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Effect of Steel Drying Time on the Thickness of the Zinc Coating during the Hot-Dip Galvanizing Process

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Abstract

The thickness of the zinc layer on galvanised steel is a significant issue in the field of hot galvanising. This study evaluates how the drying time during the hot galvanisation of 3 mm thick high-silicon steel plates influences the growth of the zinc coating. The results showed that drying times of less than approximately 15 minutes significantly reduce both the coating thickness and the average mass of deposited zinc, while longer durations reverse this trend. For temperatures of 450˚C, 451˚C, 453˚C, and 454˚C, we have a thickness reduction from 72 µm to 68 µm, from 74 µm to 62 µm, from 72 µm to 69 µm, and from 74 µm to 62 µm, respectively. This allows us to affirm that taking this parameter into account can help reduce zinc consumption and the production cost of galvanised steel.

Keywords

Galvanized Steel, Zinc, Galvanization, Drying Time

1. Introduction

Steel is considered the primary construction material. However, steel corrodes when exposed to corrosive environments. Fortunately, there are various methods to prevent corrosion. Among these methods, zinc coatings are widely used to protect steel [1]. Hot-dip galvanizing is the most important zinc coating process. During hot-dip galvanizing, a zinc coating is formed on steel substrates by immersing them in a molten zinc bath at a temperature of 450˚C [2]-[4]. During this galvanization process, iron and zinc diffuse, forming inseparable metallurgical compounds, bonded atom by atom. A layer of Fe-Zn mixture is then formed. The Fe-Zn mixture formed in the outer layer consists of Eta (η), Zeta (ζ), and Delta (δ) phases, while the layer at the steel interface consists of Gamma (γ) phase [2] [5] [6]. The Eta (η) phase is the outer layer, composed of 100% pure zinc (Zn). The Zeta (ζ) phase is the second outer layer after the Eta (η) phase. It is composed of approximately 94% Zn and 6% Fe. The next layer is the Delta (δ) layer, composed of approximately 90% Zn and 10% Fe. The last layer is the Gamma (γ) layer, composed of approximately 75% Zn and 25% Fe [6]. Hot-dip galvanizing protects steel from corrosion in an economical and environmentally friendly way and increases the service life of steel products. However, hot-dip galvanizing of reactive steels is problematic due to the presence of silicon (Si) and phosphorus (P), which significantly increase the thickness of the zinc coating and consequently give it a gray appearance and poor quality [5] [7]. Adding other chemical elements to the zinc bath affects the quality of the coatings obtained and helps to limit zinc consumption [7]. Over coating of the zinc layer in the hot-dip galvanizing process is a common problem in the galvanizing industry. The appropriate thickness of the zinc layer is an essential requirement in any galvanizing process, as the corrosion resistance of galvanized products depends on the thickness of the zinc layer. The cost of zinc coating steel depends, to a large extent, on zinc consumption. Therefore, increased production costs due to excess zinc is a major problem in the hot-dip galvanizing process. A significant amount of zinc is lost due to unnecessary zinc consumption. Any excessive or insufficient thickness is undesirable and affects the corrosion resistance of the galvanized coating [3]. A thick coating does not guarantee that the coating will protect the steel perfectly. On the contrary, according to some studies, the thicker the coating, the greater the risk of coating failure. Vischwanatha *et al.* found that the corrosion rate increases with the thickness of the zinc coating by studying the behavior of galvanized steel in a 3.5% NaCl solution [8]. The thickness of zinc is influenced by various factors. We can cite from the literature the various factors that influence the thickness of the zinc coating during the galvanizing process. These include the duration of immersion [6] [7] [9], the temperature of the zinc bath [2] [10] [11], the composition of the zinc bath and the composition of steel [7]. Among the factors likely to influence the thickness of the zinc coating, the drying time after the flux bath seems to be ignored in the literature. Contrary to the assertion by Akamphon *et al.* who claim that not using an oven would reduce zinc consumption by a further 8% and even estimate that this omission saves on bath and oven equipment, thermal energy, and labor required for the process [12]. It should be noted that the drying time in the oven plays an important role in the galvanizing process. Drying must be complete in order to prevent liquid zinc from splashing when the parts are placed in the zinc bath. This uncontrollable loss of zinc contributes to significant zinc waste [3]. Secondly, poor drying could affect the thickness of the coating on galvanized steel. The main objective of this study is to show that drying time can have a significant effect on the growth of galvanized steel thickness during hot-dip galvanizing.

