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Wiping Effect of CGL on Appearance of Hot-Dip Coated Steel Sheets

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Abstract:

During processing of steel strip in CGL (Continuous hot-dip Galvanizing Line), jet flow of wiping nozzle splashes molten zinc. The attachment of foreign material of molten zinc that is called splash to the surface of the wiping nozzle causes longitudinal striped pattern that is called linear mark on the galvanized steel strip. This paper presented a clarification of generation conditions and a quantification of linear mark based on experiments with a laboratory wiping simulator and a CFD analysis. First, the experiments revealed that although attachment of the foreign material to the front edge or the upper part of the wiping nozzle had an insignificant effect on surface quality, blocking of the slit gap greatly affected the generation of linear mark. Second, it was shown that the linear mark caused by blocking of the slit gap was quantifiable based on a CFD analysis and a wiping theory.

1. Introduction

The gas wiping process is a technique in which the coating thickness of a liquid is controlled by a jet flow. This technique has been used for many years to control the coating thickness of molten zinc in continuous hot-dip galvanizing lines (CGL). At CGLs, the coating thickness is controlled to the specified value by removing the excess molten zinc from the steel strip by blowing an air or nitrogen gas jet on the strip with wiping nozzles, which are installed above the molten zinc pot facing the front and back sides of the strip. The process that has the greatest influence on the appearance of hot-dip coated steel sheets at CGLs is this gas wiping process.

For example, the jet flow of the wiping nozzles causing splashing of molten zinc as a foreign material[1)], which is called splash, and the splash adhering to the surface of the wiping nozzles influences the jet flow, causing a longitudinal striped pattern called linear mark. Because this linear mark pattern is recognized as an appearance defect in severe cases, various countermeasures have been developed, including a cleaning device that automatically removes the foreign material adhering to the wiping nozzle[2)] and a technique for preventing the occurrence of splash as such[3)], thereby eliminating the cause of linear mark. However, there are no examples of quantitative analysis of the conditions for generation of this striped pattern, such as the influence of foreign material of a certain size, the influence of the location where the foreign material adheres, etc. Therefore, in this report, the conditions for generation of linear mark were elucidated and quantified by an experiment using a laboratory wiping simulator and a computational fluid dynamics (CFD) analysis and wiping theory.

2. Linear Mark

Figure 1 shows a photograph of linear mark that occurred at a CGL. Linear mark is a longitudinal striped pattern parallel to the transfer direction of the steel strip. **Figure 2** shows the coating thickness of linear marks and a normal coating area. The coating thickness was measured with an eddy-current film thickness meter (SWT-9000, Sanko Electronic Laboratory Co., Ltd.). The average value was calculated by

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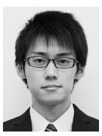
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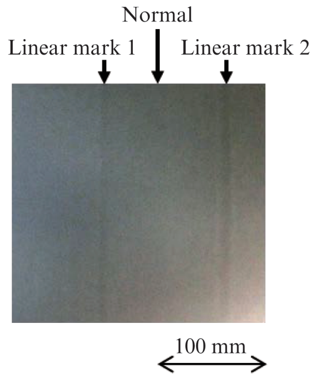

Fig. 1 Photograph of linear mark

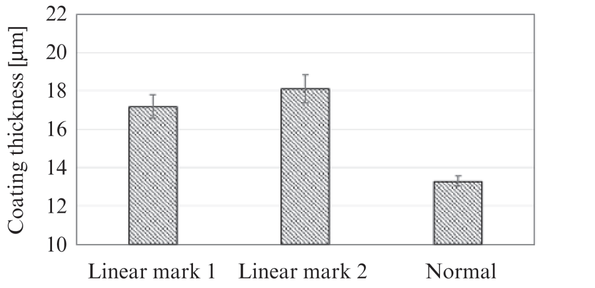

Fig. 2 Coating thickness of linear mark and normal coating (cf. Fig. 1)

measuring 10 points in the longitudinal direction of the respective areas. The measurement range of one measurement was ϕ2 mm with the position of the probe as the center. The coating thickness of the linear marks was 4–5 μm thicker than that in the normal area. Thus, these measurements revealed that due to variations in the thickness of the zinc coating, it can be recognized visually as the linear mark.

