The analysis of critical cooling rate for high-rise building steel S460

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Abstract High-rise building steel S460 is an important structure steel. The product process of the steel is Quenching\&Tempering. The critical cooling rate of steel is very important in heavy plate quenching process, and it is also the basis of the cooling process\textsuperscript{[1]}. The critical cooling rate of HSLA steel S460 is obtained from the Thermal simulation method, and the differences about the microstructure and properties of different cooling rate is also analyzed. In this article, the angle of the grain boundary and the average grain size are analyzed by EBSD under different cooling rate. The relationship between grain boundary angle and grain size with the cooling rate is obtained. According to the experiment, it provides the basis for the formulation of the quenching process of the industrial production.

1. Background

High strength structural steel has significant advantages in structure performance, construction use function social economic benefits and environmental benefits\textsuperscript{[2]}. High strength structural steel can improve the safety and reliability of structure, and can create greater use of space, and the flexible architecture, at the same time can save construction cost, belonging to the environmental protection building materials. The using condition of the high strength structural steel S460 is QT. The critical cooling rate should be cleared by experiment to determine reasonable processing technology.

2. The purpose of the test

High strength structural steel is a kind of HSLA steel, the steel grade of the critical cooling rate vary according to the composition, usually with the increasing of carbon equivalent the critical cooling rate has the tendency to decline. The critical cooling rate can be obtained by thermal simulation method. The composition of S460 as below.

| Table 1. Chemical composition of S460. |
|--------------------------------------|
| C  | Si  | Mn  | P   | S    | Alt  | CEQ  |
|----|-----|-----|-----|------|------|------|
| S460 | 0.09 | 0.28 | 1.4 | 0.01  | 0.0024 | 0.038 | 0.33 |

Quenching is to heat the steel to the temperature above Ac3 or Ac1, heat preservation for some time, cooling rate greater than the critical cooling speed, finally get the microstructure of martensite or
low bainite\[^3\]. The aim of this experiment is to grope for the critical cooling speed, and also for the microstructure difference under different quenching cooling speed.

The thin steel plate is easier to hardening, after quenching the strip shape is difficult to control. Based on this, the cooling rate has to be moderate\[^4\].

### 3. Quenching process

In this experiment, 7 round rods is selected, The size is $\Phi 6\times80$ mm, steel grade is high strength structural steel S460.

The thermal simulation testing machine GLEEBLE 2000D is used. The samples heating to Ac3 temperature (S460 is above 900 °C) from room temperature at heating rate of 10°C/S, keep 240 s, rapidly cooling to room temperature. The cooling rate is 5°C/S(1#), 10°C/S(2#), 20°C/S(3#), 30°C/S(4#), 40°C/S(5#), 50°C/S(6#), 60°C/S(7#) respectively. Schematic diagram as below.

![Figure 1. Schematic diagram](image)

### 4. Experimental analysis of quenching

Making metallographic and electron microscope observation for quenching samples, and compared the differences of the microstructure and performance at different cooling speed, to determine the critical cooling rate of S460.

#### 4.1 Microstructure and microhardness analysis

Figure 2-Figure 8 is the microstructure of samples.

![Figure 2. Microstructure of sample 1](image)  ![Figure 3. Microstructure of sample 2](image)
Microstructure microhardness and MA rate as Table 2.

| Sample | Microstructure           | Cooling Rate | Microhardness | Mean value of Microhardness | MA Rate (%) |
|--------|--------------------------|--------------|---------------|----------------------------|-------------|
| 1      | Ferrite+Bainite+Pearlite | 5°C/S        | 189.84, 197.54, 190.88 | 192                       | 6.9         |
| 2      | Ferrite+Bainite+Pearlite | 10°C/S       | 205.71, 208.13, 198.64 | 204                       | 6.6         |
| 3      | Bainite+Ferrite          | 20°C/S       | 215.72, 233.61, 229.28 | 226                       | 4.8         |
| 4      | Bainite+Ferrite          | 30°C/S       | 236.54, 236.54, 230.82 | 234                       | -           |
| 5      | Bainite+Ferrite          | 40°C/S       | 214.48, 230     |                            | -           |
From the microstructure observation result. The cooling rate of sample 1#-2# is lower. The final microstructure is Ferrite+Bainite+Pearlite. The microstructure of sample 3#(cooling rate 20℃/S)-7#(cooling rate 60℃/S) is Bainite+Ferrite. With the increasing of the cooling rate, the Bainite is more and the Ferrite is less. And sample 1#-2# also contained some Pearlite.

