DOI: 10.3901/CJME.2011.03.460, available online at www.cjmenet.com; www.cjmenet.com.cn

Heat Transfer during the Solidification of Hot Dip Aluminizing Coating

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Received February 27, 2010; revised March 11, 2011; accepted March 16, 2011; published electronically March 23, 2011

Abstract: Hot dip aluminizing is one of the most effective methods of surface protection for steels and is gradually gaining popularity. Although the pulling speed is one of the most important parameters to control the coating thickness of aluminizing products, however, there are few publications on the mathematical modeling of pulling speed during the hot dip process. In order to describe the correlation among the pulling speed, coating thickness and solidification time, the principle of mass and heat transfer during the aluminizing process is investigated in this paper. The mathematical models are based on Navier-Stokes equation and heat transfer analysis. Experiments using the self-designed equipment are carried out to validate the mathematical models. Specifically, aluminum melt is purified at 730 ℃. The Cook-Norteman method is used for the pretreatment of Q235 steel plates. The temperature of hot dip aluminizing is set to 690 ℃ and the dipping time is set to 3 min. A direct current motor with stepless speed variation is used to adjust the pulling speed. The temperature change of the coating is recorded by an infrared thermometer, and the coating thickness is measured by using image analysis. The validate experiment results indicate that the coating thickness is proportional to the square root of pulling speed for the Q235 steel plate, and that there is a linear relationship between coating thickness and solidification time when the pulling speed is lower than 0.11 m/s. The prediction of the proposed model fits well with the experimental observations of the coating thickness.

Key words: hot dip aluminizing, coating model, solidification, heat transfer

1 Introduction

Hot dip aluminizing steel has a higher corrosion resistance and more desirable mechanical properties compared with hot dip galvanizing steel[1–3]. The principle of hot dip aluminizing is that the pretreated steel plates are dipped into the molten aluminum alloys at a certain temperature for a suitable time. Aluminum atoms diffuse and react with Iron atoms to form a composite coating of Fe–Al compound and aluminum alloy that has strong bonding force with the matrix to satisfies the requirement of protecting and strengthening the surface[4–6]. In short, hot dip steel material is a kind of composite material with comprehensive properties and of low cost[7–8].

Currently, such techniques as Sendzimir, Non-oxidizing reducing, Non-oxidizing and Cook-Norteman are usually employed for hot dip aluminizing, through which large-scale productions can be realized due to their high efficiency of production, stable quality of products and less pollution[9–11]. Among the four technologies, Sendzimir, Non-oxidizing reducing and Non-oxidizing are characterized by complex processes, expensive equipment and high cost. Nowadays, the Cook-Norteman method becomes widely used owing to the advantages of flexible processes, low cost and environment friendly.

For hot dip aluminizing process, the coating thickness is an important criterion to evaluate the coating quality and plays a key role in determining the properties of the coating[12]. How to control the coating thickness during the hot dip process is therefore considered crucial in guaranteeing an excellent coating quality. As we already know, there is a close coupling correlation among the coating thickness, pulling speed and solidification time[13,14]. Therefore, in order to control the hot dip process and improve the coating quality, it is necessary to build up a mathematical model that can describe this correlation.

In this paper, the mathematical model of coating thickness and pulling speed is derived from the Navier-Stokes equation. The heat transfer during coating solidification is analyzed, and the relationship of coating thickness and solidification time is established. The experiments of hot dip aluminizing Q235 steel plates based on Cook-Norteman method are carried out with a self-made equipment. The real temperature and thickness coating are measured accordingly. The theoretical derivations are illustrated and confirmed by the experiments.

2 Mathematical Model

2.1 Correlation between pulling speed and coating thickness

The schematic diagram of pulling process is shown in

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This project is supported by Guangxi Provincial Natural Science Foundation of China (Grant No. 0832001)

Fig. 1. In x direction, Navier-Stokes equation can be written as[15]

$$\rho\frac{\mathrm{d}u_z}{\mathrm{d}t}=\frac{\partial}{\partial z}\left(2\mu\frac{\partial u_z}{\partial z}-\frac{2}{3}\mu\nabla\cdot u\right)+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u_z}{\partial x}+\frac{\partial u_x}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u_z}{\partial y}+\frac{\partial u_y}{\partial z}\right)\right]-\frac{\partial p}{\partial z}+\rho F_{x(y,z)}. \tag{1}$$

Where μ—Viscosity of liquid aluminum (Pa • s),
ρ—Ddensity of liquid aluminum (kg/m^3),
p—Pressure (Pa),
t—Time (s),
u—Speed (m/s),
$F_{x(y,z)}$—Unit mass force in x (y, z) direction (N).

