Mechanical properties and anti-corrosion properties of thin aluminum-silicon coated 2000MPa press hardening steel

Jiayue Chen[1], Yong Liu[1,a,†], Zhongbiao Zhou[1], Weilin Cao[1], Xuejun Qi[1], Erwei Li[1], Mengqi Xu[1] and Xufeng Qi [2,b]

[1]*VOYAH Automobile Technology Company Ltd., Wuhan, 430051, China*
[2]*Dongfeng Motor Group Co., Ltd. R&D Institute, Wuhan, 430058, China*
E-mail:[a,†]h-liuyong@voyah.com.cn, [b]qixufeng@dfmc.com.cn

Based on the important demand of energy saving and emission reduction, press hardening steels have been widely used in automobile. In order to avoid oxidation of the steel during hot stamping process, aluminum-silicon coating is used. The mechanical properties of thin aluminum-silicon coating press hardening steels with strength of 2000 MPa before and after hot stamping were studied. The coating structure, bending angle, low temperature impact toughness and hydrogen-induced delayed cracking of the steels were detected. The results show that the mechanical properties of thin coating steels are similar to those of conventional coating steels. The coating performance tests were carried out by phosphating and zirconium electrophoresis pretreatment respectively, and the results showed that the adhesion of the electrophoretic coatings by phosphating and zirconium electrophoresis pretreatment both met the requirements. Finally, the cyclic salt spray corrosion test was carried out in the conventional coating steels and thin coating steels after electrophoresis, and it was found that the erosion line width of the thin coating was larger.

Keywords: Thin aluminum-silicon coating; Hot stamping; Hydrogen-induced delayed cracking; Corrosion.

1. Introduction

Studies [1] show that a 10% reduction in vehicle weight can save 6-8% in fuel while reducing emissions by 4%. As a result, lightweight of automobile is the most direct and effective measure for energy-saving and emission reduction [2]. The strength of press hardening steels after hot stamping is usually as high as 1500~2000MPa, so the weight of the car can be reduced by reducing the thickness of the material to manufacture automobile parts. In order to further reduce weight, integrated hot stamping technology based on multi-part integration is proposed. Different from the traditional stamping and spot-welding process for parts, the integrated hot stamping process first laser welding blanks of different strengths and thicknesses, and then the welded blank is hot stamped, so that the overlapping area of spot welding is avoided and the weight is reduced. As mentioned above, sheets with different strengths and thicknesses are used, so the whole part can meet the crash performance. For parts like the B-pillar or this area, it is that the ductile regions which have a larger elongation for improved energy absorption is needed [3]. This part or regions have

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an excellent intrusion control in the upper section and a high energy absorption in the lower section [3]. In integrated hot stamping process, sheets with much lower strength than the typical press hardening steels are used in the energy absorption zone, and usually press hardening steels with strength of 500MPa or 1000MPa are developed [4].

In an integrated laser tailor-welding hot-stamping process, the blank needs to be heated to more than 900 ºC and transported to the tools to complete the stamping in air atmosphere. In order to avoid the oxidation of the sheet metal at high temperatures, press hardening steels are usually coated and aluminum-silicon coating is commonly used. There are two kinds of aluminum-silicon coatings, one of which is an ordinary coating, the coating quality is not less than 75g/m^2; the other is a thin aluminum-silicon coating, and the typical coating quality is 15~40g/m^2. The thin Al-Si coating has only been developed and used in recent years, mainly to break the patent limits of conventional coatings invented by ArcelorMittal. As new kinds of press hardening steels, the applicability on automotive parts, such as mechanical properties, coating properties, anti-corrosion properties, welding properties, etc., need to be studied. In this work, the mechanical properties of thin aluminum-silicon coated press hardening steels with strength of 2000 MPa before and after hot stamping were studied. The coating structure, bending angle, low temperature impact toughness and hydrogen-induced delayed cracking of the steels were detected.

2. Materials and mechanical properties

The mechanical properties of the thin Al-Si coated press hardening steels with strength of 2000 MPa before and after hot stamping were studied. The thickness of the sheet was 1.8mm. In hot stamping process, the sheets were heated to 830~930ºC and holding for 4 mins, then they were quenched by flat dies.

2.1. *Materials and chemical compositions*

The chemical compositions of the thin Al-Si coated press hardening steels were detected and the results are shown in Table 1. Unlike steel produced by other steel makers, this type of steel has a higher aluminum content, about 0.435%. The role of Al here is to fix N instead of Ti, and AlN has a smaller particle size than TiN. In addition, Al can also adjust the martensite phase transition temperature and improve the self-tempering effect, improving the toughness of martensite.

