The Influence of Heating Rate on Phase Transformation of ZnFe Coating in Hot Stamping

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Abstract. In this study, the ZnFe coated boron steel specimens were treated by rapid heating at different heating rates from 20 °C/s to 100 °C/s. The coating morphologies and phase compositions were characterized to investigate the influence of heating rate on phase transformation of ZnFe coating. The results indicated that there was no continuous α-Fe(Zn) layer formed at coating/substrate interface during the heating-up stage when the heating rate was higher than 50 °C/s. As a result, the phase transformation of the coating was facilitated. At the heating rate of 100 °C/s, a one-layer coating structure composed of α-Fe(Zn) phase was formed within 100 s, which is significantly shortened compared to the traditional furnace heating method.

Keywords: Hot stamping · ZnFe coating · Rapid heating · Phase transformation

1 Introduction

The demand for hot stamping boron steel parts with ultra-high strength of 1500–2000 MPa is dramatically increasing in automobile industry in recent years, due to the advantages including weight reduction and improved anticollision performance [1]. To protect the boron steel from oxidation, surface coatings are adopted in hot stamping [2]. Al-Si coating and zinc coating are two representative coating systems, among which the Al-Si coating has been widely used in hot stamping industry [3]. As for the zinc coating, it could provide additional cathodic protection for the substrate and decrease the risk of hydrogen embrittlement of the substrate [4].

However, the liquid metal induced embrittlement (LMIE) of zinc coated boron steel is a critical issue which limits its application in hot stamping [5, 6]. One of the effective solutions to suppress LMIE is to promote the formation of α-Fe(Zn) phase in coating during heating [5]. Nevertheless, the interdiffusion between the coating and substrate in furnace is slow due to low heating rate [6]. It is necessary to adopt efficient heating methods to facilitate the alloying of zinc coating.

Y. Zhang and M. Ma (Eds.): ICHSU 2022, AHMST 2, pp. 224–229, 2023.
https://doi.org/10.2991/978-94-6463-114-2_30

In this study, the ZnFe coated boron steel was treated by rapid resistance heating. The influence of heating rates on coating phase transformation was analyzed. Besides, the difference of coating alloying between furnace and rapid heating was discussed.

2 Materials and Experiments

2.1 Materials

The material used is ZnFe coated 22MnB5 boron steel sheet. The ZnFe coating in as-delivered condition has an average Zn concentration of 90 wt.%, and its cross-sectional morphology is shown in Fig. 1. The coating is dominated by δ phase.

2.2 Experimental Schemes

The rapid heating treatment of ZnFe coated steel was conducted by Gleeble thermo-mechanical simulator. The specimens were divided into three groups and the corresponding heat treatment conditions are shown in Table 1. For the two groups with the heating rate of 20 °C/s and 50 °C/s, the adopted holding times were 0, 30 s and 60 s. As for the specimens with the heating rate of 100 °C/s, two additional holding times, i.e., 90 s and 120 s were used. After heat treatment, a scanning electron microscopy (ESEM, FEI/QUANYA 200) was used to observe the coating microstructures. Based on the SEM images, the average coating thickness was measured.

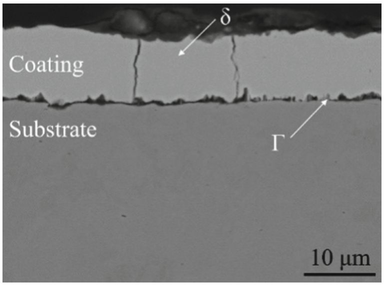

Fig. 1. The cross-sectional SEM morphology of ZnFe coating in as-delivered condition.

Table 1. Heat treatment conditions of the ZnFe coated specimens.