2. Materials and Methods

2.1. Sample Preparation

The experiments were conducted using high-silicon steel. The samples were cut into square slices measuring 80 × 80 mm and 3 mm thick. The composition of the steel substrate is shown in Table 1. The choice of a plate thickness of 3 mm is purely arbitrary and mainly experimental. No rigorous scientific study has examined the effect of the steel section thickness on the drying time of the steel after it exits the flux bath during the galvanization process. However, our feedback from industrial galvanization experiences has shown us that the drying time is dependent on the thickness of the steel plates. The thickness of the steel has a considerable influence on the drying time of the steel during the galvanization process. Indeed, a thicker steel must retain more heat. Humidity evaporates more slowly. Steel with a larger cross-sectional size must undergo a longer drying period. Nevertheless, an adequate drying time is crucial regardless of the steel section, as moisture can lead to surface defects and additional zinc consumption.

Table 1. Chemical composition of steel.

Element	C	P	Si	Mg	S	Al	Cr	Fe
Weight (%)	0.12	0.04	0.87	0.22	0.06	0.17	0.02	balance

2.2. Hot-Dip Galvanizing Process

The hot-dip galvanizing of our samples in this study was carried out in accordance with ISO 1461 under industrial conditions. The samples were first sandblasted in the sandblasting workshop. Sandblasting, like degreasing, serves to remove soluble fats, oils, and lubricants. This was followed by pickling the samples in a hydrochloric acid solution. The samples were then rinsed and immersed in a flux bath composed of ammonium chloride (NH_4 Cl) and zinc chloride ($ZnCl_2$). Before the zinc adheres to the surface of the steel, the surface of the steel must be properly dry. Otherwise, a partially dried surface causes explosions and zinc projections upon contact with molten zinc. This results in zinc losses, areas of discontinuity, or excess thicknesses. Fluxing is a crucial step in the hot-dip galvanizing process, essential for the complete removal of residual salts and iron oxides that may persist on the steel surface after pickling and rinsing. The flux (zinc chloride and ammonium chloride) must decompose thru heat. An incomplete decomposition leaves residues that act as barriers. A clean and rapid decomposition promotes immediate iron-zinc contact, allowing growth reactions to start instantly across the entire surface, ensuring a minimum regular thickness from the very first second Iron and zinc migrate toward each other to form crystalline alloy layers (Gamma(r), Delta(δ), Zeta(ζ), Eta(η)). From the moisture that evaporates to the flux that decomposes, allowing for the interdiffusion of iron and zinc, the formation of the zinc layer thickness occurs, whose evolution formally depends on physical parameters, among which is the drying time. These two steps are essential for optimal growth of the zinc coating. The samples were hot-dip galvanized in a molten zinc bath at 450˚C, 451˚C, 453˚C, and 454˚C. The oven temperature of 452˚C was deliberately omitted because it presumably gives the same results as the oven temperature of 451˚C. The temperature step of ±1˚C, depending on whether the temperature increases or decreases, strongly influences the results. The instability of the temperature between 451˚C and 452˚C was the main reason for the omission of 452˚C.

The samples are then cooled in the open air. The extraction speed and immersion time are set at 0.01 m/s and 3 min, respectively. The galvanization tests were carried out in an oven operating at 99.995% zinc. The thickness of the zinc coating after galvanization was measured using a microtest. The drying time is measured using a stopwatch. The samples are dried using the heat from the galvanizing furnace. The measurement of the drying temperature begins when the samples are placed above the galvanization bath. The duration from the exit of the flux bath to the position of the samples above the galvanization bath was not taken into account in the drying time. We assumed it to be negligible. We consider the samples sufficiently humid and have minimized the effect of ambient air temperature on the samples. For accuracy, each test was repeated twice. Temperature control was ensured by a type K thermocouple and a digital temperature regulator.

