DEVELOPMENT AND APPLICATION OF HEAVY-GAUGE X80 SSAW PIPE WITH OPTIMIZED HTP PROCESSING*

ZhangYongqing[1]
NiuTao[2]
Bi Zongyue[3]
Guo Aimin[4]

Abstract

Over the past twenty years, significant advances have been made in the field of microalloying steels and associated applications, among which one of the most successful application cases is development and application of heavy-gauge X80 coil with high temperature processing HTP practice used for China's Second West-East pipeline, the longest X80 pipe in the world. During this process, HTP design concept has been sucessfully applied to develop 18.4mm X80 coil with demanding low-temperature fracture toughness requirements. In the meanwhile, China's metallurgical workers have further optimized HTP design concept with the aid of powerful rolling mill and coiling equipment, and made it possible to develop 21.4mm X80 coil used for Russia-China East line. In the paper, we would simply review the development history of high-strength pipeline steels, and then give more priority to the fundamental points for sucessful development of 18.4mm X80 coil and SSAW pipe, which paved the way for subsequent development of 21.4mm X80 coil and SSAW pipe. Finally, we would present the test results of mass production and burst tests, and dispel the suspicion that SSAW pipes made of X80 coil are more qualified to resist ductile fracture.

Keywords:X80 coil; HTP; low-carbon bainitic microstructure, low-temperature coiling.

1 Ph.D, Senior Engineer, Niobium product department, CITIC Metal Co.Ld., Beijing, China.
2 Ph. D, Chief Engineer of pipe, Sheet department, Shougang Research Institute, Beijing, China.
3 Ph. D, Director, Steel pipe research restitute, Baoji, Shaanxi, China.
4 Ph. D, General Engineer, Niobium product department, CITIC Metal Co.Ltd, Beijing, China.

1 INTRODUCTION

As described by Greek mythology, Prometheus' theft of fire from Olympus for the benefit of humanity, and then human civilization started. Coincidentally, niobium also got its name from Greek mythology: Niobe, daughter of Tantalus, which promoted the development and application of modern microalloyed steels, or low alloy and high strength (HSLA) steels. As once stated by Mr. Mirror Cohen in his paper of Microalloying'75: "For the foreseeable future, the technology of microalloyed steels will be greatly influenced by mankind's ever-growing demands for energy. In fact, there is an inseparable reciprocity between energy and materials in general, with each mirroring the other". Among all application fields of microalloyed steels, large diameter pipeline steels was firstly studied and then spread to other structural sectors. What is more, niobium has played a significant role for its pronounced effect on retardation recrystallization and grain refinement coupled with thermo-mechanical processing (controlled rolling & controlled cooling) and currently used HTP practice (high temperature processing) for X80 steels. Just as concluded by Mr. Kozasu, a worldwide well-known expert, niobium is footstone of chemical design and metallurgy in high strength pipeline steel.

With progressive urbanization and quick industrialization, China's market demand and consumption on clean energy natural gas has increased sharply, in particular in recent years. According to official statistics data, China's consumption on natural gas has increased from 29.2 BCM in 2002 to 272.9 BCM in 2018. Correspondingly, China's pipe construction also experienced quick development from early X60 and X65 to X70 in 2000, and to X80 used for the Second West-East pipeline, the longest X80 pipeline in the world. Before Julong Steel Pipe found in 2000, no pipe-making production line was available for longitudinal welded pipe, that is the reason why SSAW pipe obtained wide use in the China. Table 1 gives basic information of SSAW pipes used for the typical pipeline projects. As we can see, with increase of strength level, both wall thickness and diameter increase to transmit more natural gas. What is more, requirements on fracture toughness also improve with strength grade to avoid crack initiation and propagation.