Table 1 The chemical compositions of the 2000MPa thin Al-Si coated press hardening steels (wt%)

Element	C	Si	Mn	P	S	Cr	Al	Mo	Ti	Nb	B
Mass fraction	0.28	0.28	1.27	0.016	$<$0.008	0.25	0.435	0.006	0.005	0.026	0.003

2.2. *Coating properties*

The thickness of the coating on both sides of the steel plate was measured before and after hot stamping according to GB/T 13298. The coating thickness before hot stamping is within the required range which is 6~14 μm. As shown in Figure 1, during heating process in hot stamping, the coating is converted into intermetallic compound layers and diffusion layers. Usually, the total thickness of the coating is 10~25 μm, of which the diffusion layer thickness is 3~13 μm. The test data in Table 3 show that the coating thickness of the test sheet meets the requirements. The test results also show that the thickness uniformity of the coating is good before and after hot stamping.

Table 2 The coating thickness of the tested sheet before hot stamping

Coating thickness	Side A (μm)			Side B (μm)		
Sample No.1	10.59	7.46	7.78	8.43	8.27	8.21
Sample No.2	7.46	9.62	8.54	8.43	9.29	7.78
Sample No.3	8.21	8.21	7.35	6.81	8.54	8.0

Table 3 The coating thickness of the tested sheet after hot stamping

Coating thickness	Side A (μm)						Side B (μm)					
	Total			Diffusion layer			Total			Diffusion layer		
Sample No.1	13.19	12.86	12.65	5.62	5.62	5.62	14.27	14.81	14.37	6.05	5.04	5.73
Sample No.2	13.19	14.59	13.4	5.84	5.4	5.84	13.08	12.32	13.51	5.4	5.62	5.84
Sample No.3	11.35	12.32	13.4	5.85	6.59	6.05	14.37	13.62	13.83	5.94	5.84	6.06

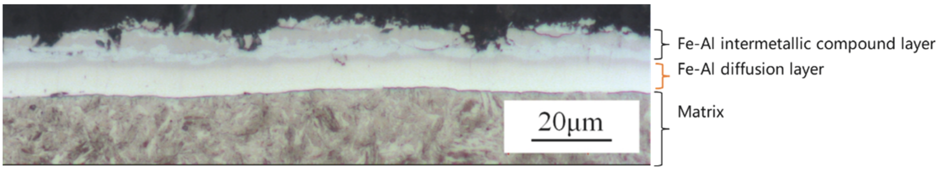


Fig. 1. Microstructure of the thin Al-Si coated press hardening steel after hot stamping.

2.3. *Strength*

The strength and elongation of the tested steel before and after baking were tested according to GB/T 228.1, and the results are shown in Fig. 2 and Fig. 3. The baking process is 185ºC×20min. It should be noted that tensile tests in the rolling direction (RD) and perpendicular to the rolling direction (TD) were both carried out. The tested results indicate that the yield strength (YS) of the steel is larger than 1300MPa, the tensile strength is larger than 1800MPa and the elongation after breaking is not less than 5%. As shown in Table 4, the yield strength increases about 10~12% after baking while the tensile strength reduces about 2~4.5% after baking and the elongation increases about 2~4.5% after baking.

Table 4 The mean strength and elongation of the tested steel.

Baking condition	Direction	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Before baking	RD	1371.6±17.2	1882.8±21.1	5.9±0.4
	TD	1389.8±33	1929.4±26.2	5.5±0.4
After baking	RD	1536.8±17.2	1838±10.7	6.4±0.2
	TD	1550.6±10.8	1842.2±8.1	5.6±0.4

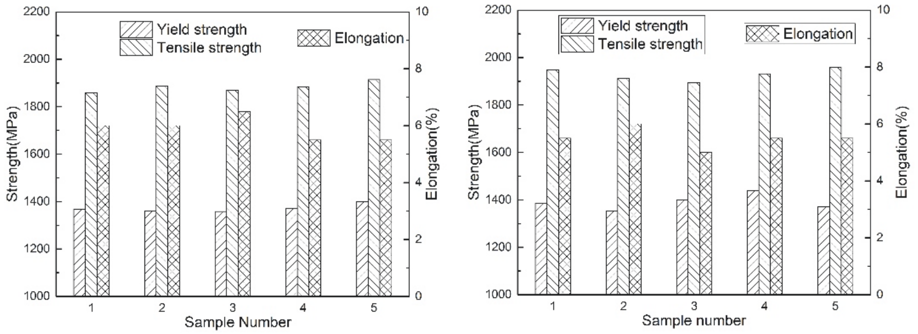


Fig. 2. The strength and elongation of the tested steel before baking in RD (left) and TD (right).

