Effect of cooling rates after annealing on the microstructure and properties of 1000 MPa grade automobile steel for cold forming

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Abstract

The effects of different cooling rates (0.05 °C s⁻¹, 0.1 °C s⁻¹, and 0.2 °C s⁻¹) on the microstructure and mechanical properties of 1000 MPa grade automobile steel for cold forming after two-phase annealing were studied. The microstructure of the experimental steel was observed by SEM and TEM, and its mechanical properties were tested by a universal tensile testing machine. The results showed that by increasing the cooling rate of two-phase annealing, more massive retained austenite, more uniform and fine ferrite, better elongation and higher ultimate tensile strength of steel can be obtained, so as to obtain better production of tensile strength and total elongation (product of tensile strength and elongation, PSE). The final result shows that after the test steel is quenched at 800 °C + 10 min and annealed in the two-phase region at 690 °C + 10 min, the faster the cooling rate, the better the mechanical properties. The mechanical properties of the steel plate are the best when the cooling rate reaches 0.2 °C s⁻¹, and PSE can reach 27.44 GPa-%.©

1. Introduction

In recent years, energy-saving and emission reduction are becoming the main development direction of the automobile industry. Weight reduction without sacrificing the safety of automobiles is one of the feasible and effective ways. Therefore, high strength and high forming performance is the new direction of researching automotive steel with residual austenite and ferrite microstructures, which can be obtained by ART (Austenite Reverted Transformation) annealing process with a chemical composition of medium-manganese steel [1–3]. Most scholars studied the effect of temperature and duration of annealing in the two-phase region on microstructure and properties in the ART process. Li et al [4] and Wang et al [5] studied the effects of annealing time and temperature on the microstructure and properties of medium-manganese steel hot-rolled sheets. Yan et al [6] studied the effect of annealing temperature in the two-phase region on microstructure and mechanical properties of cold-rolled medium-manganese steel. In addition, the effect of cooling rate on microstructure and properties was also studied. Zhao Lianrui [7] analyzed the microstructure evolution of medium manganese steel at different cooling rates through CCT simulation. Yang et al [8] studied the influence of the cooling method after hot rolling on microstructure evolution and mechanical properties of medium manganese TRIP steel. However, there are few studies on the effect of cooling rates on the microstructure and properties of cold-rolled medium manganese steel. As we know, the cooling rate is very important for the microstructures and properties of the steel. And normally, there are two kinds of annealing furnace for cold-rolled sheets in cold rolling factory such as bell-type furnace with very slow cooling rate and continuous annealing furnace with fast cooling rate, which will lead to different microstructures and properties of steel sheets. Therefore, this paper focuses on the effect of different cooling rates after annealing on the microstructures and properties of 1000 MPa grade
medium-manganese automobile steel for cold forming. It is beneficial to provide a theoretical basis for optimizing the production process of medium manganese automobile steel.

2. Experimental materials and methods

The chemical composition of the test steel is shown in table 1. The 50 kg ingot was first smelted in a vacuum induction furnace and then hot rolled into 4.5 mm thick steel plates. The plates were normalized at 950 and then cold rolled into a thickness of 1.5 mm. The cold-rolled sheets were recrystallization annealed at 570 °C for 10 min firstly, quenched at 800 °C for 10 min, then annealed in two-phase region at 690 °C for 10 min, and cooled to room temperature by three cooling rates which simulate bell-type annealing and continues annealing processes separately. The heat treatment process is shown in figure 1.

The cold-rolled sheets were divided into several tensile test samples with 10 mm width and 50 mm original gauge length, and the tensile strength and elongation of them were measured by a universal tensile testing machine. The metallographic specimen was corroded by 4% nitric acid alcohol. Microstructural studies were carried out using a combination of the scanning electron microscope (SEM) and transmission electron microscope (TEM).

