion)	CTOD J-integral value	CVN energy
	Crack arrestability	(Crack speed) Ductile fracture	DWTT DBTT	CVN DBTT, DWTT SA
		Energy required for propagation	Precrack DWTT energy Full-scale crack arrest test	CVN energy
	Weldability	Preheat temperature <(150)^{o}C	Weld cracking test	Chemical composition (Pcm, Ceq, etc)
Optional	Sour gas	No HIC, No SSC	Full size SSC test	HIC test, SSC test
	Strain based design	Bending collapse angle	Pipe bend test	L-tensile test (YS, n-value, u-El.)
		Girth weld Critical crack size	Wide plate test with weld	

It becomes more difficult for higher-strength steel to achieve high toughness. A base equation that predicts the CVN energy required to arrest a running ductile fracture. To ensure applicability to a broad range of pipeline projects, including those in cold environments, a minimum design temperature of –20°C was selected as a toughness test temperature target. To account for the reduced thickness of the Charpy specimen, a CVN test temperature of 10°C lower was selected; therefore, a CVN energy of 231J or greater at –30°C was tentatively targeted.

For the seam weld, resistance to ductile fracture propagation is not a primary concern. The CVN target for the seam weld is intended to ensure adequate resistance to fracture initiation. For screening of candidate materials, a CVN target of 84J at –30°C was developed by extrapolating the toughness requirements for lower grade steels (up to X80) in DNV OS-F101 to the 827MPa (120ksi) strength level. The Charpy test is only a rough indicator of fracture initiation resistance. The ability to resist fracture initiation should be verified by performing fracture mechanics tests such as CTOD tests or J-integral tests. Based on a fracture mechanics analysis assuming a 2-mm deep surface-breaking crack that cannot be missed by general UT methods and typical pipeline operating stress, a CTOD value of 0.08mm at –20°C was set as an initial target for the seam weld fracture toughness. This target is relevant to a 36-inch OD, 16-mm wall thickness design. The initial target properties for 36-inch, 16-mm wall, X120 design are given in Table II [4].

Table II. Target properties of X120

Property	Base pipe	Seam weld & HAZ
Tensile strength (circumferential)	YS≧827MPa (120ksi)	TS≧931MPa(135ksi)
CVN energy @-30℃	≧231J	≧84J
CTOD@-20℃	≧0.14mm	≧0.08mm
DBTT of CVN	≦-50℃	
B-DWTT SA@-20℃	≧75%	

Plate Development

<u>Microstructure of steels for high-strength linepipe</u>

Considering weldability for field construction, the carbon content of high-strength linepipe is 0.10% maximum. In order to supply a large amount of linepipe to a big pipeline project during a limited period, use of as-rolled steel or TMCP steel without heat treatment is essential. Figure 2 is a schematic illustration showing the relationship between transformation temperature and tensile strength (TS) for three steels with different carbon contents of 0.10% or lower; the figure suggests that a lower-bainite (LB) microstructure steel with a low carbon content (lower than 0.06%) and an upper-bainite (UB) microstructure steel with a rather high carbon content (close to 0.10%) are candidates for X120 steel. Considering low temperature toughness and productivity, for X120 development, the LB dominant microstructure steel was applied and the interrupted direct quench (IDQ) process was employed. The IDQ process is schematically illustrated in Figure 3 and the effect of IDQ stop temperature on strength and toughness is shown in Figure 4. Here, no attention is paid to the yield strength (YS) because it greatly increases due to pipe forming. The tensile strength gradually decreases with increasing IDQ stop temperature, while the change is relatively small up to 400°C. The ductile-to brittle transition temperature (DBTT) for the CVN test starts to increase at about 450°C and as a result, the CVN energy decreases. The microstructural change from LB-dominant to UB-dominant causes the increase in DBTT.

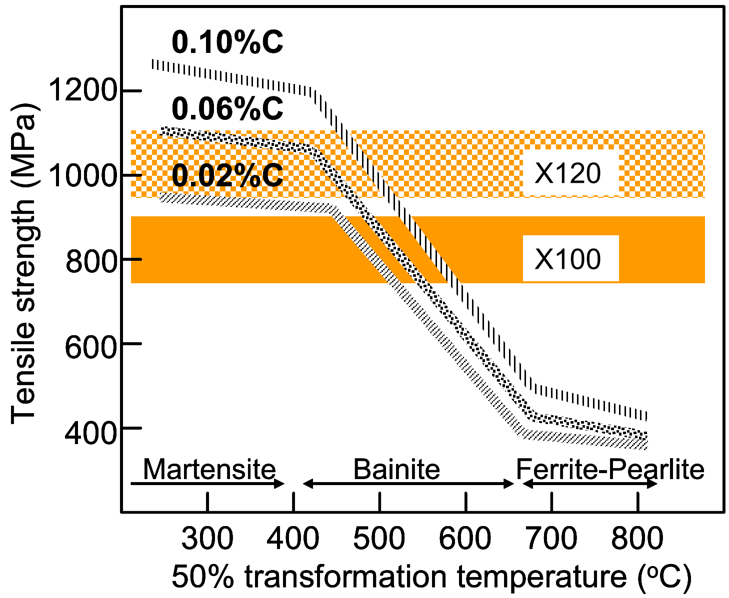


Figure 2. Schematic illustration showing the relationship between transformation temperature and tensile strength

