Microstructure Design and Properties of X100 Gas Line Pipe

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Abstract: The microstructure evolution process of X100 pipeline steel is analysed, and the influence of different alloy composition and accelerated cooling process on microstructure evolution is studied in this article. It is obtained that acicular ferrite microstructure can make the yield strength of steel reach 650 MPa through micro alloying and thermo-mechanical control process(TMCP) with the comprehensive reinforcement effect of grain refinement, micro-alloying element precipitates and dislocation substructure. Acicular ferrite has the characteristics of fine grain, cross distribution, large angle grain boundary and presence of substructure and high density movable dislocation. Test results of product quality also show that X100 pipeline steel which adopts Mn-Nb-Ti component system with a small amount of Ni (V), Mo alloy addition and TMCP process has obvious characteristics of fine grain. The Matrix is consisted of granular bainite and appropriate amount of MA as dispersion phase, which makes the tensile strength reach more than 800 Mpa. At the same time, the X100 pipeline steel has the characteristics of high toughness and good weldability, which is beneficial to ensure the safe operation of high pressure natural gas pipeline.

1. Introduction
The key factor of long distance pipeline transportation is to improve the working pressure and reduce the unit transportation cost. The wall thickness of line pipe can be reduced through the development and application of high grade pipeline steel, and the weight of line pipe and the welding time can be reduced. As a result, the weight of steel and construction costs can be reduced greatly. For example, the pipeline steel can be reduced by about 30% with use of X100 line pipe compared with X65 and X70, and the pipeline construction cost can be reduced by about 10%~12%.

X100 pipeline steel developed with micro alloying and thermo-mechanical control process (TMCP) technology appeared in the late 1980s of last century [1,2]. SMI company announced the research results of X100 line pipe for the first time in 1988. So far, China and many other countries have produced thousands of tons of X100 pipeline steel with wall thickness between 12.7 and 25.4mm.

X100 pipeline steel came into the stage of engineering demonstration application in the beginning of this century, which included several landmark projects promoted by Transcanada and JFE. For example, in September 2002, TransCanada constructed a 1km X100 test section in Canada WESTPATH project withφ1219mm×14.3mm line pipe produced by JFE/NKK. It is the first X100 application test in the world. The X100 pipeline steel used in the test section has the characters of high strength, high toughness and good weldability.

After years of development, X100 pipeline steel has gradually matured[3]. The related content of X100 was introduced in the new version of Canadian pipeline standards for the first time in 2002, and then the related content of X100 was introduced in the new version of the ISO 3183 and API SPEC 5L pipeline standards.
2. Microstructure of X100 pipeline steel

2.1. Microstructure evolution of pipeline steel

The microstructure evolution of pipeline steel has three stages: ferrite and pearlite (including little pearlite) type, ultra low carbon bainite (acicular ferrite) type and lower bainite (or bainite and martensite) type [4].

The basic microstructure type of pipeline steel is ferrite and pearlite before 1960s, which is usually processed by hot rolling and normalizing. When higher strength is required, trace niobium and vanadium should be introduced. Pearlite can improve tensile strength and has no contribution to yield strength. At the same time, Pearlite has damage to toughness of pipeline steel. Ductile-brittle transition temperature can increase up to 22℃ with presence of 10% pearlite. The carbon content, namely pearlite content, must be decreased so as to improve toughness, and the decrease of carbon content is beneficial to weldability.

Alloy of high strength pipeline steel and accelerated cooling process make the steel microstructure deviate from the traditional ferrite and pearlite type, and tiny ferrite and bainite appeared. The microstructure of bainite is quite different for steels with low and ultra low carbon content compared with steels with carbon content greater than 0.15%, the traditional concept of bainite is no longer applicable. As a result, the bainite in low carbon steel caused concern.

It is obtained that acicular ferrite microstructure can make the yield strength of steel reach to 650 MPa through micro alloying and thermo-mechanical control process with the comprehensive reinforcement effect of grain refinement, micro-alloying element precipitates and dislocation substructure. Acicular ferrite has the characteristics of fine grain, cross distribution, large angle grain boundary and presence of substructure and high density movable dislocation [5-6], as a result, the pipeline steel and weld joint has the characteristic of high toughness.