3. Experiment with Laboratory Wiping Simulator

3.1 Experimental Method

As mentioned above, it was known that adhesion of the molten zinc as a foreign material called splash on the wiping nozzle is the cause of linear mark, but the influence of the adhesion position and size of the foreign material was not known. Therefore, the influence of these factors was investigated with a wiping simulator. **Figure 3** shows a schematic diagram of the experimental set-up. As the equipment composition, after a preheated steel strip is immersed in the molten zinc pot, the zinc coating thickness is adjusted by the gas jets of the wiping nozzles, and the strip is then coiled. **Table 1** shows the experimental conditions.

Figure 4 shows a schematic diagram of the wiping nozzle used in this experiment. The nozzle has an axially symmetrical shape with the centerline of the slit gap as its axis. As the dimensions of the nozzle tip, the

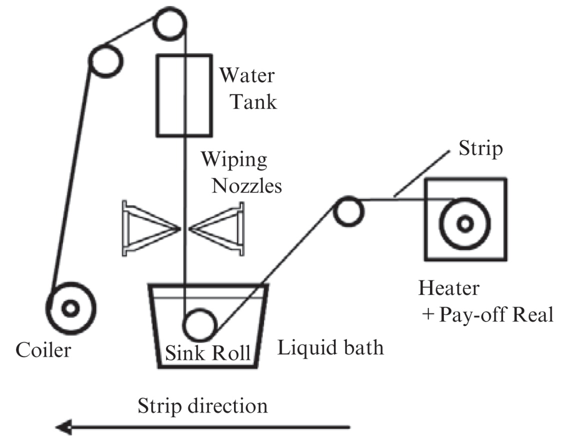

Fig. 3 Schematic of wiping simulator

Table 1 Experimental condition

Coating material	Zinc
Strip size [mm]	0.45 t×100 w
Bath temperature [˚C]	470
Transfer speed [m/min]	50
Nozzle-strip distance [mm]	10
Plenum pressure [kPa]	20

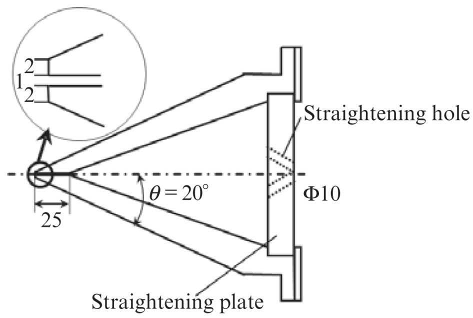

Fig. 4 Schematic of wiping nozzle

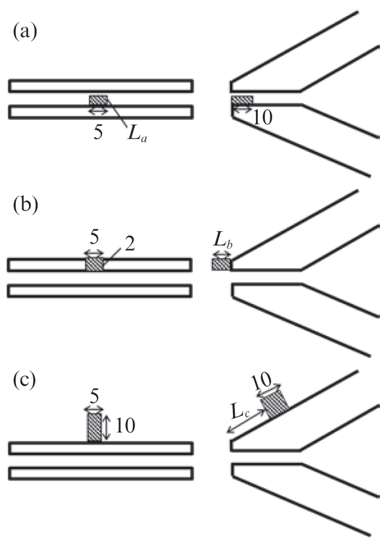

Fig. 5 Attachment position of block to wiping nozzle
(a) Slit gap (b) Front edge of nozzle (c) Upper part of nozzle

