Study on Microstructure and Properties of 1000MPa Grade Steel Plate for Hydropower Station

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Abstract. The influences of heat treatment on the microstructural and mechanical properties of 1000M hydropower station steel plate were studied. The changes in the microstructure and mechanical properties of the investigated steel at different quenching and tempering temperatures were analyzed. It was found that test steel at lower-temperature quenching was transformed into granular bainites and at high quenching temperatures were transformed into lath bainites. Moreover, With the increasing tempering temperature, the yield strength of the test steel first increased and then gradually decreased after reaching the maximum value at 630 °C, whereas the tensile strength decreased unilaterally until the tempering temperature reached 650 °C. Furthermore, the percentage elongation and the low-temperature(-40 °C) impact toughness increased significantly during tempering. Therefore, the quenching treatment was carried out 930 °C, whereas tempering temperature was selected in the range of 600–630 °C.

1. Introduction

As a clean and renewable energy source, hydropower plays an important role in our daily life. High-strength hydropower steels are generally used in the construction of large-capacity hydropower stations, pressure pipes and volutes, and branch pipes due to their high toughness and excellent welding performance[1]. Hydropower steels are generally produced by quenching and tempering. Wu Li et al. [2] performed a trial production of high-strength penstock steel for hydropower stations, but its strength grade of test steel plate as only 610 MPa. Tang Zhenglei et al. [3] produced Q690CFE steel plates for penstock pipe and volute vessels by quenching and tempering. Zhao Yanqing et al. [4] studied the effects of quenching temperature on the microstructure and mechanical properties of 780 MPa hydropower steel plate and found that 930 °C was the most reasonable quenching temperature. Chen Jie et al. [5] studied the influences of online quenching and high-temperature tempering on the microstructure and mechanical properties of 1000 MPa hydropower steel. The cooling capacity of online quenching was found to be lower than that of offline quenching, thus thinner steel plates were produced. Therefore, the thick and high-grade 1000MPa hydropower steel plate needs to be produced by quenching and tempering process, but there is no detailed quenching and tempering process have been reported in the published papers. In particular, the transformation of microstructure and properties at different tempering temperatures after quenching were not analyzed. In the present experiment, different heat treatment processes were employed for the trial production of 1000MPa
The effects of different quenching and tempering temperatures on the microstructure and mechanical properties of the test steel were discussed.

2. Experimental Methods
The test steel was designed with the low-carbon steel composition. Nb, V, and Ti were added to refine grains, and Cr and Mo were added to improve the hardenability of the test steel. A small amount of Ni was added to improve the low-temperature toughness and also to reduce the ductile-brittle transformation temperature of the examined steel. Moreover, trace B element was added to further improve the hardenability of the steel. Slabs were produced by iron melt desulfurization, LF converter furnace refining, RH vacuum furnace refining, continuous casting, and slab cleaning. The chemical composition of the investigated steel is presented in Table 1.

Slabs were rolled to 50 mm thick steel plates by 4300 mm 4-High Reversing Cold Rolling Mills. The tested steel was first quenched at 930 °C, and 950 °C and subsequently, tempered at 600 °C, 630 °C, and 650 °C. The microstructures of the steel after rolling, quenching, and tempering were analyzed by optical microscopy (OM; Olympus BM51) and scanning electron microscope (SEM, Sirion 200). The tensile properties and the low-temperature impact toughness of the hydropower steel plate were tested by a 100 kN hydraulic universal tensile testing machine (TS–1000KN–100T) and a low-temperature impact toughness testing machine (JB-W300DZ).