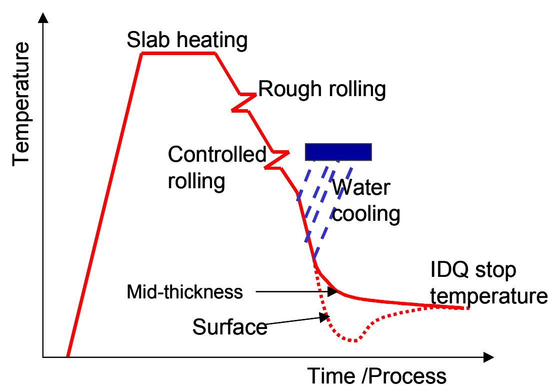


Figure 3. Interrupted direct quench (IDQ) process.

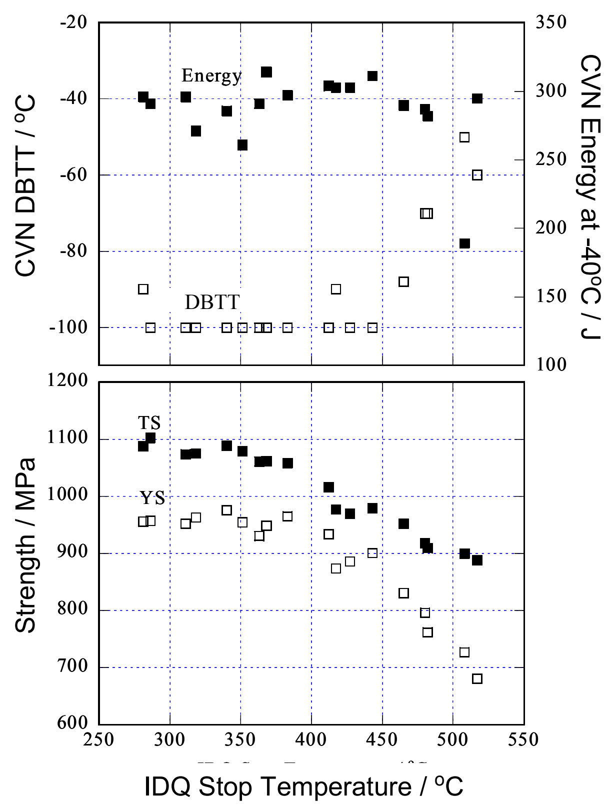
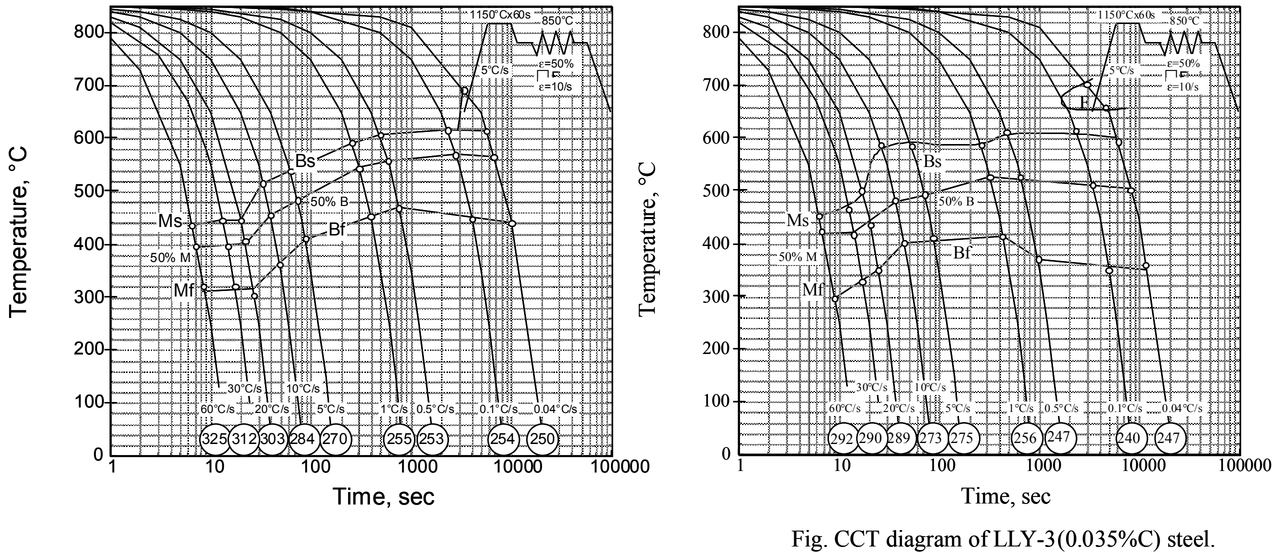


Figure 4. Effect of IDQ stop temperature on strength and toughness.