Table 2 Conditions of L_a, L_b and L_c

L_a [mm]	0.05, 0.125, 0.25, 0.5, 1
L_b [mm]	1, 3, 5
L_c [mm]	0, 10, 20

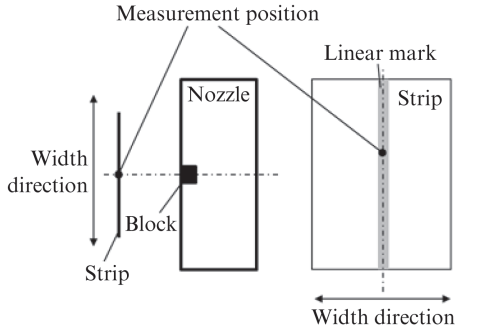

Fig. 6 Example of coating thickness measurement position

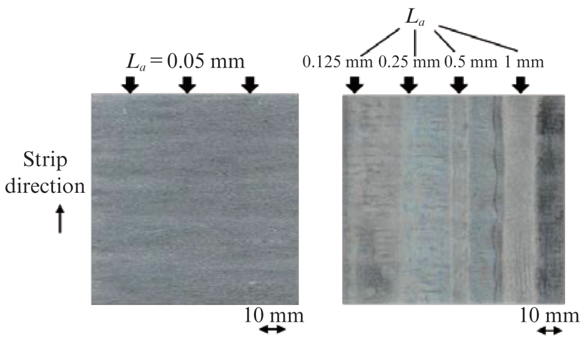

Fig. 7 Photograph of linear mark (Fig. 5 (a))

slit gap is 1.0 mm, the slit length is 25.0 mm and the lip width is 2.0 mm. The nozzle width is 200 mm.

A sponge or cellophane tape was used in place of the actual foreign material. **Figure 5** shows the attachment positions and sizes of the block on the wiping nozzle. The attachment positions of the block were Fig. 5(a) “Slit gap”, Fig. 5(b) “Front edge of nozzle” and Fig. 5(c) “Upper part of nozzle”. As the parameters of the block, L_a is the block height, L_b is the block length and L_c is the distance from the tip.

Table 2 shows the experimental conditions of the parameters in Fig. 5. For comparison, an experiment was also performed in the normal condition (without block).

The coating thickness was measured by the same method as in Fig. 2. **Figure 6** shows an example of the coating thickness measurement positions. Measurements were made at the position directly facing the block attachment position.

3.2 Experimental Results

Figure 7 shows photographs of the steel sheet after the experiment under condition (a), in which the block was attached in the slit gap. A linear mark is not visible at L_a=0.05 mm, but becomes visible at $L_a \geqq 0.125$ mm. Moreover, the linear marks become increasingly visible as L_a increases.

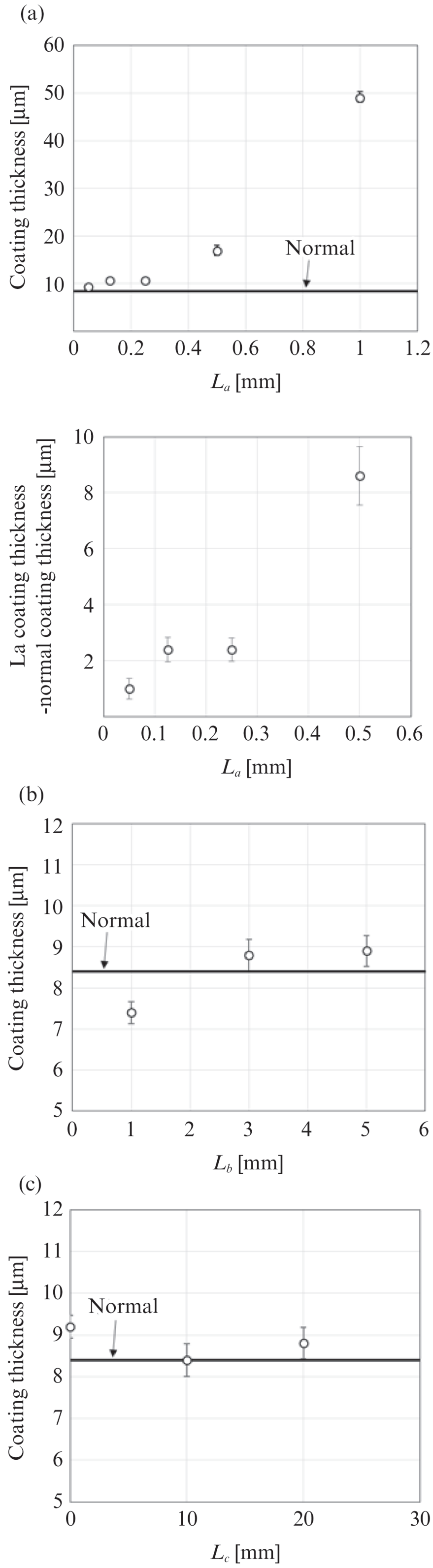

Fig. 8 Influence of block on coating thickness
(a) Slit gap (b) Front edge of nozzle (c) Upper part of nozzle

Figure 8(a) shows the coating thickness under the condition in Fig. 5(a) “Slit gap”, and the difference between the coating thickness of the linear mark and the normal area. Here, "Normal" means the condition without a block. The coating thickness tends to increase as L_a increases. Compared with Fig. 7, it can be understood that the linear mark becomes increasingly visible as the difference in the coating thickness increases. Moreover, because the linear mark is clearly visible at $L_a \geqq 0.125$ mm, the visibility threshold of the coating thickness is considered to be approximately 2 μm.