Table 1. Typical pipeline projects and used steels

Project	Grade	Dia. , in	W.T., mm	Year
1st Shaanjing	X60	26	7.1	1997
Sudan	X65	28	10.7	1999
1st West-East	X70	40	14.6	2004
2nd West-East	X80	48	18.4	2011
Russia-China East line	X80	56	21.4	2018

Thermo-mechanical processing and accelerated cooling were regarded the foundation for microalloyed steels, based on which HTP was proposed by Isao Kozasu in 1975, and then was applied to develop X80 steels used for America's Cheyenne Plains pipeline projects. From another point of view, HTP was developed to resolve the heavy loads resulted from older rolling mills. With powerful 2250mm hot continuous rolling mills, China's metallurgical workers have more room to practice and optimize controlled rolling and controlled cooling processing.

2 China's pipeline construction and West-East pipeline projects

Although started late, China's pipeline construction has made big progress in the past twenty years, in particular development and application of X80 coil and SSAW pipe. Figure 1 shows the history of high-strength pipeline steels in China. During this process, China's West-East pipeline projects accelerated the development and application of high strength pipeline steels, as shown from Figure 2. Up to now, China's CNPC, the largest producer of oil and gas, had constructed the first, second and third West-East pipeline projects, and is planning to build fourth West-East pipeline projects. According to pipe industry statistics data, China's X80 pipelines in length have reached 16,000km in length.

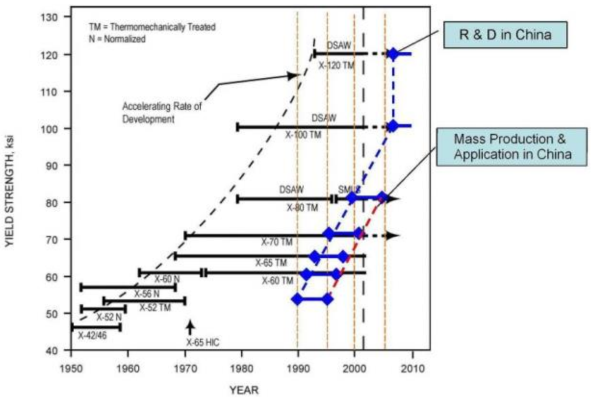


Figure 1. Development and application history of high-strength pipeline steels

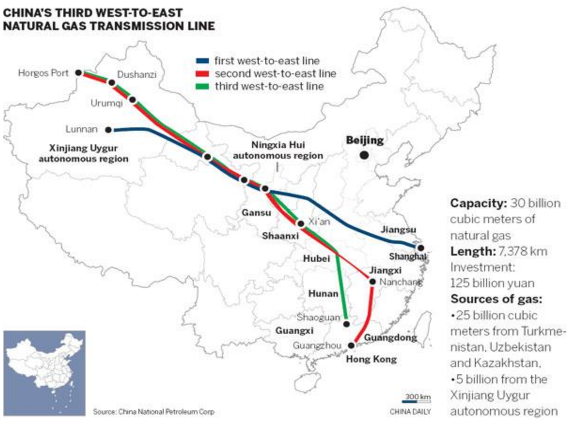


Figure 2. China's West-East pipeline projects

The first West-East pipeline was initiated in 2000, and completed in 2004. For this pipeline project, X70 SSAW pipe with acicular ferrite microstructure was firstly introduced, but niobium addition was limited to 0.060%, and then lifted to 0.08% for subsequent X70 pipeline projects. Table 2 shows the actual chemical compositions of X70 coil, as shown, Mo was added to obtain required acicular ferrite microstructure. At that time, some foreign experts thought X70 SSAW pipe was not good choice due to longer weld seam compared with longitudinal submerged arc weld (LSAW) pipe. For this argument, CNPC's experts carried out burst test, and verified SSAW pipe is more reliable to resist crack initiation due to special stress feature, and paved the way for subsequent application of X80 SSAW pipe for second West-East pipeline project.