(A) B-added steel, β-value =3.2, (B) B-free steel, β-value =3.4

Figure 5. CCT diagrams after hot-working.

In order to promote a LB-microstructure with leaner chemistry, an addition of boron (B) was investigated. Figure 5 illustrates the continuous cooling transformation (CCT) diagrams after hot-working for B-free and B-added steels with very similar transformation behavior. For these steels, LB microstructure is formed at a constant bainite-start (Bs) temperature of around 450^{o}C over a wide range of cooling rates that can be achieved in IDQ process. However, it should be noted that much higher alloy content is required for the B-free steel than the B-added steel. “β-value[3)]” of the B-added steel is 3.2 and that of the B-free steel is 3.4. This difference corresponds to about 0.6% higher Mo content in the B-free steel if a Mo content of the B-added steel is assumed as being 0.2%.

Chemistry required for the seam HAZ

The fracture toughness in the heat affected zone (HAZ) formed by seam welding is an important consideration in the design of the steel chemistry.

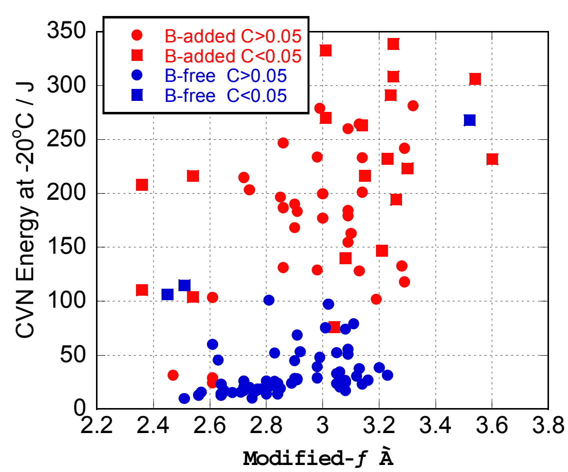


Figure 6. Effect of alloy system on relationship between β-value and CVN energy at -20^{o}C of simulated HAZ.

[3)] For B-free steel, β-value = 2.7C + 0.4Si + Mn + 0.8Cr + 0.45(Ni + Cu) + 2V + Mo – 0.5. For B-added steel, β-value = 2.7C + 0.4Si + Mn + 0.8Cr + 0.45(Ni + Cu) + 2V + 1.5Mo. These are modified from the original β-value to apply to hardenability in IDQ process.

Degraded toughness in the seam HAZ of the double-submerged-arc welded (DSAW) pipe is expected in the coarse-grained HAZ (CG-HAZ) and re-heated CG-HAZ that is sometimes regarded as the local brittle zone (LBZ). Because the assumed flaw for crack initiation was a surface-breaking defect, the toughness in CG-HAZ is thought to be more important and is considered here. Steels with chemistries that can be used for high-strength linepipe were subjected to a simulated HAZ thermal cycle corresponding to CG-HAZ of the DSAW seam weld. The peak temperature was 1400^{o}C. CVN energy values at -20^oC are illustrated as a function of hardenability index, β-value in Figure 6. The CVN energy for B-added steel, especially with C content of 0.05% or lower, is high. The CVN energies of B-free steel are in general lower than those of B-added steel, especially with C content exceeding 0.05%. This is well understood from the transmission electron micrographs shown in Figure 7. LB microstructure is formed in the CG-HAZ of the B-added steel, while UB microstructure is dominant for the B-free steel. For the UB microstructure, long and large black images of carbides or martensite-austenite constituents (MAs) are observed between the lathes.

Excessive softening in the seam weld HAZ should be suppressed. Figure 8 illustrates trans-weld hardness distribution at the mid-thickness and at the 2-mm position from outside surface for the B-added steels with and without Nb. The HAZ of the mid-thickness position was exposed to a double thermal cycle and that of the near-surface position to a single thermal cycle. The softening is reduced for 0.03% Nb steel in the case of the double cycle, while no pronounced effect appears in the case of the single cycle because the hardnesses are determined by a LB microstructure.

