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Effect of Rapid Resistance Heating on Mechanical Properties and Microstructure of Ultrahigh-Strength Boron Steel

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Abstract

Resistance heating (RH) has broad prospects in hot stamping due to its rapid heating rate and high energy efficiency. In this work, the ultra-high strength boron steel was heated by a high current and then water quenched. The effects of heating temperature and current density on mechanical properties and microstructure were explored, and the hydrogen embrittlement issue was also investigated. The results indicated that resistance heating method can significantly shorten the heating time, and even the soaking stage can be ignored when overheating is adopted; thus, the whole heating period can be reduced from 5 min to 15 s. Besides, the oxide scale is inapparent on the uncoated sheet with rapid heating, which improves the surface quality evidently. Furthermore, the mechanical properties of the boron steel after resistance heating are better than those after furnace heating (FH), including both strength and elongation. The microscopic characterization confirms that the grain size of the resistance heating sample is obviously finer than that of the furnace heating, and the final structure includes a certain amount of retained austenite. These characteristics ensure that the boron steel has excellent properties after resistance heating and quenching. Meanwhile, the rapid heating leads to non-homogeneous chemical composition and higher dislocation density. Thus, a slightly higher hydrogen embrittlement sensitivity can be observed, which can be alleviated by baking treatment.

Keywords: Hot stamping steel, Rapid resistance heating, Grain refinement, mechanical properties, hydrogen embrittlement

1 Introduction

Hot-stamped ultra-high strength steels have been widely applied in automotive industry, utilizing the hot stamping technique to simultaneously achieve ultra-high-strength and complex component geometry. Specifically, the steel is heated to austenization temperature (~920 ℃) and soaked for nearly 5 min, then quickly transferred to the cooling mold to finish forming and quenching [1]. The entire process takes about 6 min, with over 80% of the time spent on heating. Moreover, the slow heating rate (~10 ℃/s) and low energy utilization rate (below 60% [2]) of traditional furnace heating (FH) promote an urgent need for a rapid heating method to improve efficiency and shorten the hot stamping process.

Resistance heating (RH) technology involves connecting two or more electrodes to either side of a blank through which the current passes, utilizing Joule's law to achieve heating [3]. The heating rate of RH can reach as high as 400 ℃/s and achieve a high energy utilization rate (87%), which is suitable for metal forming processes [1]. For instance, Mori et al. [4] utilized a rapid resistance heating method to heating a sheet to 800 ℃ within 2 s. The heated sheet shows improved spring back, formability and hardness, indicating that RH is fully applicable to real forming operations. Notably, the heating parameters, including heating temperature and heating rate, certainly have a significant impact on the microstructure and mechanical properties of materials. Pedraza et al. [5] illustrated that a considerably higher austenite transformation temperature (Ac3) is required for rapid heating of boron steel. Theoretically, as the austenitizing temperature rises, the size of lath martensite gradually increases [6], while the grains size after rapid heating is considerably finer than that of conventional heating [7, 8] which provides a potential to improving the mechanical properties of the samples. However, the suitable heating parameters of RH for ultra-high strength steel and the comprehensive comparison and analysis of FH and RH have not been disclosed.

In this work, the RH method without soaking was introduced in the hot stamping process for ultra-high-strength boron steel. The effects of austenitizing temperature and current density on mechanical properties and microstructure were discussed, subsequently, suitable process parameters were confirmed. Then, the confirmed RH sample was selected to compare with FH sample, including mechanical properties and microstructure. Finally, the risk of hydrogen embrittlement of RH sample was evaluated which provides a basis for the application of RH in practical hot stamping production.

2 Experiments

The uncoated boron steel B1500HS provided by BaoSteel Co., Ltd was used. Then, a high-frequency pulse power supply was adopted to heat samples which is in form of rectangular and with dimension of 150 × 20 × 1.4 mm3. The narrow sides were selected as the connecting end to achieve various austenitizing/final temperatures at a current density of 30(±1) A/mm2, followed by water quenching. Likewise, a target temperature (1100(±10) °C) was heated at the current densities of 12.32 A/mm2, 14.29 A/mm2, 19.46 A/mm2 and 29.11 A/mm2 in 120 s, 60 s, 30 s and 15 s, respectively. Notably, the temperature changes of the sample were recorded in real-time by the thermal imager FLIR A615 during the heating process. The length of the uniform heat area is approximately 100 mm; thus, the tensile test samples were selected from this area to ensure the reliable and repeatable results. The counterpart FH was carried out at 920 ℃ for 5 min, followed by water quenching. More details about mechanical testing and microstructure characterization can be acquired in our previous work [9, 10].

