Study on Microstructure and Properties and Deformation Resistance of Low Carbon Bainitic High Strength Steel

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Abstract. In this paper, the microstructure and properties of a laboratory low-carbon bainitic high-strength steel were analyzed. On the Gleeble-3500 thermal simulator, the effects of different deformation temperature and deformation rate on the deformation resistance of the test steel were studied. The experimental results show that the test steel has a yield strength of 625MPa, a tensile strength of 740MPa, an elongation of 20%, a yield ratio of 0.84 and an average effective grain size of 4.5μm. It can meet the requirements of most engineering machinery steel. The microstructure of the test steel is lath bainite containing large density dislocations. The precipitated particles are dispersed and the sizes are different. It can be found that the carbon and nitrogen composites of Nb and Ti are precipitated by energy spectrum analysis. Through the thermal simulation test, the deformation resistance model of the test steel was developed.

1. Introduction
The carbon content of low-carbon bainite high-strength steel is very low, and the strength of this kind of steel is mainly ensured by means of fine grain strengthening, dislocation and substructure strengthening, and precipitation strengthening of niobium and titanium microalloying elements, etc., instead of relying on the carbon content of steel. Low carbon content is not enough to adversely affect the toughness of bainite structure. Therefore, a very fine bainite matrix structure containing a high dislocation density can be obtained after controlled rolling and controlled cooling. As a green and environmentally friendly steel material, low carbon bainite high strength steel has high strength, high toughness and excellent welding performance, so it is widely used in heavy-duty vehicles, marine facilities, mining machinery, containers, bridges, pipelines, containers and construction machinery, etc.[1].

Deformation resistance is an important factor affecting the rolling force of steel in determining the rolling mill load and establishing a reasonable rolling process specification. At the same time, in the field of modern rolling, more and more enterprises use computer and rolling mill[2] to achieve computer control, and establish a more complete mathematical model of deformation resistance[3] to reflect the mechanical properties of metal materials and thermal deformation process parameters. In order to further improve the control precision of the rolling process, improve the industrial efficiency and obtain high-quality products, the deformation resistance law of material processing needs to be studied more thoroughly.

2. Composition design and microstructure control of test steel
The test steel was selected from the laboratory trial production of 5mm thick low-carbon bainite high-strength steel, and its chemical composition is shown in table 1. As shown in table 1, the bainite high-
strength steel in this trial production adopts low-carbon design with 0.05%C. 0.2%Mo element was added to enhance the hardenability of the steel to produce bainite structure in a wide temperature range. 0.035%Nb was added to increase the recrystallization temperature of the test steel, so as to reduce the rolling difficulty of the test steel and produce precipitation strengthening effect in the subsequent cooling process. 0.02%Ti element was added to strengthen the precipitation and fine grain of the steel. 0.45%Cr element was added to increase its hardenability and 0.05%V element was added to precipitate strengthening effect of test steel.

The mechanical properties of the test steel are shown in table 2 that the trial steel has a yield strength $R_{P0.2}$ of 625MPa, a tensile strength $R_m$ of 740MPa, an elongation $A$ of 20%, and a yield ratio of 0.84. The low-carbon bainitic steel produced this time has the characteristics of high strength, high elongation and low yield.

The metallographic structure of the trial-produced low-carbon bainitic steel is shown in figure 1. It can be seen that the microstructure of the test steel is composed of granular bainite and a very small amount of quasi-polygonal ferrite, and the microstructure is fine and uniform. The rolled surface, longitudinal section and cross section are substantially all granular bainite structure and the core structure is slightly coarse and contains a certain amount of ferrite structure. Figure 2 shows the EBSD pattern of the test steel. It can be seen that the grains in the test steel are mostly small-angle grain boundaries and the average effective grain size of the test steel is 4.5µm.
Figure 1. Microstructure of low carbon bainite test steel
(a: cross-sectional surface; b: center of cross section; c: longitudinal section surface; d: center of longitudinal section)