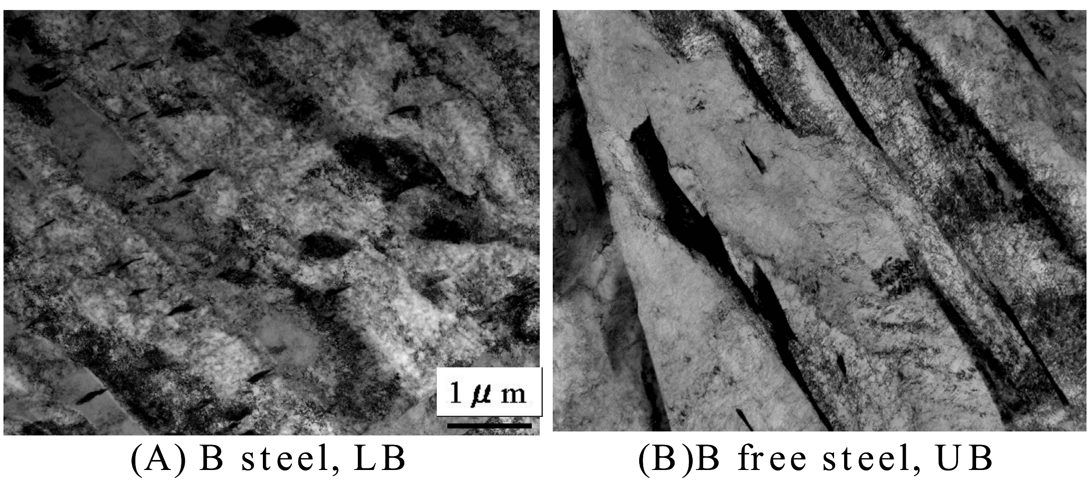


Figure 7. Transmission electron micrographs of simulated HAZ microstructure

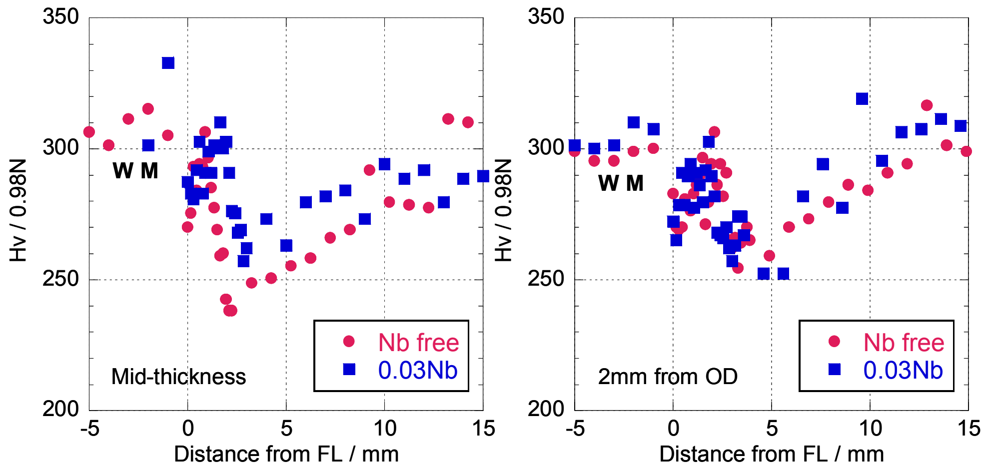


Figure 8. Effect of Nb on trans-weld hardness distribution

<u>Chemical composition of plate</u>

The better toughness of the boron-added steel in both the base metal and the HAZ strongly suggests that an addition of boron is preferable or essential to attain the combination of high strength and high toughness required for X120. Furthermore, the boron-added steel avoids excessive high alloy costs that could erode the benefit of high strength steel application. Careful care, however, is required to successfully employ boron in the chemistry of a linepipe steel. To improve hardenability, boron must be present in solution along grain boundaries. First, to prevent formation of BN, N is fixed as TiN by adding stoichiometric amount of Ti. The formation of boron carbide of $Fe_{23}(CB)_6$, which can precipitates during cooling in the austenite region, must be suppressed. The amount of boron added should be limited to a very narrow range above the minimum content necessary because excess boron accelerates the formation of boron carbide. Including Mo [5] and/or Nb [6] is also useful to stabilize the effect of boron.

For martensite and LB dominant steel, TS (or hardness) is principally governed by carbon content. Figure 9 illustrates the relationship between carbon content and TS for martensite and for X120 plate; for reference, the reported data for X100 and X80 are also plotted. The graph indicates that TS of X120 linearly correlates to carbon content and, therefore, that carbon content should be controlled to a narrow range to obtain the targeted strength of a LB steel. For a given carbon content, the difference between the hardness of martensite and the hardness of LB (X120) is small. Since the martensite hardness is the maximum hardness that can be expected in a HAZ, the maximum increase in hardness in the HAZ from the level in the base metal is limited, even if the hardenability, or Pcm is very high. This differs from the case of UB or ferrite steels such as X100, X80 and X65.

