Study on the Color Transformation Law of Al-Si Coating with Different Weight After Press Hardening

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Abstract. For Al-Si coated press hardening steel, the users preliminarily determine whether the parts meet the requirements according to their color after press hardening. The color is not only related to press hardening conditions such as heating atmosphere and process, but also to the weight of Al-Si coating. In this work, the color transformation law of Al-Si coating with different weight after press hardening was studied under the common heating atmosphere (air), and the appropriate color range was determined in combination with the changes in the coating structure and properties after press hardening. In this work, samples of Al-Si coating with different weight were prepared from the Al-Si production line, and the box-type resistance furnace and plate quenching press were used to simulate the heating and press hardening process of production line, and the Hunter Lab color tester was used to detect the color of the final samples, and the scanning electron microscope and energy spectrum analyzer were used to analyze the coating structure, coating composition after press hardening. The results show that: (1) The color transformation law of Al-Si coating with different weight after press hardening: AS40 and AS80 are silver-brown-blue-yellow-red, while the AS150 is silver- yellow/red-blue-yellow-red; (2) In order to ensure a suitable alloying level, for AS40 and AS80, the preferred heating process is (900–930 °C) + (3–7 min), and the preferred color is brown-blue, but for AS150, the preferred heating process is (900– 930 °C) + (4– 7 min), and the preferred color is blue, and the Lab values of the three kinds of coating are $L \leq 40$ and $a \leq 1$ and $b \leq 0$.

Keywords: Al-Si coating · Press hardening · Color transformation

1 Introduction

In recent years, with the increasing attention to environmental protection and safety issues, automobile manufacturing is also developing towards a trend of light weight and safety. Press hardening steel has become the first choice for ultra-high-strength steel due to its excellent formability, ultra-high-strength after press hardening and low cost [1]. The press hardening steel without coating developed at first has the problems of oxidation and decarburization at high temperature. The Al-Si coated press hardening steel has the

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advantages of high temperature oxidation resistance and improved corrosion resistance [2], and it has become the most mature product in the market.

The Al-Si coating is silver-white before press hardening. With the different conditions of press hardening, the parts show different colors, and the color transformation corresponds to the changes of the coating structure [3]. However, there is no systematic study on the color transformation law of Al-Si coating with different weight after press hardening. Therefore, having a study on the color transformation law of Al-Si coating with different weight after press hardening to determine the appropriate color range in combination with the changes in the coating structure and properties, which is of great significance for formulating the press hardening process and guiding the production.

2 Experimental Materials and Process

The test samples of Al-Si coating with different weight were prepared from the Al-Si production line. The substrate is 22MnB5, 1.4 mm, and the composition of the plating solution is Al-10%Si-2%Fe. In this work, three kinds of typical coating weight were used, namely, the target value of double-sided coating weight is 40 g/m^2 (AS40), 80 g/m^2 (AS80), and 150 g/m^2 (AS150). X-ray fluorescence spectroscopy was used to detect and analyze the fluctuation of the coating weight along the width direction of the steel plates. The actual coating weight is shown in Table 1.

The size of test steel plates is 1.4 mm × 75 mm × 150 mm. The plates were heated and quenched by a box-type resistance furnace and a flat quenching press, and the cooling rate is above 30 °C/s. The specific heating process is shown in Table 2.

The Hunter Lab color tester was used to detect the color of the final samples, and the scanning electron microscope and energy spectrum analyser were used to analyse the coating structure, coating composition after press hardening.

Table 1. Double-sided coating weight (g/m^2).

Target	Edge 1	Centre	Edge 2	Average
40	50	48	49	49
80	79	77	78	78
150	148	146	150	148

Table 2. Heating process.

Variation	Heating temperature/°C	Heating time/min
Heating temperature	840/870/900/930/960/1000	5
Heating time	930	1/2/3/4/5/6/7/8/9/10/12/15

3 Results and Discussion

3.1 Influence of Heating Temperature on the Color Transformation of Al-Si Coating with Different Weight

With the change of heating temperature, the color of the samples with different Al-Si coating weight is shown in Table 3, and the Lab values and analysis results are shown in Table 4 and Fig. 1.

