# Analysis of Effect of Coating Crack on Hot-Formed Al-Si Coated Steel Sheet After Heating

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**Abstract.** Through analyzing the number of cross-section cracks of different coating thickness under the same heating process, the same coating thickness under the conditions of different heating temperature, different holding time and different drawing rate, it provides the control direction for decreasing the number of cracks in al-si coating after hot forming process.

**Keywords:** Hot forming · Al-Si coating · Heating temperature · Holding time · Crack

## 1 Foreword

Hot stamping forming steel can reduce body weight, reduce fuel consumption, improve crash safety, and provide an effective way to realize vehicle lightweight. Such as A, B pillar, bumper and so on. In the hot stamping process, the Boron Steel is heated to 850–950 °C for 3–10 min to make it uniform austenitizing, then it is rapidly transferred to the die with cooling system, formed and quenched at the same time,promoted martensitic transformation, to Greatly improved its strength (≥1500 MPa) [1]. If there is no coating on the surface of the steel plate, the steel plate will produce a lot of iron oxide scale at high temperature, which will pollute the die and affect the working rate. For the thinner Sheet Parts, shot peening results in surface residual stress and deformation [2]. Al-Si coating hot-formed steel is widely used in hot-formed process because of its characteristics such as no scale falling off when heated, no shot peening after stamping, high forming precision and no nitrogen protection. The cracking or spalling of the coating during hot deformation will provide a channel for the air and water corrosion environment, which will lead to oxidation and corrosion of the coating and the substrate [3], and may also be the source of fatigue failure of the part [4]. In this paper, the influence of different thickness of coating, different heating temperature, holding time and different deformation rate of hot forming process on coating crack is analyzed, the theoretical support is provided for controlling the number of cracks in the coating after hot forming, ensuring the integrity of the coating.


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# 2 Test Materials and Methods

## 2.1 Test Material

The steel plate used for the test is continuous hot dip Al-Si coating, the composition of coating is 10% Si. The plate substrate is 22MnB5. 1) The different weight coatings of microstructure and AS60 before and after heating were studied and analyzed. Different coatings include AS150, AS120, AS100, AS80. 2) Analysis and study on the number and morphology of cracks in the coating at different heating temperatures. 3) Analysis and study on the number and shape of cracks in the coating under different holding time. 4) Analysis and research on the effect of different deformation rate on the number and shape of coating cracks.

## 2.2 Test Methods

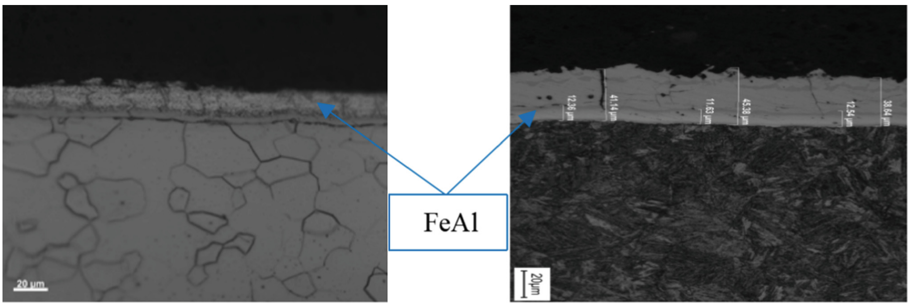
150 mm × 70 mm samples with different Al-Si coating weights were austenitized in a box-type heating furnace. When the holding time is over, water quenching is carried out immediately. When the heated holding is finished, water quenching is carried out immediately. By means of optical microscope (VHX-1000C), The microstructure of Al-Si coating with different weights was analyzed before and after thermal simulation.

# 3 Test Results

## 3.1 Effect of Coating Weight on Crack After Hot Forming

The composition of Al-Si coated plate from steel base to coating surface is adhesive layer $Fe_2Al_5$ layer, Al-Si-Fe alloy layer and pure aluminum layer. After hot forming, the iron in the steel base is alloyed with the coating, and each of the coating is alloyed with the other phases. The specific shape before and after hot forming is shown in Fig. 1.