Table 1. Chemical composition of the tested steel (mass fraction/%).

| element | C   | Si  | Mn  | P   | S | Alt | Nb | V | Ti | Cr | Ni | Cu | Mo | B | Fe | Pcm |
|---------|-----|-----|-----|-----|---|-----|----|---|----|----|----|----|----|---|---|-----|
| content | 0.09| 0.24| 1.35| 0.010| 0.001| 0.038| 0.026| 0.03| 0.015| 0.46| 0.20| 0.011| 0.20| 0.0016| Bal.| 0.22|

3. Results
3.1. Microstructures and Mechanical Properties of the Test Steel after Quenching
The microstructures of the test steel at different quenching temperatures are displayed in Figure 1. There are some granular bainite microstructure and a lot of lath bainites were obtained after quenching at 930 °C, as shown in the (Figure 1 (a)). Due to a low heating temperature, undissolved alloy carbides existed in the form of islands and granules and were transformed into granular bainites after quenching[6] (Figure 2). With the increase in the quenching temperature, cementite and alloy carbides completely dissolved into austenites, the lath bainite microstructure was obtained after quenching at 950 °C[7-8] (Figure 1 (c)). In addition, with the increasing quenching temperature, the lamellar spacing of lath bainites increased significantly (Figure 1 (b)).

Figure 1. Optical microstructure of test steel after quenching (a) 930°C; (b) 950°C.
The mechanical properties of the test steel at different quenching temperatures are presented in Table 2. The yield strength and the tensile strength at different quenching temperatures always remained above 790 MPa and 1000 MPa, respectively; however, its elongation rate was quite low (13.5-15%). Moreover, due to the fast cooling of the test steel during quenching, dissolved carbides in austenites had no time to spread and remained in bainites. When the plastic deformation occurred, a large number of carbides experienced screw dislocation[7–8]; therefore, the test steel manifested a higher strength after quenching. Due to the plastic deformation, the cracks appearing after dislocations evolved into macroscopic cracks and then rapidly got fractured. The low-temperature (−40 °C) impact toughness of the test steel during quenching fluctuated between 33 J and 71 J (Table 2). It happened due to the increased brittleness of the test steel during quenching. A large number of dislocations, twin crystals, and sub-structure defects were present in the microstructure (carbides existing on twin crystal grain boundaries caused an increase in brittleness). Moreover, the quenching stress and a large number of micro-cracks were also detected in the test steel, and these micro-cracks became the main sites of stress concentration and could not absorb the large impact energy[9].

Table 2. Mechanical properties of tested steels under quenching.

| Quenching temperature/°C | $R_{p0.2}$/MPa | $R_m$/MPa | $\delta$ (%) | $A_{KV}$ (-40°C)/J |
|--------------------------|---------------|-----------|--------------|-------------------|
| 930                      | 796           | 1010      | 13.5         | 61, 54, 71        |
| 950                      | 798           | 1020      | 15           | 36, 33, 56        |

3.2. Microstructures of the Test Steel at Different Tempering Temperatures

The microstructures of the test steel after quenching at 930 °C and tempering at 600 °C, 630 °C, and 650 °C are displayed in Figures 3 (a-c). Granular bainites were transformed into ferrites and carbides during tempering. Carbides precipitated on ferrite grain boundaries and formed the tempered bainite. With the increase in the tempering temperature, dislocations, twin crystals, and substructure defects formed during quenching were further recovered, some dislocations gradually recombined and disappeared, and a large number of carbides precipitated on the ferrite matrix[10-12].

The microstructures of the test steel after quenching at 950 °C and tempering at 600, 630, and 650 °C are showed in Figures 3 (d-f). Lath bainites were recovered, positive and negative dislocations recombined, and ferrites gradually grew into quasi-polygonal and polygonal shapes. With the increasing tempering temperature, the number and volume of polygonal ferrites and carbides increased significantly and subsequently, the tempered bainite microstructure was obtained.