It is found that: (1) With the increase of heating temperature, the color transformation law of AS40 and AS80 is: brown-blue-yellow-red, while the AS150 is: yellow/red-blue-yellow-red; (2) At lower temperature (840–870 °C), for AS40 and AS80, the absolute values of a and b are small, $0 \leq a \leq 1$ and $-1 \leq b \leq 1$, that is to say, red、yellow and blue are all not obvious, the samples are brown. But for AS150, the value of a or b is larger, $a > 1$ or $b > 1$, so the samples are yellow/red; (3) With the increase of heating temperature, the value of b gradually decreases (more negative) for the three kinds of coating, that is, the samples gradually appear blue. For AS40 and AS80, the value of b is the smallest at 930 °C, but for AS150, the value of b is the smallest at 900 °C; (4) When the heating temperature is further increased, the values of b and a gradually increase, that is, the samples gradually change to yellow-red; (5) The value of L has no obvious regularity for the three kinds of coating.

Table 3. The color of the samples after different heating temperature.

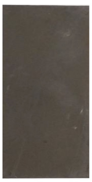
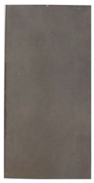
Coating	Heating temperature/°C					
	840	870	900	930	960	1000
AS40						
AS80						
AS150						

Table 4. The Lab values after different heating temperature.

Coating	Heating temperature/°C	L	a	b
AS40	840	34.69	0.00	−0.71
	870	33.64	0.77	−0.30
	900	32.68	0.86	−1.05
	930	30.32	0.58	−5.54
	960	36.95	−0.32	1.29
	1000	33.78	1.27	1.69
AS80	840	33.34	0.08	0.88
	870	35.92	0.30	−0.15
	900	32.83	0.65	−0.68
	930	33.14	0.29	−3.36
	960	33.45	−0.47	−2.68
	1000	36.40	1.14	0.73
AS150	840	30.99	2.70	2.71
	870	34.38	1.33	−1.02
	900	31.10	0.54	−6.78
	930	33.14	0.29	−2.68
	960	38.81	−1.15	−1.74
	1000	36.76	1.87	0.70

3.2 Influence of Heating Time on the Color Transformation of Al-Si Coating with Different Weight

With the change of heating time, the color of the samples with different Al-Si coating weight is shown in Table 5, and the Lab values and analysis results are shown in Table 6 and Fig. 2.

It is found that: (1) With the increase of heating time, the color transformation law of AS40 and AS80 is: silver-brown-blue-yellow-red, while the AS150 is silver-yellow/red-blue-yellow-red; (2) When the heating time is short (1–3 min), e.g., 1 min, the value of L for the three kinds of coating is above 50, the samples are mainly the original silver. When the heating time reaches 3 min, the value of L rapidly drops to below 40, and the color of the samples is similar to the lower heating temperature (840–870 °C), that is, AS40 and AS80 appear brown, while AS150 appears yellow/red; (3) The heating time continues to increase, the value of b for the three kinds of coating gradually decreases (more negative), that is, the samples gradually appear blue. For AS40 and AS80, the value of b is the smallest at 6 min, but for AS150, it is 4 min; (4) When the heating time is further prolonged, the values of b and a gradually increase, that is, the samples gradually change to yellow-red; (5) The variation law of the L for the three kinds of

