Effects of electromagnetic induction hardening on the microstructure and mechanical properties of B1500HS steel

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Abstract. The effects of electromagnetic induction hardening process on the microstructure, original austenite grain sizes and mechanical properties of B1500HS steel are investigated in this paper. The results indicate that the electromagnetic induction hardening samples can obtain completely martensite with fine lath bundle size, and high tensile strength, which is up to 1626 MPa, and the original austenite grain size is fine and uniform when the heating temperature reaches 900 °C. Compared with that of the resistance furnace heating quenching process, the samples treated by rapid heating process can obtain finer lath martensite structure and better mechanical properties after quenching.

1. Introduction

As the current environment is becoming increasingly serious, more and more attention is paid to the automobile lightweight. High strength steel is one alternative and has been widely used to reduce the weight of automobile body instead of traditional steel. The use of high strength steel can not only reduce the fuel consumption but also improve the safety in automobiles [1]. B1500HS as one of high strength steel in automobile lightweight has been widely used in the manufacture of the automobile anti-collision beam, A-pillar, B-pillar and other parts [2]. Hot stamping technology is one of the important method to reduce the automobile weight and increase the impact resistance and crash performance. A series of research works on the hot stamping process using quenchable boron steel plate have been carried out. Lu et al. [3] studied the effects of deformation conditions on the volume fraction of martensite and ferrite in the boron steel. Bariani et al. [4] analyzed the formability of B1500HS in hot stamping process. Naderi et al. [5] studied the optimal austenitizing heat treatment parameters of different 22MnB5 samples. Mekrlein et al. [6] studied the relationship between hot flow and rolling direction of high strength boron steel, and the relationship between temperature and strain rate. Li et al. [7] obtained the constitutive equation of B1500HS boron steel by high temperature tensile experiments.

To date, B1500HS high strength steel is mainly heated by resistance furnace in hot stamping process [8-10]. However, the heating equipment occupies a large area with low production efficiency and high investment cost. In order to solve this problem, the electromagnetic induction heating device
is developed as an alternative to replace the traditional resistance furnace. Thus, in this paper the effects of austenitization temperature on the quenched microstructures, grain sizes and mechanical properties of B1500HS is studied by electromagnetic induction heating method, and the results are compared with those by the resistance furnace, and the results can provide a reference for the improvement of the heating process of B1500HS steels in hot stamping process.

2. Experimental methods

2.1. Experimental materials

The experimental material is 1.2mm B1500HS boron steel plate produced by Baosteel Group Shanghai. Its chemical composition is shown in Table 1. Figure 1 showed the original microstructure of B1500HS, which is composed of pearlite and ferrite. The tensile strength of the original B1500HS is 541 MPa.

Table 1. Chemical composition of B1500HS (mass fraction, %).

| Steel   | C  | Si | Mn | S  | P  | Cr | Ti | V  | Mo | B  | Fe  |
|---------|----|----|----|----|----|----|----|----|----|----|-----|
| B1500HS | 0.23 | 0.25 | 1.35 | 0.006 | 0.015 | 0.19 | 0.03 | 0.004 | 0.04 | 0.003 | balance |

Figure 1. Original microstructure of B1500HS.

2.2. Experimental procedures

In order to study the difference of martensite structure after induction heating and quenching, SP-25 high frequency electromagnetic induction heating equipment and SX2-4-10T conventional resistance furnace are used in the experiment, respectively. During the experiment, the range of heating temperature is from 750 °C to 930 °C with the interval of 30 °C, and finally quenched to the room temperature with cold water. The heating rate of electromagnetic induction heating is about 30 °C/s, and that of resistance furnace is about 30 °C/min. The microstructure and the original austenite grain boundary are etched by using 4% nitric acid alcohol solution and supersaturated picric acid solution, respectively. The microstructure is observed by Leica DM2500M metallographic microscope. The austenite grain size along the rolling direction is measured by the software of Image Pro Plus 5.0. The wire cutting is used to cut the tensile samples along the rolling direction and the shape is shown in Figure 2. The tensile strength of three samples is tested on WDW-300 testing machine, and the average value is taken as the test result of final tensile strength. Finally, the changes of microstructures and properties of B1500HS after quenching by electromagnetic induction heating are analyzed.

3. Experimental results and discussion

3.1. Microstructures characterization

Figure 3 and Figure 4 are the microstructures of the samples after quenching at different temperature by electromagnetic induction heating and resistance furnace heating, respectively.
Figure 3. Microstructure of samples after quenching by the electromagnetic induction heating at 750°C (a), 780°C (b), 810°C (c), 840°C (d), 870°C (e), 900°C (f), 930°C (g).

