



Article

Influence of Selected Parameters of Zinc Electroplating on Surface Quality and Layer Thickness

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Abstract: Surface treatment technologies are pivotal across diverse industrial sectors such as mechanical engineering, electrical engineering, and the automotive industry. Continuous advancements in manufacturing processes are geared towards bolstering efficiency and attaining superior product quality. This study aimed to empirically compare practical outcomes with theoretical insights. Employing galvanic zinc plating under constant voltage with varying plating durations unveiled a correlation between coating thickness and electrolyte composition alongside plating duration. The graphical representation delineated the optimal electrolyte composition conducive to maximal coating thickness. Notably, an evident decrease in leveling ability was noted with prolonged plating durations. The experiment corroborated the notion that theoretical formulas for coating thickness estimation possess limited accuracy, often resulting in measured values surpassing theoretical predictions. These findings underscore the imperative for refined theoretical models to comprehensively grasp galvanic surface treatment processes.

Keywords: galvanic zinc; coating; surface quality; roughness



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1. Introduction

Electroplating, an electrolytic process, plays a crucial role in the industrial application of protective zinc coatings onto metal surfaces to mitigate corrosion and degradation risks. This method hinges on the principle of electrodeposition, where metal is transferred from an electrolyte solution onto a metal substrate under the influence of an electric current [1]. The process begins with meticulous preparation of the metal surface slated for zinc plating. Thorough cleaning to eliminate contaminants such as dirt, grease, and oxides is essential, as it fosters enhanced adhesion and uniform deposition of zinc. Following surface preparation, a protective coating is applied to shield the metal from corrosion during handling and storage [2].

Central to the electroplating process is the electrolyte, typically comprising aqueous solutions of zinc salts like chloride, sulfate, or acetate. Within the electrolyte, zinc ions facilitate the formation of the coating by providing essential zinc atoms. Proper formulation of the electrolyte, including considerations of zinc content, pH, and temperature, is imperative to optimize conditions for effective zinc deposition [3].

The electrolytic system consists of three key components: an anode, a cathode, and an electrolyte. The cathode, made from the metal intended for zinc plating, interfaces with the electrolyte, which is the metallic material requiring protection with a zinc coating. Upon connection to a voltage source, an electrical circuit is established, facilitating the flow of electrons from the anode to the cathode, thereby driving the electroplating process [4].

When the current is switched on, two main processes take place: electrolyte–oxidation at the anode and reduction at the cathode. At the anode, zinc oxidation occurs, releasing zinc ions into the electrolyte according to the following equation:



Zinc ions are reduced at the cathode, forming a layer of zinc on the cathode surface according to the following equation:



Zinc atoms adhere to the cathode's surface, gradually forming a uniform and strongly bonded coating. Enhanced electron flow accelerates the zinc electrodeposition process. The concentration of zinc ions within the electrolyte significantly impacts the coating's quality. While higher concentrations can yield thicker coatings, maintaining uniform current distribution across the entire cathode surface is vital [5]. Electrolyte temperature plays a crucial role, typically rising during the process and heightening reaction rates at both the cathode and the anode. Elevated temperatures often result in improved adhesion and coating density [6]. The voltage applied during electroplating is another critical factor. While higher voltages can expedite electrodeposition rates, they may also lead to thicker coatings that are prone to cracking [7]. Plating duration, or immersion time in the electrolyte, directly influences coating thickness. Extended immersion times tend to produce thicker coatings, but finding the optimal duration is essential to achieve desired thickness without compromising quality [8].

Modern electroplating technologies are undergoing significant advancements, integrating automation and parameter monitoring to enhance production efficiency, accuracy, and reproducibility. In the realm of surface treatment, galvanizing is a widely studied method. Kanani's book, "Electroplating: Basic Principles, Processes, and Practice", provides an exhaustive overview, while Mordechay Schlesinger's works also delve into modern electroplating methods [9,10].

An important insight into electroplating is also provided by J.R. Davis in his book "Surface Engineering for Corrosion and Wear Resistance", where the issue of coatings in the context of corrosion resistance is addressed [11]. Z.C Feng, in his book "Handbook of zinc oxide and related materials: volume two, devices and nano-engineering", presents information on the properties and processing of zinc and its use in electroplating [12].

The book "Electrodeposition of alloys: principles and practice" by A. Brenner discusses the science of materials in electrodeposition, including electroplating [13]. Cole, in "Recent progress and required developments in atmospheric corrosion of galvanized steel and zinc", provides findings on advances in galvanic corrosion and insights into protective coatings [14]. Dornbusch, in the paper "The use of modern electrochemical methods in the development of corrosion protective coatings", analyzes electrochemical technologies in industry, including galvanizing [15].

Pattankude's paper "A Review On Coating Process" focuses on the basic principles of electroplating and their applications [16], while N. Kannani's "Electroplating and Electroless Plating of Copper and Its Alloys" offers a look at electroplating copper [17].

Similarly, the literature includes sources such as "Corrosion engineering" by M.G Fontana et al. which includes a chapter on electroplating and its use in corrosion protection [18]. MF Montemor, in his review, "Functional and smart coatings for corrosion protection: A review of recent advances", describes the effectiveness of protective coatings, including zinc coatings [19].

The book "The metallurgy of zinc-coated steel" by A.R. Marder provides a comprehensive overview of the properties and applications of zinc [20], as does Stan Grainger in "Engineering Coatings: Design and Application", which focuses on the design and application of engineering coatings, including electroplating [21].

Together, these resources provide an overview of the theoretical and practical aspects of electroplating, providing information on the development of the technology, the influence of parameters, and the quality aspects of this method in the field of coatings.

2. Materials and Methods

The zinc plating process was implemented using four different electrolytes, each distinguished by their zinc (Zn) and sodium hydroxide (NaOH) content. In total, 24 samples were zinc-plated, with 12 samples plated at a constant time of 25 min under three different voltages: 2 V, 4 V, and 6 V. For zinc plating with a constant voltage, the voltage was set at 4 V, and the plating times were 15, 25, and 45 min.

Circular disks, as shown in Figure 1 on the left, were selected as the samples, while the hanging apparatus is depicted in Figure 1 on the right. Subsequently, the disks were divided into four sections, taking into account material efficiency and minimizing the thickness of the applied metallic (zinc) coating. They were made of E355 steel.



Figure 1. The sample before surface treatment (left), method of suspension in the electrolyte (right).

A technological procedure has been devised for the zinc plating process utilizing an alkaline non-cyanide zinc plating electrolyte known as Pragopal Zn 3400, recognized for its high depth efficiency and coverage capability. This electrolyte is adaptable for both bulk and rack plating methods. Shiny coatings with excellent depth efficiency are precipitated from the electrolyte at cathodic current densities. Coatings generated using this electrolyte exhibit high chromatization potential.

The graphical representation of the technological process is illustrated in Figure 2. The procedure is initiated with the receipt of materials via selected transport mechanisms, followed by a visual inspection of the received materials. Based on this assessment, a decision is made regarding the progression of the material to subsequent operations or its return to stock. Upon meeting the criteria, the degreasing process ensues to eliminate various impurities and greases, and is succeeded by rinsing with water.

Subsequent to degreasing and rinsing, a further visual inspection determines the material's suitability for continuation in the zinc plating process or its return to degreasing. Successful passage through visual inspection prompts the commencement of the pickling operation. Post-pickling, another visual inspection verifies the effectiveness of the pickling process. If unsuccessful, the part is re-subjected to the pickling process. However, successful visual inspection after pickling leads to the deplating operation.

Following deplating, rinsing with water occurs, paving the way for the actual zinc plating process. Post-implementation of the zinc plating process, another water rinse is performed, succeeded by chromatization. After chromatization, the part undergoes a final water rinse, followed by drying, thereby completing the entire process.