3 Results and Discussion

The mechanical properties of samples with different austenitizing temperature are illustrated in Figure 1f. Obviously, when the austenitizing temperature over 1041 ℃, the samples show a good combination of tensile strength and elongation, i.e., tensile strengths are higher than 1650 MPa and elongations are in range of 7.89%~9.5%. Additionally, the hardness of the sample gradually increases with temperature. When the austenitizing temperature is between 1100 ℃ and 1200 ℃, the hardness of the sample is basically equal to even slightly higher than that of FH (526 HV). The corresponding microstructure of the samples is revealed in Figures 1a-e. The relative lower austenitizing temperature resulted in incomplete austenitization, i.e., the banded ferrite is retained along the rolling direction and subsequently leads to a relatively lower tensile strength and Vickers hardness. Sun et al. [11] indicated that the increment of overheating was parabolic with increasing heating rate. Thus, a higher austenitizing temperature is required for RH samples. When the austenitizing temperature ranges from 1100 ℃ to 1200 ℃ (Figures 1c-e), samples exhibits a fully martensitic microstructure, and the hardness is close to that of FH (Figures 1f). Notably, as the temperature increases to 1202 ℃, a slight decrease in hardness and tensile strength can be observed, which is the result of high temperature-induced decarbutization and grain coarsening. Therefore, higher temperatures should be avoided, and the range of 1100 to 1200 ℃ should be considered appropriate for resistance heating.

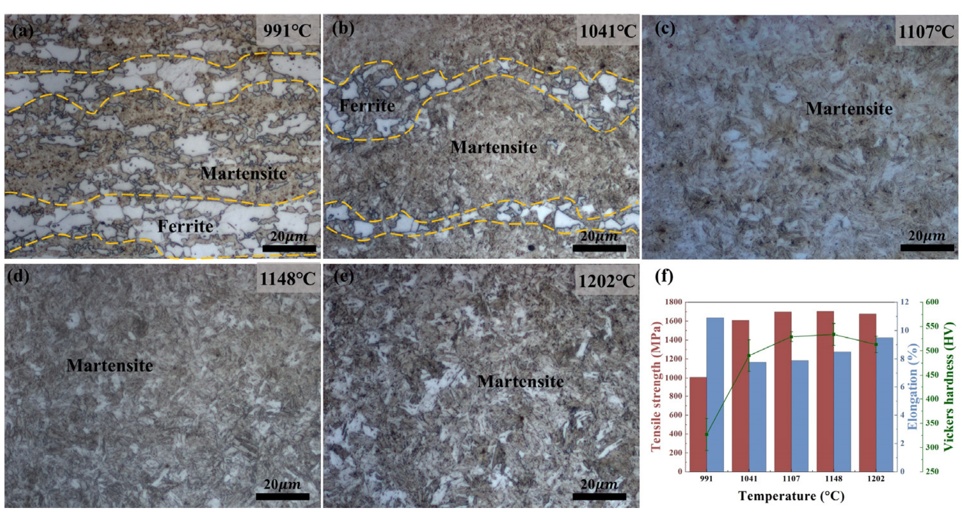

Figure 1: *Optical microscopic pictures and mechanical properties of samples with different austenitizing temperature*

Then, the effect of current density on mechanical properties and microstructure was thorough investigated. Outstanding performances are obtained at the four current densities cases, with tensile strengths higher than 1600 MPa and elongation ranging from 7.91%±0.46% to 10.03%±0.76%, as shown in Figure. 2. The tensile strength of sample increases gradually with the increase of current density. Especially, when the high current density of 29.11 A/mm2 is adopted, the strength of the samples reaches roughly 1700 MPa with an acceptable elongation of 9.01%±0.83%, and the heating process only takes 15 s. Interestingly, with the increase of current density, the average prior austenite grain (PAG) size is slightly decreasing (Figure 2b). The refinement of the PAG contributes to a finer and denser martensitic structure, which leads to the improvement of tensile strength, as shown in Figure 2a.