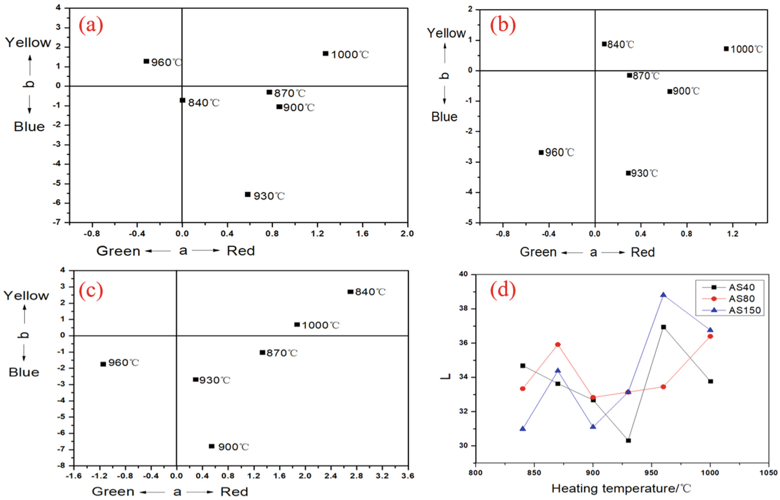
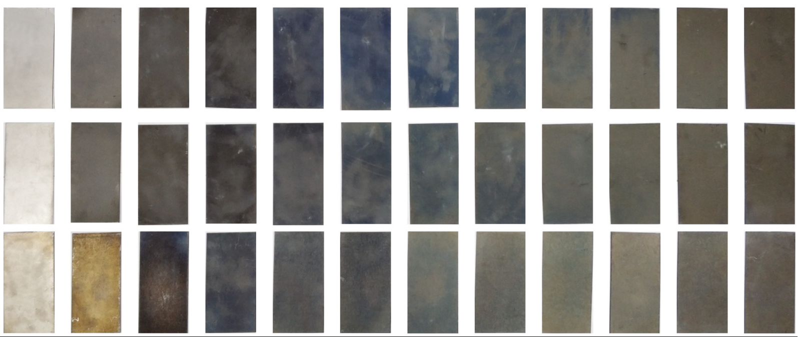


Fig. 1. The Lab values after different heating temperature (a. The ab values of AS40; b. The ab values of AS80; c. The ab values of AS150; d. The L value of AS40/AS80/AS150).

Table 5. The color of the samples after different heating time.

Coating	Heating time/min											
	1	2	3	4	5	6	7	8	9	10	12	15
AS40												
AS80												
AS150												



coating is the same with the heating time increasing, it first decreases, then increases, and finally tends to be stable.

3.3 Results Discussion

The coating structure of the three kinds of coating before press hardening is similar: from the substrate to the surface of the coating, it is Fe-Al layer (<1 μm), Fe-Al-Si layer (τ_5, about 4.5 μm), Al layer and Fe-Al-Si alloy phase (τ_6) dispersed in the Al layer [4], which differs in the thickness of the Al layer. When heated, the τ_5 layer reacts with Al layer to form a liquid phase. At this time, Si rapidly diffuses into the liquid phase to form a Si-rich

Table 6. The Lab values after different heating time.

Coating	Heating time/min	L	a	b
AS40	1	56.57	−0.37	0.27
	2	42.25	0.13	0.29
	3	35.53	0.16	−0.12
	4	30.02	0.89	−1.24
	5	30.32	0.58	−5.54
	6	32.04	−0.37	−5.93
	7	33.16	−0.66	−5.73
	8	35.50	−0.40	0.03
	9	35.10	−0.67	0.26
	10	35.95	−0.50	1.14
	12	35.39	0.41	3.18
	15	33.72	0.80	3.46
AS80	1	64.46	−0.35	0.70
	2	42.96	0.02	−0.22
	3	35.62	0.36	−0.17
	4	32.25	0.73	−1.08
	5	33.45	0.29	−2.68
	6	33.19	−0.16	−3.51
	7	35.00	−0.72	−2.74
	8	35.50	−0.40	0.03
	9	36.05	−0.55	0.55
	10	35.69	−0.30	2.43
	12	35.28	0.38	3.83
	15	34.54	0.84	3.88
AS150	1	53.79	−0.54	2.72
	2	43.52	1.34	8.88
	3	34.91	2.70	1.59
	4	33.72	0.40	−4.45
	5	35.50	−0.08	−1.50
	6	34.77	−0.12	−0.40
	7	39.57	−1.15	0.29
	8	38.37	−0.17	1.85

(*continued*)

Table 6. (*continued*)