Fig. 8(b) shows the coating thickness under the condition in Fig. 5(b) "Front edge of nozzle", and Fig. 8(c) shows the coating thickness under the condition in Fig. 5(c) "Upper part of nozzle". Although a linear mark was not visible under either of these conditions, this is thought to be because the difference in the coating thicknesses of the linear mark and the normal area was less than 2 μm.

The results presented above revealed that adhesion of foreign material to the front edge or upper part of the wiping nozzle has an insignificant influence on surface quality, but blocking of the slit gap has a serious effect on the generation of linear mark.

4. CFD Analysis and Wiping Theory

Quantification of linear mark generated by blocking of the slit gap was attempted based on a CFD analysis and wiping theory.

First, the wiping theory will be explained. As a wiping theory, a model like that in **Fig. 9** is known, and it is possible to calculate the coating thickness[4–6]. Here, t is the coating thickness, g is acceleration of gravity, τ is shear stress, p is impingement pressure, ρ_L is the density of a liquid, μ_L is the viscosity of the liquid and V is the strip transfer speed.

Next, the CFD analysis will be explained. **Figure 10** shows the numerical analysis model. The commercial

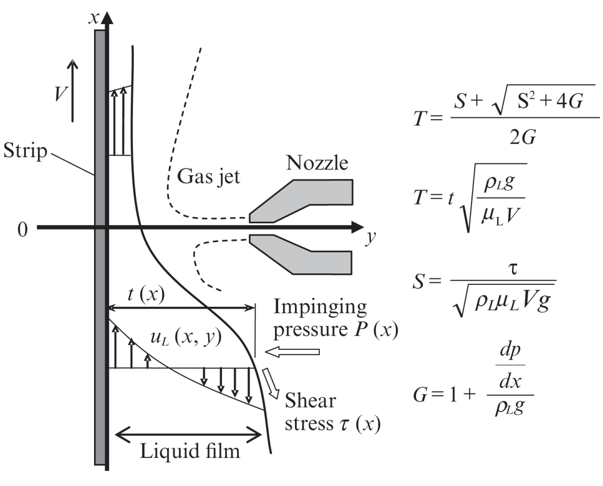

Fig. 9 Wiping theory model

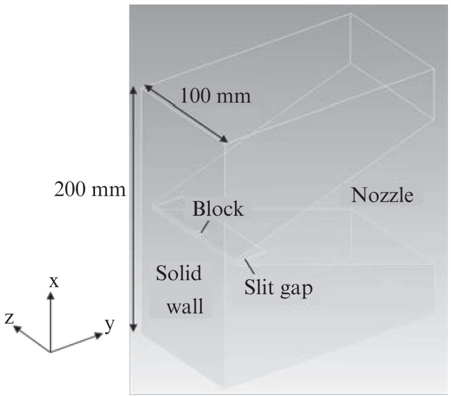

Fig. 10 Numerical analysis model

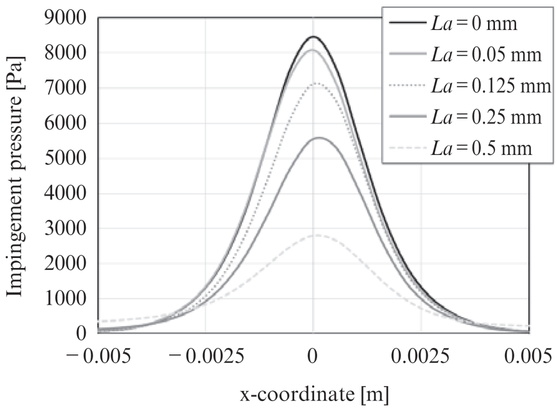

Fig. 11 Distribution of impingement pressure

software, Fluent 15.0, was used in the numerical analysis, and 3-dimensional compressible Navier-Stokes equations were solved. A standard k-ε model was used in the turbulence model, and a standard wall was used in the wall function. The other analytical conditions were the same as those in Tables 1 and 2, but molten zinc was not simulated. The geometry of the wiping nozzle was the same as in Fig. 4. The number of mesh elements was approximately 2.5 million, with some differences depending on the size of the block.