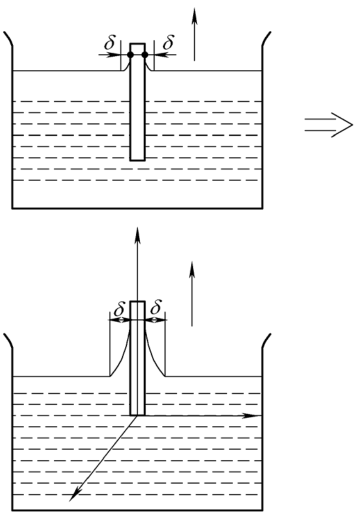

Fig. 1. Schematic diagram of pulling process of coating parts

If u is uniform, then

$$\begin{cases} u_x=u_y=0, \\ \dfrac{\mathrm{d}u_z}{\mathrm{d}t}=0, \\ \dfrac{\partial u_z}{\partial z}=0. \end{cases} \tag{2}$$

Eq. (1) will be abbreviated to

$$\rho g_x+\mu\frac{\mathrm{d}^2u_x}{\mathrm{d}x^2}=0, 0\leqslant x\leqslant\delta. \tag{3}$$

The boundary conditions are as follows.
When δ=0, u=0; when $x=\delta$, $\mathrm{d}u_z/\mathrm{d}t=0$, then

$$u=\frac{\rho g}{\mu}\left(\delta x-\frac{1}{2}x^2\right), \tag{4}$$

When $x=\delta$,

$$u=\frac{\rho g\delta^2}{2\mu}, \tag{5}$$

or

$$\delta=\sqrt{\frac{2\mu u}{\rho g}}, \tag{6}$$

where δ—Coating thickness (m),
g—Acceleration of gravity (m/s^2).

2.2 Heat transfer during the solidification of coating

Since the aluminum coating is very thin, it can be taken as parallel fluid flowing on the flat surface of plated pieces. Then it can be analyzed from x direction. The schematic diagrams of coating-substrate are presented in Fig. 2 and the temperature distribution is shown in Fig. 3.

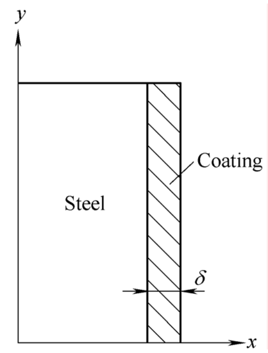

Fig. 2. Schematic diagram of coating-substrate

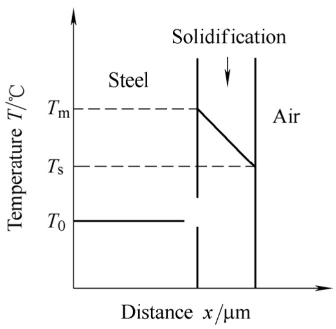

Fig. 3. Temperature distribution of coating-substrate

After the steel is pulled out from the molten aluminum, an aluminum film is formed on the steel surface. According to Newton's law of cooling, the heat flux density between the coating and the air can be written as

$$q_1=h(T_s-T_0), \tag{7}$$

where T_s—Interfacial temperature (℃),
T_0—Ambient temperature (℃),
h—Heat transfer coefficient (W/(m^2 • ℃)).

Equally, according to Fourier's law[16], the heat flux between the coating and the steel can be written as

$$q_2 = \lambda \frac{T_m - T_s}{\delta}, \tag{8}$$

where T_m—Coating temperature (℃),
λ—Thermal conductivity (W/(m • ℃).

Taking the heat balance into consideration, we have $q_1 = q_2$, and then T_s can be solved by Eqs. (7) and (8):

$$T_s = \frac{\lambda T_m + \delta h T_0}{\delta h + \lambda}, \tag{9}$$

therefore, q_1 can be expressed by

$$q_1 = h\left(\frac{\lambda T_m + \delta h T_0}{\delta h + \lambda} - T_0\right), \tag{10}$$

or

$$q_1 = (T_m - T_0)\left(\frac{\delta}{\lambda} + \frac{1}{h}\right)^{-1}. \tag{11}$$

During the solidification process, the released latent heat q_3 can be written as

$$q_3 = \rho H \frac{d\delta}{dt}, \tag{12}$$

where H—Latent heat of solidification (J/kg).