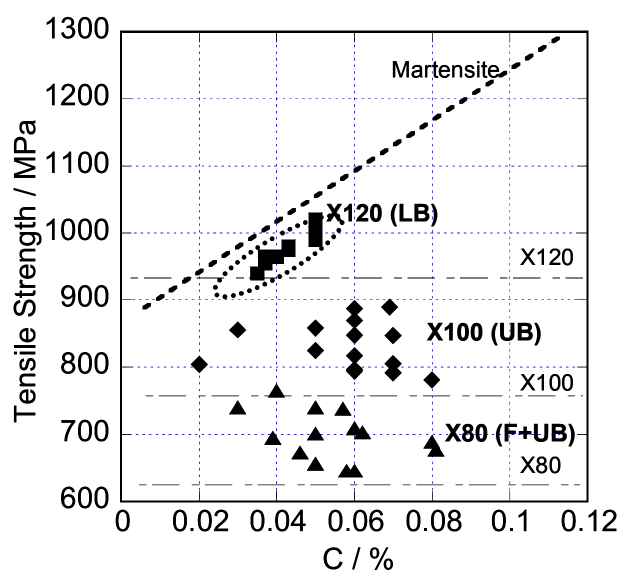


Figure 9. Effect of carbon on tensile strength for martensitic,X120, X100 and X80.

Thus, the chemistry of 0.04/0.05%C-Mo-Nb-Ti-B was selected. In order to achieve enough hardenability to transform the through-wall into a LB dominant microstructure, high Mn and other alloy elements such as Ni, Cu, Cr are additionally introduced.

Plate production

Molten steel, after being subjected to secondary refining in order to reduce sulfur, oxygen, and so on, is continuous-cast and reheated for hot-rolling. Following rolling in the recrystallization temperature range, plates are rolled in the non-recrystallization temperature range. During non-crystallization rolling, the austenite grains are elongated and form a “pancake” structure that is elongated in the direction of rolling. The LB packets often occupy the full thickness of the pancake grains, and thus the thickness of the austenite grains (pancake thickness) determines the packet size. Therefore, DBTT decreases with decreasing pancake thickness.

Weldability

One of the major concerns of B-added steel might be occurrence of cold-cracking. In order to assess the cold-cracking susceptibility, y-groove cold cracking tests were conducted using two kinds of MIG wires at varied pre-heat temperatures. As illustrated in Figure 10, no cold-cracking occurred even without pre-heating. This is probably because of low C chemistry more than low Pcm. Pre-heating at a moderate temperature, however, is necessary to prevent cold-cracking in the girth-weld [7].

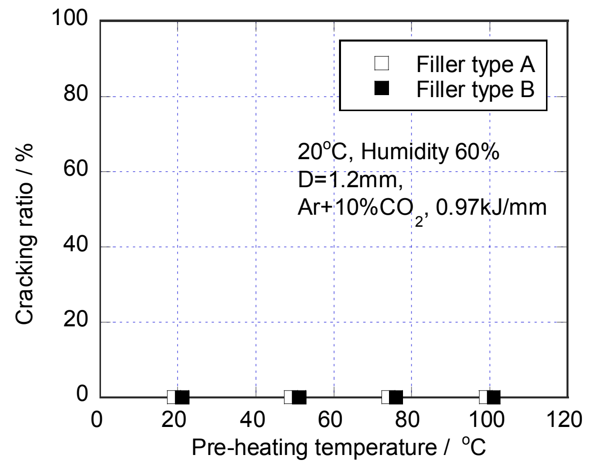


Figure 10. Results of y-groove weld cracking test. (TS of A =956MPa, TS of B = 993MPa)

Pipe making technology

Pipe forming

A big technological issue for the development of X120 is to form a pipe with good dimensional properties in a UOE process by mitigating the high strength and thus large spring back that is unavoidable in pressing high strength steel. Through an FEA simulation of the pipe forming and pipe-making tests in the actual UOE mill, the pipe forming technologies were established. Figure 11 shows the pipe sizes which Nippon Steel succeeded in making so far. About 500 pipes have been made. Distribution of ovality for 40-inch OD and 19-mm WT pipes are shown in Figure 12, as an example. Further improvements are expected with additional manufacturing experience and optimization of the mill tooling.