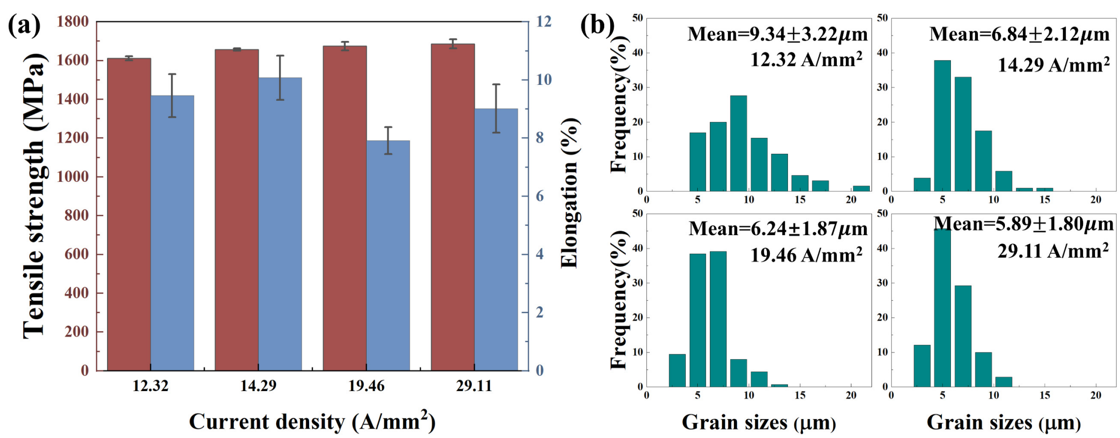

Figure 2: *Mechanical properties and microstructure of samples with different current density.*

Thus, a relatively high current density (29.11 A/mm2) and shortened heating time (15 s) are selected for comparison to their counterparts, i.e., the FH samples. The tensile test reveals (Figure 3a) a slightly increased tensile strength and elongation for RH sample than FH one. SEM characterization reveals the finer PAG (whited dotted line) sizes in RH samples, as shown in Figure 3c. Moreover, in RH samples, the finer lath structure prevails, while in FH samples, the detection of the coarse block structure is more frequent. Notably, laths are the smallest martensite units and are defined by low angle grain boundaries which are essentially dislocation walls [12]. Thus, this structure usually contains a high density of dislocations which facilitates the higher tensile strength. EBSD analysis is provided to reveal the relationship between mechanical properties and microstructure. Figures 3e and 3f give the semi-transparency band contrast (BC) figure and phase maps for FH and RH samples. The phase maps reveal the full martensite transformation has been achieved in FH samples, while a portion of retained austenite have been detected in RH samples. The histograms of prior austenite grain (PAG) size distribution also reveal the finer average grain size in RH samples (Figure 3d). When the grain size is comparatively small, the plastic deformation caused by external force can be dispersed in more grains, and the plastic deformation is relatively uniform, which is conducive to the improvement of elongation. In addition, the finer the grains, the more tortuous the grain boundaries are, which makes it difficult for cracks in the sample to propagate, thereby contributing to the improvement of tensile strength.