The released latent heat q_3 during the solidification process is equivalent to the heat flux q_1, or

$$(T_m - T_0)\left(\frac{\delta}{\lambda} + \frac{1}{h}\right)^{-1} = \rho H \frac{d\delta}{dt}, \tag{13}$$

or

$$\frac{(T_m - T_0)\lambda h}{\delta h + \lambda} = \rho H \frac{d\delta}{dt}. \tag{14}$$

Then, Eq. (14) can be changed to

$$(T_m - T_0)\lambda h t = \frac{1}{2}\rho H h \delta^2 + \rho H \lambda \delta, \tag{15}$$

Because the coating is extremely thin，the first term with δ^2 on the right of Eq. (15) can be neglected, then

$$t = \frac{\rho H}{(T_m - T_0)h}\delta. \tag{16}$$

Eq. (16) indicates that the solidification time of the coating has a linear correlation with the coating thickness.

3 Experiments

The hot-dip aluminizing experiments were carried out to validate the mathematical models. Q235 steel plates with 3 mm thick were used and the details of the chemical composition were shown in Table 1. The steel plate was cut into 70 mm×30 mm×3 mm blocks, and on each block a hole of diameter 10 mm was drilled by using a bench drilling machine, as shown in Fig. 4.

Table 1. Chemical composition of Q235 for experiment

Element	C	Mn	Si	S	P	Fe
Weight percentage w/%	0.12	0.60	0.45	0.053	0.046	Bal.

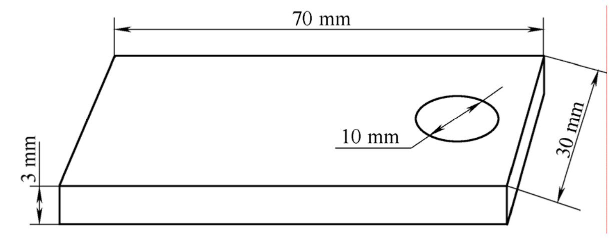

Fig. 4. Schematic diagram of experiment sample

Industrial pure aluminum was used for the hot dip material and its chemical composition is shown in Table 2.

Table 2. Chemical composition of Aluminum coating

Element	Fe	Si	Mg	Zn	Cu	Al
Weight percentage w/%	0.12	0.08	0.03	0.03	0.005	Bal.

The coating thickness was measured by an optical microscope equipped with image analysis software. An infrared radiation thermometer was used to record the coating temperature continuously in the solidification process. Schematic diagram of temperature curve recording is shown in Fig. 5.

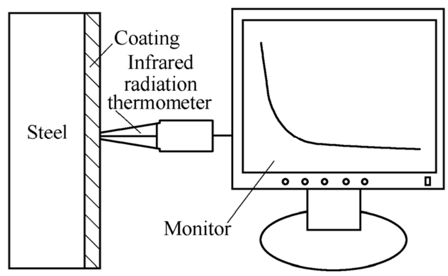

Fig. 5. Schematic diagram of temperature curve recording

The procedure of hot dip aluminizing is as follows.

(1) Preparation. The pure Al was melt at 800 ℃. After all of the materials were melt, the furnace must be reduced to the temperature of 730 ℃ for melt treatment. All of the tools used in the experiment were coated by the aqueous solution of ZnO and Na_2SiO_3.

(2) Melt-treatment. The C_2Cl_6 powders with weight percentage of 1% of the Al were used to degas the pure Al

melt. The C_2Cl_6 powders wrapped by pure Al foil were pressed into melt by using bell jar at the temperature of 730 ℃. The melt was stirred for about 10 min, and then was deslagged thoroughly.

(3) Degreasing with alkali. The samples were degreased in the mixture solution of 10–15% NaOH with 15 g/L Na_2CO_3 at the temperature of 50–80 ℃ for 10 min, and then washed clean with hot water.

(4) Pickling with chlorohydric acid. In order to remove the rust, the samples were pickled in 31% HCl solution for 2 min and then washed clean with water. Afterwards, groups of 9–12 samples were immersed into aqueous solution of 30–50 g/L vitriol and 200–300 g/L chromium trioxide for 2–3 min for further cleansing.