When the Strip is heated to Austenitizing temperature 930 °C, there are holes in the inner layer of coating, the surface layer of coating and the diffusion layer, and the number and size of holes increase with the increase of temperature. According to the literature




(a) Microstructure of coating before heating. (b) Microstructure of coating before heating.

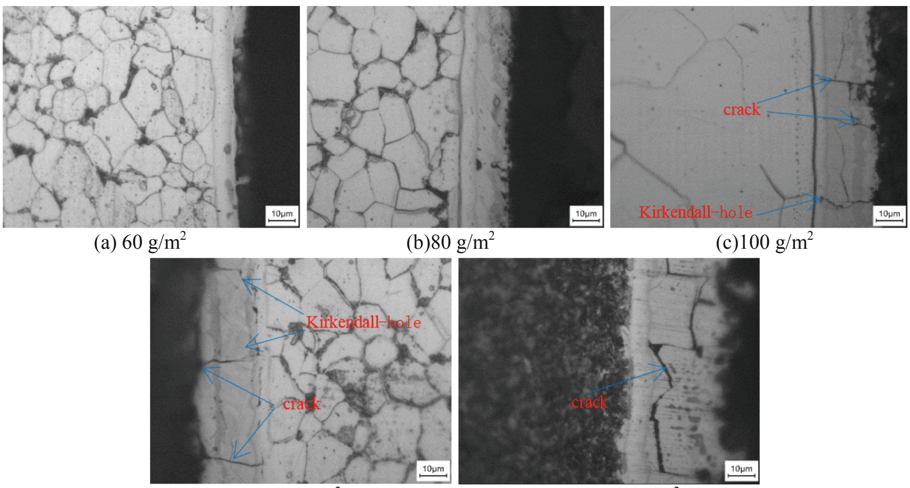
**Fig. 1.** Microstructure of Al-Si coating before and after heating.

analysis, the holes in the coating surface and diffusion layer is due to the research of Cheng, When Fe-Al-Si or Fe-Al metal compounds with low density are transformed into $Fe_3(Al, Si)_5$ 、 Fe-Al with high density, the volume shrinkage of the coating will be caused τ Tensile stress will be generated around T1-$Fe_3(Al, Si)_5$ and Fe-Al resulting in the formation of micro-cracks and holes. The holes formation mechanism in the diffusion layer is consistent with Kirkendall effect [5], that is, the different diffusion coefficients of iron and aluminum lead to the formation of voids at the interface and the aggregation of voids to form holes [6]. At the same time, the crack is formed because the brittle intermetallic compound is not consistent with the coefficient of thermal expansion of the Steel material, and the crack extends along the thickness of the coating until it reaches the diffusion layer (α-Fe phase). The holes and cracks reduce the adhesion between the coating and the Strip and the protection of the Strip. The corrosion resistance and the formability of the Strip after high temperature heating are decreased.

### 3.2 Effect of Coating Weight on Crack

Five samples, 60 g/m$^2$, 80 g/m$^2$, 100 g/m$^2$, 120 g/m$^2$, 150 g/m$^2$ were prepared. The samples are heated to 930 °C and the holding time is 8 min, and then the water is quenched to room temperature. Observed the cracks condition of different original coating thickness after heat treatment (Fig. 2).

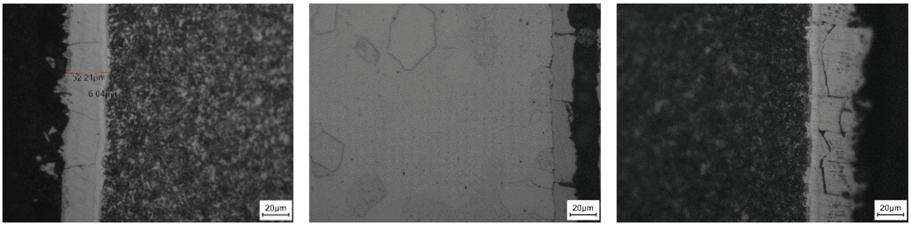
As can be seen from the Figure, no obvious cracks were found in the coatings of 60 g/m$^2$ and 80 g/m$^2$. But the width of crack is fine. At the same time, a row of kirkendal holes distributed along the interface between the steel substrate and the coating appears. There are three cracks in the 120 g/m$^2$ coating, and the width of the cracks is wider than that of the 100 g/m$^2$ coating. The crack extends from the surface to the interior, and a crack appears through the adhesive layer, which indicates that the cracking tendency of the heated coating is more serious. The Kirkendal holes on the interface between the




