Strengthening Mechanism of 550MPa Grade High-Ductility Automotive Structural Steel

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Abstract. The microstructure, properties and strengthening mechanism of 550MPa Grade high-ductility automotive structural steel were investigated by utilizing optical microscope (OM) and transmission electron microscopy (TEM). The results showed that with the decrease of the finish rolling temperature and the coiling temperature, the ferrite grain size become finer and the distribution of the second phase precipitate dispersed in the studied temperature range. The optimal mechanical properties were obtained when the finish rolling temperature and the coiling temperature were 840 and 570 °C respectively, which the yield strength, tensile strength and elongation were 537MPa, 578MPa and 33.5% respectively. The strengthening of grain refinement was the most important strengthening modes, which accounted for more than 49 percent to the yield strength. The strengthening of solid solution was the second strengthening modes, it's accounted for 23 to 27 percent while the strengthening of precipitation only contributed 3.8~8.2 percent.

1. Introduction
In recent years, electric vehicles and hybrid cars have developed rapidly, and the vehicle exhaust pollution has reduced significantly, which meet the green low-carbon concept of environmental protection. Studies have shown that a reduction of 0.05mm, 0.10mm and 0.15mm of the steel thickness can decrease 6%, 12% and 18% of the body weight. The fuel consumption can be reduced by 6% to 8% when the weight of a vehicle is reduced by 10% [1-5]. Therefore, in the premise of ensuring the reliability of a vehicle, the lightweight of the vehicle can reduce fuel consumption and increase mileage range.

Square pipe steel accounts for about 33.3 percent of the total weight of a new energy bus, and lightweight directly influences its overall performance. At present, the body of a bus mainly uses Q235 square pipe steel or seamless pipe steel, so the key of lightweight is to choose new materials to replace the existing materials [2-6]. Technology and cost are the main restrictions on the application of new materials for new energy buses. Therefore, it is of great significance to design and develop a type of high strength thin-walled square pipe steel, which is suitable for mass production [7-10].

It is known that the chemical composition and thermo-mechanical processing determine the microstructure. The alloying elements added in the high strength steels to obtain the desired microstructure and mechanical properties commonly include Nb, V, Ti and Mo. In the processing of high strength steels, controlled thermo mechanical processing is the preferred route because it provides the desirable and fine-grained microstructure [11-20].
Based on the above background, a low cost of 550MPa Grade high-ductility automotive structural steel was designed, and the microstructure, properties and strengthening mechanism with different thermo-mechanical processing were investigated.

2. Experimental materials and methods

2.1. Materials

The 550MPa Grade high-ductility automotive structural steel described here was continuously cast and hot rolled to 3mm in industry production. The chemical composition (in wt. %) of the steel contained 0.05~0.07C, 0.03~0.10Si, 0.9~1.1Mn, 0.02~0.04Nb and 0.01~0.03Ti.

The total solution temperature of the steel can be calculated by equation 1[21]:

\[
\frac{w_{Ti} \cdot w_C}{10^{2.75-7000/T_{AS}}} + \frac{w_{Nb} \cdot w_C}{10^{2.96-7510/T_{AS}}} = 1
\]

(1)

where \(w_{Ti}\), \(w_{Nb}\) and \(w_C\) are the mass fraction of Ti, Nb and C elements in the steel, \(T_{AS}\) is the total solution temperature of the steel. According to the equation 1, the total solid solution temperature of the steel was 1013~1136°C. Therefore, the heating temperature of the 550MPa grade high-ductility automotive structural steel was select to be 1150°C.

In order to study the effect of finish rolling temperature on the properties, the finish rolling temperature was selected as 880°C and 840°C. In order to study the effect of coiling temperature on the properties, the coiling temperature were set as 630, 600, as 570°C. Figure 1 shows the illustration of hot rolling process for the 500MPa grade high-ductility automotive structural steel.

![Figure 1](image)

**Figure 1.** Illustration of hot rolling process for 550MPa Grade high-ductility automotive structural steel

2.2. Tensile testing

Standard tensile tests were conducted at room temperature on longitudinal specimens with proportional gauge prepared per ASTM E8 specification using a tensile testing machine (MTS810).

2.3. Microstructural characterization

Metallographic specimens were cut parallel to the rolling direction from the hot plate, grinded, polished and etched with 4% natal and then observed with MEF4A optical microscopy and S3400N field emission scanning electron microscope. Foils and carbon extraction replicas were examined by using JEM-2000FX transmission electron microscopy operated at 200 KV using standard bright field to study the precipitation and dislocation.
3. Results and discussion

3.1. Mechanical properties

The yield strength, tensile strength, and elongation obtained of the 550MPa Grade high-ductility automotive structural steel are listed in Table 1. When the coiling temperature was kept constant, with the decrease of the finish rolling temperature, the yield strength, tensile strength, elongation and yield ratio increased. When the finish rolling temperature was 880°C, the yield strength, tensile strength, elongation and the yield ratio were 478MPa, 540 MPa, 16% and 0.89, respectively. When reduced to 840°C, the yield strength and tensile strength were increased to 500MPa and 554 MPa, and the elongation and yield ratio were increased to 31.0% and 0.90, respectively.

