Microstructure and Mechanical Properties of X80 HTP Pipeline Steel Produced by Steckel Mill

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Abstract: The demand for energy becomes a bottleneck in development of China. Economically delivering natural gas and oil through pipeline is an urgent problem to be solved. In the present work, X80 pipeline steel with high toughness and thickness 21.0 mm was produced through HTP (High Temperature Processing) by Steckel mill rolling. And the microstructure and mechanical properties of the X80 pipeline steel, which produced by different processing parameters such as reheating temperature of slabs, resume temperature, finishing temperature, accelerated cooling exit temperature and cooling rate, were analyzed. The results show that finishing temperature of 800 – 820℃ and cooling rate above 20℃/s are necessary to obtain fine and uniform acicular ferrite with high solute niobium in X80 pipeline steel.

Key words: pipeline steel; HTP; Steckel mill; strength; toughness

1 Introduction

Steckel mill is basically a four-high reversing plate mill with the addition of heated coiler furnaces on the entry and exit sides of the mill. This enables the production of long products due to the mitigation of temperature loss. In recent years, the demand for energy becomes a bottleneck in development of China and a large number of pipelines need to be constructed. At present, X70 pipeline steel is extensively used at pipeline projects in China, while X80 pipeline steel began to be open-applied in projects [1]. Moreover, higher requirements for the strength and excellent tougnness of the pipeline steel are put forward in order to reduce the construction cost. So the development of X80 pipeline steel with low cost and high product quality by Steckel mill is an urgent problem to be solved.

An attractive processing method, named HTP (high temperature processing), which produces an acicular ferrite (AF) microstructure with Nb up to 0.11 % and free Mo has been developed in recent years [2]. The high Nb content of this alloy design has a unique capability of allowing thermomechanical rolling at higher processing temperatures than usual processing temperatures. The ability to have enough solute Nb available to retard recrystallization at the elevated temperatures ensures that a fine, high strength AF microstructure can be formed through thermomechanical rolling.

The new Steckel mill at Nanjing Iron & Steel Union Co., Ltd, was commissioned in 2004 and was originally designed for the controlled rolling of high strength steels for pipeline used for gas and oil transmission. Now, much effort has been directed toward the development of X80 pipeline steel plate by HTP rolling techniques.

2 Alloy Design Considerations

Microalloyed steels constitute a large amount of rolled steel products today. Pipeline steels with high strength and excellent toughness usually contain ultra low carbon content, microalloying of niobium, vanadium and titanium, and controlled alloying of molybdenum. They are used in composition design for the X80 pipeline steel plate with acicular ferrite (AF) microstructure. The plate specifications of the X80 pipeline steel are as follows: (1) Strength. 560 ~ 570 MPa and > 625 MPa are required for yield strength and tensile strength, respectively. And, a low yield ratio < 0.90 is a must. (2) Toughness. Transverse CVN impact energy minimum average of 220 J at – 20 ℃ and DWTT shear area minimum average of 85% at – 15 ℃ with demonstrated low temperature capability. (3) Weldability. A low Pcm < 0.25 is required. (4) Hardness. 265 Hv10 maximum in the pipeline plate. (5) AF microstructure generated upon HTP processing for improved toughness [3-6].

To meet the design needs of high strength and

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toughness pipeline steel, there is an evolution of alloying approaches over three decades driven by cost and steelmaking and rolling technologies. The composition characterization of the new generation pipeline is low C, S and P, cleaner steels. The loss of strength due to lower C can be made up by other strengthening mechanisms such as microalloying, solute alloys and post-rolling accelerated water cooling practices.

Recently, the newly-developed of X80 and X100 have a mixed microstructure comprising of low carbon bainite along with small quantities of martensite/austenite islands in the ferrite base. It is also called (AF) microstructure [5-8]. The approach to alloy design for X80 and X100 is based on a low C-Mn-Si system. In general, the main elements of microalloy are Nb, V and Mo which play a supporting role when additional strength is required. Alloy designs for X80 HTP pipeline steel, can be started with the C-Mn-Si plus microalloy base. The microalloy is composed of 0.11 % Nb, free Mo, small quantities of solute alloys such as Cu, Ni, Cr.

The main composition of the trial X80 HTP pipeline steel is listed in Table 1. It can be seen that the carbon equivalent Ceq and Pcm of the X80 steel designed in ultra low carbon acicular ferrite are very low, in this case, the weldability of the X80 steel with acicular ferrite should be better.