Table 2. Typical chemical compositions of X70 coil

Steel	C	Mn	Mo	Nb	V
1	0.04	1.43	0.19	0.052	0.045
2	0.03	1.40	0.16	0.054	0.048
3	0.04	1.43	0.20	0.053	0.044
4	0.05	1.40	0.19	0.057	0.048
Req.	0.09	1.60	0.30	0.060	0.060

The second West-East pipeline project was initiated in 2008, and finished in 2011. The second West-East pipeline project was composed one trunk line and eight branches, of which X80 grade was confirmed for the trunk line with a length of 4,895km. Due to tight schedule and limitation of production capacity of LSAW pipe, 70.0% X80 steels would adopt SSAW pipe made of 18.4mm X80 coil. Before starting of second West-East pipeline, CNPC, together with steel mills had developed 15.3mm X80 SSAW pipe and 18.4mm LSAW pipe used for Ji-Ning demonstration successfully, but actual subsequent development of 18.4mm X80 SSAW pipe was far beyond the anticipation. Since 2006, CNPC and China's steel mills had organized three round trials, all failed. Table 3 shows the requirements of 18.4mm X80 coil used for second West-East line. Compared with LSAW pipe made of X80 plate, one big difference is that all properties are required at 30° to the rolling direction, which is the most weak due to anisotropy. Figure 3 shows test results of tensile tests at different directions, as we can see, yield strength at 30° direction is most weak.

Table 3. Requirements of 18.4mm X80 coil

Properties	Specified value
YS (Rt0.5)	555-690 MPa
TS (Rm)	625-825 MPa
Y/T (Rt0.5/Rm)	0.94 (max)
CVN at -20 °C	180/240J (Sin./Ave.)
DWTT at -15 °C	70/85% (Sin./Ave.)

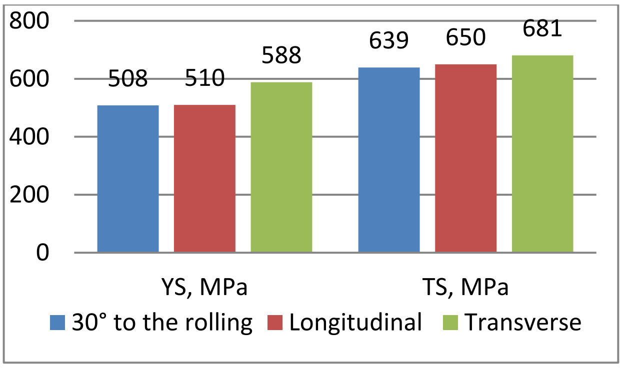


Figure 3. Test results of X80 in different directions

Besides 30° tensile property, demanding toughness requirements were very challenging. In one sense, successful development of 18.4mm X80 coil and SSAW pipe decided if X80 steels were adopted for second West-East pipeline project.

With the aid of powerful hot continuous rolling mills, China's metallurgy workers had successfully developed 18.4mm X80 coil with optimized HTP practice, and paved the way for development of 21.4mm X80 coil used for Russia-China East line. Since the Second West-East pipeline project, X80 grade has been the main steel grade used for big natural gas pipeline projects. Up to now, about 16,000km X80 pipeline have been completed, accounting for 68 percent of total X80 pipeline in the world. Here we firstly take 18.4mm X80 coil as target to introduce some design concepts, including alloy design and production processing, and then discuss the development of 21.4mm X80 coil used for Russia-China East line.

3 Metallurgical design and Industrial trials

It is well known that a low carbon bainitic microstructure (acicular ferrite) offers the optimum combination of strength and toughness, especially when formed from nonrecrystallized austenite, namely TMCP (typical thermo-mechanical processing), and grain refinement and precipitation strengthening are two basic ways for required strength and toughness. conventional controlled cooling (CCR) through heavy reduction below the recrystallization stop temperature (T_{nr}) is very effective way to obtain pancaked austenite grains, but heavy mill loads is one problem for older rolling mill. For this problem, two methods were developed, stated by Michael Korchynsky in his paper titled "TWENTY YEARS SINCE MICROALLOYING '75".

One way is to improve T_{nr} temperature by adding high niobium contents, and make it possible to obtain grain refinement effect at high finishing temperature, namely HTP, as shown from Figure 4. IPSCO had adopted HTP to produce X80 coil in Steckel mill for Cheyenne Plains pipeline. In 2003, CBMM organized seminar to promote HTP for high strength pipeline steels, and then introduced this design concept to China for X80 development.