Figure 2. EBSD of low carbon bainite steel

The low carbon bainite test steel was sampled and sample preparation was carried out by electrolytic double spray thinning method. The test steel was observed under the JEM-2000FX transmission electron microscope. The TEM morphology of the test steel is shown in figure 3. It can be seen from the figure that the microstructure of the test steel is a bainite structure, the bainite is mainly lath-like, and the bainite lath is composed of bainitic ferrite sub-slabs and residual austenite between the sub-slabs, and the sub-slabs are separated by a residual austenite film. Usually each bainite slat consists of 3 to 5 sub-slats, and the sub-slab width is 200~600nm. Large density dislocations can be observed in the strip.
The low carbon bainite test steel was sampled and the sample was made into a carbon extraction replica sample. The second phase precipitated particles of the test steel were observed under a JEM-2000FX transmission electron microscope. The morphology of the precipitated particles is shown in figure 4. It can be seen from the figure that the distribution of precipitated particles in the test steel is more diffuse, and the size range fluctuates greatly, ranging from a few nanometers to tens of nanometers or even hundreds of nanometers.

The morphology of precipitated particles mainly consists of square and ellipsoidal. It can be found that the carbon and nitrogen composites of Nb and Ti are precipitated by energy spectrum analysis. However, due to the reasons of the cooling rate and the final cooling temperature during the rolling of the test steel, the precipitation of the V element was small, and the appearance of the V element was not observed under the transmission electron microscope.
3. Single channel compression thermal simulation experiment scheme

On the Gleeble-3500 thermal simulation tester, the single-pass compression test was used to study the hot deformation behavior of high-strength steel sheets. The process road map is shown in Figure 5. The specific experimental scheme is designed as follows: the test steel slab is processed into a $\Phi 8 \times 15$ mm cylindrical sample, heated to 1200°C at a heating rate of 10°C/s, and the steel is austenitized at this temperature for 5 minutes, and then the cooling rate of 1.5°C/s was cooled to 800°C, 850°C, 900°C, 950°C, 1000°C, 1050°C and 1100°C, respectively, followed by a single pass compression of the sample at 60% engineering strain, and finally quench to room temperature.
4. Analysis of experimental results and influencing factors

4.1. Effect of deformation temperature on deformation resistance

Figure 6 shows the stress-strain curves at different deformation temperatures for deformation rates of 5s$^{-1}$, 10s$^{-1}$, and 25s$^{-1}$. Taking the curve of figure 6(a) as an example, when the low-carbon bainite high-strength steel is just beginning to deform, the deformation resistance increases rapidly with the increase of the deformation amount, and the growth rate is fast. When the strain is less than 0.3, the tendency of the increase in the deformation resistance gradually decreases as the strain value increases, which is caused by the effects of dynamic recrystallization and dynamic recovery accompanied by the decay of the work hardening speed. When the strain is greater than 0.3, the deformation resistance does not change much with the increase of strain, and the curve of change is nearly a horizontal line. The main reason is that work hardening is eliminated. In addition, it is found that the elevated deformation temperature, under the same strain conditions, the corresponding stress will be reduced. The main reason is that as the temperature continues to increase, the original strong interatomic force will continue to weaken, and the stability of the metal structure will be weakened, and the corresponding critical shear stress will be reduced. The above factors will further enhance the metal. The recovery and recrystallization, as well as the ability of atomic diffusion motion and dislocation slip, all cause a negative relationship between deformation resistance and deformation temperature.

![Stress-strain curves at different deformation temperatures](image)

Figure 6. Stress-strain curves at the same deformation rate and different deformation temperatures
(a) deformation rate: 5s$^{-1}$; (b) deformation rate: 10s$^{-1}$; (c) deformation rate: 25s$^{-1}$

4.2. Effect of deformation rate on deformation resistance

Figure 7 shows the stress-strain curves at different deformation rates for the same deformation temperature. On the one hand, throughout the figure, the deformation resistance of the metal increases with the increase of the deformation rate. The reason is that the deformation rate has a positive relationship with the dislocation movement speed, so that the increase of the deformation rate requires a larger shear stress, thereby increasing the deformation resistance. On the other hand, with the gradual increase of the deformation rate, due to the plastic deformation, the softening time of the low-carbon
bainite high-strength steel is reduced, and the recovery and recrystallization on this basis are not enough, so it will increase. The ability to work harden ultimately increases the deformation resistance of the metal. Of course, the degree of increase in deformation resistance is closely related to temperature. Occasionally, due to the significant temperature effect, the metal temperature is too high, so the deformation rate is accompanied by the temperature effect on the deformation resistance. However, the intensity of the deformation resistance is not the same in each temperature range.