Coating	Heating time/min	L	a	b
	9	39.72	−1.39	1.86
	10	40.93	−0.80	2.44
	12	39.83	−0.35	2.34
	15	39.39	0.24	2.10

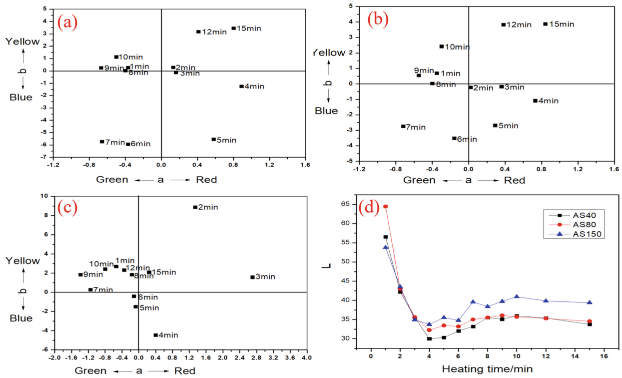


Fig. 2. The Lab values after different heating time (a. The ab values of AS40; b. The ab values of AS80; c. The ab values of AS150; d. The L value of AS40/AS80/AS150).

Fe-Al-Si layer (different from τ_5), and Fe-Al layer forms on both sides of the Fe-Al-Si layer. Besides, due to the strong diffusion of Fe and Al close to the substrate side, it is transformed into a diffusion layer (Fe + Fe_3Al). At this time, the coating structure from the substrate to the surface is the diffusion layer (Fe + Fe_3Al) Fe-Al layer, Fe-Al-Si layer and Fe-Al surface layer [5], and it is fully alloyed. When the coating is not fully alloyed, there is unreacted Al coating orτ_5 on the surface of the coating. At this time, the surface roughness of the coating is low, which reduces the corrosion resistance of the coating, and the unreacted Al orτ_5 is detrimental to welding performance. However, it is not that the higher the alloying level (Fe content in the coating), the better. It is found that if the alloying level is too high, the number and size of Kirkendall holes in the coating increase, which also deteriorates the painting and welding performance. Coating structure of the three kinds of alloying level is shown in Fig. 3, and the composition is shown in Table 7.

With the heating going, the alloying level increases (Fe content increases), resulting in the change of the oxidation state of the outermost Fe, Al and other alloy elements, which is the fundamental cause of the color transformation. That is to say, the color transformation of Al-Si coating reflects the different alloying level. The alloying level is closely related to the performance of the coating. In order to ensure good painting and welding performance, we need to ensure a suitable alloying level, that is, the coating needs to be fully alloyed, but not over alloyed, so Al-Si coating presents a certain color range.

The color detection and analysis of this test is carried out by the Hunter Lab color space, which L represents the brightness of the object: 0–100 means from black to white, a represents the red-green of the object: positive values represent red, negative values represent green, 0 represents a neutral color, and b represents the yellow-blue color of the object: positive values represent yellow, negative values represent blue, and 0 represents a neutral color. Specifically, the presenting color is the combined effect of the L, a, and b values.

The effect of heating temperature and heating time on the color transformation of Al-Si coating with different weight is similar, that is, the color transformation law of AS40 and AS80 is: silver-brown-blue-yellow-red, while the AS150 is: silver-yellow/red-blue-yellow-red. Specifically, (1) when the heating temperature is low (840–870 °C) or the heating time is short (1–3 min), AS40 and AS80 present silver-brown, while AS150 is silver-yellow/red. And the silver mainly shows that the L value is particularly large, generally above 50. When the heating time reaches 3 min, the L value rapidly drops below 40. At this time, for AS40 and AS80, the absolute values of a and b are small, $0 \leq a \leq 1$ and $-1 \leq b \leq 1$, that is to say, red, yellow and blue are all not obvious, the samples are brown, but for AS150, the value of a or b is larger, $a > 1$ or $b > 1$, so the samples are yellow/red. The study shows that when the $L \geq 40$ or $a > 1$ or $b > 1$, the three kinds of coating are not fully alloyed; (2) When heating temperature increases or heating time is prolonged, the color transformation of the three kinds of coating is mainly shown as the value of b gradually decreases (more negative), and the value of a does not change much, that is, $-1 \leq a \leq 1$ and $b \leq 0$. At this stage, the samples gradually present blue, and the coating is fully alloyed. For AS40 and AS80, the value of b is the smallest at 930 °C + (5–6 min), but for AS150, it is (900–930 °C) + (4–5 min), at this time, blue is the most obvious. (3) When the heating temperature is further increased or the heating time is further increased, the values of b and a gradually increase, that is, the samples gradually change to yellow-red. The study shows that when the heating temperature is too high such as 960 °C or the heating time is too long such as 8 min, at this time, $a > 1$ or $b > 0$, the number and size of Kirkendall holes in the coating increase significantly, that is, the coating is over alloyed.