(a) 60 g/m$^2$ (b)80 g/m$^2$ (c)100 g/m$^2$

(d) 120 g/m$^2$ (e) 150 g/m$^2$

**Fig. 2.** Microstructure and morphology of different coating weight after hot forming.




(a) 850 °C (b) 890 °C (c) 930 °C

**Fig. 3.** Effect of heating temperature on microstructure of coating.

coating and the steel substrate are more clear and aggregate to form larger-scale holes. In the 150 g/m$^2$ coating, several large cracks parallel to the surface of the coating and several cracks tend to merge, at which time the adhesion between the coating and the steel substrate the decreases seriously outside the crack, and then causes the coating to fall off. A lot of holes mergers makes the Kirkendal holes become inconspicuous, and the interface between the coating and the steel substrate becomes rougher and discontinuity.

### 3.3 Effect of Heating Temperature on Crack

150 g/m$^2$ Al-Si samples were heated to 850 °C, 890 °C, 930 °C for 8 min, then water quenched to room temperature. And then observed the effect of different heating temperature on the crack (Fig. 3).

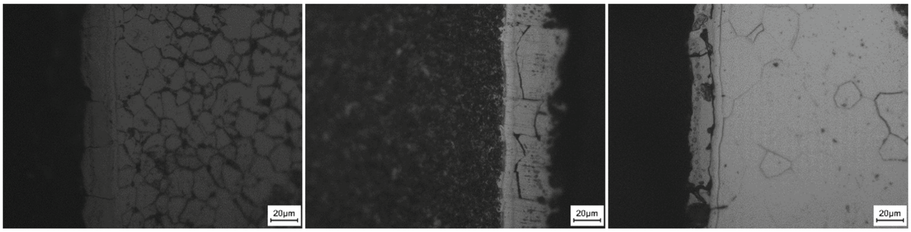
The Specimens were observed at a field of view of 500 times. When the sample was heated to temperature 850 °C, three cracks appear in the coating and extend to the interface between the adhesive layer and the Al-Si layer. When the sample was heated to 890 °C, three cracks appear also. The cracks extend from the surface to the interior, and the length and width of the cracks are larger than that when the temperature is 850 °C. When the heating temperature is 930 °C several large cracks parallel to the surface of the coating are formed in the field of view, and several cracks tend to merge. The adhesion between the coating (near the crack) and the steel substrate decreases seriously, and then causes the coating to fall off at that location.

To sum up, the increase of the heating temperature leads to the rapid growth of the cracks, which connect and merge with each other, and the trend of the cracks changes from Longitudinal to transverse. The transverse crack is parallel to the interface between the alloy layer and Al-Si layer, so the risk of spalling is increased.

### 3.4 Effect of Holding Time on Crack

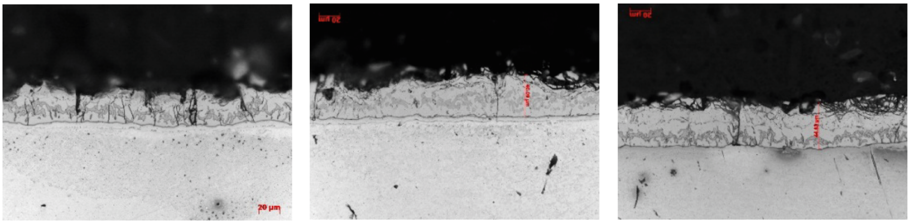
150 g/m$^2$ Al-Si samples were heated to 850 °C, 890 °C, 930 °C for 8 min, then water quenched to room temperature. And then observed the effect of different holding time on the crack (Fig. 4).