Figure 4. Microstructure of samples after quenching by the resistance furnace heating at 750°C (a), 780°C (b), 810°C (c), 840°C (d), 870°C (e), 900°C (f), 930°C (g).

Under the quenching temperature of 750°C, the microstructure after electromagnetic induction heating and resistance furnace heating are ferrite and pearlite. Neither has austenite transformation and the martensitic phases can not be observed in the microstructure after quenching as shown in Figure 3 (a) and Figure 4 (a). When the heating temperature is 780°C, there are no martensitic structures in the sample after the electromagnetic induction heating and quenching as shown in Figure 3 (b), but the heating temperature of resistance furnace has reached the temperature of $A_{C1}$, so the martensitic structure begins to appear in the sample after quenching as shown in Figure 4 (b). When the heating temperature is 810°C, as shown in Figure 3 (c) and Figure 4 (c), the temperature of electromagnetic induction heating starts to reach the temperature of $A_{C1}$, so the martensite begins to appear after quenching. The temperature heating up slowly by the resistance furnace made the austenitizing process get a certain evolution time, so a large number of martensite structures are obtained after quenching. With the further increase of the heating temperature, as shown in Figure 3 (d) and Figure 4 (d), B1500HS steel reaches the austenitic transformation temperature at the heating temperature of 840°C. The microstructure of the sample under electromagnetic induction heating consists of fine martensite. While under the resistance furnace condition, the temperature reaches the complete austenitizing temperature and the microstructure consists of complete martensite. When the heating temperature reaches 870°C, as shown in Figure 3 (e) and Figure 4 (e), the electromagnetic induction
heating temperature reaches complete austenitizing temperature and most of structure is martensite after the quenching. The martensite with uniform beam size is obtained after quenching in the resistance furnace condition. When the heating temperature reaches 900 °C, as shown in Figure 3 (f) and Figure 4 (f), the microstructures of the sample heated by the electromagnetic induction heating are complete martensite, and the size of the martensitic lath bundles is even and small. The structure of the samples under the resistance furnace heating after quenching are also complete martensite, but the size of the martensitic structure is larger and the martensitic lath bundles appear to be widened and sharpened. When the heating temperature is further increased to 930 °C, the microstructure of the samples under the two heating conditions are shown in Figure 3 (g) and Figure 4 (g), respectively. Martensitic lath bundles significantly increase in both of the microstructures, however, the microstructures are obviously coarsening by the resistance furnace heating after quenching.

![Figure 5. SEM of optimal martensite obtained by induction heating at 900°C (a) and resistance furnace heating at 870°C (b).](image)

Figure 5 shows the SEM of the sample heated by electromagnetic induction heating quenched at 900 °C. It can be seen that the microstructures consist of fine lath martensite, and the sample heated by the resistance furnace heating has fine lath martensite at 870 °C quenching temperature. Under the electromagnetic induction heating, namely rapid heating mode, the austenite grains can not have enough time to grow up, so the martensite formed after quenching is much smaller than that obtained under the slow heating mode as the resistance furnace heating.

3.2. Austenite grain size

According to the austenite grain size formula as show in formula (1):

$$ \bar{L} = \frac{L}{M \cdot P} = \frac{1}{\bar{p}} $$  (1)

Where, $L$ is the length of straight line segment with the unit mm, $\bar{L}$ is the average value of (1X) grain intercept on test surface of sample, $M$ is the magnification for observation, $P$ is the number of section points in the line, $\bar{p}$ is the average number of cross-sections per millimeter on the sample surface.

Average grain size grade $G$ is shown in formula (2):

$$ G = 6.643856 \lg(\frac{M \cdot P}{L}) - 3.288 $$  (2)

3.2.1. Electromagnetic induction heating. Figure 6 is the picture of the original austenite grains observed by metallographic microscope after quenched at different temperature under electromagnetic induction heating. It can be seen from the above analysis that the $A_{C3}$ temperature is 860 °C under
rapid heating mode, so when it is heated at 750 °C and 780 °C, there is no austenite transformation in the sample, and the microstructures are pearlite and ferrite. When the heating temperature reaches 810 °C, a small amount of austenite grains can be observed in the microstructure of the quenched sample. This is because the heating rate is fast, the holding time can be effectively shortened, thus the sample is not fully austenitized, and its structure is composed of austenite and ferrite. When the heating temperature increases to 840 °C, the amount of austenite in the microstructures increases obviously, and the austenite grain size is about 7.34 μm. When the heating temperature reaches 870 °C, the austenite grain growth trend is not obvious, and the average grain size is about 8.84 μm. When the heating temperature reaches 900 °C, the temperature exceeded the austenitizing temperature and recrystallization occurs. At this time, the austenite grain grows obviously, and the average grain size is about 12.34 μm. When the heating temperature further increased to 930 °C, the austenite grain size grows rapidly, and the grain size is about 26.39 μm.