Group	Heating rate (°C/s)	Temperature (°C)	Holding time (s)
1	20	885	0, 30, 60
2	50		0, 30, 60
3	100		0, 30, 60, 90, 120

3 Results and Discussion

Figure 2 shows the coating morphologies of the specimens in Group 1 and Group 2. At the heating rate of 20 °C/s, the microstructures of ZnFe coating without holding changed significantly compared with the initial condition, as shown in Fig. 2a. The phase structure of the coating consisted of the bottom α-Fe(Zn) layer, the middile Γ layer, and the upper δ layer with the highest proportion. At 30 s (Fig. 2b), the continuous morphology of upper δ phase disappeared, and the α-Fe(Zn) phase was dominated in the coating. On the one hand, the bottom continuous α-Fe(Zn) layer thickened significantly. On the other hand, the upper α-Fe(Zn) phase showed a granular morphology, and the dispersive α-Fe(Zn) grains were surrounded by Γ phase. As the holding time increased to 60 s, the δ phase disappeared. As a result, the coating showed a two-layer structure with a thin Γ layer above the continuous α-Fe(Zn) layer (Fig. 2c).

At the heating rate of 50 °C/s, the coating microstructure without holding was much different with Group 1. The coating was mainly composed of δ phase interface (Fig. 2d), which was similar with the initial condition. In addition, a small amount of island-like Γ phase was dispersed in the δ layer. The coating did not demonstrate a multi-layer structure. Besides, a little isolated α-Fe(Zn) phase was formed at the coating/substrate interface. After holding for 30 s, the three-layer structure dominated by α-Fe(Zn) phase was formed (Fig. 2e). Therefore, at the heating rate of 50 °C/s, the formation rate of α-Fe(Zn) phase during 0–30 s holding was dramatically increased relative to the coating heated at 20 °C/s. With the holding time prolonged to 60 s, the two-layer structure similar with Group 1 was formed (Fig. 2f).

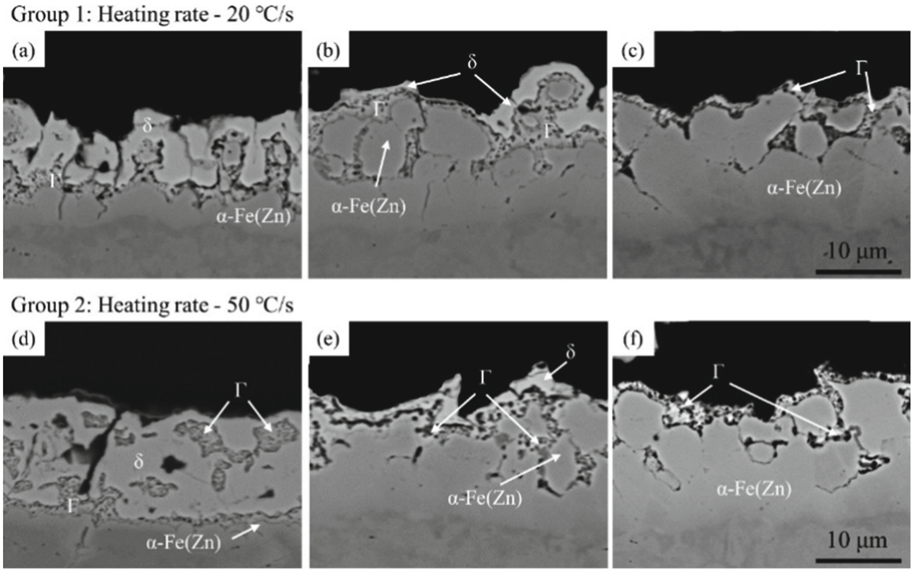

Fig. 2. The SEM cross-sectional coating morphologies of the specimens in Group 1 and Group 2 under different holding times: (a, d) 0 s; (b, e) 30 s; (c, f) 60 s.