In general, in order to ensure a suitable alloying level, for AS40 and AS80, the preferred heating process is (900–930 °C) + (3–7min), and the preferred color is brown-blue, but for AS150, the preferred heating process is (900–930 °C) + (4–7 min), and the preferred color is blue, and the Lab values of the three kinds of coating are $L \leq 40$ and $a \leq 1$ and $b \leq 0$.

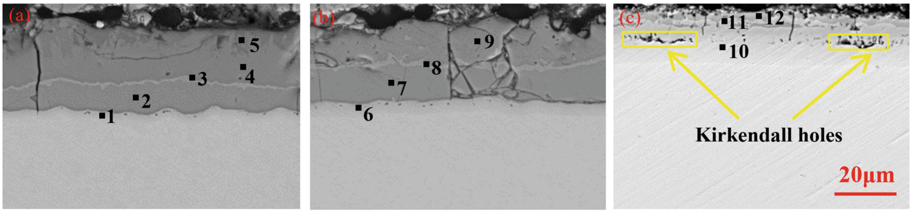


Fig. 3. Coating structure corresponding to the three kinds of alloying level (a. Not fully alloyed (AS150–930 °C + 3min); b. Fully alloyed (AS150–900 °C + 5 min); c. Over alloyed (AS80–960 °C + 5 min)).

Table 7. Coating composition corresponding to the three kinds of alloying level.

a/b/c	Analysis area	Fe	Al	Si	Phase
a	1	86.2	11.4	2.4	Fe_3Al (Diffusion layer)
	2	45.4	52.0	2.6	Fe_2Al_5 (Fe-Al layer)
	3	50.3	37.5	12.3	Fe_2SiAl_3 (Fe-Al-Si layer)
	4	38.6	56.3	5.1	$FeAl_3$ (Fe-Al layer)
	5	34.8	53.9	11.3	Fe_2SiAl_7 (τ_5)
b	6	89.7	8.3	1.9	Fe_3Al (Diffusion layer)
	7	45.8	51.2	3.0	Fe_2Al_5 (Fe-Al layer)
	8	52.9	31.7	15.4	Fe_2SiAl_2 (Fe-Al-Si layer)
	9	45.4	52.5	2.1	Fe_2Al_5 (Fe-Al layer)
c	10	93.7	4.8	1.5	Fe + Fe_3Al (Diffusion layer)
	11	65.2	30.8	4.0	Fe_8SiAl_8 (Fe-Al-Si layer)
	12	47.5	51.8	0.7	Fe_2Al_5 (Fe-Al layer)

4 Conclusions

(1) The color transformation law of Al-Si coating with different weight after press hardening: AS40 and AS80 are silver-brown-blue-yellow-red, while the AS150 is silver-yellow/red-blue-yellow-red.

(2) In order to ensure a suitable alloying level, for AS40 and AS80, the preferred heating process is (900–930 °C + (3–7 min), and the preferred color is brown-blue, but for AS150, the preferred heating process is (900–930 °C) + (4–7 min), and the preferred color is blue, and the Lab values of the three kinds of coating are $L \leq 40$ and $a \leq 1$ and $b \leq 0$.

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