Experimental research and optimized process of heavy gauge X80 steel with excellent mechanical properties

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Abstract: This paper reports on the experimental research and manufacturing technology of heavy gauge X80 pipeline steel up to 33mm in wall thickness used for gas transmission project in China. The continuous cooling phase transformation behavior of the material under deforming condition was investigated. Slab reheating temperature was controlled to inhibit austenite grain coarsening. An optimized control cooling process was developed to achieve proper desired final microstructure. The result showed that the microstructure of heavy gauge X80 was composed of uniform acicular ferrite containing amount of small precipitates with a size of below 35nm. The 5000 metric tons plates produced by this process achieved good tensile strength and excellent low temperature toughness. The yield strength and ultimate tensile strength in transverse direction reached 600MPa and 710MPa respectively, which are far higher than requirements of API-X80, such as 555MPa and 625MPa. Even with this X80 strength level and heavy wall thickness the low temperature fracture toughness achieved was excellent. Transverse Charpy impact testing resulted in absorbed average energy of 390 J @ -60 °C with 100% shear.

1. Introduction

The use of natural gas is growing worldwide and is expected to represent an increasing portion of the total energy supply. With the development of economy and society, the demand for natural gas are increasing progressively throughout the world, and especially in China in recent years. In order to resolve the energy requirement and optimize the structure of energy, the third West-East Gas Pipeline Project was constructed in 2013. In this project, heavy gauge X80 pipeline steel up to 33mm in wall thickness and 1219mm in diameter with excellent mechanical properties was applied.

One of the most challenging aspects in developing heavy thickness X80 pipeline steel is to balance the high strength and the good toughness. Low temperature toughness of pipeline plates is an important quality index, which comprehensively reflects the materials’ toughness properties. In order to meet the requirements, 33mm X80 heavy plates with enhanced low temperature toughness was developed in China by optimized manufacturing technology.

2. Experimental research of X80 Steel

For high grade and thick-walled pipeline plates, how to control the balance between the strength, the toughness and the weld ability is very important. Figure 1 gives the main technological frameworks of X70-X100 steel, which is the premise to achieve high strength and high toughness.
As shown from Figure 1, the composition design for the heavy X80 plates is reduced carbon content, high manganese and micro-alloyed by niobium and molybdenum, as well as containing nickel, chromium, copper and titanium to achieve the strength and toughness concurrently. In addition, it is essential to make the most of transformation strengthening concepts, such as a high cooling rate and low cooling stop temperature.

![Fig 1. Technological frameworks of X70-X100 steel](image)

Table 1 shows chemical composition of the heavy gauge X80 pipeline steel. Ultra low carbon micro-alloyed steel was used to obtain excellent toughness, such as the Charpy impact toughness, DWTT performance and the weld ability. Certain amount of molybdenum element can affect CCT curves, to avoid uneven cooling inside and outside the heavy plate, the acicular ferrite can be obtained in a wide range of cooling rate.

| C  | Si | Mn  | P  | S   | Nb+V+Ti | Ni+Mo+Cu+Cr |
|----|----|-----|----|-----|---------|-------------|
| 0.05 | 0.25 | 1.75 | 0.008 | 0.0015 | ≤0.12 | ≤0.80 |

The sample of X80 steel was reheated to 1200℃ and holding 10 minutes on the Gleeble-2000 thermal simulation machine, then cooled at 15℃/sec to 1050℃, for 20% of compression deformation, the deformation rate was 20S-1, and then cooled to 800℃ by 15℃/sec, 30% deformation, then cooled to room temperature, the cooling speed respectively 20℃/s, 13℃/s, 10℃/s, 5℃/s, 2℃/s, 0.5℃/s.

According to the thermal simulation tests, the continuous cooling phase transformation characteristics of thick-walled X80 pipeline steels were researched and analyzed. The microstructure at different cooling rates was observed by microscope. From Figure 2, we can conclude that the ferrite (F) and pearlite (P) were obtained at a lower cooling speed below 2℃/s. Granular bainite (GB) was obtained when the cooling speed increase to range 2~5℃/s. With the increase of the cooling speed, the transformation phase were mainly composed of acicular ferrite (AF). With the increase of the cooling rate, the microstructure was gradually refined.

![image](image)
Fig 2. The microstructure of X80 with different cooling rate
(a) 0.5°C/s; (b) 2°C/s; (c) 5°C/s; (d) 10°C/s; (e) 13°C/s; (f) 20°C/s

Fig 3. The curve of continuous cooling transformation

Figure 3 shows the curve of continuous cooling transformation (CCT). It was shown that the acicular ferrite (AF) microstructure was obtained in a wider cooling speed range, and with the increases of the cooling rate, the microstructure was gradually refined.

3. Manufacturing technology of X80 Steel

The sample of X80 steel at the 1/4 slab was reheated to 1100°C, 1140°C, 1180°C, 1200°C with 10°C/s speed using thermal simulation machine, and the austenite grain size was observed.

