Effect of Boron on Microstructure and Properties of Ultra-Low Carbon Steel

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Abstract. The effect of boron on microstructure, mechanical property and conductivity of ultra-low carbon steel wire rod with diameter 6.5 mm was studied. The results show that boron has little influence on the grain size and mechanical property of ultra-low carbon steel wire rod when adding 0.0020% boron alone and under the same process conditions; but when 0.0055% boron is added, the ASTM grain size number of the wire rod is coarsened from the 7.5 grade to 6 grade, at the same time, the tensile strength is reduced by 20 MPa and the electrical conductivity is increased from 16.2%IACS to 16.3%IACS. The effect of Boron on tensile strength is mainly caused by coarsening grain diameter. The effect of boron on grain diameter is related to $[B]/[N]$, when the $[B]/[N]$ is relatively high(for example 1.34), the grain diameter growth is obvious, conversely, when the $[B]/[N]$ is relatively low(for example 0.44), the grain diameter growth is not obvious.

Keywords. Ultra-low carbon steel, boron, grain size, strength, conductivity.

1. Introduction
The typical function of boron is to improve the quenching strength of steel. Based on this, carbon steel with boron for high strength bolts has been widely used [1-2]. The other typical function of boron is to improve the drawing performance of low carbon steel wire rod by reducing the yield ratio and strain aging, which has been widely developed at home and abroad [3-5]. Ultra-low carbon steel wire rod is mainly used to produce industrial pure iron, deep drawing pure iron, copper clad steel wire and other products. Therefore, ultra-low carbon steel is required to have lower tensile strength, better plasticity and higher conductivity. At present, there are few reports about the role of boron in ultra-low carbon steel. In this research, the effect of boron on the grain size, mechanical property and conductivity in ultra-low carbon steel wire rod is studied, which provides guidance for the application of boron in ultra-low carbon steel.

2. Test Materials and Procedure
Table 1 shows the weight ratio of different elements in the test steels, which were supplied by Xingtai steel. The test steel bloom with the section size of 280*325mm$^2$ were blooming and rolling into wire rod with 6.5mm diameter by twice-heating. Table 2 shows the process conditions of test steels. The process is the same with different steel number. Universal testing machine of WDW50 is used for mechanical properties test and Leica DM2700M is used for microstructure observation. The resistance
of steel was measured by DC low resistance tester and converted into the conductivity according to the equation (1).

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\text{Conductivity (}%\text{IACS}\text{)} = 0.2195 \times L \times (d^2 \times R_{20})^{-1} \times 100\%
\] (1)

where IACS-International annealed copper standard; \(L\)-gauge length of metal wire rod, unit m; \(d\)-diameter of metal wire rod, unit m; \(R_{20}\)-DC resistance of metal wire rod at temperature 20\(^\circ\)C, unit \(\Omega\).

**Table 1.** Composition of test steels (wt, %).

| Steel number | C          | Si | Mn | P          | S          | B          | N          |
|--------------|------------|----|----|------------|------------|------------|------------|
| 1# steel     | 0.0025     | 0.005 | 0.05 | 0.008 | 0.006 | 0.0001 | 0.0041 |
| 2# steel     | 0.0026 | 0.005 | 0.05 | 0.007 | 0.005 | 0.0020 | 0.0045 |
| 3# steel     | 0.0028 | 0.005 | 0.05 | 0.008 | 0.005 | 0.0055 | 0.0042 |

**Table 2.** The process conditions of test steels.

| Steel number | Heating temperature \((^\circ\)C) | Finish rolling temperature \((^\circ\)C) | Laying head temperature \((^\circ\)C) | Cooling mode |
|--------------|---------------------------------|---------------------------------|---------------------------------|---------------|
| 1# steel     | 1180                            | 900                             | 900                             | Slow cooling  |
| 2# steel     | 1180                            | 900                             | 900                             | Slow cooling  |
| 3# steel     | 1180                            | 900                             | 900                             | Slow cooling  |

3. Results and Discussion

3.1. Microstructure of Ultra-Low Carbon Steel with Different Boron

Figure 1 shows the microstructure and grain size number of test ultra-low carbon steel wire rod with different boron content. It can be seen that the microstructure of different steels is ferrite, but the ferrite grain diameter of 3# steel with 0.0055% boron is larger than other steels. Table 3 shows the ferrite average diameter (short for \(D_{ave}\)) and the ASTM grain size number (short for GSN). The \(D_{ave}\) and GSN of 1# steel without boron addition are 25 \(\mu\)m and 7.5 grade, respectively. When 0.0020% boron was added, the \(D_{ave}\) and GSN of 2# steel were 27 \(\mu\)m and 7.5 grade, respectively. When 0.0055% boron was added, the \(D_{ave}\) and GSN of 3# steel were 46 \(\mu\)m and 6 grade, respectively. The addition of 0.0020% boron in ultra-low carbon steel wire rod has no obvious effect on the GSN, but when the amount of boron increases to 0.0055%, the \(D_{ave}\) increases obviously, and the GSN decreases.