According to Fig. 9, the coating thickness is determined by the impingement pressure of the wiping gas and the shear stress of the gas flowing along the steel strip. Therefore, the influence of the block in the slit gap on the impingement pressure and shear stress was evaluated.

Figures 11 and **12** show the numerical analysis results of the distribution of impingement pressure and the distribution of shear stress, respectively. Figs. 11 and 12 show the distributions in the longitudinal direction at the position directly facing the block, and x=0 is positioned on the centerline of the slit gap. For example, under the condition L_a=0.5 mm (ratio of slit gap blockage: 50%), the maximum impingement pressure decreases by approximately 67% and the maximum shear force decreases by approximately 59% in compar-

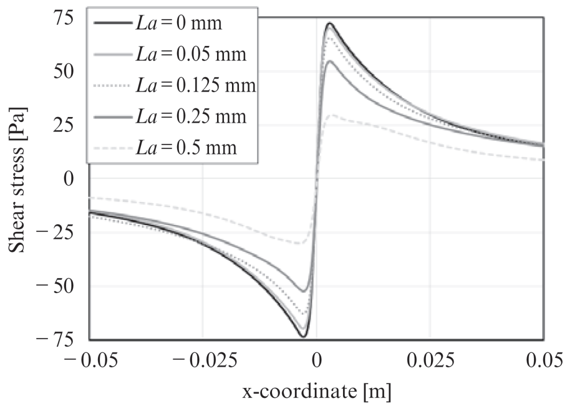

Fig. 12 Distribution of shear stress

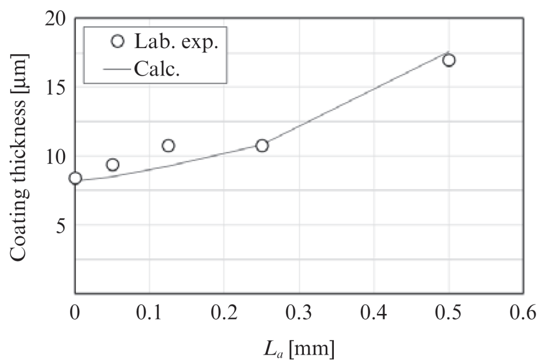

Fig. 13 Influence of slit gap block on coating thickness

ison with the normal condition L_a=0 mm. Moreover, under the normal condition L_a=0 mm, the impingement pressure is symmetrical about an axis at x=0, but as L_a increases, the axis of symmetry shifts in the positive direction of x (i.e., upward in the slit gap). This occurs because the wiping gas flows from the upper part of the slit gap, where its path is not impeded by the block.

Based on the results in Figs. 11 and 12, the coating thickness when the slit gap is partially blocked was calculated using the model in Fig. 9. **Figure 13** shows the calculated results of the coating thickness together with the results of the laboratory experiment (Fig. 8(a)). The calculated results are generally in agreement with the experimental results. This result clarified the fact that it is possible to quantify linear mark generated by blockage of the slit gap by a CFD analysis and wiping theory.

5. Conclusions

In order to elucidate and quantify the conditions for generation of the longitudinal striped pattern called linear mark that occurs in CGLs, an experiment using a laboratory wiping simulator and a CFD analysis were performed. The following conclusions were obtained.

(1) Linear mark becomes visible when the coating thickness difference between the linear mark and the normal area is approximately 2 μm or more.

(2) Although adhesion of foreign material to the front edge or the upper part of the wiping nozzle had an insignificant effect on the coating thickness difference (< 2 μm), blocking of the slit gap greatly affected the coating thickness difference (2 μm or more).

(3) Linear mark generated by blocking of the slit gap is quantifiable based on a CFD analysis and wiping theory.

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