2.3. Measurement of Average Coating Mass

The determination of the average deposited mass is governed by ISO 1460. The average mass per unit area is calculated as follows:

$$m_z = m_f - m_o \tag{1}$$

where m_f represents the final mass of the sample, mass before immersion in the solution of dissolution and m_o initial mass, mass after dissolution of coating.

The chemical dissolution solution consists of 3.5 g of hexamethylenetetramine, 500 mL of hydrochloric acid, and 1000 mL of distilled water. The samples are first degreased, weighed before dissolution, completely immersed in the dissolution solution at room temperature, rinsed with running water, brushed to remove any residue adhering to the surface, immersed in alcohol, dried quickly, and finally weighed again.

The air volume of the exposed surface of each sample must be known precisely. The average mass Y per unit surface area is calculated as follows:

$$Y = \frac{m_z}{A_S} \tag{2}$$

The average coating weight is expressed in g/m², m_z, average zinc weight, and A_S being the surface area of the sample.

3. Results and Discussion

A series of experiments was conducted by varying the drying time of reactive steel samples at different zinc bath temperatures while keeping the immersion time and extraction speed constant. The coating thickness and average mass of zinc deposited per unit area were then calculated for each test and plotted against drying time. This gave us the various figures shown below:

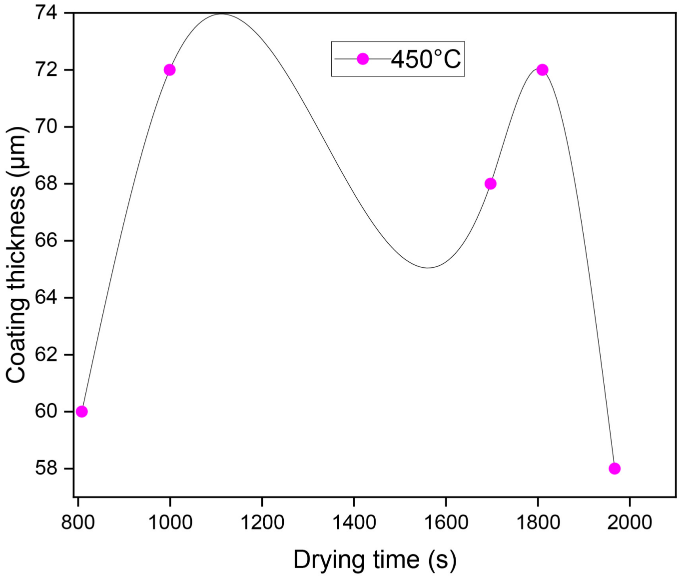

Figure 1. Effect of drying time on the thickness of the coating on galvanized steel at 50˚C.

Figure 1 shows that between 800 s and 1000 s, there is an increase in coating thickness from 60 µm to 72 µm. From 1100 s to 1500 s, there is a decrease in coating thickness from 72 µm to 68 µm. From 1700s to 1800s, there is an increase in coating thickness from 68 µm to 72 µm. And finally, between 1800s and 1980s, there is a decrease in coating thickness from 72 µm to 58 µm.

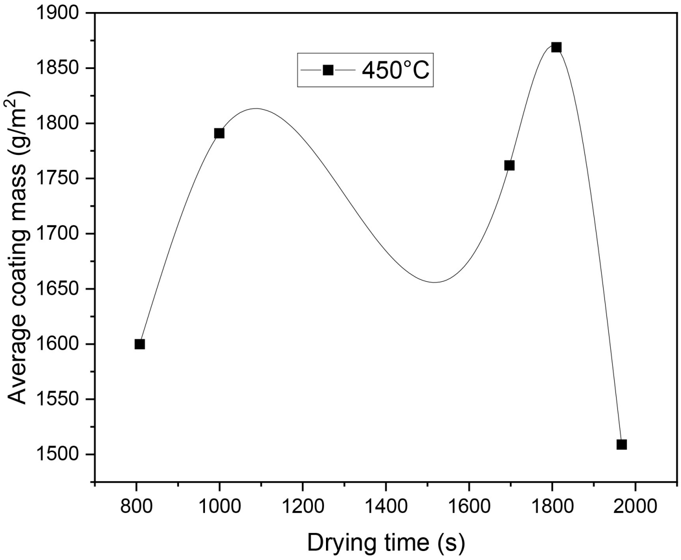

Figure 2. Effect of drying time on the average mass of the coating on galvanized steel at 450˚C.