3. Results and analysis

3.1. Static CCT curve

In order to understand the influence of different cooling rates on the microstructure and mechanical properties of the experimental steel, the CCT curve of the experimental steel was measured with a full-automatic transformation measuring apparatus. The specimens with $\varphi 3 \times 10$ mm were heated to 800 °C for 5 min at a rate of $10 \degree C \text{s}^{-1}$, and then cooled to room temperature at $0.03 \degree C \text{s}^{-1}$, $0.05 \degree C \text{s}^{-1}$, $0.2 \degree C \text{s}^{-1}$, 1 °C $\text{s}^{-1}$, and 2 °C $\text{s}^{-1}$ respectively, as shown in figure 2. The microstructures were observed as shown in figure 3. The Rockwell hardness of specimens at different cooling rates was also measured. In figure 3(a), it can be seen that when the cooling rate is $0.03 \degree C \text{s}^{-1}$, there is equiaxial ferrite with cementite surrounding its boundary. So the hardness of the specimen because of lots of ferrite existing is lower with only 33.3HRC. Meanwhile, the presence of the network cementite leads to the brittle boundary so that the elongation of the material is reduced, which shows that the lower cooling rate does not apply. When the cooling rate is $0.05 \degree C \text{s}^{-1}$, as shown in figure 3(b), the microstructures are equiaxed ferrite and pearlite, but the grain size is smaller than that of the $0.03 \degree C \text{s}^{-1}$ cooling rate. At this time, the hardness of the specimen is 39.9HRC. When the cooling rate gradually increases to $0.2 \degree C \text{s}^{-1}$, 1 °C $\text{s}^{-1}$, and 2 °C $\text{s}^{-1}$, as shown in figures 3(c)–(e), the microstructures of them are all martensitic, and with the increase of cooling rate, the martensite becomes finer and finer and presents needle-like structure. At this time, the hardness of them is 46.3HRC, 48.8HRC, and 49.3HRC respectively as shown in figure 4. Although the microstructure of all samples are martensitic, the hardness of sample with $2\degree C \text{s}^{-1}$ cooling rate is

![Figure 1. Heat treatment process of test steel.](image)

| Table 1. Chemical composition of test steel (%) |  |
|---|---|---|---|---|---|---|---|---|---|
| Element | C | Si | Mn | Al | S | P | Nb | V | Ni |
| Content | 0.13 | 0.03 | 5.38 | 0.045 | 0.0069 | 0.0076 | 0.032 | 0.017 | 0.24 |
higher than that of specimens with 0.2 °C s⁻¹ and 1 °C s⁻¹ cooling rate, which is due to the higher cooling rate leads to the finer lath of martensite. When the cooling rate is 1 °C s⁻¹ and 2 °C s⁻¹, microstructures are nearly all acicular fine martensite, which promotes the transformation of martensite to austenite during ART. It provides kinetic energy to obtain more austenite for subsequent annealing in two-phase region.

3.2. Microstructural evolution

As we know, recrystallization annealing can homogenize the structure and improve the ductility of the steel sheets [9–11]. The SEM images of the cold-rolled sheet before and after recrystallization annealing are shown in figure 5. Figure 5(a) shows the typical cold deformed grains before annealing, and the grains in figure 5(b) are recovered and recrystallized after annealing. It can be seen that the grains after recrystallization annealing are smaller and evenly distributed. According to the heredity of microstructure, the final grains of the cold-rolled sheets annealed in a two-phase region should be finer and more uniform than those without recrystallization. Therefore the tensile strength of them will be higher because of Hall-Petch theory.

All specimens were subjected to recrystallization annealed at 570 °C, quenched at 800 °C, and then annealed at 690 °C in the two-phase region. Figure 6 shows the microstructures obtained by three different cooling rates after annealing in the two-phase region. The Microstructure after annealing is mainly a dual-phase of ferrite and retained austenite, in which the black part is ferrite, and the bright white part is retained austenite. The distinctions in the microstructure with different cooling rates are the morphology of retained austenite. In figure 6(a), the austenite grains are arranged in fine lath bundles, while in figures 6(b) and (c), the microstructure has no obvious regularity, the width of retained austenite lath is large, and block structure appears at the same time [12–16]. As we know, the quantity of C and Mn elements are the main factors influencing the stability of retained austenite, thus, the block-like retained austenite with less C and Mn has poor stability, which is beneficial to the occurrence of the TRIP effect during deformation. Furthermore, the conversion rate of residual austenite is increased, which improves the mechanical properties of the steel sheet.