(5) Assistant plating. The sample assistant plating was carried out in the solution of $B(OH)_3$ and NaCl at the temperature of 70–80 ℃, for more than 2 min. The sample drying temperature was set to 300 ℃. The equipment of assistant plating was shown in Fig. 6.

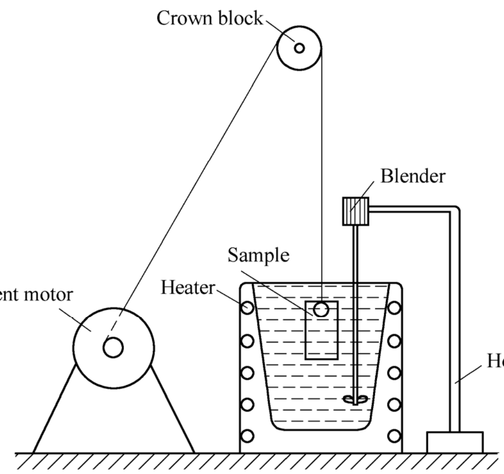

Fig. 6. Apparatus of assistant plating

(6) Dipping. The aluminizing temperature was set to 690 ℃ and the time set to 3 min. The pulling speeds in these experiments were set to 0.02 m/s, 0.05 m/s, 0.08 m/s, 0.11 m/s and 0.14 m/s. The dipping equipment was shown in Fig. 7. The direct current motor with stepless speed variation can provide any pulling speed for the samples to finish the experiment conveniently.

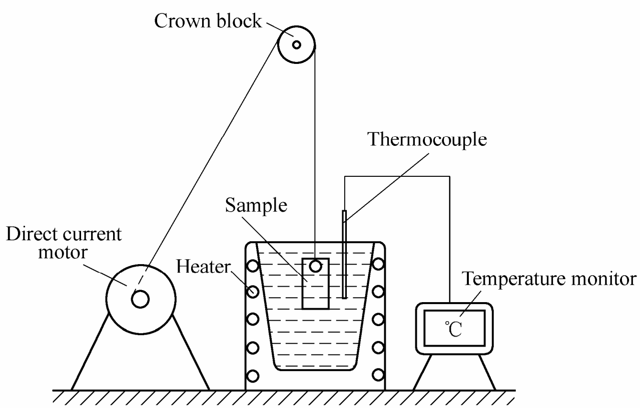

Fig. 7. Apparatus of hot dipping

(7) Cooling. Air cooling.

4 Discussion

Fig. 8 shows the appearance of a pure aluminum dipped steel with a pulling speed of 0.08 m/s. The cooling curve recorded by the infrared radiation thermometer is shown in Fig. 9.

Fig. 8. Appearance of dipped steel

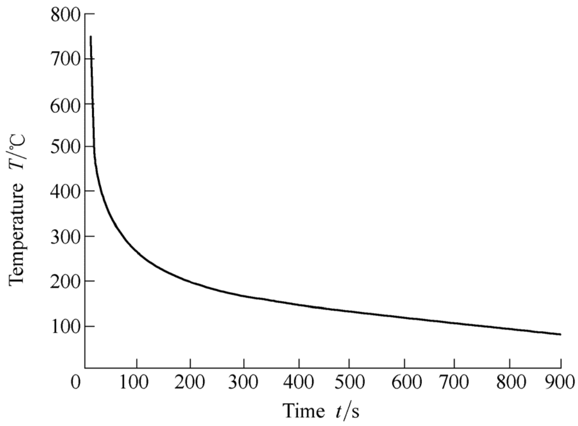

Fig. 9. Cooling curve of plated sample

The temperature of the surface dropped sharply within a short time period after the sample had been pulled out. In the tested curve, there is a brief moment when the temperature remains 654 ℃, which shows that the coating is in the solidification stage. During the hot dip process, the pulling speed has a key impact on the reflux of molten aluminum, which is crucible to the coating's thickness.

Fig. 10 is the metallograph of the sample with a pulling speed of 0.08 m/s. The measurement of the coating thickness of samples is carried out with the help of image analysis. The result is shown in Fig. 11.

As shown in Fig. 11, the calculated result is in good agreement with the experiment when the speed is lower than 0.11 m/s. It should be pointed out that the coating thickness could not increase without limit as described in Eq. (6). In fact, when the pulling speed exceeds 0.11 m/s, the coating thickness does not increase any more. As long as the pulling speed is below this threshold, the coating thickness can be controlled by means of changing the pulling speed.