Fig 4. Austenite grain of different reheating temperature
(a) 1100°C; (b) 1140°C; (c) 1180°C; (d) 1200°C
This clearly demonstrates that with the rising of reheating temperature, the austenite grain of X80 plate growing. When the reheating temperature was below 1180°C, the austenite grain size was fine and uniform, when the reheating temperature reached to 1200°C, the great and uneven austenite grain began to appear. So using a lower reheating temperature can inhibit the original austenite grain size coarsening.

Post rolling cooling was controlled to achieve the appropriate cooling stop temperature and cooling rate to obtain the ideal microstructure. Figure 5 shows the two pieces of cooling equipment, one is ACC which was designed by SMS, the other is UFC which has more powerful capability. The optimized cooling process is based on the combination of two pieces of cooling equipment to achieve a more flexible and optimum cooling condition.

Fig 5. Cooling equipment of UFC and ACC

When the finish rolled plate enters the UFC equipment, it will be quickly cooled to the temperature of intermediate transformation temperature range with a cooling rate of 20°C/s (for 33mm thickness of plate). And then the plate will be cooled with ACC with a lower cooling rate about 15-20°C/s to the aimed cooling stop temperature. This optimized cooling process enhances the grain refinement after the plate rolling, as shown in Figure 6.

Fig 6. Different microstructures after ACC and UFC+ACC processes
(a) Microstructures after ACC ; (b) Microstructures after UFC+ACC

Figure 6 shows the differences in microstructures produced by ACC and UFC+ACC process. The microstructures from the ACC process consist primarily of bainite and some polygonal ferrite (PF). While the microstructures from the UFC+ACC process consists of a refined acicular ferrite (AF). The average grain size of ACC process is coarser than the UFC+ACC grain.

4. Mechanical properties of X80 Steel
On the basis of the above experimental research, a low carbon micro-alloyed X80 steel has been developed. As can be seen in Table 2 both yield strength and tensile strength fulfill the specified requirements of X80 steel. Charpy impact energy and fracture shear area percentage have been shown in Table 3 respectively at different testing temperatures.
Table 2. The tensile test results of thick-walled X80

| Direction   | Specimen    | $R_{0.5}$ (MPa) | $R_m$ (MPa) | $R_{0.5}/R_m$ | $A_{50.8}$ (%) |
|-------------|-------------|-----------------|-------------|---------------|----------------|
| transverse  | Flat        | 600             | 710         | 0.84          | 45             |
|             | Round bar   | 620             | 725         | 0.85          | 26             |

Table 3. The Charpy impact results of thick-walled X80

| Temperature (℃) | Charpy impact energy (J) | Fracture shear area (%) |
|-----------------|--------------------------|-------------------------|
| 20              | 420/433/440              | 100/100/100             |
| 0               | 450/440/430              | 100/100/100             |
| -20             | 440/425/430              | 100/100/100             |
| -40             | 400/410/425              | 100/100/100             |
| -60             | 370/420/390              | 100/100/100             |

The full transition curve for Charpy impact test and the fracture at -60 ℃ were shown in Figure 7, the ductile to brittle transition was below -60 ℃, and the fracture at -60 ℃ were composed of large volume of dimples typical of ductile fracture.

Fig 7. The transition curve of Charpy impact test and the fracture at -60 ℃
(a) The curve of ductile-brittle transition; (b) The fracture at -60 ℃

For these excellent mechanical properties, lower carbon content and Pcm values play an important role. Excellent performances are dependent on the microstructure of the steels. Figure 8 shows the typical optical micrograph of thick-walled X80 pipeline plate. Matrix microstructure of the thick-walled X80 plates was composed of uniform acicular ferrite from the surface to center of the heavy plate. Figure 9 shows the typical scanning electron micrograph and the precipitates of thick-walled X80 pipeline plate. The result showed that the microstructure of heavy gauge X80 was composed of uniform acicular ferrite containing amount of small precipitates with a size of below 35nm.

Fig 8. Optical micrographs of thick-walled X80 plate
(a) Surface; (b) Quarter; (c) Center
Fig 9.  SEM image of thick-walled X80 plate and the precipitates
(a) The SEM of thick-walled X80; (b) The precipitates of thick-walled X80

As shown from optical, scanning electron and transmission micrograph, the uniform acicular ferrite structure and fine precipitation provide both high strength and excellent toughness.

5. Conclusions
Heavy thickness, high strength, and excellent toughness represent the development trend in the present and in the future for large diameter transmission pipelines. According to the production practice on 33 mm X80 pipeline steel, the following conclusions can be drawn:

1. The optimized control cooling process was developed and applied to produce low temperature heavy gauge X80 pipeline plates. The plates obtained high strength, low Y/T ratio, and good low temperature toughness.

2. By using the optimized control cooling process, a stable control of uniform microstructure can be realized and further more result in the consistent and stable control of mechanical properties of plates.

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