Figure 7 shows the TEM images of the final microstructure after cooling at 0.2 °C s⁻¹. From which, it can be seen that the structure has not only lath-like residual austenite of 0.4 μm length and 0.1 μm width (in figure 7(a)), but also blocky residual austenite of about 1 μm (in figure 7(b)). The difference in its shape is related to the position of its nucleation and growth. The austenite nucleated along the martensitic lath boundary will grow along with the martensitic lath, so it will form austenite similar to martensitic lath, which is called lath-like austenite. However, the austenite nucleated at the grain boundary of the original austenite can grow freely, and the formed austenite structure is similar to the equiaxed blocky austenite [17]. Lath austenite is more stable than blocky austenite. This is because the lath austenite formed between the martensitic laths has high carbon content, which is more stable than blocky austenite and not easy to produce the TRIP effect. In addition, during the quenching process, with the formation of martensitic, volume expansion occurs, and the shear strength of austenite between martensitic laths increases, which makes it difficult to transform into martensite again [18].

In the deformation process, blocky retained austenite is very unstable, and it is prone to martensitic transformation, delay necking, and improve the tensile strength, elongation, and formability of the test steel. Therefore, the mechanical properties of the steel plate after quenching at 800 °C, two-phase annealing at 690 °C, and cooling to room temperature at 0.2 °C s⁻¹ is the best.
Figure 3. SEM images of the experimental steel at different cooling rates. (a) 0.03 °C s\(^{-1}\) (b) 0.05 °C s\(^{-1}\) (c) 0.2 °C s\(^{-1}\) (d) 1 °C s\(^{-1}\) (e) 2 °C s\(^{-1}\).

Figure 4. Hardness of the test steel under different cooling rates.
3.3. Mechanical properties

Table 2 shows the mechanical properties of the test steel at three different cooling rates after 690 °C annealing for 10 min. The TRIP effect of reverse transformation austenite at different cooling rates has a significant impact on the elongation of the test steel. The tensile strength (1270 MPa) of the test steel at a cooling rate of 0.05 °C s⁻¹ is higher than the cooling rate of 0.1 °C s⁻¹ and 0.2 °C s⁻¹, but its total elongation (14.61%) is significantly lower.

Figure 5. SEM images of cold-rolled sheet before and after recrystallization annealing. (a) Before (b) after.

Figure 6. SEM images of the test steel with different cooling rates after annealing in the two-phase region. (a) 0.05 °C s⁻¹ (b) 0.1 °C s⁻¹ (c) 0.2 °C s⁻¹.

Figure 7. Appearance and diffraction spot of different retained austenite. (a) Fine laths (b) block.
than the other two cooling rates. Under the condition of the cooling rate of 0.2 °Cs⁻¹, the tensile strength can reach 1120 MPa and the elongation rate is 24.5%, so PSE obtains the excellent performance of 27.44 GPa·%, Which is because the microstructure of test steel contains unstable austenite at a faster cooling rate, and the TRIP effect occurs during the deformation process.

4. Conclusion

(1) Due to the heredity of microstructure, the grains of the cold-rolled sheets after recrystallization annealing are finer and more uniform after the ART process.

(2) Static CCT curve shows that faster cooling rate is beneficial to get finer acicular martensite, which promotes the transformation of martensite to austenite during ART. It provides kinetic energy to obtain more austenite in two-phase region annealing.

(3) When the cooling rate is slow, the retained austenite is mostly small and stable of lath-shaped, which leads to a poor TRIP effect so that the PSE of test steel is reduced. When the cooling rate is faster, there is more unstable massive retained austenite in the microstructures of the test steel, which is prone to occur the TRIP effect during deformation process, thereby improving the PSE of steel. When the cooling rate is 0.2 °Cs⁻¹, the highest PSE with of 27.44 GPa·% is obtained.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Table 2. Mechanical properties of steel with different cooling rates after two-phase region annealing.

| Cooling rates, °Cs⁻¹ | Tensile strength, MPa | Elongation, A50% | PSE, GPa·% |
|---------------------|-----------------------|------------------|------------|
| 0.05                | 1270                  | 14.61            | 18.54      |
| 0.1                 | 1140                  | 18.15            | 20.69      |
| 0.2                 | 1120                  | 24.50            | 27.44      |

Table 2. Mechanical properties of steel with different cooling rates after two-phase region annealing.
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