Figure 2 shows an increase in average mass from 1600 g/m^2 to 1800 g/m^2 for drying times between 800 s and 950 s. From 950 s to 1625 s, there is a slight decrease in average coating mass from 1800 g/m^2 to 1750 g/m^2. From 1700 s to 1800 s, there is a slight increase in the average mass of the coating from 1750 g/m^2 to 1850 g/m^2. Finally, between 1800 s and 1980 s, there is a decrease in the average mass of the coating from 1875 g/m^2 to 1500 g/m^2.

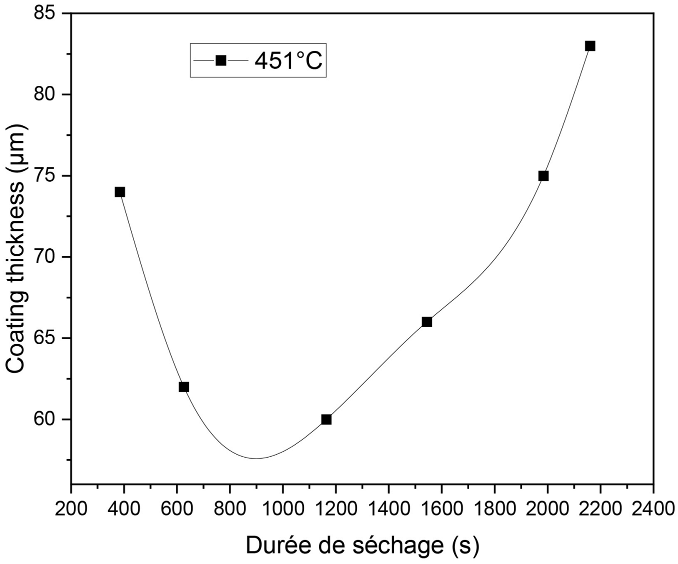

Figure 3. Effect of drying time on the thickness of the coating on galvanized steel at 451˚C.

Figure 3 shows that the thickness of the zinc coating gradually decreases for drying times of less than 900 seconds (15 minutes). Beyond 15 minutes, we observe an increase in coating thickness. Below 15 min of drying, the coating thickness decreases from 74 μm to 62 μm. After 15 min of drying, the coating thickness increases rapidly from 59 μm to 83 μm.

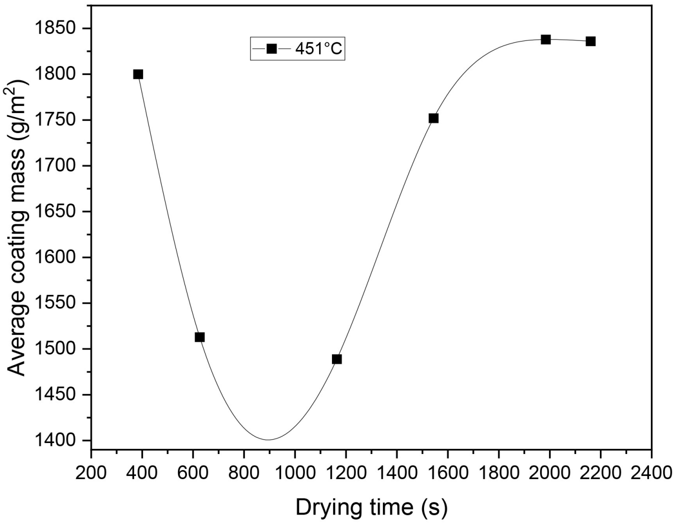

Figure 4. Effect of drying time on the average coating weight of galvanized steel at 451˚C.

Figure 4 shows that the average coating weight decreases when the drying time is less than 900 seconds, or 15 minutes. It increases for drying times longer than 15 minutes. Below 15 minutes of drying. The coating thickness decreases from 1800 g/m^2 to approximately 1500 g/m^2. A drying time greater than or equal to 15 minutes causes a rapid increase in the average mass of zinc deposited to approximately 1825 g/m^2.