The Specimens were observed at a field of view of 500 times. After holding for 5 min, four obvious longitudinal cracks appeared in the coating, one of which penetrated the whole coating thickness to the steel base and the other three extended to the adhesive layer of coating. When holding time for 8 Min, several large cracks parallel to the surface




(a) 5 min (b) 8 min (c) 10 min

**Fig. 4.** Microstructure of coating with different holding time.



(a) 0.05 $s^{-1}$deformation rate (b) 0.1 $s^{-1}$deformation rate (c) 0.2 $s^{-1}$deformation rate

**Fig. 5.** Microstructure after 10% deformation at different rates after heated.

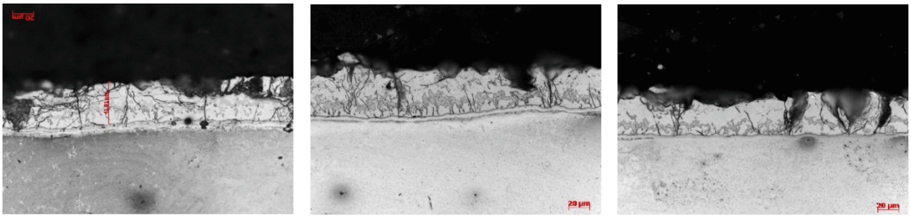
of the coating are formed, and several cracks tend to merge. And the direction of the crack has changed, from the original vertical and coating, began to appear and coating parallel to the direction. When holding time for 10min, a transverse crack is formed through the field of view, accompanied by several vertical cracks. As the temperature is too high, the coating around the crack will soften or even melt, and the migration of atoms will be more intense, which will lead to part of the longitudinal crack to non-straight shape.

In a word, when the holding time is short, the coating forms longitudinal cracks. With the increase of holding time, the coating begins to form transverse cracks along the interface between the adhesive layer and the Al-Si layer, the holding time further increases, and the cracks merge with each other, causes the coating to appear the sign which falls off.

### 3.5 Effect of Deformation Rate on Crack

Prepare 2.0 mm thick, 150 $g/m^2$ by weight Al-Si coating samples. The samples were heated to 930 °C, and the tensile tests of 10% and 30% deformation were carried out at high temperature at 0.05 $s^{-1}$,0.1 $s^{-1}$ and 0.2 $s^{-1}$ deformation rates, respectively, the influence of tensile rate on the microstructure of the coating was examined (Fig. 5).

The microstructure of Al-Si coating is almost the same, the morphology of adhesive layer is not obviously different, the Al-Si layer is composed of Al-rich phase and Si-rich phase, the proportion is similar. The deformation rate of 0.1 $s^{-1}$ is better than that of 0.2 $s^{-1}$ is better than that of 0.05 $s^{-1}$. The reason for this phenomenon is that the 0.05 $s^{-1}$ deformation rate makes the whole experimental process last longer and the micro-crack has more sufficient time to grow (Fig. 6).



(a) 0.05 $s^{-1}$deformation rate (b) 0.1 $s^{-1}$deformation rate (c) 0.2 $s^{-1}$deformation rate

**Fig. 6.** Microstructure after 30% deformation at different rates after heated.

The structure of the coating was similar under 30% deformation. A large number of cracks appeared from the surface layer to the adhesive layer. In comparison, the number of cracks and flaking off of 0.1 $s^{-1}$ and 0.05 $s^{-1}$ coatings are the lightest, and the cracking and flaking off degree of 0.2 $s^{-1}$ and 0.05 $s^{-1}$ coatings are similar.

Based on the above results, it is shown that a suitable tensile rate will result in a coating with fewer cracks. And a lower tensile rate will lead to a longer deformation time and more cracks, too high drawing rate makes the coating easy to flaking off at the later stage of deformation. In comparison, the coating with 0.1 $s^{-1}$ deformation rate has the least crack and flaking off in the whole tensile process at high temperature.

## 4 Conclusion

(1) At the same heating temperature and holding time, the thicker the coating is in the range of 60–150 g/$m^2$, the more the holes and cracks are.
(2) With the same coating thickness, the higher the heating temperature, the longer the heat holding time, the more cracks in the coating after heating, the greater the width of the crack, and the direction of the crack will be vertical to the coating from the original vertical to vertical & parallel.
(3) Under the same coating thickness and the same heating process, the number of cracks in the coating varies with different tensile rate. The proper tensile speed can reduce the number of cracks. The slower or faster the drawing rate is, the more cracks there are.

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