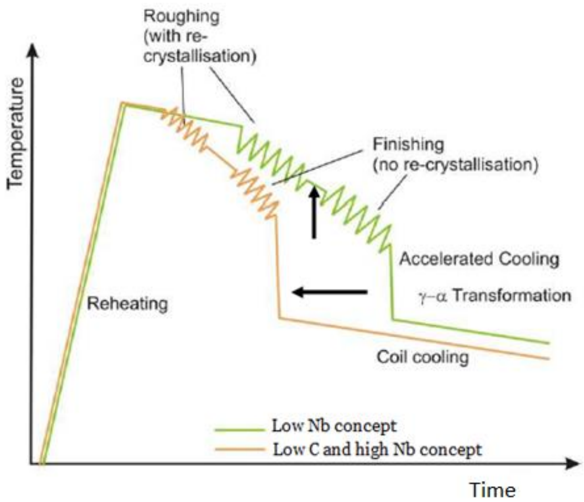


Figure 4. Low carbon and high niobium concepy

Another way is recrystallization controlled rolling (RCR) by adding Ti and V, to realize grain refinement by repeated recrystallization rolling above T_{nr}, but this way has it's limitation for required low temperature toughness due to room microstructure of ferrite plus pearlite.

3.1 Optimized HTP concept for X80 coil

HTP was firstly proposed by Japanese expert Isao Kozasu (as shown in Figure 5), and then practiced by Mr. Klaus Hulka and

J. M Gray for Cheyenne Plains pipeline project. It's theory foundation is high niobium contents can strongly retard recrystallization to high finishing temperature, which is specially suitable to older rolling mill. For newly built powerful 2,250mm hot continuous rolling mill in China, metallurgy workers have more room to optimize alloy design and production processing.

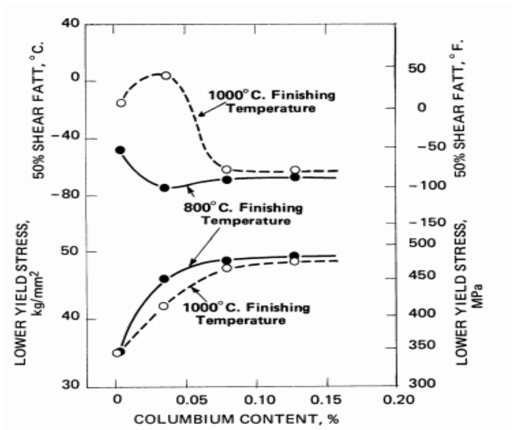


Figure 5. HTP concept proposed by Isao Kozasu

Considering demanding toughness, low carbon and high niobium alloy design concept is firstly adopted for development of 18.4mm X80 coil. Considering tensile strength at 30°, metallurgical design concepts developed by EUROPIPE were referred to develop approach D for 18.4mm X80 coil, as shown from Figure 6.

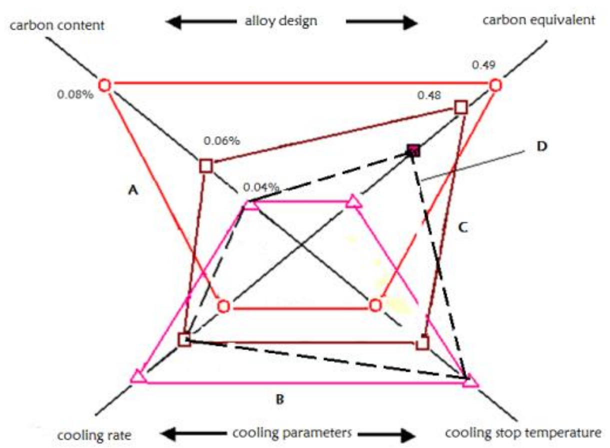


Figure 6. Design concept for 18.4mm X80 coil

Combining equipment features and requirements, following points were important for successful development of 18.4mm X80 coil:

- Strict control S, P and N contents;
- Low carbon high niobium alloy design;
- High carbon equivalent with high Mn, Mo, Cu and Ni;
- lower cooling stop temperature was preferred for low carbon bainitic microstructure;
- Due to powerful rolling ability, finishing rolling temperature can be lower than that of older Steckel mill;
- Mo adding is necessary for required microstructure due to bigger thickness than that of Cheyenne Plains pipeline.