Table 1 Chemical composition of the X80 plates

wt%

C	Mn	Si	P	S	Nb	Ti	Alt	Cr + Ni + Cu	Ceq	Pcm
0.053	1.58	0.21	0.007	0.000 6	0.096	0.011	0.034	0.55	0.39	0.17

Note: (1) $Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$

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

3 High Temperature Processing of X80 Pipeline Steel

By applying clean steel production technology, harmful elements such as S, P etc. have been well controlled and restricted in the molten iron, and through degassing and refining the molten steel, S can be controlled below 0.002 wt%, P below 0.012 wt% and N below 0.003 wt%. Inclusion shape also has been well controlled through Calcium treating. Soft reduction has been used before solidification so as to improve the homogeneity of the composition and microstructure.

High strength and excellent toughness pipeline steel can be obtained through proper HTP [2]. In practice, the reheating temperature is controlled at 1 260 ℃ in order to solute the microalloyed elements completely. For the rough rolling stage, it is important to ensure that all rolling steps have been finished above the austenite recrystallization temperature. Because of the high content of niobium in X80 steel, the austenite recrystallization temperature is above 950 ℃, and an intermediate thickness of 3 - 4 times the final thickness can be applied to enhance strength and toughness. If the accelerated cooling entry temperature were too low, acicular ferrite formation would be replaced with pearlite formation, and thus strength would be lowered. The finish temperature can't below 800 ~ 820 ℃. This work demonstrated that the optimum temperature of ACC exit temperature was between 550 ~ 600 ℃, however, a range of 450 ~ 500 ℃ could be used to generate higher yield strength. The cooling rate is a key processing parameter that must be higher than 20 ℃/s in order to obtain the required acicular ferrite microstructure. Steckel mill rolling parameters of X80 pipeline steel by HTP processing are shown in Table 2.

Table 2 Steckel mill rolling parameters of X80 pipeline steel

No.	Reheating temperature /℃	Resume temperature /℃	Finishing temperature /℃	ACC exit temperature /℃	Cooling rate /℃ · s^{-1}
A - 1	1 260	950	815	450	30
A - 2	1 260	970	820	550	20
B - 1	1 230	885	785	550	20
B - 2	1 230	890	790	550	20

4 Microstructure of X80 HTP Pipeline Steel

The typical microstructure of X80 HTP pipeline steel with an optical metallographic microscope is shown in Fig. 1. It can be seen from Fig. 1 that the microstructure of the X80 steel is mainly composed of fine-grained acicular ferrite with large quantity of fine M-A island structures dispersed on the matrix. These island structures do not deteriorate the toughness because of fine size and uniform distribution [7-10]. At the condition of high cooling rate of 30 ℃/s after finishing rolling, the M-A island structures in A - 1 steel are more than those in A - 2, B - 1 and B - 2 steels. Moreover, some bainite laths appear in A - 1 steel at the cooling rate of 30 ℃/s. There is a similar microstructural characterization in Fig. 1(b), Fig. 1(c) and Fig . 1(d) with the cooling rate of 20 ℃/s. Because the finishing temperature is below 800 ℃, the big pro-eutectoid ferrite appears in B - 1 and B - 2 steels as shown in Fig. 1(c) and Fig. 1(d).

The thick film of retained austenite along the bainite ferrite lath boundary and the dense dislocation inside the bainite ferrite lath in X80 HTP pipeline steel were observed by a transmission electron microscope as shown in Fig. 2(a). This is easily understood that the effective grain size was very small because of the existence of those interwoven nonparallel bainite ferrite laths. There are a large number of very fine precipitated particles whose sizes are about a nanometer level in the X80 HTP pipeline steel, as shown in Fig.2(b). It can be seen from Fig .2(b) that some precipitates with different sizes uniformly distributed into the acicular ferrite matrix. The precipitates present in the final microstructure were analyzed based on their chemical composition, size, location and morphology. Generally speaking, there are cubic and sphereical precipitates in the acicular ferrite matrix. The cube is the typical morphology of niobium precipitate. A small amount of niobium was present in the bulk of the precipitate as shown in Fig. 2(c). The cube precipitates is almost in the range of 10 nm to 40 nm. So niobium precipitations in ferrite subsequent to transformation can be provided substantial precipitation strengthening for the X80 HTP pipeline steel [11-13]. Otherwise, solute niobium also acts to enhance the harden ability of the steel by promoting the formation of an acicular ferrite microstructure [14, 15].

