Effect of controlled rolling and cooling process on microstructure and properties of X65 pipeline steel

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Abstract. Effect of rolling and cooling process on microstructure and properties of X65 pipeline steel was studied by means of tensile test at room temperature, oscillographic impact test and metallographic microscope. And the impact fracture process of samples with different microstructures was analyzed by oscillographic impact curve. The results indicate that controlled cooling process has important influence on the microstructure of the sample. The strength and toughness of sample with acicular ferrite microstructure are better than this with ferrite and pearlite microstructure. The crack initiation energy of the acicular ferrite microstructure is similar to that of ferrite and pearlite microstructure. However the crack propagation energy of the acicular ferrite microstructure is different from that of ferrite and pearlite microstructure.

1. Introduction

At present, pipeline transportation has developed into the main way of long-distance transportation of oil and nature gas. Because usually it is far from the oil and gas production area to consumption area and with the increase of oil and gas consumption, in order to improve transportation efficiency and reduce the cost of pipeline construction, the pipeline transportation pressure is increasing, and wall thickness of pipeline is decreasing. In addition, the geological conditions along the pipeline laying are complex, and the climate is changeable and service environment is bad. Thus, the requirement for strength and toughness of pipeline steel is getting higher and higher.

Pipeline steel is mainly produced by controlled rolling and cooling process, and the process parameters have important influence on final microstructure, strength and toughness of pipeline steel. And some researches on above aspect have been reported\textsuperscript{[1-4]}. However, most of the researches focus on the direct impact of process parameters on strength and toughness and there is no in-depth explanation of the reason for the impact. Especially for impact toughness, most studies consider that different microstructures have different impact toughness, but do not pay attention to the difference of crack behaviour of different microstructures during the impact fracture process. Therefore X65 pipeline steel was researched in this paper and the influence of different process parameters on its microstructure and properties was analyzed, and especially the characteristics of crack initiation and propagation in the impact process of the X65 pipeline steel with different microstructures were revealed through oscillographic impact test. And this research is expected to provide a meaningful reference for the microstructure control and process control required for pipeline steel to achieve excellent strength and toughness.
2. Experiment procedure

2.1. Materials
The material studied in this research was industrially produced X65 pipeline steel plate and its chemical composition is shown in table 1. The test X65 steel plate is produced by controlled rolling and cooling process and the process parameters of the test plate is shown in table 2.

Table 1. Chemical compositions of test steel.

|       | C    | Si   | Mn   | P    | S    | Nb+V+Ti | Cr   |
|-------|------|------|------|------|------|---------|------|
| Value | 0.064| 0.12 | 1.5  | 0.010| 0.0005| ≤0.12   | ≤0.3 |

Table 2. Process parameters of test steel.

| Number | Finish rolling temperature/℃ | Start cooling Temperature/℃ | Finish cooling temperature/℃ |
|--------|------------------------------|----------------------------|------------------------------|
| 1#     | 760                          | air cooling                |                              |
| 2#     | 810                          | 780                        | 580                          |

For convenience of description, the test plates obtained by different rolling processes are numbered 1# and 2# respectively. The rolling reduction rules of the test plates were the same. The heating temperature of both steel plates is 1180℃ and the start rolling temperature of both steel plates is 1153℃. And the controlled rolling temperatures of two steel plates are 935℃ and 940℃, respectively. It is shown in table 2 that the finish rolling temperature of 1# was 760℃. After rolling, 1# steel plate was not water cooled, but it is air cooled to room temperature. The finish rolling temperature of 2# was raised to 810℃ and after rolling, 2# steel plate was water cooled to 580℃.

2.2. Experiment methods
Tensile and Charpy impact test specimens were taken in the transverse direction at the center of the width of the test plate. Then the specimens were subjected to a room temperature tensile test and Charpy impact test respectively according to ASTM A370 standard. Charpy impact test temperature is -20℃, and the displacement, load and impact energy during the impact test were recorded. Metallographic samples were taken at the center of the width of the test plate and then the samples were mechanically ground in sequence with different sandpaper. After that, the samples were polished and etched with 4% nital solution to observe the microstructure by optical microscope.

3. Results and discussion

3.1. Mechanical properties
The room temperature tensile properties of the specimens are shown in table 3. As can be seen from table 3, yield strength and tensile strength of 1# plate which was produced by air cooling after rolling are 446 MPa and 518 MPa respectively. And the elongation of 1# plate is 45.5%. In contrast, yield strength and tensile strength of 2# plate obtained by water cooling after rolling are improved. Specifically, the yield strength of 2# plate increased to 490 MPa and the tensile strength increased to 593 MPa and the elongation decreased to 37%.