2.2. Microstructure design of X100 pipeline steel

In order to achieve the target performance for X100, it is necessary to refine the structure of fine or ultra-fine bainite ferrite. At the same time, promotion of reasonable bainite type is also extremely important. For example, the type and distribution of the second phase have great influence on toughness, so it is very important to understand and control the morphology of bainite. However, the morphology of bainite is complex and diverse, and quantitative analysis is very difficult. The morphology of bainite is very difficult to be observed with general optical microscope, which needs to be confirmed with advanced SEM and electron backscatter analysis. Bainite is usually defined as the decomposition product of eutectic austenite. The content of carbon for proeutectoid ferrite and bainite ferrite is significantly different. The residual carbon content of the bainitic ferrite would decrease due to precipitation of second phase which locates between the ferrite or in the grain.

The microstructure composed of granular bainite as matrix phase and appropriate number of MA as dispersed phase is proved to be the best choice for X100 pipeline steel. The X100 pipeline steel produced with TMCP technology has obvious characteristics of fine grain. As a result, the tensile strength could reach to 800MPa, and the toughness is not significantly reduced, so as to ensure the high strength pipeline steel has proper DWTT toughness.

2.3. Correlation of composition, microstructure and properties of X100 pipeline steel

The influence of micro alloying elements on the mechanical properties of the final products is mainly reflected in two aspects. Firstly, stable carbide and nitride phases are formed during controlled rolling process, which prevents austenite recrystallization and grain growth. As a result, austenitic packages with very fine grain size would generate, which eventually transform to fine grain ferrite. The pipeline steel would have the characters of high toughness and high strength. Secondly, the other aspect attribute to the dispersion strengthening effect of micro alloying elements. Fine carbide and nitride (50nm-1μm) would prevent dislocation movement so as to improve the strength.
Therefore, in order to evaluate the effect of micro alloying elements on the mechanical properties, it is necessary to consider the effects of micro alloying elements on microstructure. Different phase characters including the size, shape and density of the precipitates would affect the mechanical properties[7].

The effect of micro-alloying precipitates on properties is not isolated. Other parameters such as rolling temperature, rolling speed and cooling conditions must be considered.

The formation of acicular ferrite is usually accompanied with island-shape hard phase, and the hard phase is composed of martensite with high carbon content and residual austenite, namely MA component. The mixed microstructure of acicular ferrite and MA components are sometimes referred to granular bainite. The strength and toughness of pipeline steel are determined by the volume fraction, size and substructure of granular bainite, as well as the volume fraction and distribution of MA island.

The new microstructure control process is composed of three stages: Accelerated cooling terminates above the bainite transition temperature, and the untransformed austenite remains. At this stage, the microstructure is composed of bainite and untransformed austenite. Then the on-line heat treatment was carried out. During the heating process, the carbon diffused into austenite. After heating process, the residual carbon content in austenite is high due to carbon concentration, and air cooling would promote it transform into MA.

The volume fraction of MA was affected with chemical composition, ACC and heating condition. The effect of MA volume fraction on yield ratio is shown in Figure1. It can be obtained that lower yield ratio (below 80%) can be obtained by increasing the content of MA to more than 5%.

![Figure1](attachment:image)

Figure1  The effect of MA volume fraction on yield ratio

Obviously, carbon equivalent of X100 is higher than that of X80 so as to increase the strength[8]. But the values locate in the same range, which is close to Pcm value of low carbon steel whose carbon content is below 0.12%. The carbon content of X100 is lower than X80. The carbon mass fraction of X100 ranges from 0.02% to 0.08%, and the carbon mass fraction of X80 ranges from 0.04% to 0.09%.

the tensile strength of X100 (759MPa~923MPa) is much higher than that of X80 (646MPa~805MPa), which indicates that the controlled rolling process has played a full role[9,10]. The yield ratio of round bar specimens ranges from 0.90 to 0.97, while the yield ratio of strip specimens is below 0.90. Bauschinger effect caused by smooth processing of strip specimens should be the main reason [11,12,13].