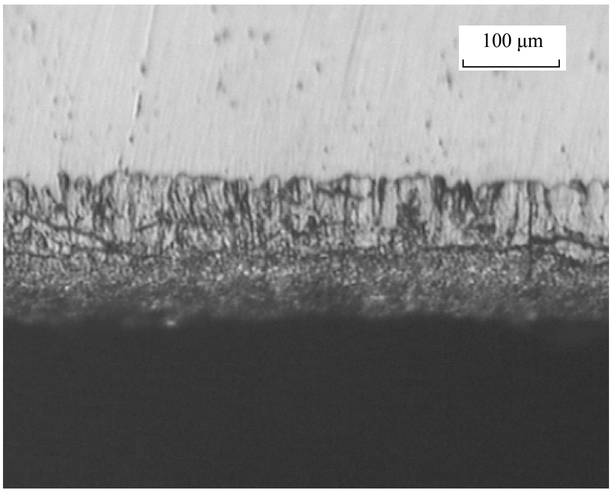

Fig. 10.　Metallograph of the sample with a pulling speed of 0.08 m/s

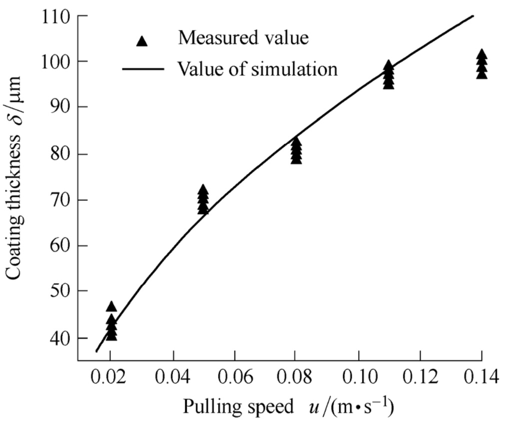

Fig. 11.　Relationship between pulling speed and coating thickness

According to the previous analysis, the pulling speed also has a certain impact on the solidification time. The faster the pulling speed is (as long as it's under the 0.11 m/s threshold), the longer the solidification process requires. The experimental result of solidification time of the coating is shown in Fig. 12. It can be seen that the solidification time is almost linear to the thickness of the coating in the displayed range.

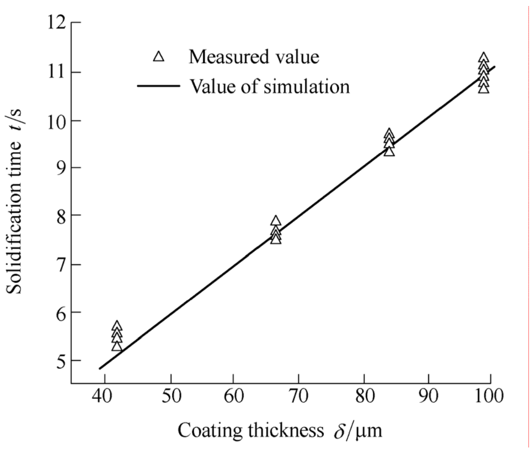

Fig. 12.　Relationship between coating thickness and solidification time

As a numeric example, let u=0.08 m/s, μ=1.196 Pa • s, g=9.8 m/s^2, ρ=2 700 kg/m^3, H=397.4 kJ/kg, T_m=660 ℃, T_0=20 ℃. According to Eq. (6),

$$\delta = \sqrt{\frac{2\times 1.196\times 10^{-3}\times 0.08}{2\,700\times 9.8}} = 84\times 10^{-6}\ \text{m}.$$

Put δ into Eq. (16), the solidification time t can be obtained:

$$t = \frac{84\times 10^{-6}\times 2\,700\times 397\,400}{15\times(660-20)} = 9.4\ \text{s}.$$

Fig. 12 shows that the calculated value is in agreement with the experiment.

5　Conclusions

(1) The mathematical model among the pulling speed, coating thickness and the solidification time is built. The coating thickness is proportional to the square root of the pulling speed. The solidification has linear correlation with the coating thickness.

(2) For the Q235 steel plate, the coating thickness is proportional to the square root of pulling speed when the speed is lower than 0.11 m/s. If the pulling speed exceeds 0.11 m/s, the thickness does not increase accordingly. The coating thickness has a linear correlation with the solidification time.

(3) The mathematical model fits well with the experimental results and can be used to predict the coating thickness. The model is applicable in industrial production.

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