3.2 Industrial trials

China's steel mills organized industrial trials with four alloy designs, as shown from Table 4. After pipe-making and testing, only steel 3 passed the assessment by TGRI, CNPC's research institute. Strictly speaking, no big difference for steel 2, steel 3 and even steel 1 about alloy design and additions, but almost half of test results of steel 1 and steel 2 failed to meet the requirements. By further analysis, low temperature coiling below 520℃ was used, even up to 300℃. According to design ability of 2,250mm hot continuous rolling mill, minimum coiling temperature for 18.4mm X80 coil should be higher than 500℃, but Shougang's metallurgy workers firstly employed ultra-low temperature coiling processing to achieve it, which was regarded another key reason for successful development of 18.4mm X80 coil in the beginning.

Table 4. Four alloy designs for X80 coil

Steel	C	Mn	Nb	Mo+Cu+Ni
1	0.04	1.78	0.075	0.88
2	0.04	1.84	0.10	0.67
3	0.04	1.82	0.10	0.73
4	0.06	1.69	0.071	0.30

Based on trial results, thermo-simulation tests of CCT were performed, as shown from Figure 7. As we can see from simulation results by steel 3, we can obtain

100% low carbon bainitic microstructure when coiling temperature is lower than 520℃matched quick cooling after rolling.

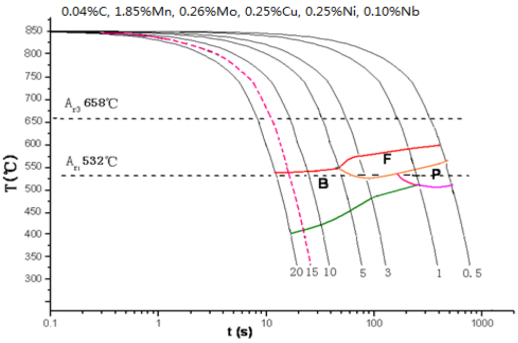


Figure 7. CCT simulation results of steel 3

For heavy-gauge X80 coil, low carbon and high niobium alloy design, and low-temperature coiling were regarded the two key factors. Compared with X80 used for Cheyenne Plains pipeline, Mo addition is essential to obtain higher volume of bainitic microstructure. In addition, powerful rolling mill make it possible to adopt low finishing rolling temperature.

4 Mass production of 18.4mm X80

For second West-East pipeline project, about 2.0 million tons X80 were produced. Figure 8 and Figure 9 show the test results of yield strength of X80 coil and X80 SSAW pipe. As shown from yield strength of coil and pipe, yield strength of pipe is a little higher than that of coil because round bar sample is used to remove Bauschinger effect.