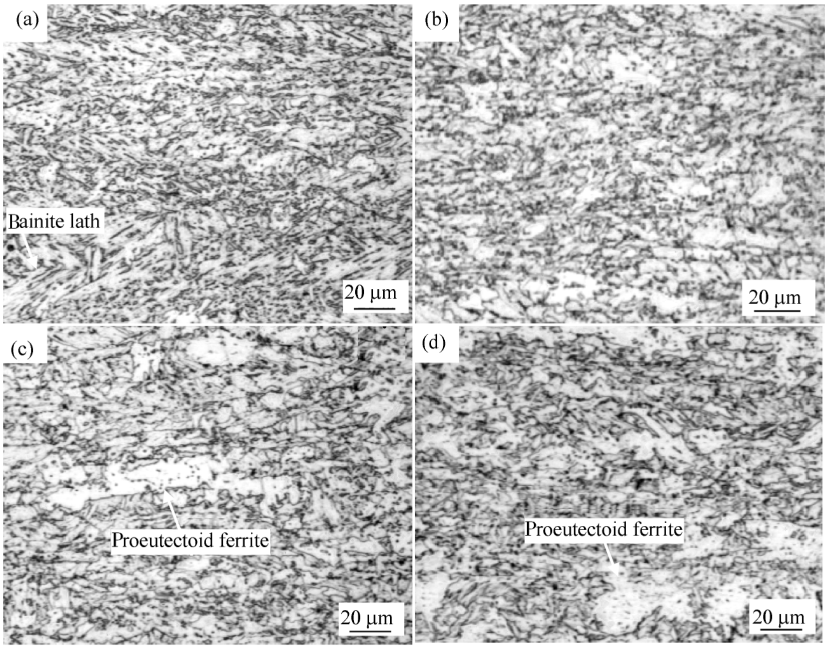

Fig.1 Microstructure of X80 HTP pipeline steel in those samples:(a) A-1,(a) A-2,(a) B-2

5 Mechanical Properties of X80 HTP Pipeline Steel

The mechanical properties of the acicular ferrite 21.0 mm thick X80 HTP pipeline plates developed by Steckel mill at Nanjing Iron & Steel Union Co. Ltd. are listed in Table 3. The A-1 steel and A - 2 steel have high strength and high toughness and their mechanical properties meet the requirements of the technical specification of hot rolled plates. The yield strengths of B-1 steel and B-2 steel are less than that of A-1 and A-2, contrary to the tensile strength. Therefore, the yield ratio of A steel and B steel are obviously different and B steel cannot satisfy the requirements of the technical specification of hot rolled plates.

The strength difference between A and B steels results from the different reheating temperature, resume temperature and finishing temperature. The yield strength of A steel is greatly improved when the reheating temperature and the resume temperature is 1 260 ℃ and 970 ℃ respectively, for the reason that the latent capacity of solute niobium, when the content of Nb reaches 0.10 %, can be fully exploited. But, as for B steel, due to the low reheating temperature (1 230 ℃) and resume temperature (890 ℃), the solute niobium is much less than that of A steel and large amount of big niobium precipitation appears. Besides, the big Pro-eutectoid ferrite appears in B steel as shown in Fig. 1(c) (d). They are the reasons for the reduction of yield strength of B steel. The higher tensile strength of B steel comes from more big, hard and stable M/A islands in microstructure than A steel.

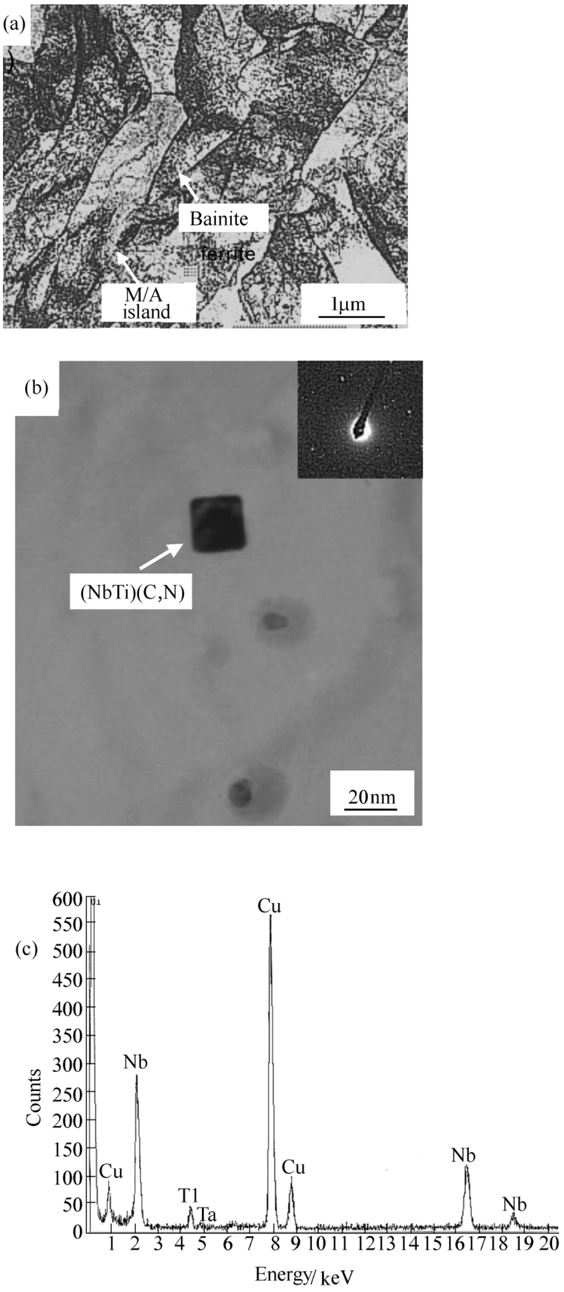

Fig. 2 (a) TEM micrograph of typical substructure and (b) niobium precipitation with (c) EDX spectra in the X80 HTP pipeline plates