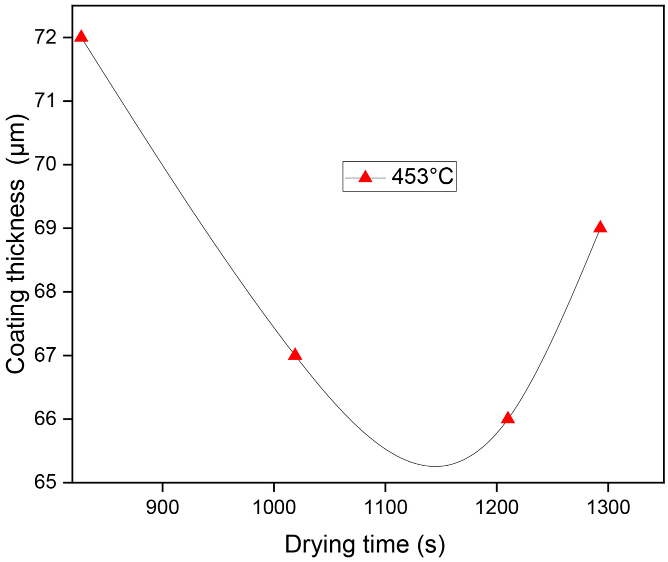

Figure 5. Effect of drying time on the thickness of the coating on galvanized steel at 453˚C.

Figure 5 shows that at 453˚C, the thickness of the zinc coating decreases for drying times of less than 1150 s (19 minutes). The thickness decreases from 72 µm to 65 µm. An increase in coating thickness from 64 µm to 69 µm is observed for drying times longer than 1150 s (19 minutes).

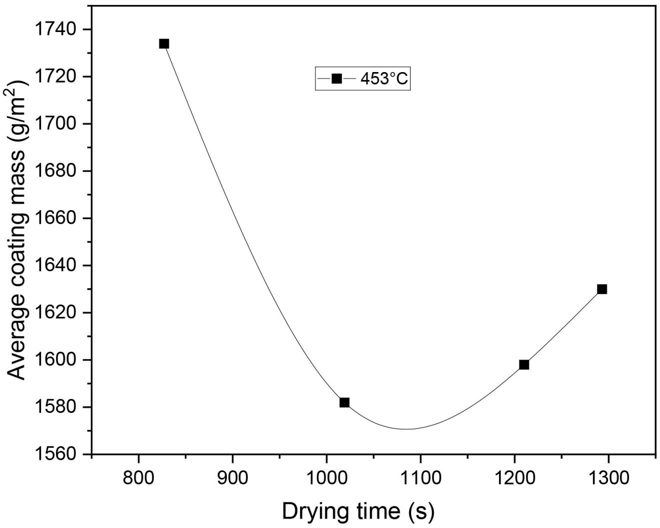

Figure 6. Effect of drying time on the average mass of the coating on galvanized steel at 453˚C.

Figure 6 shows that the average mass of the zinc coating decreases for drying times between 800 s and 1025 s, with the average mass value falling from 1730 g/m^2 to 1580 g/m^2. This decrease is followed by an increase to 1630 g/m^2 for a drying time of 1300 s.

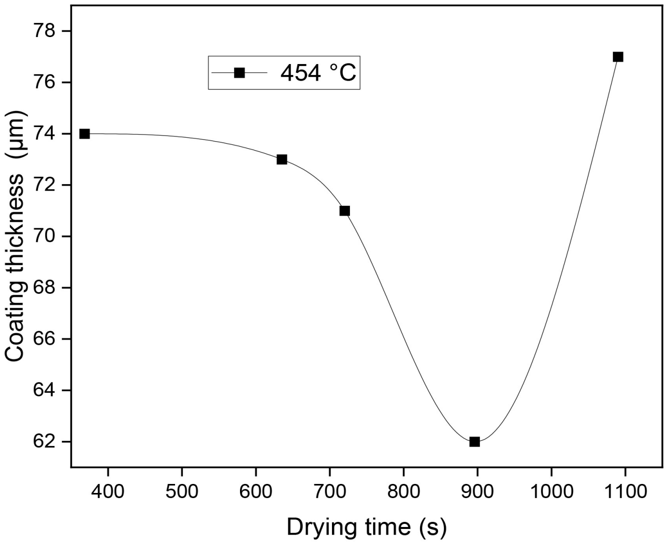

Figure 7. Effect of drying time on the thickness of the coating on galvanized steel at 454˚C.