During the zinc plating technology process with a fixed duration, 12 samples were carefully selected. Prior to treatment, the samples underwent weighing, and their surface roughness was measured. Subsequently, these samples were subjected to zinc plating in four distinct zinc baths, designated as Bath 1, Bath 2, Bath 4, and Bath 5. The zinc plating

process was conducted at three varying voltages, 2 V, 4 V, and 6 V, while maintaining a consistent plating duration of 25 min.

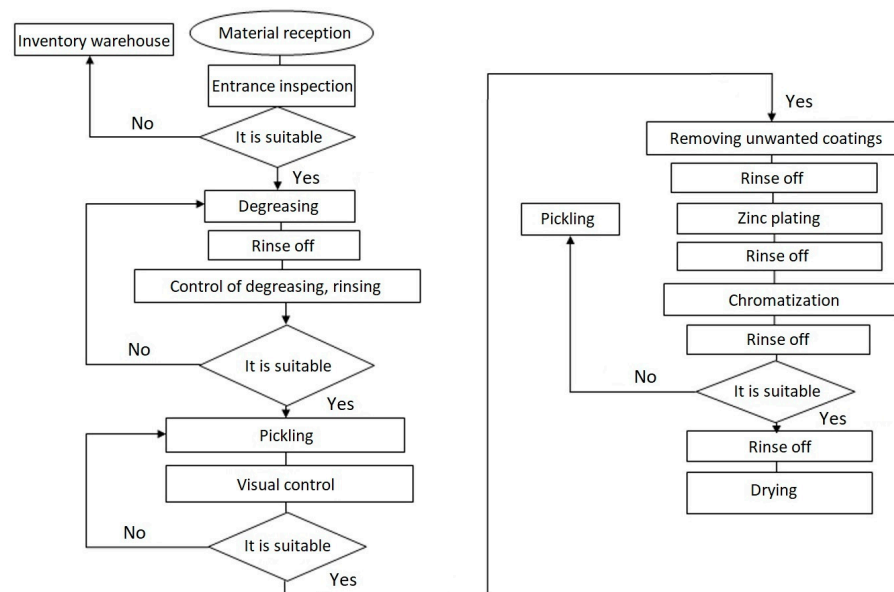


Figure 2. Technological procedure of the zinc plating process in the form of a flowchart.

Following degreasing, the samples were individually immersed in the designated zinc baths utilizing hanging devices secured with copper wire. Each sample remained in the electrolyte for the predetermined duration of 25 min. Upon completion of this immersion period, the samples were carefully removed from the electrolyte, followed by subsequent operations of chromatization, rinsing, and drying. Following the completion of the zinc plating, chromatization, rinsing, and drying procedures, the samples underwent a second weighing to determine the weight increase. Additionally, surface roughness measurements were conducted to evaluate any alterations resulting from the plating process.

For the zinc plating process, the same equipment and baths employed in cyanide zinc plating electrolytes were utilized. Maintaining an optimal working temperature between 20 to 25 degrees Celsius was essential during zinc plating, and was achieved through the utilization of titanium or steel heating elements. Due to the high current load on the electrolyte during normal operation, cooling measures were imperative. Insoluble iron anodes made of perforated low-carbon steel, along with zinc dissolving compartments in steel baskets, facilitated cooling. These baskets were alternately submerged and withdrawn from the zinc plating electrolyte to regulate the zinc content in the working baths.

A filtration apparatus connected the dissolving bath to the circulation circuit of the zinc bath. Intensive stirring of the electrolyte in the dissolving bath prevented the formation of hardly soluble zinc compounds, which could impede the dissolution of zinc anodes. The surface area of the zinc basket exceeded that of the zinc anodes by approximately threefold. Suction mechanisms were integrated into the dissolving bath to prevent the escape of electrolyte aerosols and hydrogen into the galvanizing area.

The use of zinc anodes within the working space facilitated strong chemical dissolution. Given the high alkalinity of the electrolyte and gas evolution at the electrodes, effective extraction of the working space of the bath was essential. This extraction system was meticulously designed and operated to minimize the concentration of harmful substances in the working space, ensuring compliance with permissible values. Additionally, the exhaust air at the outlet had to adhere to all environmental protection regulations.

The electrolyte operated without stirring, and the precise quantity of each electrolyte component required for the use of 100 L of electrolyte is defined in detail in Table 1.

Table 1. Contents of individual components for the deployment of the Pragogal Zn 3400 electrolyte.

Component	Hanging Plating		En Mass Plating	
	Optimal	Range	Optimal	Range
Sodium hydroxide	13 kg	12–14 kg	13.5 kg	12.5–15 kg
Zinc oxide	1.25 kg	1–1.4 kg	1.8 kg	1.6–1.9 kg
Pragogal Zn 3401	0.6 L	0.4–0.7 L	0.6 L	0.4–0.7 L
Pragogal Zn 3402	0.4 L	0.3–0.5 L	0.4 L	0.3–0.5 L
Pragogal Zn 3403	1 L	1–1.4 L	1 L	1–1.4 L

The deployment of the electrolyte was executed by dissolving the calculated amount of pure sodium hydroxide in cold water. Subsequently, zinc anodes in zinc baskets were added. The electrochemical cell between zinc and steel significantly accelerated the dissolution of zinc. Upon reaching the desired metal concentration and subsequent cooling, the electrolyte was transferred through a filter into the working bath. Then, the calculated amounts of additives—Pragogal Zn 3401, Pragogal Zn 3402, and Pragogal Zn 3403—were dosed, and the electrolyte was processed under normal working conditions, which lasted approximately 12 h. During operation, the amounts of basic components of the zinc electrolyte and sodium hydroxide were regularly determined several times a day. These components were maintained within the ranges shown in Table 2.

Table 2. Analytical values of the Pragogal Zn 3400 electrolyte.

Electrolyte Component	Hanging	En Mass
Zinc [g/L]	6–11	12–15
Sodium hydroxide [g/L]	100–130	110–135
Sodium carbonate [g/L]	Max. 80 g/L	

The zinc content in the electrolyte could be adjusted during operation by changing the surface area of the zinc anodes. For the optimal composition of the electrolyte, the reduction in the zinc content in the electrolyte was performed on an insoluble steel anode. The composition of zinc and sodium hydroxide in individual baths during the experiment is described in Table 3. From the table, it can be observed that in Bath 1, there was the lowest zinc content as well as the lowest sodium hydroxide content. Conversely, in Bath 5, both the zinc and sodium hydroxide contents were the highest. The ratio of the mixture of individual components had an impact on the quality and thickness of the deposited zinc layer.

Table 3. Content of Zn and NaOH in individual electrolytes.

Bath Number	Contents Zn	Contents NaOH
Bath 1	7.68	117
Bath 2	6.54	110
Bath 3	13.08	129
Bath 4	15.36	138

The measurement of the coating layers was carried out using a microprocessor-based thickness gauge of the type Minitest 4000 (ElektroPhysik, Köln, Germany) shown on the Figure 3. The measurement was carried out using the touch method, by applying the point sensor of the measuring device to the measuring point. The sensor was calibrated using an etalon, which can cause a zero shift when measuring the thickness of the sample layer. The measurement output was subsequently read from the display of the measuring device. In order to minimize the measurement error, each measurement point was measured five times, and the measured values were subsequently averaged. Deviation ranges between individual measurements were at the level of statistical error.



Figure 3. Device for measuring layer thickness: Elektro-Physik MiniTest 4000.