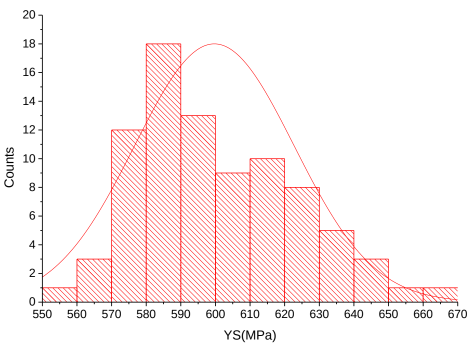


Figure 8. Statistics results of X80 coil

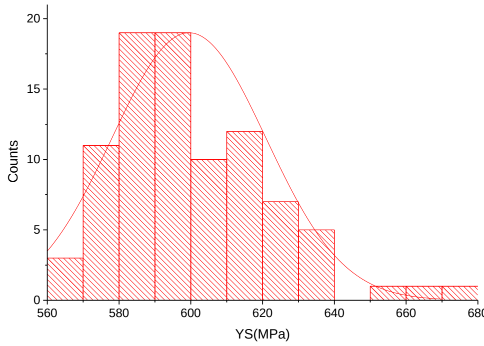
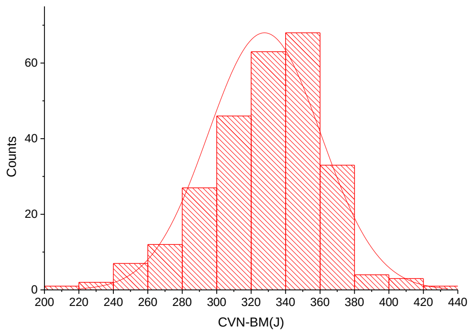
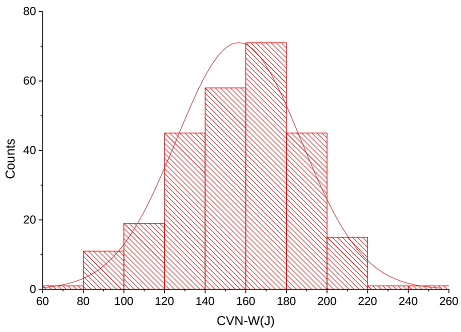


Figure 9. Statistics results of X80 SSAW pipe

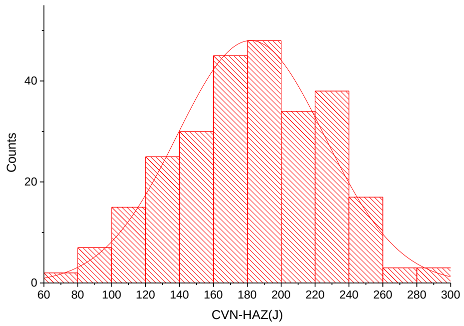
Figure 10 shows the test results of Charpy impact energy of base metal, weld and HAZ of X80 SSAW pipe respectively. As we can see, average impact energy of base metal is 332J, far higher than required 240J at -20℃. Besides lower P, S and N control, metallurgical design with low carbon and high niobium is the key to ensure excellent toughness. In addition, test results of both weld and HAZ are very excellent.



a. Base Metal



b. Weld



c. HAZ

Figure 10. Test results of Charpy impact

Among all properties, it is very difficult to meet DWTT requirement with traditional ferrite pearlite microstructure for heavy gauge X80 steels. With traditional ferrite and pearlite structure, the grain size in the middle along the thickness is bigger than that of surface, which make it difficult to achieve needed toughness. However, with low carbon bainitic structure, the microstructure gradient from surface to middle is smaller, and what is more, high dislocation density and dispersed precipitates also play a positive role to improve upon DWTT property. Figure 11 shows the test results of DWTT of mass production.

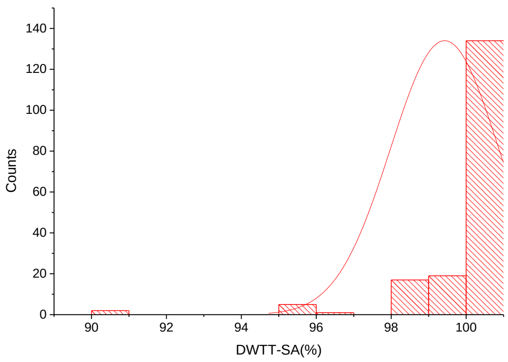
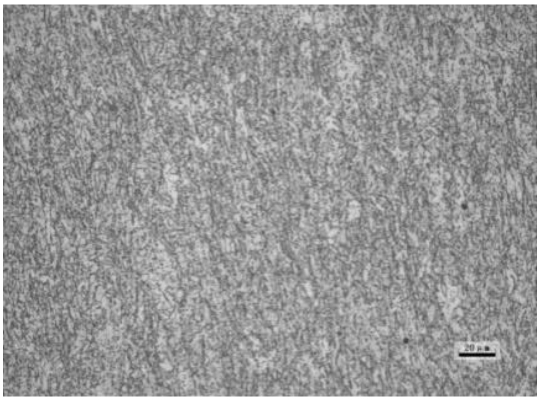