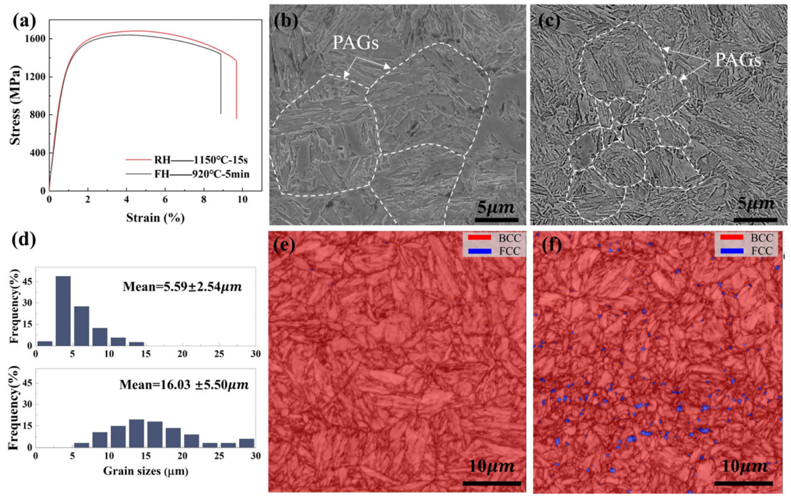

Figure 3: *Microstructure and mechanical properties of FH and RH samples.*

Apparently, RH can certainly contribute to the performance improvement of ultra-high strength steel parts when applied in the hot stamping process, and effectively shorten the production cycle time. However, there is still a serious issue to be concerned about, i.e., hydrogen embrittlement. It is commonly accepted that hydrogen embrittlement sensitivity increases with strength. Thus, we adopted the slow strain rate test to evaluate the pre-hydrogen-charged RH samples. After hydrogen charging, the mechanical properties of RH samples show a significant deterioration (Figure 4a). Even after 10 min hydrogen charging, the fracture surface shows a mixture of quasi-cleavage (QC) and intergranular (IG) features. With the increasing of hydrogen charging time, the fracture surface is dominated by intergranular features (Figure 4c). Meanwhile, the baking treatment (180℃-20min, RH+Baking) can effectively improve the resistance of hydrogen embrittlement (Figure 4d). Especially for sample with 10 min hydrogen charging, the mechanical properties show a slightly decrease compare that of non-hydrogen charged samples. Moreover, fractographic observations indicated the improved hydrogen embrittlement resistance, i.e., dimples and quasi-cleavage modes is prevailing (Figure 4c-f).

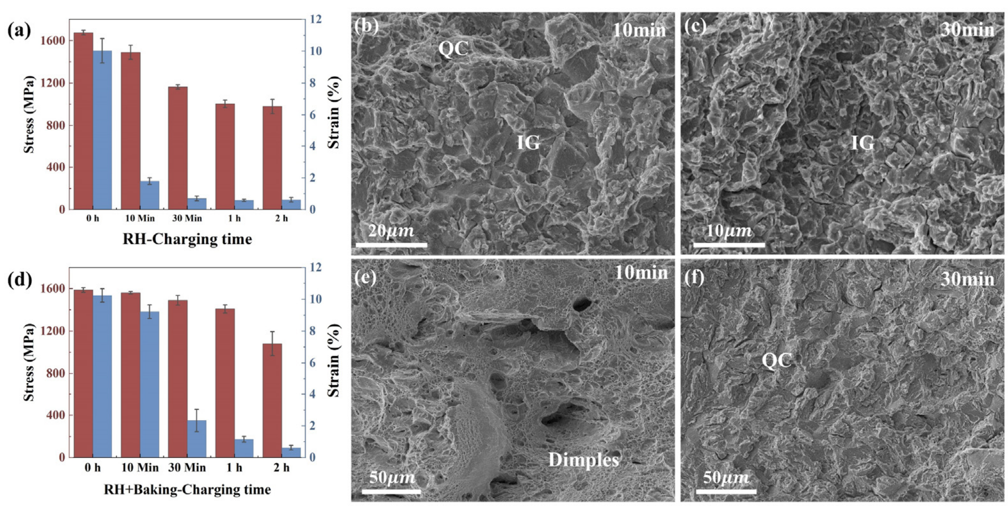

Figure 4: *Mechanical properties and fracture surface of RH and RH+Baking samples.*

4 Conclusions

1) The RH method can significantly shorten the heating time, i.e., the whole heating period can be reduced from 5 min to 15s.
2) The RH boron steel presents a higher tensile strength and an acceptable elongation than those FH. The microscopic characterization confirms that the PAG size of the RH sample is obviously finer than that of the FH, and the final structure includes a little portion of retained austenite.
3) The RH boron steel exhibits high hydrogen embrittlement sensitivity, with the fracture surface characterized by QC and IG. Baking treatment can slightly improve the resistance of hydrogen embrittlement and result in a mixture fracture mode featuring dimples and QC.

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