Working Conditions

- **Electrolyte temperature:** The temperature of the acidic galvanizing electrolyte most often coincides with room temperature, i.e., it ranges between 20–30 °C. If working with higher temperatures, then coatings with a coarser crystalline structure and dark color are excluded.
- **The current density is controlled** according to whether the electrolyte is at rest or the electrolyte is mixed. In a calm electrolyte, the anodic and the cathodic current density range from 1 A/dm² in the electrolyte, which is mixed depending on the efficiency of the mixing system, between 3 and 10 A/dm², occasionally even more. At a lower current density than 2 A/dm², matte coatings are deposited, whereas at a higher current density than 6 A/dm², coatings with a coarse crystalline structure are deposited in places of higher current density.
- **Terminal voltage:** This voltage ranges from 2–5 V.
- **The cathodic current yield is around 75%–90%.** When calculating the thickness of zinc coatings, an 85% current yield is considered. The anodic current yield is over 90%.
- **The time of excretion is governed by the required thickness of the zinc coating** under the given working conditions. At a current density of 1 A/dm², a zinc coating with a thickness of 1 micron is eliminated in 3.5 min.

3. Results

Individual values that were measured were subsequently processed in Tables 4 and 5. From these values, graphs were compiled in the Minitab 21.1 program, where outlier values were identified. After identifying these outlier values, they were excluded to obtain accurate measurement data. Following the exclusion of outlier values, these data points were exported to the Statistica program, where 3D graphs were created from these values.

Regarding the graphical dependency shown in Figure 4, the increase in layer thickness at low voltage, which is in the range of 1.5–3 V, is within the interval of 11–13 g/L. Upon exceeding this zinc quantity in the electrolyte, a reduction in the created thickness of the zinc coating layer can be observed. A similar trend can be observed with a low amount of zinc in the electrolyte, exceeding 11 g/L. In general, it can be stated that as the voltage increases, the thickness of the deposited layer also increases.

Table 4. Measured values of coating layer thickness at constant plating time [μm].

Time: 25 min											
U1 [V]				U2 [V]				U3 [V]			
Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4
−2	−0.8	7.6	1.6	5.2	6.4	9.8	7.6	7.1	12	15	18
−1.3	0.3	7.5	0.6	7.7	7.7	7.6	8.8	7.3	11	15	17
−0.3	3	5.1	1.1	5.2	4.1	4.3	4.4	10	8.4	15	16
2.3	1.2	6.1	−1.3	4.1	−1.2	6.8	7.8	5.5	9.9	15	18
−3.1	−0.6	5.8	0.4	6.9	4.3	6.9	5.2	5.9	8.3	15	17
1.4	5	3.7	−1.9	3.5	5.4	7.4	7.9	9.6	8.6	17	21
1.7	2.9	7.4	−1	2.7	5.9	8.7	10	7.7	8.9	14	15
−2.1	−0.2	7	−0.2	1	3.3	7.5	7.7	7.2	7.9	15	17
3.4	1.5	5.3	1.7	2.1	3.5	7.7	12	5.9	6.9	12	17
2.4	1.6	5.1	1.7	2.8	3.3	9.5	9.1	13	10	14	22

Table 5. Measured values of the standard [51 μm].

Time: 25 min											
U1 [V]				U2 [V]				U3 [V]			
Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4
44	43	41	40	41	40	40	42	40	41	41	41
43	43	40	42	42	41	41	40	41	42	41	41
41	43	43	41	41	43	43	41	45	42	42	41
41	41	42	43	43	41	41	42	42	41	41	42
41	42	42	41	42	40	40	41	43	46	43	40
41	42	40	41	40	40	40	41	42	42	41	40
41	42	43	42	41	40	40	41	40	42	41	41
41	42	42	41	44	41	41	42	43	42	42	47
42	40	40	42	40	41	41	44	42	41	42	40
43	40	41	42	43	42	42	42	41	40	42	41

Time: 25 min.
Material: E355

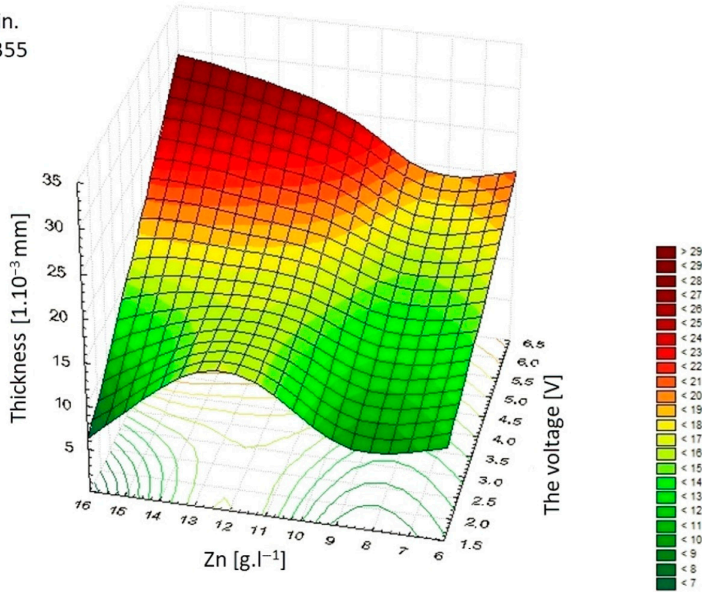


Figure 4. Graphical dependence of layer thickness on voltage and zinc content at a constant time.

In Figure 5, it can be observed on the axis representing the sodium hydroxide quantity that there is a jump in the thickness of the deposited coating layer within the range of values from 125 to 130 g/L. In the range of sodium hydroxide content values from 105 to

125 g/L, the thickness changes very slowly. Depending on the sodium hydroxide content, it can be said that with an increase in its quantity, the layer thickness proportionally increases, and at the value of 125 g/L, there is an increase in thickness, followed by a decrease in the thickness of the deposited coating layer. In terms of voltage, it can be stated that with an increase in voltage, the thickness of the deposited zinc coating layer proportionally increases. The measured values are provided in Tables 6 and 7.

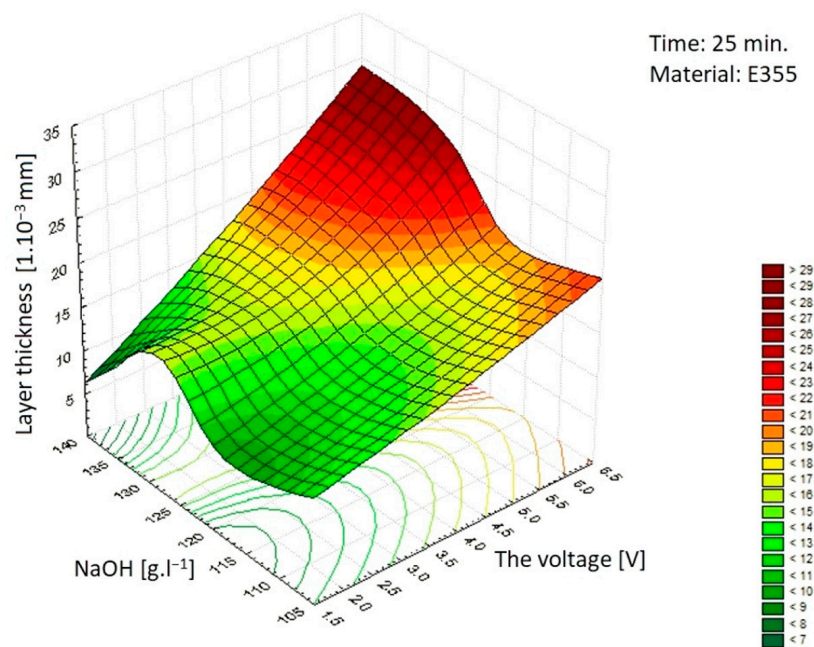


Figure 5. Graphical dependence of layer thickness on voltage and sodium hydroxide content at constant time.

Table 6. Measured values of coating layer thicknesses in zinc plating with constant voltage.