Table 3. Tensile properties of the test steel.

| Number | Rt0.5/MPa | Rm/MPa | Rt0.5/Rm | A%  |
|--------|-----------|--------|----------|-----|
| 1#     | 446       | 518    | 0.86     | 45.5|
| 2#     | 490       | 593    | 0.83     | 37  |

The results of Charpy impact test of the specimens at -20℃ is shown in table 4. Table 4 shows that the minimum single value of the -20℃Charpy energy of the 1# plate is 267J and the maximum single value is 280J and the average value is 273J. And the minimum percentage of ductile fracture surface is 90% and the rest are 100%. In contrast, the minimum single value of the -20℃Charpy energy of the 2#
plate is 333J and the maximum single value is 342J and the average value is 337J. And the percentage of ductile fracture surface is all 100%. The single value and average value of impact energy of 2# plate are higher than those of 1# plate.

Table 4. Charpy impact test results of the test steel

| Number | -20℃ Akv/J | SA% |
|--------|------------|-----|
| 1#     | 267        | 271 | 280  | 90   | 100  | 100  |
| 2#     | 342        | 333 | 336  | 100  | 100  | 100  |

Figure 1 is oscillographic impact curve of specimens drawn according to the data of displacement, load and energy recorded during the impact test, and the oscillographic curves of the two specimens with the maximum impact energy were selected to be compared. The comparison result shows that the shape of load-displacement and energy-displacement curves of the two specimens are similar. The initiation energy of impact crack of 1# plate is about 80J and propagation energy of impact crack is about 200J. However, the initiation energy of impact crack of 2# plate is 70J and propagation energy of impact crack is about 272J.

3.2. Microstructure

Figure 2 shows the microstructure of the two specimens. In figure 2, (a), (b) are optical microscope photographs and (c), (d) are SEM photographs. As it can be seen from figure 2, the microstructure of 1# plate is composed of ferrite and pearlite. Meanwhile the microstructure of 2# plate is different from that of 1# plate and mainly consists of acicular ferrite with a small amount of M/A islands.

3.3. Analysis and discussion

According to the above results, under the condition of the same composition, the cooling method after rolling has a great influence on microstructure type of the specimen. The microstructure of specimen obtained by air cooling after rolling is ferrite and pearlite. In contrast, the microstructure of specimen obtained by water cooling after rolling is mainly acicular ferrite. Previous studies\(^\text{[5,6]}\) have shown that acicular ferrite has high dislocation and fine substructure. In order to observe the sub-structure morphology of acicular ferrite more, in this paper the 2# specimen with acicular microstructure was observed by TEM. The specimen for TEM was pre-thinned to 70–80μm from 200μm by sandpaper, then it was punched out with a diameter of 3mm. The specimen is then thinned by double-jet electrolytic thinner and the electrolyte used was 5% perchloric acid and acetic acid solution. The polishing voltage was 10–20V and the current was 60–70mA. The specimen was observed by JEM-2100F TEM. The result of TEM observation was shown in figure 3. As can be seen from the figure 3, the acicular ferrite is composed of fine ferrite lath which are distributed with each other. And there is
high density of dislocations inside the ferrite lath. So compared to ferrite and pearlite microstructure, acicular ferrite microstructure has higher strength and better toughness. This view explains the reason why the tensile property and impact toughness of 2# plate are better than that of 1# plate in this paper.

From the result of oscillographic impact curves of the specimens, it is found that the initiation energy of impact crack is basically the same for both specimens and the difference of impact energy between the two specimens is mainly attributed to the difference of propagation energy of impact crack. The 2# specimen with acicular ferrite microstructure has higher propagation energy than the 1# specimen with ferrite and pearlite microstructure and the difference of propagation energy between the two specimens is 72J. The effective grain of the acicular ferrite is ferrite lath, and during the process of crack propagation, the crack will be hindered by these fine laths which occlude and interlace with each other, thus effectively improving the strength and toughness\[^{5,7,8}\]. Figure 4 is a schematic view showing a propagation path of a crack in acicular ferrite microstructure. So it is precisely because the acicular ferrite laths hinder the crack to change the direction of crack propagation and increase the path of crack propagation, so that more energy is consumed in the process of crack propagation. Thus the 2# specimen shows higher propagation energy of crack.

4. Conclusions
1. The cooling method after rolling affects the microstructure of pipeline steel, and for the X65 pipeline steel studied in this paper, ferrite and pearlite microstructure is obtained by air cooling after rolling and acicular ferrite mixed with a small amount of M/A islands is obtained by water cooling after cooling.
2. Compared with pipeline steel with ferrite and pearlite microstructure, pipeline steel with acicular ferrite microstructure has higher strength and better low-temperature toughness.
3. The ferrite and pearlite microstructure and acicular ferrite microstructure have similar initiation energy of crack but acicular ferrite microstructure has higher propagation energy of crack which makes its low-temperature impact toughness better than ferrite and pearlite microstructure.

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