The microstructure of the tempered steel was similar to that of the quenched one. Tempered bainites and polygonal ferrites obtained after quenching at 950 °C and tempering inherited the morphology of as-quenched lath bainites. Moreover, the average grain sizes of tempered bainites and polygonal ferrites were higher than that of the quenched steel obtained after quenching at 930 °C [13].
3.3. Mechanical Properties of the Test Steel under Different Processing Stages

Elongations of the test steel at different quenching and tempering stages are compared in Figure 4. The elongation of the test steel after quenching was about 14%; however, after tempering, the value increased to ~20%. As the cooling rate was very fast during quenching, certain thermal stress was generated in the microstructure due to thermal expansion and contraction. During high-temperature tempering, the quenched microstructure was recovered, the thermal and microstructural stresses were released due to phase transformation, and stress concentrations were alleviated[7]. Moreover, dislocations formed during quenching gradually recombined and disappeared during tempering. Hence, the probability of fracture was greatly reduced and the elongation was improved[14].

The yield and tensile strengths and the low-temperature impact toughness of the test steel during tempering are presented in Figure 5. The tensile strength of the quenched steel decreased continuously during tempering. When the tempering temperature reached 650 °C, the tensile strength decreased to below 780 MPa and the impact toughness increased significantly. With the further increase in the tempering temperature, the low-temperature impact toughness reached >250 J. However, the yield strength of the test steel first decreased, then increased, and finally, gradually decreased. When the tempering temperature reached 630 °C, the maximum yield strength was achieved.

The lath bainite microstructure obtained after quenching manifested high strength and poor impact toughness[14-16]. Substructure changes occur during tempering, dislocation merging disappear, which decreases the strength and improves the impact toughness at low temperature. With the increasing tempering temperature, a large number of carbides precipitated on the matrix and grain boundaries of ferries and obstructed dislocation movements during plastic deformation. The strength loss due to substructural changes was offset by the increase in precipitation strengthening; therefore, the yield strength of the test steel was greatly improved[17]. However, when the tempering temperature reached 650 °C, dislocations disappeared and carbides gather and develop, the effects of precipitation intensification decreased gradually, and the yield strength also decreased[18].
Figure 4. Comparison of elongation of test steel

Figure 5. Mechanical properties of test steel under different heat treatment processes. (a) 930°C quenching; (b) 950°C quenching

4. Discussion
Granular bainite is formed after quenching, the tempering bainitic and alloy carbide will occur during high temperature tempering. The SEM photos of the 930 °C quenched test steel tempered at 630 °C are shown in Figure 6. A large of carbides are precipitated on the ferrite matrix, carbon atoms diffuse at 630 °C and precipitate carbides from bainite ferrite, which are dispersed and scattered on the ferrite matrix[19]. When plastic deformation occurs, the dislocation will be pinned and the dislocation will be entangled, which will improve the strength of the test steel. According to the theory of Glad et al. [20], the Ashby Orowan modified model is used to improve the precipitation strength as show in formula :

$$\sigma_p = \frac{10\mu b}{5.72\pi^{3/2} f} \left( \frac{r}{b} \right)^{3/2} \ln \left( \frac{r}{b} \right)$$  \hspace{1cm} (1)$$

Where \( r \) is the average particle radius, \( \mu \) is the shear coefficient, \( b \) is the Burgers Vector, and \( f \) is the volume fraction of precipitated carbide. It can be seen from formula (1) that the strength of the test steel is directly related to the size and volume fraction of the precipitated carbides. The smaller the carbide size and the higher the volume fraction, the higher the strength of the steel.
5. Conclusion
1) The granular bainite microstructure was obtained after quenching at 930 °C and the lath bainites microstructure was obtained after quenching at 950 °C. During quenching, the yield strength and the tensile strength of the test steel always remained above 790 MPa and 1000 MPa, respectively, whereas its low-temperature (–40 °C) impact toughness ranged between 33 J and 71 J.
2) After tempering, the elongation of quenched test steels is increased to ~20%. The low-temperature impact toughness of the 950 °C quenched steel decreased noticeably; hence, the quenching temperature should be selected 930 °C.
3) During 630 °C tempering, the yield strength of the test steel reaching the maximum value. During 650 °C tempering, the tensile strength is unqualified. Furthermore, the low-temperature (–40 °C) impact toughness increased significantly during tempering. Therefore, the tempering temperature was selected in the range of 600–630 °C.

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7. Reference
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