Figure 7 shows that the thickness of the zinc coating gradually decreases over 900 seconds, *i.e.*, 15 minutes of drying. The coating thickness decreases from 74 µm to 62 µm. After 15 minutes of drying, a sudden increase in coating thickness is observed. The coating thickness increases from 62 µm to over 77 µm. Therefore, at a temperature of 454˚C, a drying time of more than 15 minutes promotes an additional layer of zinc of approximately 15 µm. The maximum coating thickness achieved below 15 minutes of drying is 74 µm.

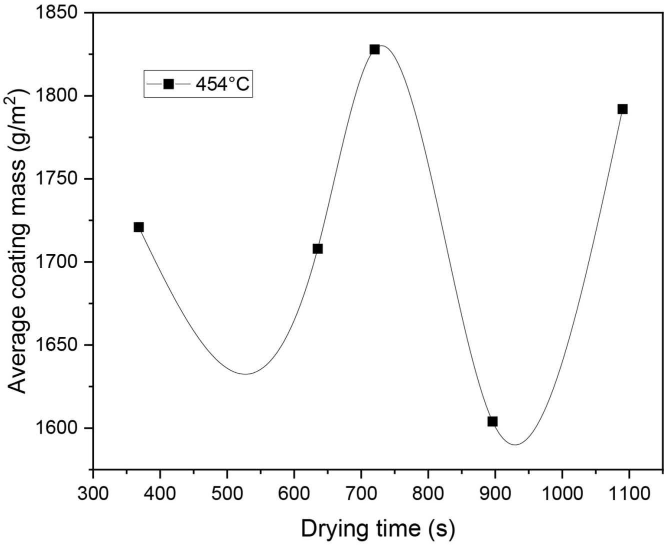

Figure 8. Effect of drying time on the average coating weight of galvanized steel at 454˚C.

Figure 8 shows that between 350 s and 600 s, there is a decrease in the average coating mass from 1725 g/m^2 to 1700 g/m^2. For 700 s of drying, the average mass value reaches 1825 g/m^2. The average mass drops when the sample is dried for 900 s. However, there is a sharp increase after 900 s (15 minutes) to reach 1800 g/m^2. As shown in **Figures 1-8**, the thickness of the zinc coating and the average mass of zinc deposited on the samples is not constant. It decreases and increases with increasing drying time at fixed temperatures. This variation in the thickness and average mass of zinc deposited was also observed by [13] when they studied the effect of withdrawal speed on the thickness of the zinc layer in pure zinc coatings by hot-dip galvanizing.

Table 2 below shows a low and uniform standard deviation value of 1.25. This low standard deviation indicates that the found values are close and not widely dispersed. This shows the reliability of our results.

Table 2. Validation test results.

Température	**Durée de séchage**	**Valeur**	**Moyenne**
˚C	min	µm	µm
450˚C	15	64 65 67	65.33 + 1.25
451	15	55 57 58	56.67 + 1.25
453	15	70 69 67	68.67 + 1.25
454	15	62 63 65	63.33 + 1.25

Mean: $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$

Variance: $\sigma^2 = \frac{\sum (x_i - \bar{x})^2}{n}$

Standard deviation: $\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}}$

$\bar{x}$: Value of each thickness

n : Number of tests per temperature

4. Conclusion

Through this study, we can conclude that drying time can play an important role in the evolution of coating thickness and the average mass of zinc deposited on galvanized steel in the galvanizing process. In fact, the coating thickness and average mass of zinc deposited per unit area appear to be lower when the drying time of our 3 mm thick steel samples is less than 15 minutes (900 s). This study sought to draw attention to drying time as a determining factor in the thickness of the zinc layer in the galvanizing process. Drying time can be a significant means of reducing zinc consumption. This factor should be seriously considered for better control of the Fe/Zn phases resulting from the hot-dip galvanizing of reactive steels. However, we are convinced that further studies are needed to detect and investigate other physical and chemical factors involved in this process. This study did not take into account the drying temperature.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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