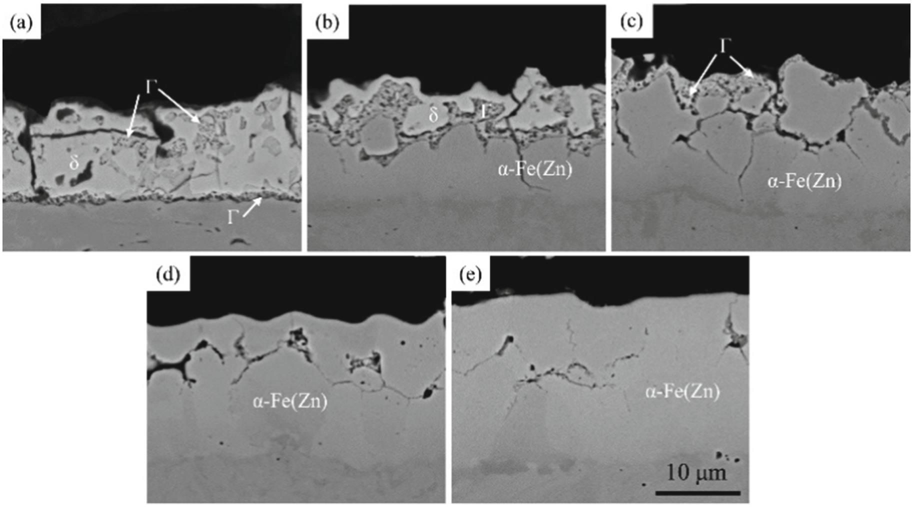

Fig. 3. The SEM cross-sectional coating morphologies of the specimens with a heating rate of 100 °C/s (Group 3) under different holding times: (a) 0 s; (b) 30 s; (c) 60 s; (d) 90 s; (e) 120 s.

The coating morphologies of the specimens in Group 3 (100 °C/s) are shown in Fig. 3. For the coating without holding (Fig. 3a), compared with the coating in Fig. 2d, the coating/substrate interface was flatter and the Γ phase proportion was decreased due to further shortened heating-up stage. In addition, there was hardly any α-Fe(Zn) phase formed at the coating/substrate interface. After holding for 30 s, the coating transformed into the three-layer structure mainly composed of α-Fe(Zn) phase (Fig. 3b). However, the thickness of the continuous α-Fe(Zn) layer was smaller than that in Group 2. At the holding time of 60 s, the coating demonstrated a two-layer structure without δ phase (Fig. 3c). It is worth noting that the phase proportions were approximately the same with that of the specimen treated at the heating rate of 50 °C/s. It suggests that the overall formation rate of α-Fe(Zn) phase during 30–60 s holding was faster at the heating rate of 100 °C/s. The Γ phase almost disappeared after holding for 90 s, and the one-layer coating structure composed of α-Fe(Zn) phase was formed (Fig. 3d). Under this condition, the sufficient alloying of ZnFe coating was considered to be achieved. With the holding time prolonged to 120 s, the thickness of this α-Fe(Zn) coating gradually increased (Fig. 3e).

In our previous study on phase evolution of ZnFe coating under furnace heating procedure, a total heating time of 300 s (holding for 190 s) was required for the coating to achieve sufficient alloying and transform into the one-layer structure composed of α-Fe(Zn) phase [7]. As a contrast, the total heating time required for the coating to achieve sufficient alloying was 98.85 s (holding for 90 s) at the heating rate of 100 °C/s, which was significantly shortened.

4 Conclusion

As the heating rate was greater than 50 °C/s, there was no continuous α-Fe(Zn) layer formed at coating/substrate interface during heating-up stage, resulting in faster inter-diffusion and α-Fe(Zn) phase formation during the holding stage. With the heating rate increased to 100 °C/s, the overall formation rate of α-Fe(Zn) phase during 30–60 s holding was faster than that under the heating rate of 50 °C/s. Compared with traditional furnace heating, the time required for the ZnFe coating to achieve sufficient alloying was dramatically shortened by rapid heating.

Acknowledgments. This research work is supported by the National Natural Science Foundation of China (Grant No. 52205422).

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