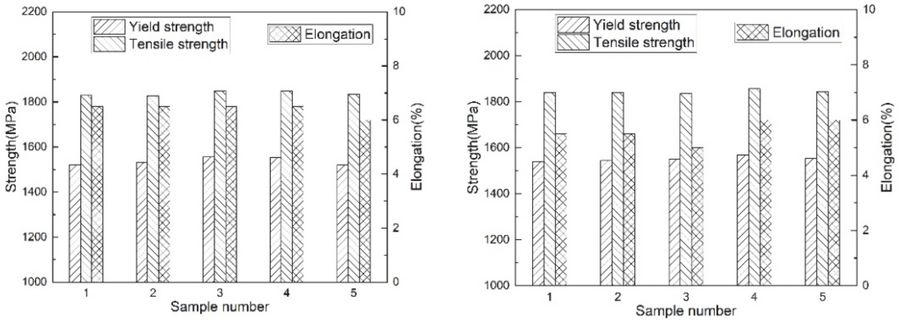


Fig. 3. The strength and elongation of the tested steel after baking in RD (left) and TD (right).

2.4. *Bending performance*

The bending angels of the tested steel before and after baking were tested according to VDA 238, and the results are listed in Table 5. The results show that the bending angles in RD is less than that in TD regardless of whether it is baked or not. The bending angles are 41.4±2.0º and 44.1±0.8º before and after baking in RD.

Table 5 The bending performance of the 2000MPa thin Al-Si coated press hardening steels

Bending angle(º)			RD					TD		
Before baking	40.8	44.8	39.9	40	41.6	43.8	43	44.7	43.3	43.8
After baking	44.8	43.8	43.9	45.1	43	49.3	51.6	50	50.8	50.1

3. Low temperature impact toughness

The low temperature impact toughness of the tested steel before and after baking were tested according to GB/T 229 at different temperatures, namely, -60ºC, -40ºC, -20ºC, 0ºC, and 20ºC. The absorbed energy values were fitted by the Boltzman function and the results indicate that the tough-brittle transition temperature of the press hardening steel after hot stamping is not within the test temperature range, namely, -60ºC~20ºC. Scanning electron microscopy was used to observe the impact fracture morphology, as shown in the Figure 5. There are many dimples in the fracture at different test temperatures, which further proves that the fracture form at the test temperature is ductile fracture.

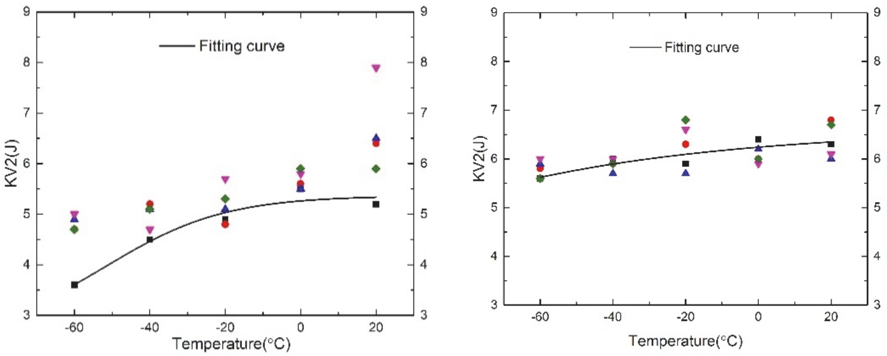
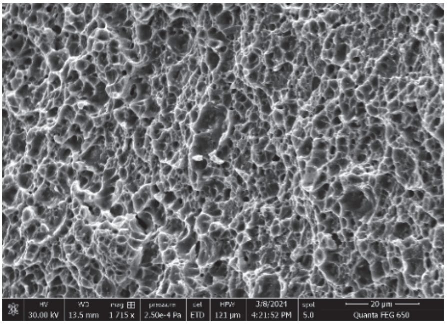
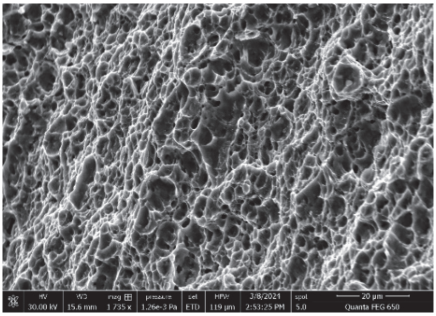