In Fig. 3, as the experimental temperature rises, the Charpy V notch impact energy of the X 80 HTP pipeline also increases; however, when the experimental temperature is above −20 ℃, it changes very little. It decreases rapidly when the experimental temperature is reduced from −20 ℃ to −80 ℃. The Charpy V notch impact tests at different experimental temperatures showed that the ductile brittle transition temperature of A − 1 and B − 1 steel are −70 ℃ and −50 ℃, respectively. So, the X80 HTP pipeline steel has low ductile brittle transition temperature and high fracture toughness.

Table 3 Tensile test results of X80 HTP pipeline plate

No.	R_{el}/MPa	R_m/MPa	A_{50}/%	$R_{t0.5}$/ R_m
A − 1	595	680	35	0.88
A − 2	583	658	37	0.89
B − 1	538	713	33	0.75
B − 2	559	714	32	0.78

Note: The mechanical properties were obtained from the 1/4 breadth part of the plate.

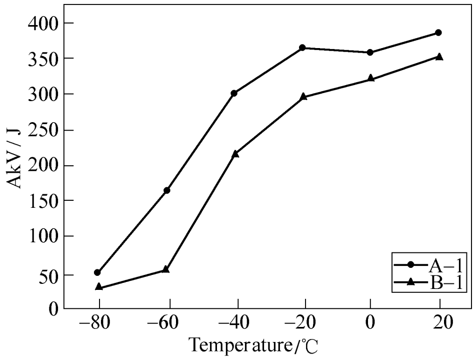

Fig. 3 Charpy V notch impact energy of X80 HTP pipeline tested at various temperatures

Charpy V notch impact and DWTT results of X80 plates at −20 ℃ are shown in Table 4. The average Charpy V notch impact energy of the X80 HTP steel is more than 270J at −20 ℃ and the average shear area is more than 90 %. But there is a significant difference between shear area of A and B X80 HTP pipeline steel for the DWTT tests at −20 ℃ as shown in Table 4. The shear area of DWTT tests of A − 1 steel and A − 2 steel is more than 90 %. But the shear areas of B − 1 and B − 2 of DWTT tests are less than 85 % and the poor DWTT fracture toughness at low temperature cannot meet the requirements for oil and gas transmission pipeline.

As shown in Fig. 1 the microstructure in A − 1 steel is more uniform than B − 1 steel and large amout of irregular pro-eutectoid ferrite and big M/A islands appear in microstructure of B − 1 steel. The difference in microstructure leads to the different Charpy V notch impact energy in A − 1 steel and B − 1 steel (Fig. 3). In general, the influencing factors on the DWTT performance include inclusion, carbide segregation, microstructure uniformity and microstructure types. As for the very low shear areas of DWTT tests in B − 1 and B − 2 steels, which mainly come from low solute niobium. , non-uniform microstructure and carbide segregation.

Table 4 Charpy V notch impact and DWTT results of X80 strip at -20 ℃ temperatures

No.	Charpy V notch impact energy/J				Charpy impact shear area /SA%				DWTT /SA% Single		
		Average		Single		Average		Single	Average		
A - 1	373	363	360	365	100	100	100	100	100	98	99
A - 2	258	327	267	284	90	90	100	93	90	90	90
B - 1	279	303	309	297	95	90	90	92	85	80	83
B - 2	333	330	321	328	100	100	100	100	65	70	68

Note: The DWTT and Charpy impact properties were obtained from the 1/4 breadth part of the plate.

6 Conclusions

1) The 21.0 mm thick X80 HTP pipeline steel was obtained through appropriate alloy design and proper HTP processing. The X80 HTP pipeline steel is an acicular ferrite microstructure. The X80 steel has high strength, high toughness, low ductile brittle transition temperature and high fracture toughness.

2) The HTP processing parameters such as reheating temperature of slabs, resume temperature, finishing temperature, accelerated cooling exit temperature and cooling rate for the production of X80 plates are very important to achieve the required combination of strength and toughness necessary for safety in construction.

3) By using optical metallographic microscopy and transmission electron microscope, the microstructure of acicular ferrite X80 has been analyzed. It is shown that the excellent properties of the steel come from fine and uniform low carbon acicular ferrite with high solute niobium.

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