The Voltage: 4 V											
Time: 5 min				Time: 25 min				Time: 45 min			
Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4
−6.3	−0.1	0.7	3.8	5.3	4.1	3.6	8.9	9.5	9.5	15	14
−0.6	−2.3	2.4	3.1	6.1	8.6	5.1	3.9	8	11	15	13
−0.4	0.7	1.8	3	5	6.6	3.5	7	8.6	11	26	11
−0.7	−1.9	0.1	3.4	4.3	7.2	6.8	5.1	8.2	12	13	13
−2.8	3	1	2.8	6.5	6.9	7.1	6.7	18	10	22	15
−3.7	−0.1	0.2	2.1	2.8	4.1	9.9	6.1	11	11	16	11
2.9	−1.2	0.5	2.4	1.8	2.9	7.9	8.1	8.1	11	14	12
−0.5	−0.3	1.3	3.5	5.9	−2	9.1	7.4	11	14	15	8.2
2.2	−1.7	4.7	4.6	0.2	4.4	9	5.5	6.9	14	16	14
3.3	0.8	0.1	2.2	1.9	3.6	7	8.8	10	11	17	17

In Figure 6, the values of the coating layer thickness in relation to the zinc content in the electrolyte and plating at constant voltage, set at 4 volts, are graphically displayed. The individual plating times were staggered at intervals of 5 min, 25 min, and 45 min. Based on the graphical representation, it can be observed that as the time (plating duration) increases, the thickness of the zinc coating layer also increases. From the graph, it can be seen that the zinc composition also affects the thickness of the deposited layer, but the plating duration plays a crucial role. Based on this graphical dependence, it can be concluded that the maximum thickness of the deposited zinc coating layer on the given part (sample) is achieved at the maximum plating time value (45 min). Due to internal pressure

stresses exceeding 40 μm , the deposited zinc coating layer is compromised, leading to cracking of the surface layer. For this reason, it is advisable to limit the thickness of the zinc coating layer on the given parts to a maximum of 40 μm .

Table 7. Measured values of the standard [51 μm].

The Voltage: 4 V											
Time: 5 min				Time: 25 min				Time: 45 min			
Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4	Bath 1	Bath 2	Bath 3	Bath 4
43	42	43	43	43	44	43	44	43	43	42	43
42	42	42	43	43	45	44	43	43	42	41	43
44	41	44	44	42	45	48	44	45	42	43	43
43	44	44	44	45	44	46	45	43	44	46	43
45	43	43	43	44	43	42	45	47	44	44	45
43	41	42	41	42	42	43	42	43	42	42	44
42	41	43	43	43	43	44	42	44	44	42	43
45	43	43	42	43	41	44	41	43	45	44	43
43	44	43	43	44	42	45	42	46	46	45	44
42	44	44	43	43	43	44	42	44	44	46	44

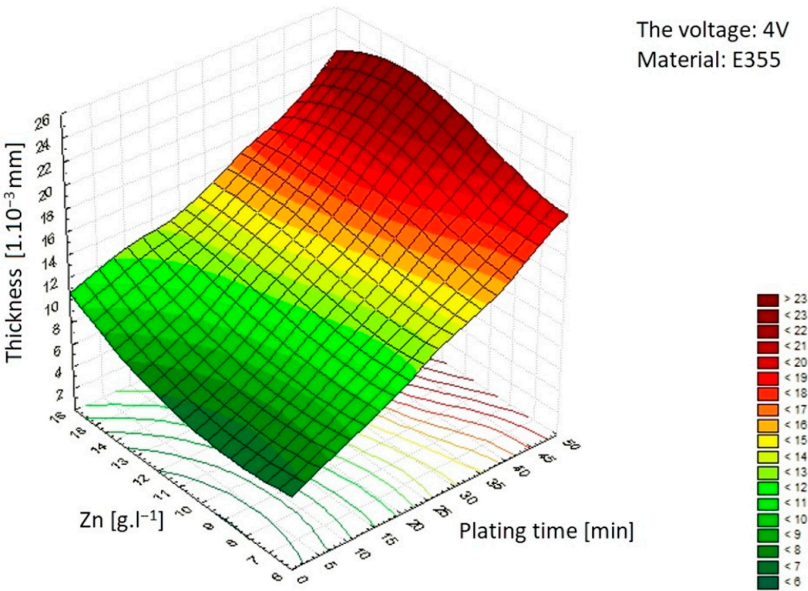


Figure 6. Graphical dependence of layer thickness on time and zinc content at constant voltage.

In the graphical representation in Figure 7, it can be observed that within the range of values from 105 to 120 g/L, the coating thickness slightly decreases. Subsequently, after exceeding the value of 120 g/L, the thickness of the deposited zinc coating layer increases. Also, the plating time has a significant impact on the thickness of the layer. As the plating time increases, there is a proportional increase in the thickness of the zinc coating.

The graphical representation in Figure 8 shows that the composition of the electrolyte has a significant impact on the thickness of the deposited coating layer. The blue curve represents tank number 1. Here, in tank number 1, where the zinc content is 7.68 g/L and the sodium hydroxide content is 117 g/L, the thickness of the deposited zinc coating layer increases proportionally with the voltage. In tank number 2, depicted in red, with a zinc content of 6.54 g/L and a sodium hydroxide content of 110 g/L, a similar phenomenon can be observed as in tank number 1, meaning that the thickness of the deposited zinc coating layer increases proportionally with the voltage. In tank number 5, shown in pink, with a zinc content of 15.36 g/L and a sodium hydroxide content of 138 g/L, it can be seen that, compared to tanks number 1 and number 2, a greater thickness of the zinc coating layer

is deposited at the same voltages. In tank number 4, depicted in green, after a voltage of 4 V, a similar trend can be observed as in tanks number 1 and 2, and at voltages higher than 4 V, the curve resembles the curve of tank number 4. In general, it can be said that increasing voltage values lead to an increase in the thickness of the deposited zinc coating layer. Values of Zn and NaOH content are in Table 8.

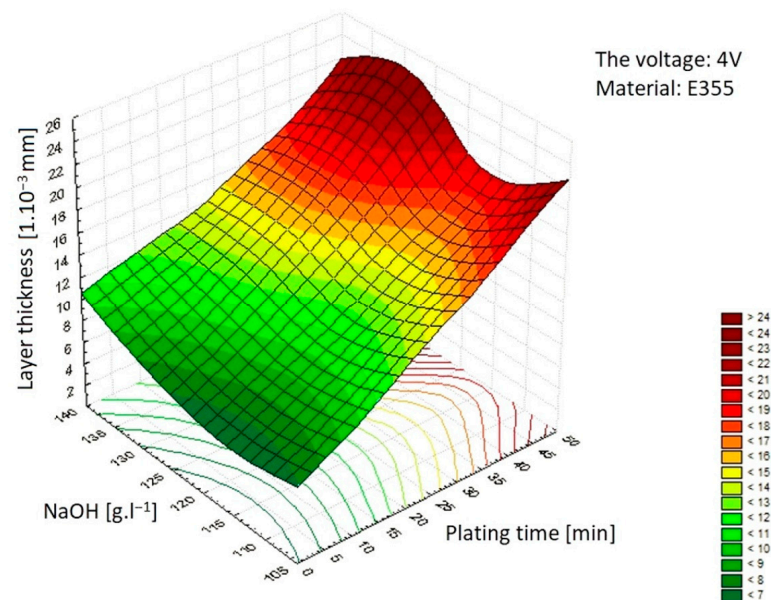


Figure 7. Graphical dependence of layer thickness on time and sodium hydroxide content at constant voltage.