Figure 6. Austenite grain of samples by induction heating at 750°C (a), 780°C (b), 810°C (c), 840°C (d), 870°C (e), 900°C (f), 930°C (g).

Figure 7. Austenite grain of samples heated by resistance furnace at 750°C (a), 780°C (b), 810°C (c), 840°C (d), 870°C (e), 900°C (f), 930°C (g).

3.2.2. Resistance furnace heating. Figure 7 shows the microstructures of the samples heated by the resistance furnace heating at different temperatures. Table 2 shows the average austenite grain size.
When the heating temperature is lower than 900 °C, the samples heated by electromagnetic induction heating with rapid heating rate and resistance furnace all have austenitization and the austenite growth trend is relatively slow. In fact, the formation mechanism of this phenomenon from the two heating methods is quite different. The $A_{c3}$ temperature is around 860 °C due to the fast heating rate in the electromagnetic induction heating mode, so the increase of austenitization is not obvious at 900 °C. When the temperature is below 900 °C in the resistance furnace heating, namely the slow heating rate mode, the nucleation rate and growth rate of austenite are still low, although the actual formation temperature of austenite is low. Therefore, the microstructures of the samples heated by the resistance furnace heating under 900 °C is not different from that of samples heated by the electromagnetic induction heating.

When the heating temperature reaches 900 °C, the faster heating rate leads to the higher nucleation rate. At the same time, the heating time is shortened, so the fine and uniform austenite grains are obtained. However, the austenite grains in the samples heated by slow heating rate and high temperature are much coarse after quenching. When the heating temperature reaches 930 °C, the effects of heating rate on the austenite grain growth are small. Because the critical nucleation radius of austenite decreases at high temperature, the concentration fluctuation required for the formation is smaller and the atomic diffusion rate is faster, so the growth of the austenite grains is obvious [11].

### Table 2. Average size of austenite grain.

| Temperature / °C | Induction heating | Resistance furnace heating |
|------------------|------------------|--------------------------|
| 750              | 2.68             | 2.68                     |
| 780              | 2.84             | 3.04                     |
| 810              | 5.29             | 6.25                     |
| 840              | 7.34             | 7.77                     |
| 870              | 8.84             | 12.34                    |
| 900              | 10.50            | 19.84                    |
| 930              | 26.39            | 44.12                    |

#### 3.3 Tensile properties

Figure 8 shows the tensile strength of the samples heated by electromagnetic induction heating and resistance furnace at different temperatures after quenching respectively.

![Figure 8](image.png)

It can be seen that the tensile strength of B1500HS steel after quenching is closely related to the degree of austenitizing. With the increase of austenite phases, the tensile strength also increases. If the temperature is further increased after reaching the maximum value, it will lead to the decrease of tensile strength and tend to be stable. The influence of heat treatment parameters on tensile strength is great. The peak value of tensile strength under the electromagnetic induction heating is 1626 MPa, which is significantly higher than that under the resistance furnace heating. The $A_{c3}$ temperature increases under the electromagnetic induction heating, so the peak temperature is higher, but the austenite grains are fine and uniform, and the martensite lath bundles are fine after quenching, thus the
tensile strength is significantly improved. When the heating temperature is over 900 °C, the austenite grains are coarsened and the tensile strength decreases obviously after the quenching.

4. Conclusion

(1) The rapid heating rate for B1500HS steel causes the increase of austenite formation temperature. The best fine and uniform austenite grains are formed at 900 °C, and the martensitic lath after quenching have no obvious growth at the same time. The average grain size of austenite obtain by electromagnetic inducing heat with rapid heating rate is 10.50 μm, which is more uniform and smaller than that obtain by resistance furnace heating.

(2) The electromagnetic induction heating with rapid heating rate can make the size of martensitic lath smaller, which has better mechanical properties. The tensile strength can reach 1626 MPa, and the tensile properties of the samples are improved obviously.

(3) When the B1500HS steel is heated by the electromagnetic induction heating to 900 °C, the microstructure after quenching is complete martensite and the best tensile properties are obtained.

Funding

This research is funded by the National Natural Science Foundation of China (Grant No. 51374069), the Doctoral Business and Innovation Launching Plan of Yingkou City (Grant No. QB-2019-02)

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