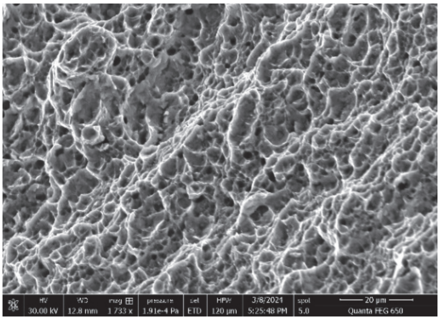
Fig. 4. The absorbed energy value in Charpy pendulum impact test before (left) and after (right) baking.



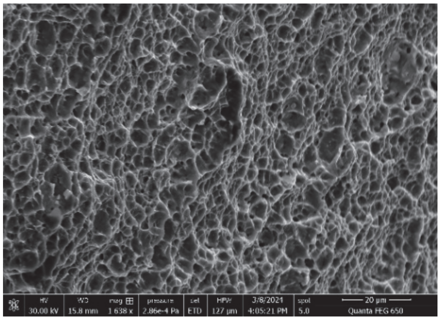
(a) -60ºC before baking



(b) -60ºC after baking



(c) 20ºC before baking



(d) 20ºC after baking

Fig. 5. The impact fracture morphology in Charpy pendulum impact test before and after baking.

4. Hydrogen-induced delayed cracking

The hydrogen-induced delayed cracking of the tested steel before and after baking were tested according to ISO 7539-2 at different stress conditions. The results indicate that the 2000MPa thin Al-Si coated press hardening steel meets the requirement of hydrogen-induced delayed cracking when subjected to less than 60% yield stress before baking, and meets the requirement of hydrogen-induced delayed cracking when subjected to less than 80% yield stress after baking.

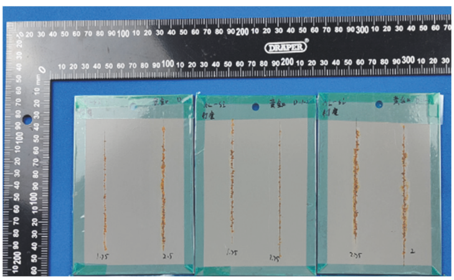
Table 6 The hydrogen-induced delayed cracking performance of the 2000MPa thin Al-Si coated press hardening steels

	Stress condition	Whether it broke after 96h	Time before fracture
Before baking	50% YS	YES	/
	60% YS	YES	/
	70% YS	NO	65h
	80% YS	NO	31h
After baking	50% YS	YES	/
	60% YS	YES	/
	70% YS	YES	/
	80% YS	YES	/

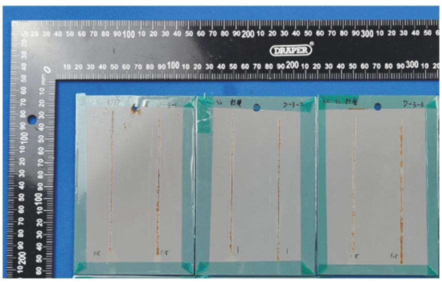
5. Coating performance and anti-corrosion properties

The coating performance tests were carried out by phosphating and zirconium electrophoresis pretreatment respectively, and the results showed that the adhesion of the electrophoretic coatings by phosphating and zirconium electrophoresis pretreatment both met the requirements. The cyclic salt spray corrosion test was carried out in the conventional coating steels and thin coating steels after electrophoresis. Except for the technical phases and transitions, the painted sheets were at a controlled temperature what is of 35 °C ± 1°C in the corrosion chamber. The operating range was between 20% and 90% relative humidity in the test. The sprayed solution during this test was a solution of 1% (± 0.05%) NaCl (10 g/l), pH4 (± 0.2) and the PH value was adjusted by sulfuric acid (H_2SO_4). The corrosion test lasted for 1000h.