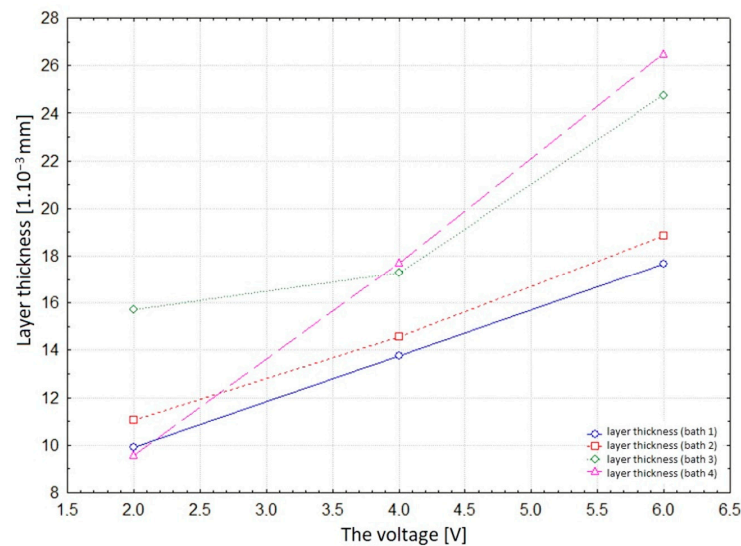


Figure 8. Graphical dependence of the coating thickness on time and sodium hydroxide content at constant voltage.

Table 8. Values of Zn and NaOH content in individual electrolytes in the zinc plating technology.

Bath Number	Contents Zn	Contents NaOH
Bath 1	7.68	117
Bath 2	6.54	110
Bath 4	13.08	129
Bath 5	15.36	138

- Equalizing capability of the deposited zinc coating.

The leveling ability of the galvanic bath can be defined as:

$$V = \frac{\text{surface roughness} - \text{coating roughness}}{\text{substrate roughness}} \times 100 \quad (3)$$

The determined value characterizes the ability of the bath to level out fine surface irregularities, such as grooves, through the deposited coating. The leveling ability value is expressed in % and indicates the reduction in the roughness (irregularities) of the substrate depending on the coating thickness.

$$V = \frac{Ra_1 - Ra_2}{Ra_1} \times 100 \quad (4)$$

Ra_1 —The roughness value of the surface of the sample before coating;

Ra_2 —The roughness value of the surface of the coated sample.

- Measured surface roughness on selected samples.

The protocols for measuring surface roughness with the SURFTEST SJ-301 measuring instrument Mitutoyo (Japanese, Tokyo) are given in Figure 9, as depicted in the following image. Measurements of surface roughness are performed using the touch method on a specified length. At the beginning and end of the measurement, there are unwanted disturbances caused by the start-up and run-down of the sensor. By removing these parts of the profile, the evaluated length is obtained. The monitored parameters of the surface roughness were the mean arithmetic deviation of the slope Ra and the arithmetic of the largest profile heights Rz .

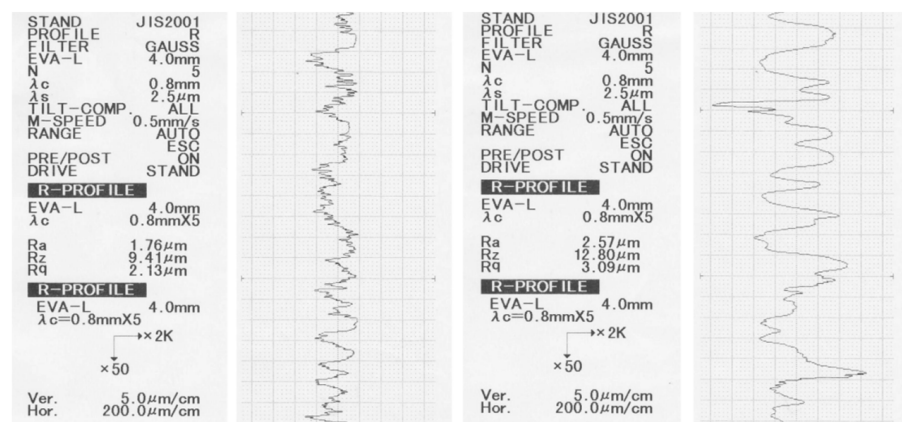


Figure 9. Surface roughness before surface treatment (**left**), surface roughness after zinc plating treatment (**right**).

- Graphical dependencies of leveling ability on plating time and voltage.

The graphical dependency shown in Figure 10 illustrates the leveling ability, expressed as a percentage, depending on the plating time at a constant voltage set to 4 V. At values of 5 and 45 min, corresponding to the minimum and maximum plating times, the maximum leveling ability of the coating was achieved. In this bath, the zinc content was 7.68 g/L, and the sodium hydroxide content was 117 g/L. The lowest percentage of leveling ability was reached at 25 min. This curve on the graph resulted from the significant influence of the bath composition, namely, the composition of zinc and sodium hydroxide, on the leveling ability.

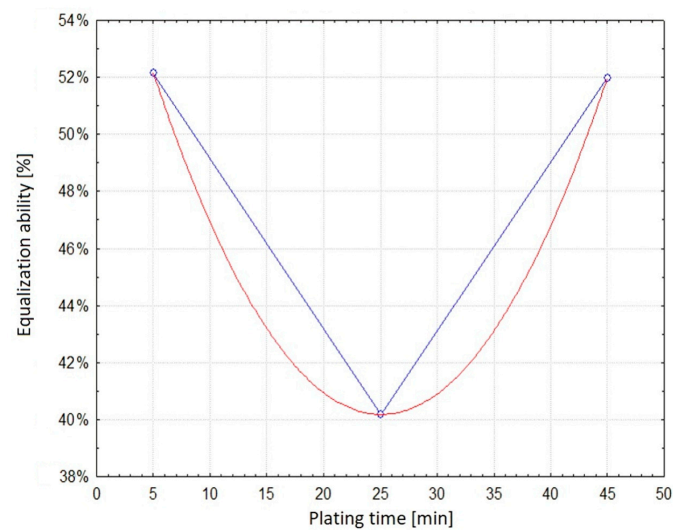


Figure 10. Graphical dependence of leveling ability based on plating time in bath number 1.

The graphical dependence of the leveling ability based on the plating time in bath number 2 is shown in Figure 11. It can be observed that, at a plating time of 5 min in bath number 2, where the zinc content is 6.54 g/L and the sodium hydroxide content is 110 g/L, the leveling ability of the coating achieved was 30%, representing the lowest value. As the plating time extended to 25 min, the leveling ability of the coating increased proportionally. A steeper increase in the leveling ability occurred after exceeding the 25 min mark. The maximum value of leveling ability, 60%, was achieved at a plating time of 45 min.

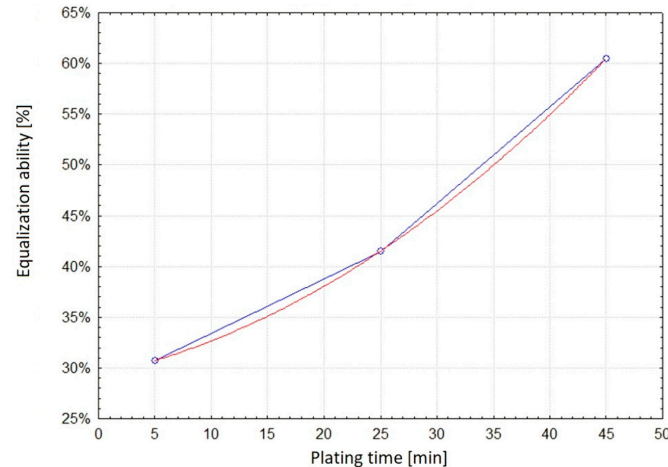


Figure 11. Graphical dependence of leveling ability based on plating time in bath 2.