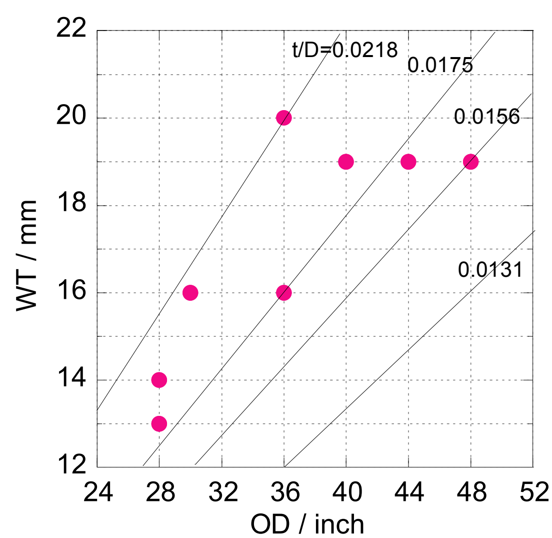


Figure 11. Sizes of pipes produced for testing.

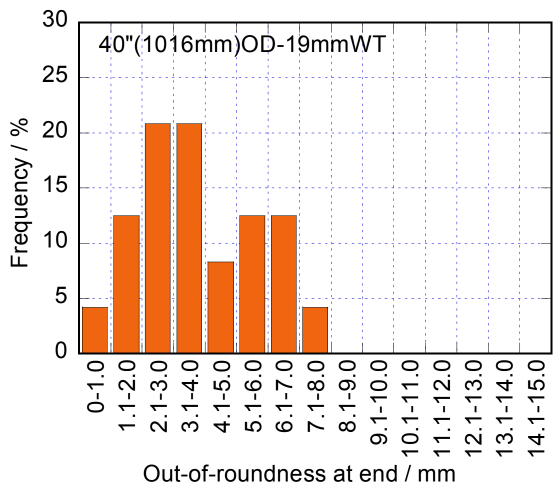


Figure 12. Out-of –roundness distribution of 40"OD-19mmWT pipe during trial production.

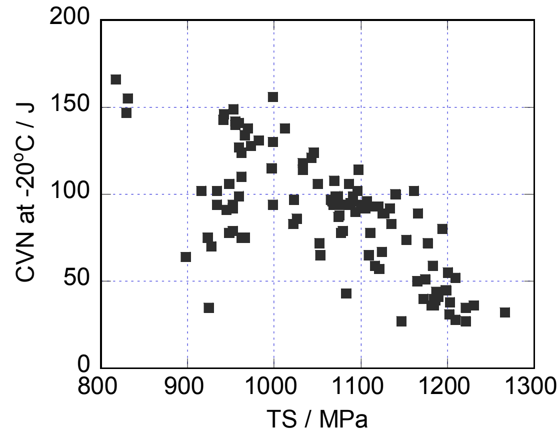


Figure13. Balance between TS and CVN energy of weld metal produced by SAW.

<u>Seam welding</u>

In order to assure the weld joint strength, weld metal with a higher strength than that of the plate and a high toughness had to be developed. Many combinations of wires and fluxes were studied in a laboratory as illustrated in Figure 13. There are some candidates that meet the required strength and toughness. The key technologies are the microstructure of UB and the chemistry of low C and low O.

Properties of pipe

<u>General properties</u>

Table III and IV indicate the typical chemical compositions of the plate and the seam weld metal. In Figure 14, representative microstructures are shown for the plate (LB) and the seam weld (DUB; Degenerated Upper Bainite). Mechanical properties for a 40-inch OD and 19mm WT are tabulated in Table V. The circumferential strengths meet the target values for both a flattened full thickness specimen and a round bar specimen. The cross weld strength is almost equal to that of the base metal (plate). The longitudinal strength that may relate to deformability of a pipe is lower than the circumferential one. Considering a very high strength pipe, a YS (yield strength) of 853MPa, Y/T (yield to tensile) ratio of 0.90 and u-El. (uniform elongation) of 3.0% are thought to be reasonably good values and allow the deformation to some extent. The CVN energy in the base metal exceeds the target. The CVN energies for the other locations shown in the table also meet the targets. However, once a LBZ that is very small area corresponding to re-heated CG-HAZ located at the mid wall is hit, a low value can occur. However, CTOD values, even for notches at the LBZ, meet the target as illustrated in Figure 15,

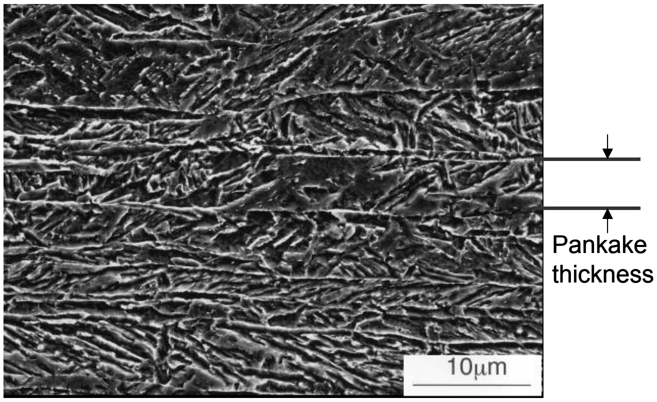
Table III. Major chemical compositions of the base metal.