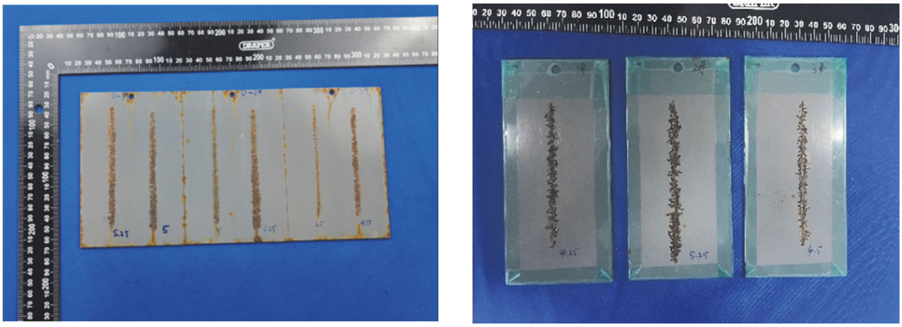
The corrosion results of the thin and normal Al-Si coated press hardening steels are shown in Fig. 6 and Table 5. It was found that the scribe line width of the thin coating was larger than that of the normal coating. The results agree with Hilary A. Onyishi [5] finding that an increase in the coating thickness improves cosmetic corrosion resistance, due to the presence of aluminium -rich protective corrosion product. However, in Hilary A. Onyishi's work [5], thin Al-Si coating is as good as normal Al-Si coating for perforation corrosion resistance but slightly much better and this good performance was due to barrier effects of corrosion products. Besides, thin Al-Si coating shows higher resistance to red-pitting corrosion than normal Al-Si coating due to finer surface-morphology of thin Al-Si coating as observed with SEM leading to a more homogeneous paint distribution.



(a) Phosphating of normal Al-Si coating



(b) Zirconium of normal Al-Si coating



(c) Phosphating of thin Al-Si coating (d) Zirconium of thin Al-Si coating

Fig. 6. The corrosion results of the thin and normal Al-Si coated press hardening steels

Table 5 The scribe line width of the thin and normal Al-Si coated press hardening steels

Width of scribe line	Phosphating			Zirconium		
Thin Al-Si coating	5	6.25	4.75	4.25	5.25	4.5
Normal Al-Si coating	2.5	1.75	2.75	1.5	1	1.5

6. Conclusions

(1) The coating thickness before hot stamping is within the required range which is 6~14 μm. The coating thickness meets the requirements after hot stamping and the thickness uniformity of the coating is good before and after hot stamping.

(2) The yield strength of the steel is larger than 1300MPa, the tensile strength is larger than 1800MPa and the elongation after breaking is not less than 5%. The yield strength increases about 10~12% after baking while the tensile strength reduces about 2~4.5% after baking and the elongation increases about 2~4.5% after baking.

(3) The bending angles in RD is less than that in TD regardless of whether it is baked or not. The bending angles are 41.4±2.0º and 44.1±0.8º before and after baking in RD.

(4) The tough-brittle transition temperature of the press hardening steel after hot stamping is not within the test temperature range, namely, -60ºC~20ºC.

(5) The 2000MPa thin Al-Si coated press hardening steel meets the requirement of hydrogen-induced delayed cracking when subjected to less than 60% yield stress before baking, and meets the requirement of hydrogen-induced delayed cracking when subjected to less than 80% yield stress after baking.

(6) The adhesion of the electrophoretic coatings by phosphating and zirconium electrophoresis pretreatment both met the requirements. The results of cyclic salt spray corrosion test after electrophoresis indicate that the scribe line width of the thin coating was larger.

References

1. M. Ma, X. Bi, J. You, Bestbury, Research Progress of Property and Its Application of Aluminium Alloy Auto Sheet, Materials For Mechanical Engineering, 34, 1 (2010).
2. Jiayue Chen, Mei Yang, Yong Liu, Zhongbiao Zhou, Xuejun Qi, Mengqi Xu, Hot stamping of a TRB part in an electric MPV vehicle, in Proc. Of the 6th International

Conference on Advanced High Strength Steel and Press Hardening (ICHSU 2022), (Wuhan, China).
3. H. Karbasian and A. E. Tekkaya, A review on hot stamping, Journal of Materials Processing Technology, 210, 2103 (2010).
4. J. Chen, X. Qi, Y. Liu, W. Cao and M. Xu, Development and application of integrated laser tailor-welding hot-forming door ring, Forging & Stamping Technology, 42, 1 (2023).
5. Hilary A. Onyishi, Anthony C. Okafor and Raj Sohmshetty, Effect of Ai–Si coating weights on corrosion of ultra-high-strength steel Usibor^{R} 1500 used in automotive structures, Corrosion Engineering, Science and Technology, 58, 659(2023).