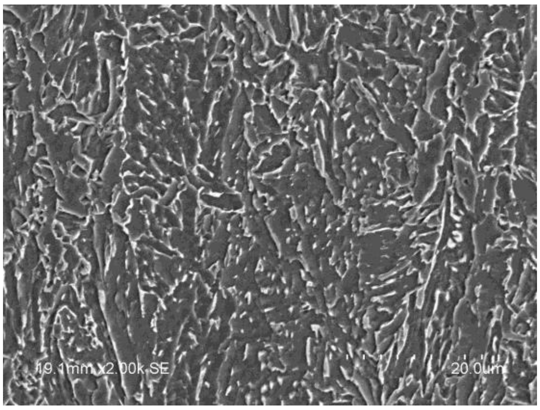
Figure 11. Test results of DWTT at -15℃

5 Microstructure analysis

Figure 12 shows the analysis results of microstructure of X80 strip by metalloscope, SEM, as shown, the microstructure is composed of fine, uniform acicular ferrite, dispersed MA constituents. Figure 13 presents the analysis results by TEM, bainitic lath and fine carbonitride precipitates were observed.



a. Metalloscope image



b. SEM image

Figure 12. Microstructure of X80 coil

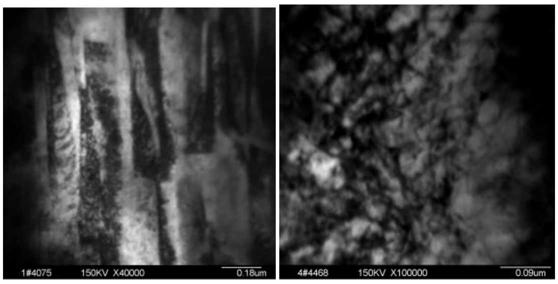


Figure 13. Analysis results by TEM

6 Development of Φ1422×21.4mm X80 coil

Since successful application of HTP X80 coil for OD1219mm pipe, low carbon and high niobium alloy design has become the fundamental metallurgical conception for high strength pipeline steels. In order to further improve annually transmitting capacity from 30.0 BCM per year to 38.0 or 45.0 BCM per year, X80 pipe with biger diameter and thickness was proposed, and CNPC organized a project to develop steel and pipes. Together with research institutes, steel mills and pipe makers, CITIC-CBMM established several projects focusing on Φ1422×21.4mm and spiral welded pipe. As validated, low carbon and high niobium with optimized HTP manifested its positive effects to enlarge processing window through higher nonrecrystallized temperature range and flexible adjustment of pass reduction. Figure 14 shows the picture of 21.4mm X80 coil.

Figure 14. X80 coil of 21.4mm in thickness

Figure 15 shows test results of tensile tests. As we can see, although tensile strengths of 30° to the rolling are the lowest, the test results of both round bar and flattened strip specimens are higher than minimum required 555MPa.

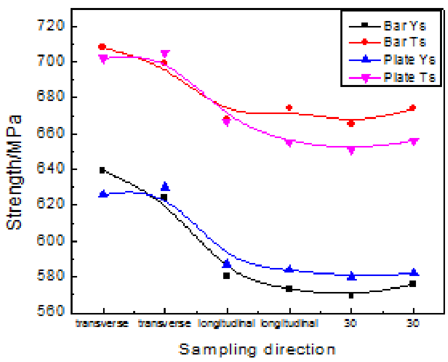


Figure 15. Test results of 21.4mm X80 tensile tests

Figure 16 shows test results of Charpy impact tests, as shown, all test results are higher than 300J, even at -60℃.