When using the electrolyte in bath 4, which contained a zinc content of 13.08 g/L and a sodium hydroxide content of 129 g/L, the opposite effect was observed compared to bath 2. In this case, with an increase in the plating time, the leveling ability of the zinc coating decreased. At the minimum plating time of 5 min, the maximum value of leveling ability was achieved, reaching 31.8%. As the plating time increased to 25 min, the leveling ability decreased to 28.6%. The lowest value of leveling ability was achieved at the maximum plating time of 45 min. In summary, it can be stated that as the plating time increases, the percentages of leveling ability decrease (Figure 12).

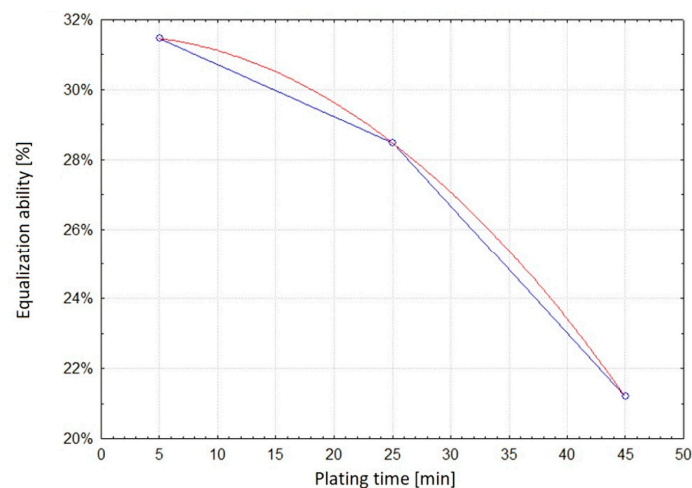


Figure 12. Graphical dependence of leveling ability in relation to plating time for bath 4.

The leveling ability of the deposited zinc coating for tank number 5, as shown in Figure 13, where the zinc composition was 15.36 g/L and the sodium hydroxide content was 138 g/L, exhibited the opposite effect compared to the electrolyte in tank number 1. In this case, at a plating time of 25 min, the leveling ability was minimal. The value of leveling ability was maximal at a plating time of 25 min, reaching approximately 53%. At the lowest plating time of 5 min, the leveling ability was minimal, corresponding to −10%. Even at the maximum plating time of 45 min, the leveling ability was not very high, reaching only 19%. In this case as well, the composition of the used electrolyte had a significant impact on the leveling ability of the zinc coating.

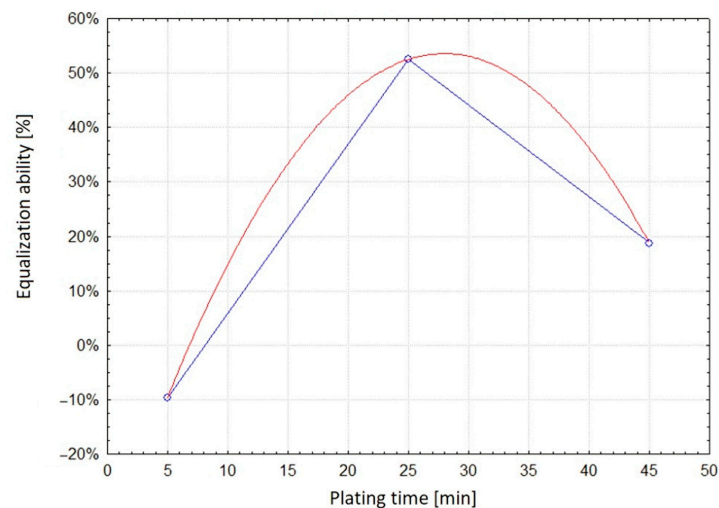


Figure 13. Graphical dependence of leveling ability in relation to plating time for tank 5.

The graphical dependence in Figure 14 illustrates how the leveling ability of the deposited zinc coating changes with the voltage. The electrolyte composition is the same as that for the constant plating time, with a zinc content of 7.68 g/L and sodium hydroxide content of 117 g/L. At minimum and maximum voltages, the leveling ability ranges from 42 to 49%. At the specified voltage of 4 V, the leveling ability is at its lowest, reaching −14%. The graph indicates that the maximum leveling ability, 49%, was achieved at the maximum applied voltage.

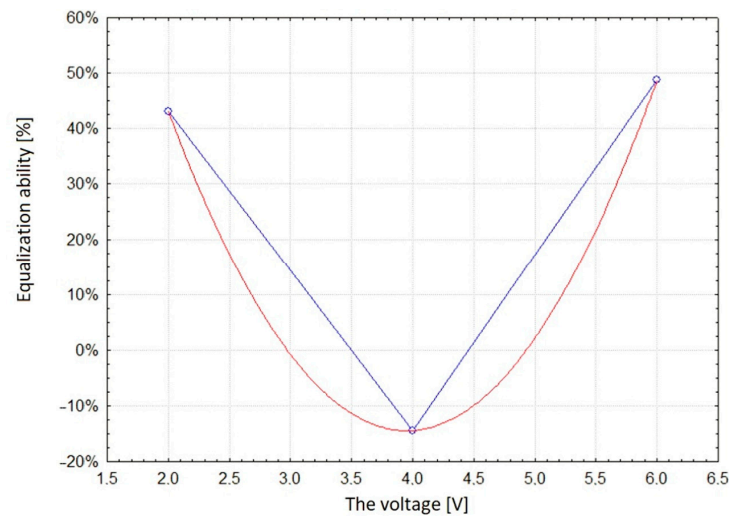


Figure 14. Graphical dependence of leveling ability in relation to voltage at a constant plating time in tank 1.

The graphical dependence in Figure 15 illustrates the relationship of the leveling ability with the voltage using the electrolyte from tank 2. In this electrolyte, the zinc content was 6.54 g/L and the sodium hydroxide content was 110 g/L—equivalent to the electrolyte composition in zinc plating with a constant plating time. The graph shows a similar effect as in tank 1, where the lowest leveling ability occurred at 4 V. At the minimum voltage, the maximum leveling ability is 53%. At the maximum voltage of 6 V, the leveling ability is slightly lower than at 2 V, reaching 48%.

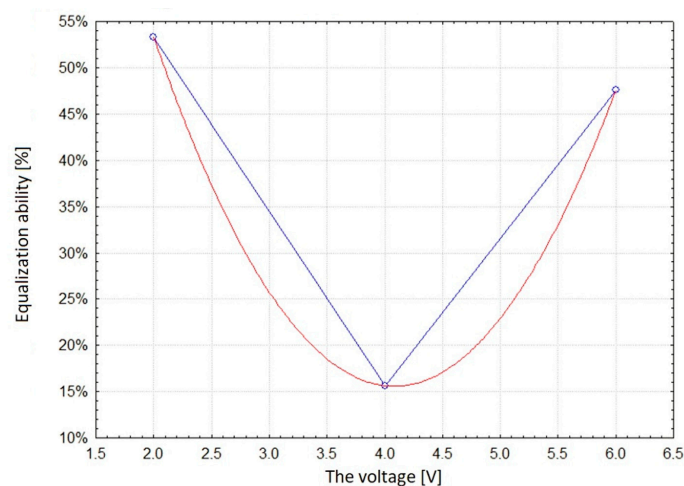


Figure 15. The graphical dependence of leveling ability on voltage at a constant plating time in tank number 2.

Regarding the graphical dependence shown in Figure 16 for tank 3, a similar phenomenon occurred at 2 V as in tank 1, where the leveling ability varied between 40% and 50%. Even at a voltage of 4 V, a similar effect could be observed as in tank 1, where at 4 V, the leveling ability was the lowest. The highest leveling ability value was achieved in this case at the maximum applied voltage of 6 V.