Microhardness value also correspond to microstructure. The microhardness of sample 1#-2# is lower because of the contained pearlite. The value is between 190~205HV. The value of sample 3#-7# is between 225~235HV. Depending on the microstructure and microhardness result, the critical cooling rate of S460 is 20℃/S.

4.2 Scanning electron microscopy (SEM) analysis
In order to further analysis the microstructure under different cooling speed, main contrast of Bainite, the electron microscope analysis is used. The cooling rate from 20℃/S~60℃/S. The microstructure is Bainite+Ferrite. The microstructure of SEM under different cooling rate as below. The difference of B+F from different samples is observed.
The differences of B+F from 3#-7# is observed by SEM. The conclusion as below. Some pearlite phase and some dot carbides, M - A island of bainite phase is observed when the phase of bainite area of sample 4# is zoom to 5000X. Little pearlite phase and some dot carbides, M - A island of bainite phase is observed when the phase of bainite area of sample 5# is zoom to 5000X. There is no pearlite phase in sample 6#-7#, the Dot bainite transform to lath bainite. It can be concluded that above the critical cooling rate, with the increase of cooling speed, bainite content increased gradually.

4.3 Electron Back-Scattered Diffraction (EBSD) analysis

Average grain size and grain boundary angle measurement analysis is carried out by EBSD on the sample. The samples are 4#-7#, Figure3 is grain boundary angle measurement analysis. Table2 is grain size and proportion of the large Angle grain boundary for each sample.
Table 3. Grain size and grain boundary angle

| Sample | Grain boundary angle (>15°) | Grain size (μm) | Average grain size (μm) |
|--------|-----------------------------|-----------------|-------------------------|
| 4      | 38.25%                      | 1.13~34.97      | 6.63                    |
| 5      | 37.53%                      | 1.13~34.02      | 5.66                    |
| 6      | 31.18%                      | 1.13~26.41      | 4.25                    |
| 7      | 34.57%                      | 1.13~18.57      | 4.21                    |

It can be concluded from Figure 3 that the grain boundary angle distribution is similar from sample 4#-7#. The proportion is higher in less than 5° and greater than 50°, and the proportion of 1.5° angle grain boundary is as high as 40%.

It can be concluded from Table 3 that the proportion of high-angle boundary (>15°) is 31-38% in sample 4#-7#. The average grain size reduced gradually from 6.63 μm ~ 4.21 μm.

5. Conclusion

- From thermal simulation experiment results and microstructure microhardness analysis of the 1#-7# samples, preliminary determine critical cooling rate of S460 is 20°C/S.
- The SEM indicate the result of metallographic observation. And low cooling rate samples as 1# 2# appears widmanstatten structure. From sample 4#, bainite structure content gradually increased, with the higher cooling rate.
- EBSD indicate that greater rate than the critical speed range, with the improvement of cooling speed, the average grain size decreases, the grain boundary Angle proportion is higher in less than 5° and greater than 50°.

References

[1] Cui Zhongqi 1998 Principle of metallography and heat treatment (Haerbin: Harbin industrial university press) p302
[2] Wang Youming 2009 The controlled rolling and controlled cooling of steel (Beijing: Metallurgical industry press) p45
[3] Yu Yongning 2006 Material science basis (Beijing: Higher education press) p433
[4] Gao Weiguo 2003 The microstructure and mechanical properties of steel widmanstatten structure vol 28 (Beijing: Journal of metal heat treatment) p39