	C	Mn	Mo	Ti	B	others	Pcm
Base metal	0.041	1.93	0.32	0.020	0.0012	Cu,Ni,Cr,Nb	0.21
	0.036	1.96	0.34	0.017	0.0012	Cu,Ni,Cr,Nb	0.21

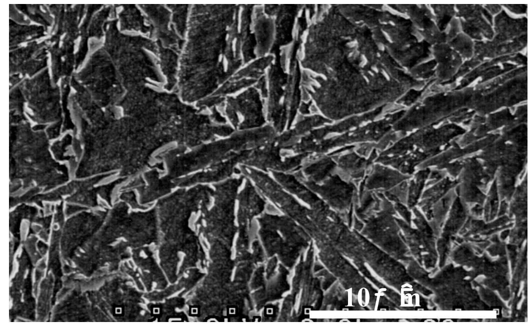
Table IV. Major chemical compositions of the weld metal.

	C	Si	Mn	Ni	Mo	Cr	Pcm
OW	0.05	0.23	1.63	2.2	0.92	1	0.31
IW	0.05	0.18	1.69	2.6	0.98	1.1	0.32

OW: Outside weld, IW: Inside weld



(A) Plate (Lower Bainite)



(B) Weld metal (Degenerated Upper Bainite)

Figure 14. Typical scanning electron micrographs

Table V. Typical mechanical properties of X120 pipe.

Size	Tensile test (API strap specimen)										Trans weld	Charpy V-notch, J ave. of three						B-DWTT	
	Circumferential					Longitudinal						Mid thickness						SA / %	
OD WT	YS MPa	TS MPa	El. %	uEl. %	Y/T %	YS MPa	TS MPa	El. %	uEl. %	Y/T %	TS MPa		Base metal	Weld metal	FL	FL+ 1mm	FL+ 2mm		Base metal
40" 19mm	**853**	**945**	**31**	**2.7**	**90**	**825**	**928**	**30**	**3.0**	**89**	**950**	-5℃		**174**	**199**	**259**	**249**	-5℃	**75,72**
												-30℃	**318**	**115**	**217**	**48**	**173**	-20℃	**65,63**
	(Rond bar specimen)											(2mm from OD)							
	YS MPa	TS MPa	El. %	uEl. %	Y/T %								Base metal	Weld metal	FL*	FL+ 2mm	FL+ 5mm		
	900	**917**	**20**	**1.9**	**98**							-5℃		**163**	**163**	**241**	**278**		
												-30℃	**335**	**94**	**110**	**162**	**305**		

FL：Intersection of the SAW　　FL*:50%HAZ/50%WM

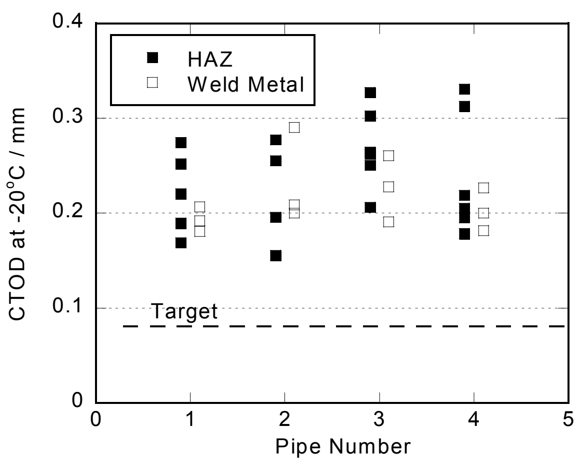


Figure 15. CTOD test results of seam weld centerline and HAZ (shallow notch, 36"OD-16mmWT)

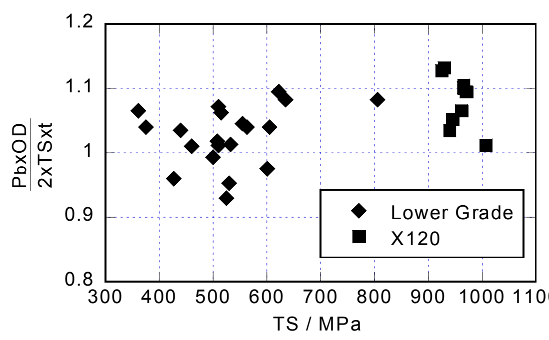


Figure 16. Normalized values of burst pressure as a function of TS.