Based on the analysis above, it can be seen that the optimal mechanical properties were obtained when the finish rolling temperature and coiling temperature were 840 and 570°C, respectively.

| Process | Finish rolling temperature/°C | Coiling temperature/°C | Yield strength /MPa | Tensile strength /MPa | Elongation/ % | Yield ratio | 180°cold bending |
|---------|-------------------------------|------------------------|---------------------|-----------------------|---------------|-------------|-----------------|
| 1       | 880                           | 630                    | 478                 | 540                   | 30.5          | 0.89        | d=a, pass       |
| 2       | 840                           | 630                    | 500                 | 554                   | 31.0          | 0.90        | d=a, pass       |
| 3       | 840                           | 600                    | 543                 | 585                   | 32.0          | 0.93        | d=a, pass       |
| 4       | 840                           | 570                    | 537                 | 578                   | 33.5          | 0.93        | d=a, pass       |

3.2. Microstructure

Figure 2 shows the OM images of 550MPa Grade high-ductility automotive structural steel with different finish rolling temperatures and coiling temperatures. The microstructure was composed of ferrite and a small amount of pearlite distributed at the ferrite grain boundary.

When the coiling temperature was 630°C, the size of ferrite and pearlite decreased with the decrease of finish rolling temperature. When the finish rolling temperature was 880°C, the ferrite was polygonal ferrite, the grain boundary was smooth and straight, the grain size was 13.0 grade, the average size of ferrite grains was about 5.2μm, and the ferrite grains with the size less than or equal to 2.5μm accounted for about 9.8 percent, as shown in Figure 2a. When the finish rolling temperature reduced to 840°C, the uniformity was better than that at 880°C. The ferrite grain size was obviously decreased to 4.0μm and reached 14.0 grade, and the amount of the ferrite grains with the size less than or equal to 2.5μm increased to about 21.0 percent, as shown in Figure 2b.

When the finish rolling temperature was 840°C, the size of ferrite and pearlite grains decreased gradually with the decrease of the coiling temperature. When the coiling temperature was 600°C, the ferrite grains were further refined compared with 630°C, and the average size was about 3.3μm, the amount of ferrite grains with the size less than or equal to 2.5μm reached 42.1 percent, as shown in Figure 2c. When the coiling temperature decreased to 570°C, the average grain size of ferrite was further refined to 2.7μm. Especially, the number of the ferrite grains with the size less than or equal to 2.5μm reached 55 percent, as shown in Figure 2d.
Figure 2. OM images of 550MPa Grade high-ductility automotive structural steel with different finish rolling temperature and coiling temperature

3.3. Precipitates

The precipitates were shown in figure 3. The precipitates had the same morphological characteristics (cubic, spherical, ellipsoidal, and so on) at different finish temperatures and coiling temperatures.

When the finish rolling temperature and coiling temperature was 880°C and 630°C, respectively, the size of the precipitates was mainly distributed in the range of 50 ~ 240nm, and the mean value was about 85nm. These precipitates were identified by EDS as (Nb,Ti)C where Ti element accounted for a higher proportion, as shown in figure 3a and b. When the finish rolling temperature and coiling temperature was 840°C and 630°C, respectively, the amount of the precipitates increased slightly, and the size of the precipitate refined a little. Their size range was 30 ~ 240 nm, and the mean value was about 67 nm. The EDS analysis showed that it was also a composite precipitate of (Nb, Ti) C, and the Nb element was slightly more than that at 880°C, as shown in figure 3c and d. When the coiling temperature was constant (840°C), with the decrease of the coiling temperature, the size of the precipitates decreased gradually and the number of them increased first and then decreased. When the coiling temperature was 600°C, the size of the second phase precipitates was between 5~90nm, and the mean value was about 46nm, which was obviously larger that at 630°C. These precipitates were identified by EDS as (Nb, Ti) C, and the number of Nb element significantly increased, as shown in Figure 3e and f. When the coiling temperature was reduced to 570°C, the size of the precipitates was almost the same as that at 600°C, but the amount of the precipitates decreased. Their size range was 4 ~ 90nm, and the mean value was about 40nm. The EDS analysis showed the precipitate was also (Nb, Ti) C, as shown in figure 3g and h.
Figure 3. TEM images of the size and morphology of precipitates in 550MPa Grade high-ductility automotive structural steel with different finish rolling temperature and coiling temperature.

3.4. Dislocation
Figure 4 shows the STEM images of dislocation configuration in the 550MPa Grade high-ductility automotive structural steel. The distribution of dislocations was inhomogeneous in the ferrite grains,
where some grains and some parts of a grain had higher density of dislocations than the others, as shown in figure 5a~d. As observed in the OM images, the ferrite grain size decreased gradually as the decrease of the coiling temperature. The precipitates precipitated not only in the ferrite grains, but also at the ferrite grain boundaries and along the dislocation lines. That is (Nb, Ti) C precipitated by uniform nucleation, grain boundary nucleation and dislocation nucleation under different processes.

![STEM images of dislocation](image)

(a)880 °C, 630°C; (b)840°C, 630°C; (c)840°C, 600°C; (d)840°C, 570°C

**Figure 4.** STEM images of dislocation in 550MPa Grade high-ductility automotive structural steel with different finish rolling temperature and coiling temperature

4. **Results**

(1) The microstructure of the 550MPa Grade high-ductility automotive structural steel was composed of ferrite and a small amount of pearlite. With the decrease of finish rolling temperature and coiling temperature, ferrite grains refined gradually, and the size of precipitates reduced gradually and distributed more dispersedly.

(2) The yield strength, tensile strength and elongation increased with the decrease of the finish rolling temperature. The yield strength and tensile strength showed the regularity that increased first and then decreased. The elongation monotonically increased as the coiling temperature decreased.

(3) The optimal mechanical properties were obtained when the finish rolling temperature and coiling temperature was 840 and 570°C respectively, which the yield strength, tensile strength and elongation were 537MPa, 578MPa and 33.5% respectively.

(4) The grain refinement strengthening was the most important strengthening modes, which accounted for 49–51 percent of the yield strength.
5. References

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