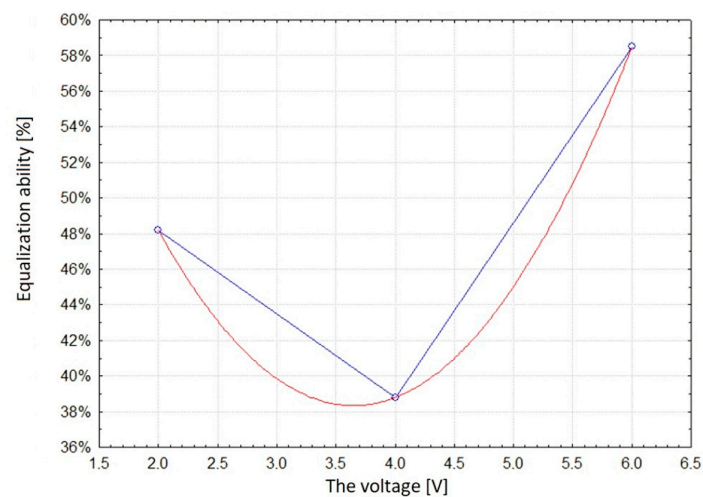


Figure 16. Graphical dependence of leveling ability in relation to voltage with constant tinning time in tank number 3.

Regarding the graphical dependence shown in Figure 17, it can be observed that in the range of voltage values from 2 to 4 V, the leveling ability of the deposited zinc coating gradually increased up to a value of 48%. Upon exceeding the voltage value of 4 V, the graph shows a sharp decrease in leveling ability, and at a voltage of 6 V, the leveling ability was at 0%. Therefore, it can be concluded that at this voltage, the zinc coating had no leveling ability.

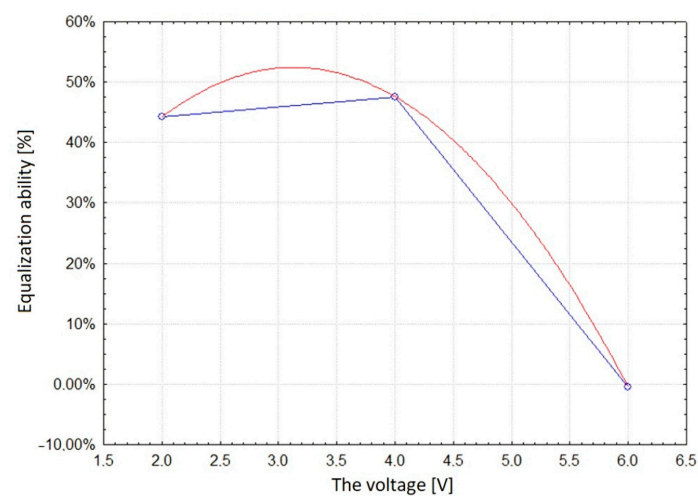


Figure 17. Graphical dependence of leveling ability in relation to voltage at a constant plating time in tank number 4.

Regarding the graphical dependence shown in Figure 18, leveling ability is depicted in relation to the content of electrolyte components, specifically the content of Zn and NaOH. As the NaOH content in the electrolyte increased, the leveling ability of the deposited zinc coating decreased. Conversely, when the Zn content increased in the electrolyte, the leveling ability of the coating increased. Therefore, it can be stated that, to achieve a high leveling ability, it is necessary to mix the electrolyte so that it has the highest possible Zn content and the lowest possible NaOH content.

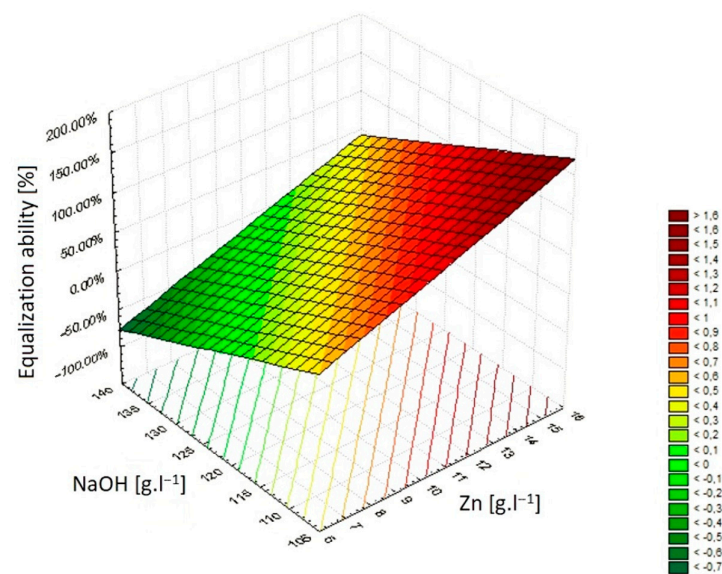


Figure 18. Graphical dependence of leveling ability on Zn and NaOH content.

If the leveling ability depends on voltage and Zn content, the graphical dependence has a shape in which the leveling ability decreases at voltage values from 3 V to 5 V. Conversely, at minimum and maximum voltage values, the leveling ability increases, as shown in Figure 19. In terms of Zn content in the electrolyte, it can be said that the leveling ability remains relatively constant.

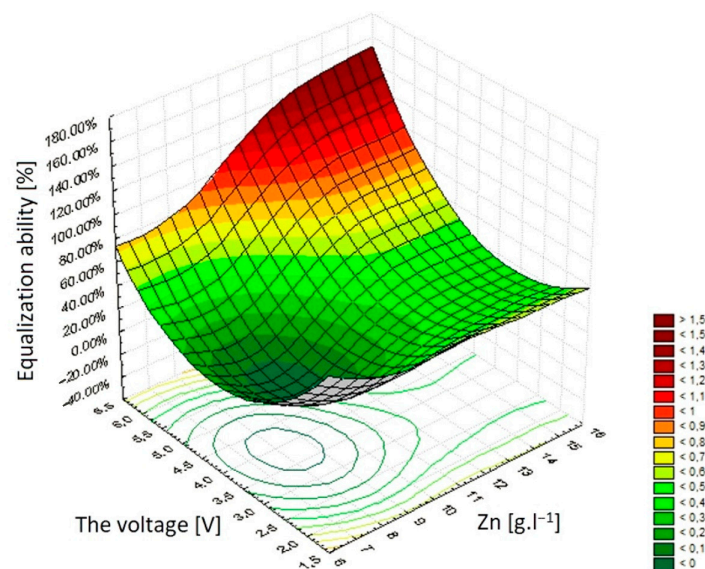


Figure 19. Graphical dependence of leveling ability in relation to voltage and Zn content in the electrolyte.

If the leveling ability of the zinc coating depends on both the voltage and the NaOH content in the electrolyte, a similar phenomenon can be observed as in the graphical dependence of the leveling ability on the voltage and Zn content. Similarly, at voltage values ranging from 3 V to 5 V, there is a decrease in the leveling ability, and at the minimum and maximum voltage values, the leveling ability increases, as shown in Figure 20.

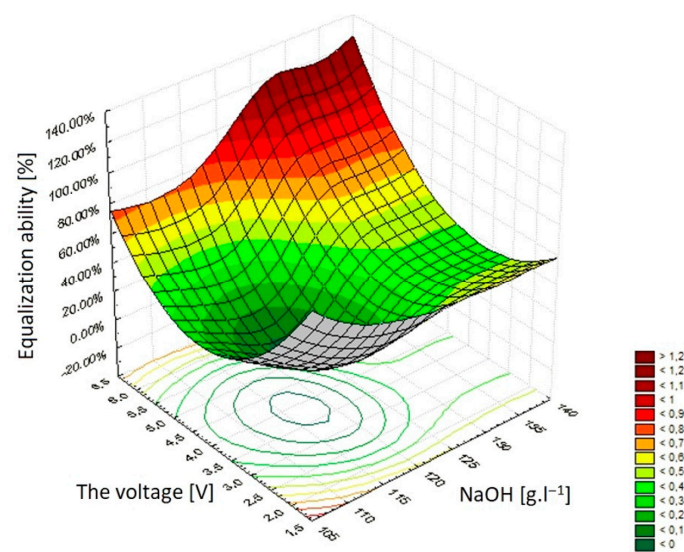


Figure 20. Graphical dependence of leveling ability on voltage and NaOH content in the electrolyte.