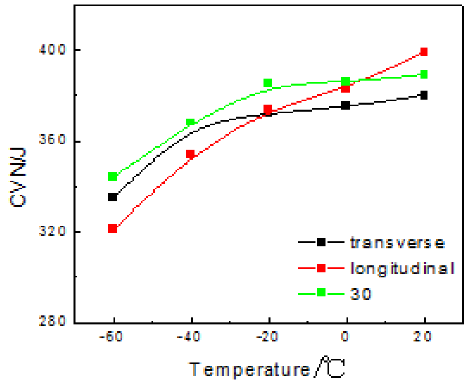


Figure 16. Test results of Charpy impact tests

Among all requirements, DWTT is regarded the most difficult property to achieve. As shown from Figure 17, test results at -20℃ are higher than required value of 85%, in particular 30° to the rolling. What is more, the fracture morphologies of 21.4mm X80 demonstrate no separation (Figure 18), which reflects higher steelmaking and rolling ability.

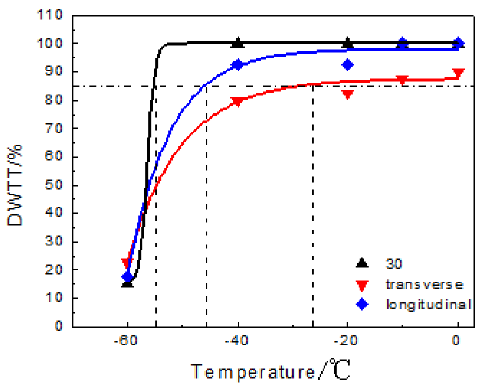


Figure 17. Test results of DWTT

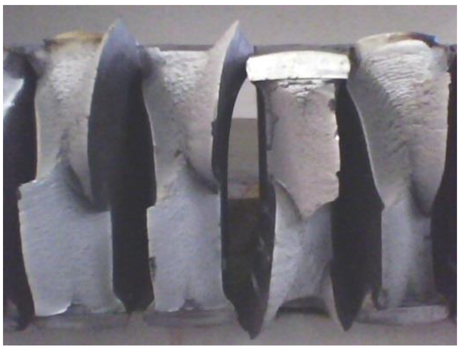


Figure 18. fracture morphology of 21.4mm X80 coil

4 CONCLUSION

While late, China's steel mills and pipe makers made big progress for high strength and high toughness X80 steels by the aid of China's West-East pipeline projects. In the meanwhile, China's metallurgy workers have enriched microalloying knowledge with powerful rolling mill and coiling equipment.
While HTP was one result of older rolling mill, low carbon and high niobium have become the fundamental metallurgical concept for high strength and high toughness pipeline steels.

Acknowledgments

The authors are grateful to the support by CBMM and its consultants like Pascoal Bordignon, Malcolm Gray, and China's steel mills and pipe makers.

REFERENCES

1 Gray, J. M. 2014. “Application of High Strength Linepipe Steels Worldwide: Historical Perspective, Development, Specification and Application.” Presented at the 2014 China Oil & Gas Forum, China.
2 Korchynsky, M. 1995. “Twenty Years since Microalloying ’75.” Presented at the Conference Microalloying ’95, Pittsburgh, PA.
3 DeArdo, A. J. 1995. “Modern Thermomechanical Processing of Microalloyed Steel: A Physical Metallurgy Perspective.” Presented at the Conference Microalloying ’95, Pittsburgh, PA.
4 Graf, M., Schroder, J., Schwinn, V., and Hulka, K. 2002. “Production of Large Diameter Grade X70 with High Toughness Using Acicular Ferrite Microstructure.” Presented at the International Conference on Application and Evaluation of High Grade Linepipes in Hostile Environments, Yokohama, Japan.
5 Pizzimeni, N., DeVito, A., Bufalini, P., and Pontremoli, M. 1981. “Production and Properties on Pipeline Steels with Non-Polygonal Ferrite Microstructure.” Presented at the International Symposium Niobium ’81, San Francisco, California.
6 Webster, S., and Drewett, L. 2010. “The EU Project HIPERC-Performance, Economic Steel Concept for Linepipe and General Structural Use.” Niobium Bearing Structural Steels.