Figure 7. Stress-strain curves under the same deformation temperature and different deformation rates
(a) deformation temperature 850°C; (b) the deformation temperature is 950°C; (c) deformation temperature 1000°C

5. Mathematical model of deformation resistance
The deformation resistance of low-carbon bainite high-strength steel directly plays a guiding role in determining various rolling process parameters in actual production. At the same time, it also plays a decisive role in the rationalization of the processing technology and the safety of the processing equipment[4–5]. Therefore, it is of great significance to study the deformation resistance law of low carbon bainite high strength steel and establish a suitable mathematical model of deformation resistance.

5.1. Selection of mathematical model of deformation resistance
In order to intuitively study the deformation resistance law of low-carbon bainite high-strength steel, the following mathematical model was established and its regression analysis was carried out[6].

\[ \sigma = Ae^{a \varepsilon \dot{\varepsilon} \exp(cT + d \varepsilon)} \]  \hspace{1cm} (1)

Where \( \varepsilon \) is the true strain; \( \dot{\varepsilon} \) is the deformation rate, \( s^{-1} \); \( T \) is \( t+273 \), \( t \) as the deformation temperature, °C; \( \sigma \) is deformation resistance, MPa; \( A, a, b, c \) and \( d \) are data related to the material itself, respectively.

5.2. Regression results and analysis of mathematical model of deformation resistance
According to the selected deformation resistance model[7], available from formula (1.1):
\[
\ln \sigma = \ln A + a \ln \varepsilon + b \ln \dot{\varepsilon} + cT + d\varepsilon
\]  

(2)

SPSS software was used to conduct multiple linear regression analysis on equation[8](1.2), and the expected values of \( \ln A, a, b, c \) and \( d, \ln A, \dot{\varepsilon}, \dot{\varepsilon} \) and \( \dot{\varepsilon} \), were obtained as follows: \( \ln A=8.133; \ a=0.346; b=0.021; c=0.002; d=0.254 \). Substitute into equation (1.2):

\[
\sigma = 3543.96e^{0.346 \dot{\varepsilon}^{0.021}} \exp(-0.002T - 0.524\varepsilon)
\]  

(3)

The correlation coefficient of this model is R=0.980, and the linear correlation of the regression equation is very significant. Then select two low carbon bainite high strength steel samples, and substitute the experimental data into the regression equation, such as sample 1 (1050°C, 10s^{-1}) and sample 2 (1000°C, 5s^{-1}). The obtained regression equation is compared with the experimental data, and the comparison results are shown in Figure 8. It can be seen from the figure that the fitting degree of the two curves is relatively close, especially in the stage of small deformation degree, the simulated value and the measured value are closer, and the error is particularly small.

![Figure 8](image)

Figure 8. Regression results of deformation resistance under different deformation conditions are compared with experimental results  
(a: 1050°C, 10s-1; b: 1000°C, 5s-1)

6. Conclusion

In this paper, by studying the influence of deformation temperature and deformation rate on deformation resistance, the corresponding mathematical model is established and the following conclusions are obtained:

(1) The low carbon bainite test steel of this trial is 5mm thick, the yield strength \( R_{0.2} \) is 625MPa, the tensile strength \( R_m \) is 740MPa, the elongation \( A \) is 20%, the yield ratio is 0.84, and the average grain size of the test steel is 4.5μm, the microstructure is bainite structure, and the bainite is mainly in the form of laths. Each bainite strip generally consists of 3 to 5 sub-slats, and the width of the sub-slab is 200–600nm. Large density dislocations can be observed in the sub-slabs;

(2) The precipitated particles of the second phase in the test steel are evenly distributed, ranging in size from tens to hundreds of nanometers. It is found by the energy spectrum analysis that the carbon and nitrogen of the Nb and Ti elements are precipitated;

(3) The selected deformation resistance model was analyzed by SPSS statistical analysis software to obtain the mathematical model of the test steel: \( \sigma = 3543.96e^{0.346 \dot{\varepsilon}^{0.021}} \exp(-0.002T - 0.524\varepsilon) \). The regression results can provide reference for industrial production of low carbon bainite high strength steel.

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