Burst pressure

In order to ensure sufficient pressure capacity, burst tests were conducted by ExxonMobil. The results shown in Figure 16 demonstrate that the burst integrity of the X120 is similar to, or better than, the burst integrity of lower grade pipe [8]. Based on these results, the X120 has sufficient strength in the pipe body and seam weld to allow it to be designed to the same % SMYS pressure as lower grade pipelines. The Y/T (SMYS/SMTS) ratio of X120 is 0.89 (=120/135) and this substantially low value in general secures the X120 against bursting.

Properties in girth weld

Mechanical properties were examined on a girth weld prepared by a commercial pipeline construction contractor using a CRC Evans welding system. Details concerning the development of X120 girth welding technology have been described elsewhere[9]. Table VI tabulated joint tensile property, CVN energy and CTOD value. These all values meet the targets. Figure 17 and Figure 18 illustrate the hardness distribution across the girth weld and the T-cross.

Table VI. Properties of girth weld.

Joint TS	HAZ (Fusion Line)				Weld Metal (Center Line)			
MPa	CVN* / J		CTOD / mm		CVN* / J		CTOD / mm	
954	-5℃	185	-20℃	0.155 0.161 0.169	-5℃	115	-20℃	0.145 0.125 0.137
955	-30℃	105			-30℃	111		

* average of three, CTOD; standard notch

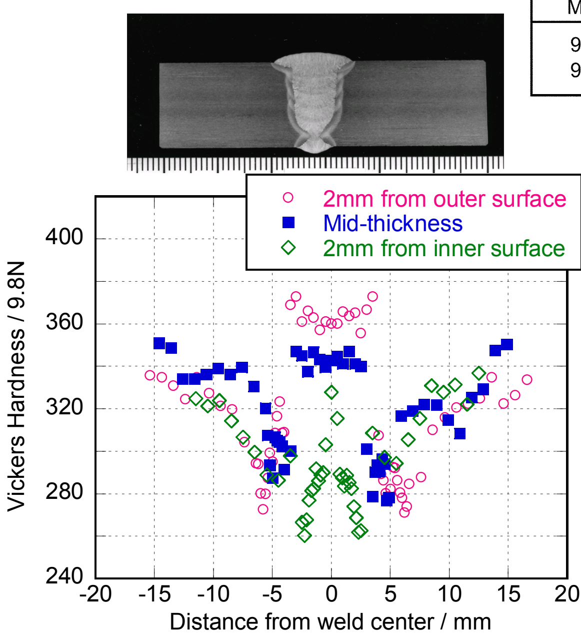


Figure 17. Hardness distribution in girth weld.

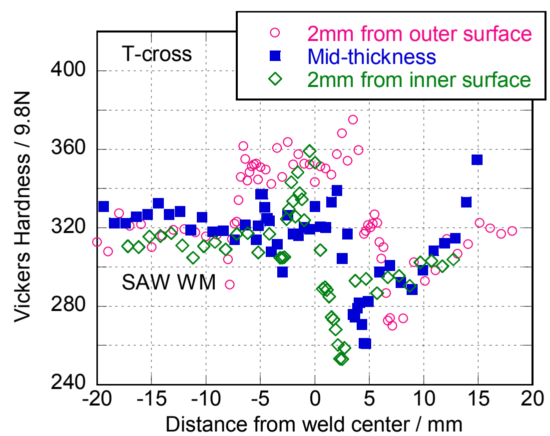


Figure 18. Hardness distribution in T-cross.

Demonstration line

The 36-inch OD, 16-mm WT X120 pipes were used for the construction of a 1.6 km long demonstration pipeline. Figure 19 shows the demonstration line installation. This length of X120 pipeline was constructed in February 2004 as part of a 3.6 km natural gas pipeline loop operating in Northern Alberta, Canada. Outside temperatures were as low as –30°C. A minimum preheat/interpass temperature of 125°C was specified and no cracks were identified during the project [7]. Figure 20 shows a section of field bend X120 used in this pipeline. The demonstration line provided the opportunity to obtain cold whether field construction experience with the new X120 material. All aspects of field construction, including field bending, girth welding, and material handling, were successfully implemented.

Figure 19. Views of demonstration line before lowering.

Figure 20. View of field bend of X120.

Conclusions

1) Plate production, seam welding and pipe forming technology suitable for manufacturing X120 UOE linepipe have been developed. Low C - high Mn - Mo- Nb - Ti - B steel with fine-grained LB dominant microstructure realizes high strength, excellent low temperature toughness and also good seam CG-HAZ toughness.
2) Several hundred pipes with outside chambers from 24 to 48-inch OD were made. The pipe properties meet the target values of the X120 in general.
3) Suitability for use as linepipe was demonstrated through an extensive development program that covered burst testing, fracture toughness evaluation, girth welding technology, etc.

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