3. Product quality of X100 pipeline steel

The chemical composition and mechanical properties of X100 pipeline steel developed in foreign countries are shown in Table1 and Table2[14]. The X100 pipeline steel adopt Mn-Nb-Ti component system with a small amount of Ni (V), Mo alloy addition. The composition has the characters of low carbon and high manganese content. The manganese content of X100 ranges from 1.7% to 2%. The niobium content of X100 ranges from 0.04% to 0.06%. Other components of X100 produced by various manufacturers varies slightly, but there is no boron addition. CE (IIW) value generally ranges
from 0.38% to 0.50%, and the properties of X100 can be obtained through appropriate TMCP process. The Pcm value of X100 is about 0.20% so as to acquire good weldability. Bainitic ferrite microstructure acquired through TMCP process is beneficial to ensure high strength and high toughness for X100 pipeline steel. At the same time, the mass fraction of carbon in steel should be reduced, and the inclusions should be removed. It is also necessary to improve steel purity and reinforce steel refining process. The mass fraction of components should meet the requirements as below: P≤20×10-6, S≤5×10-6, N≤20×10-6, O≤10×10-6, H≤1.0×10-6.

| Number | C    | Si   | Mn   | Nb  | Mo  | Ti   | others | Ceq  | Pcm |
|--------|------|------|------|-----|-----|------|--------|------|-----|
| D      | 0.06 | 0.25 | 1.8  | 0.04| 0.19| 0.02 | Cu,Ni,V | 0.44 | 0.2 |
| E      | 0.07 | 0.25 | 1.93 | 0.05| 0.28| 0.02 | Cu,Ni   | 0.48 | 0.21|

Table 1. The chemical composition of X100 pipeline steel in foreign countries (wt%)

| Number | Rt0.5/Mpa | Rm/Mpa | CVN/J (-20℃) | DWTT 85%SA | Pipe body | HAZ | Transition temperature /℃ |
|--------|-----------|--------|--------------|------------|-----------|-----|---------------------------|
| D      | 706       | 870    | 179          | 154        | -25       |     |                           |
| E      | 739       | 792    | 235          | 135        | -15       |     |                           |

The domestic X100 pipeline steel also adopt Mn-Nb-Ti component system with a small amount of Ni (V), Mo alloy addition. The carbon content is very low for steel A, which is close to 0.04%. The manganese content ranges from 1.8% to 2%, and the manganese content of X100 is higher, as shown in Table 3 and Table 4. The niobium content ranges from 0.04% to 0.06%, while the niobium content of steel C is higher, which is close to 0.1%. The metallographic analysis shows that the main microstructure of the three domestic X100 pipeline steel is granular bainite ferrite, and a small amount of low carbon martensite would be found in some specimens. Comparative analysis results of product quality shows that HAZ toughness of steel C is lower, and the change of DWTT ductile-brittle transition temperature is not obvious [15].

| Number | C    | Si   | Mn   | Nb  | Mo  | Ti   | Other | Ceq  | Pcm |
|--------|------|------|------|-----|-----|------|-------|------|-----|
| A      | 0.043| 0.23 | 1.86 | 0.04| 0.29| 0.01 | Cu,Ni,V | 0.5  | 0.19|
| C      | 0.07 | 0.23 | 1.86 | 0.096| 0.27| 0.01 | Cu,Ni,V | 0.47 | 0.21|

Table 3. The chemical composition of X100 pipeline steel in China (wt%)

| Number | Rt0.5/Mpa | Rm/Mpa | CVN/J (-20℃) | SA/% |
|--------|-----------|--------|--------------|------|
| A      | 795       | 845    | 225          | 95   |
| C      | 710       | 790    | 300          | 95   |

Table 4. The mechanical properties of X100 pipeline steel in China

4. Conclusions
(1) The X100 pipeline steel usually adopts Mn-Nb-Ti or Mn-Nb-V component system with a small amount of Mo, Ni and Cu alloy addition.

(2) The microstructure composed of granular bainite as matrix phase and appropriate number of MA as dispersed phase is proved to be the best choice for X100 pipeline steel. The necessary strength and good toughness of X100 pipeline steel can be obtained through the comprehensive reinforcement effect of grain refinement, solid solution strengthening, precipitation strengthening, dislocation strengthening.
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