- Thicknesses of Zinc Coating Layers.

The thickness of the deposited coating layer can be calculated using the formula:

$$h = \frac{m_1 - m_2}{\rho \times S} \quad (5)$$

m_1 —weight of sample after coating;

m_2 —weight of sample before coating;

ρ —the density of the coating;

S —the area of the sample.

The measured and calculated (theoretical) thicknesses of the deposited zinc coating layers are depicted in the graphical dependencies in Figures 21 and 22.

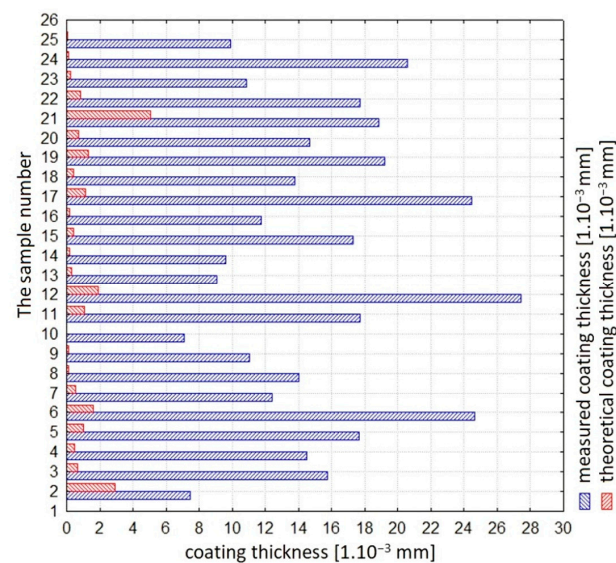


Figure 21. Graphical dependencies illustrating the measured thicknesses of the coating layer and theoretical coating layer.

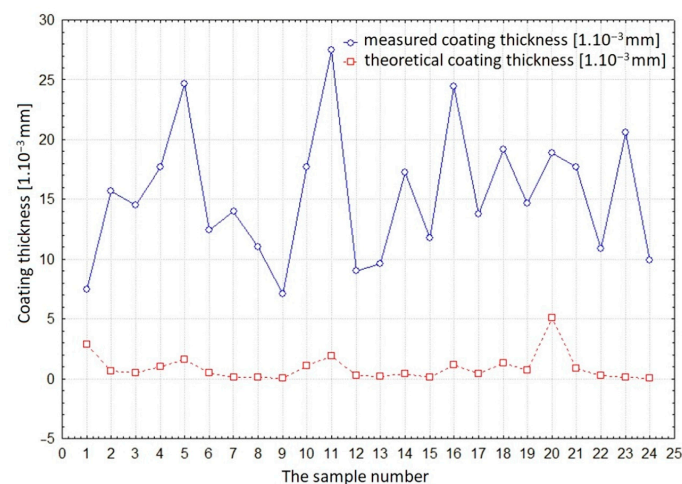


Figure 22. Graphical dependencies illustrating measured coating layer thicknesses and theoretical coating layer thicknesses.

A graphical representation depicts the measured thickness values of coating layers for each individual sample. The red curve portrays the thicknesses of the electrodeposited zinc coating layer, recalculated based on a specific formula. In contrast, the blue curve displays the directly measured values of the zinc coating layer thickness. Analysis of this graph leads to the conclusion that the formula utilized for calculating the thickness of the zinc coating layer is impractical. Consequently, its application in practical settings is deemed unfeasible.

4. Discussion

The presented study is centered on evaluating the surface quality of machine components, particularly focusing on the surface characteristics of samples composed of E 355 steel post-implementation of surface treatment via galvanic zinc coating. Several experiments were conducted utilizing different surface treatment technologies for these components (samples).

In the initial experiment concerning zinc coating technology, a constant voltage of 4 V was employed with varying immersion times: 15 min, 25 min, and 45 min. Analysis of this experiment through graphical representation revealed that a higher zinc content in the electrolyte corresponded to a thicker deposited zinc coating layer. Similarly, increasing the immersion time led to a higher value of the deposited zinc coating layer. The relationship between the NaOH content in the electrolyte and the deposited zinc layer thickness exhibited a similar trend, indicating that augmenting the zinc and sodium hydroxide content in the electrolyte resulted in an increased thickness of the deposited zinc coating. In the subsequent experiment, maintaining a constant immersion time but varying voltage values (2 V, 4 V, and 6 V), it was observed that the thickness of the deposited zinc coating layer increased within the range of zinc content in the electrolyte from 11 to 13 g/L. This implies that the highest thickness of the zinc coating layer was achieved within this specified range of zinc content. A similar effect was observed concerning the dependence of the coating thickness on the sodium hydroxide content, with the maximum value of the coating layer thickness attained at sodium hydroxide content values ranging from 120 g/L to 130 g/L.

Furthermore, the experiment aimed to assess the leveling ability of the zinc coating. After measuring the surface roughness, the collected data were processed based on theoretical principles, and comparisons were made with practical measurements. The results indicated a decrease in the surface roughness of the components after the implementation of surface treatment through galvanic zinc coating.

The graphical representation illustrating the relationship between leveling ability and immersion time in electrolyte number 1 revealed that, at an immersion time of 25 min, a minimum leveling ability value of 40% was achieved. Conversely, at minimum and

maximum immersion times of 5 and 45 min, respectively, a maximum leveling ability value of 52% was attained.

5. Conclusions

Surface treatment technologies hold significant importance across various industrial sectors, such as mechanical engineering, electrical engineering, automotive, and others. Like many other technological domains, surface treatment processes undergo continuous refinement to bolster efficiency and achieve optimal product quality. Researchers are dedicated to continual improvement, whether through refining chemical compositions or optimizing process parameters, all aimed at realizing desired outcomes. The objective of this study was to conduct experiments facilitating a comparison between practical findings and theoretical predictions. The experiments were designed to explore the galvanic zinc coating process under a constant voltage of 4 V, with varying immersion times set at intervals of 5 min, 25 min, and 45 min. Practical observations revealed that increasing zinc content in the electrolyte led to a slight augmentation in the deposited zinc coating thickness. Similarly, when examining the dependency of coating thickness on increased NaOH content, a marginal increase in zinc coating thickness akin to the rise in zinc content in the electrolyte was observed.

Graphical representations illustrating coating thicknesses across different electrolytes offer insights into the requisite electrolyte compositions to achieve maximum coating thickness. These graphs indicate that electrolyte number 1 yielded the lowest zinc coating thickness, while electrolyte number 2 exhibited a similar dependency, with the coating thickness slightly increasing with rising voltage. In contrast, electrolyte 4 showed a pronounced increase in coating thickness values at 4 V compared to electrolytes 1 and 2. In tank number 5, the coating thickness increased proportionally with escalating voltage. Another significant finding is the notable decrease in leveling ability with prolonged immersion time, plummeting to 40% in electrolyte 1. Upon evaluation of the experiment, it became evident that the theoretical calculations for determining the thickness of the deposited coating were imprecise. This realization stemmed from measurements and calculations of layer thicknesses of individual samples using formulas based on Faraday's laws. Graphical representation clearly illustrates that, as per the formula and theoretical knowledge, the thicknesses of electrolytically deposited zinc coatings remain low, ranging from 1 μm to a maximum of 5 μm . Conversely, the measured thickness values represented by the blue curve in graph 18 significantly surpass theoretical values.

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