![Figure 1](image_url)
Table 3. The grain size of test steels.

| Steel number | Average diameter of ferrite grain (μm) | The ASTM grain size number (grade) |
|--------------|---------------------------------------|-----------------------------------|
| 1# steel     | 25                                    | 7.5                               |
| 2# steel     | 27                                    | 7.5                               |
| 3# steel     | 46                                    | 6                                 |

3.2. Mechanical Properties and Conductivity of Ultra-Low Carbon Steel with Different Boron

The mechanical properties and conductivity of test steels were shown in table 4. The mechanical properties and conductivity of 1# steel and 2# steel are almost the same, that is to say, adding 0.0020% boron has no obvious effect on the mechanical properties and conductivity; however, the tensile strength of 3# steel with adding 0.0055% boron is obviously reduced, the average tensile strength is 275 MPa, which is 20 MPa lower than the average tensile strength of 1# steel without adding boron, and the conductivity is slightly increased from 16.2%IACS to 16.3%IACS. The reduction of area and elongation of different steels have little change after adding 0.0020% or 0.0055% boron.

Table 4. Mechanical properties and conductivity of different steels.

| Steel number | Tensile strength (MPa) | Reduction of area (%) | Elongation (%) | Conductivity (%IACS) |
|--------------|------------------------|-----------------------|----------------|----------------------|
| 1# steel     | 295                    | 86                    | 49             | 16.2                 |
| 2# steel     | 294                    | 88                    | 49             | 16.2                 |
| 3# steel     | 275                    | 88                    | 50             | 16.3                 |

3.3. Discussion

It has been reported [5-6] that the influence of Boron on the GSN and mechanical property of low carbon steel is related to boron content and boron nitrogen ratio. For example, the research of paper [5] shows that when 0.0067-0.0117% boron is added to low carbon steel, the grain growth and tensile strength decrease obviously.

In this paper, different content of boron was added to the ultra-low carbon steel. According to the test results, when 0.0020% boron was added (the [B]/[N] is 0.44), the influence of boron on the grain size and mechanical property of the wire rod was not obvious, and the effect of boron on the conductivity was not obvious; when 0.0055% boron was added (the [B]/[N] is 1.34), the ASTM grain size number decreased, the tensile strength decreased, and the conductivity increased.

It can be seen from the experiment that the effect of boron on tensile strength is mainly through the effect on grain size. In this experiment, the average ferrite grain diameter of 3# steel increased from 25 μm to 46 μm, which reduced the tensile strength by 20 MPa. The average ferrite grain diameter of 2# steel changed little, and the tensile strength did not improve significantly.

The influence of boron on the GSN should be related to the boron nitrogen ratio. After boron was added into the steel, the BN precipitated first, which help to reduce the solution strengthening caused by nitrogen, while the precipitation of BN will not cause precipitation strengthening. It is reported that the formation of Fe23(C, B)6 phase can also promote the grain growth [6]. From this experiment, when the [B]/[N] is 0.44, the effect of grain coarsening is not obvious, while when the [B]/[N] is 1.34, the effect of grain coarsening is obvious. The specific critical value of the [B]/[N] on grain coarsening effect needs to be further confirmed.

The conductivity of steel is affected by many factors, among which chemical composition and grain size are the main factors. It is found that the larger the grain diameter is, the higher the conductivity is [7]. With the bigger of Dave, the grain boundary number will be reduced, and the electronic wave will be less hindered when passing through the grain boundary, the loss of energy will be reduced, and the conductivity will be increased. The higher the purity of the material is, the higher the conductivity is. The addition of boron in the steel will cause the precipitation of the second phase, such as BN, and reduce the purity of the material, which is unfavorable to the conductivity in theory.
However, the conductivity of the 3# steel in this experiment did not decrease, but increased, which shows that the contribution of grain coarsening to the increase of conductivity is greater than that of BN precipitation to the decrease of conductivity.

4. Conclusion
From the experiment and analysis, the following conclusions can be obtained for the test steels:

1) The addition of 0.0020% boron has little influence on the ferrite grain diameter of rolled $\Phi$ 6.5mm wire rod; the addition of 0.0055% boron will make the ferrite grain diameter coarsen, and the ASTM grain size number will be reduced from 7.5 grade to 6 grade.

2) The addition of 0.0020% boron has little influence on the tensile strength and conductivity of rolled $\Phi$ 6.5mm wire rod; but the addition of 0.0055% boron will reduce the tensile strength of wire rod by 20MPa and increase the conductivity from 16.2%IACS to 16.3%IACS.

3) The effect of boron on the tensile strength and conductivity is mainly caused by the effect on the grain size of the wire rod. The influence of boron on the grain size is related to the boron nitrogen ratio. When the [B]/[N] is low (such as 0.44), the grain coarsening is not obvious. When the [B]/[N] is high (such as 1.34), the grain coarsening is obvious.

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