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Optimization and utilization of the Taguchi method in the aluminum substrate industry: Effects of dipping duration, temperature, and analytical parameters on surface efficiency

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Abstract

This study focuses on improving the electroless nickel (EN) plating process for aluminum substrates in Hard Disk Drive (HDD) production. The process applies a nickel-phosphorus (Ni-P) layer to enhance surface efficiency and reduce defects, which is crucial as the demand for high-capacity HDDs grows. The research examines key factors affecting nickel-phosphorus (Ni-P) deposition, using the Taguchi method, which allows for efficient analysis with fewer experiments. Key parameters studied include nickel and phosphorus content, pH, bath temperature, and dipping time. Results show that low nickel and phosphorus levels, along with a specific pH, significantly enhance surface efficiency. The optimal conditions identified are a bath temperature of 93.5 °C and a dipping duration of 100 minutes. This study underscores the importance of controlling these parameters to improve surface efficiency, which is vital for meeting the growing demand for high-capacity HDDs. The findings can help manufacturers reduce defects, improve yields, and save costs, and the methodology may also be applicable to other plating processes in various industries.

Keywords: Hard disk drive, Manufacturing, Optimization, Efficiency, Taguchi Method.

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1. Introduction

HDDs function as essential components in diverse digital devices, spanning from computers to video recorders and car navigation systems. In today's interconnected digital landscape, HDDs remain fundamental to data storage solutions. The widespread creation and consumption of data-heavy content, from high-resolution images to high-definition videos, demands continuous advancement in HDD storage capacities. The core components of HDDs include a motorized magnetic disk assembly. These magnetic disks are engineered by depositing an ultra-thin magnetic film onto either aluminum or glass substrates, forming the essential storage medium.

Formerly, various materials used in the substrate of magnetic recording media have been studied. However, the types of HDDs installed in desktops, servers, and Hard Disk Drive-Digital Video Disc (HDD-DVD) recorders, specifically with the alternative of high quality and low-cost aluminum substrate, have not emerged. Nevertheless, future demand for aluminum substrates is expected to remain strong compared to others [1]. In the realm of lightweight engineering materials, aluminum and its alloys occupy a position of paramount significance. Their unique portfolio of properties—encompassing corrosion resistance, impressive strength relative to their minimal density, and exceptional thermal and electrical conductivity—establishes their critical role in advanced applications [2].

Aluminum substrates come in several sizes, or form factors, depending on the application. Commonly, desktop and digital home appliances use disks of size 3.5 inches (diameter) and 69 mil thickness, while laptops/notebooks and game consoles employ smaller form factors such as the size of 2.5 inches and 69 mil thickness. A significant growth opportunity for Near Line HDDs lies in meeting the expansive storage requirements of modern data centers, which use both disks with the same diameter size but thinner, with sizes of 25 mil to 35 mil thickness.

Figure 1 illustrates the basic structure of magnetic recording media that uses an aluminum substrate. This includes a lubricative layer, carbon overcoat, magnetic layer, interlayer, and soft underlayer, which are magnetic recording media that are deposited on the aluminum substrate, while the aluminum substrate consists of a Ni-P plating layer that is plated on aluminum material through the EN plating process [3].

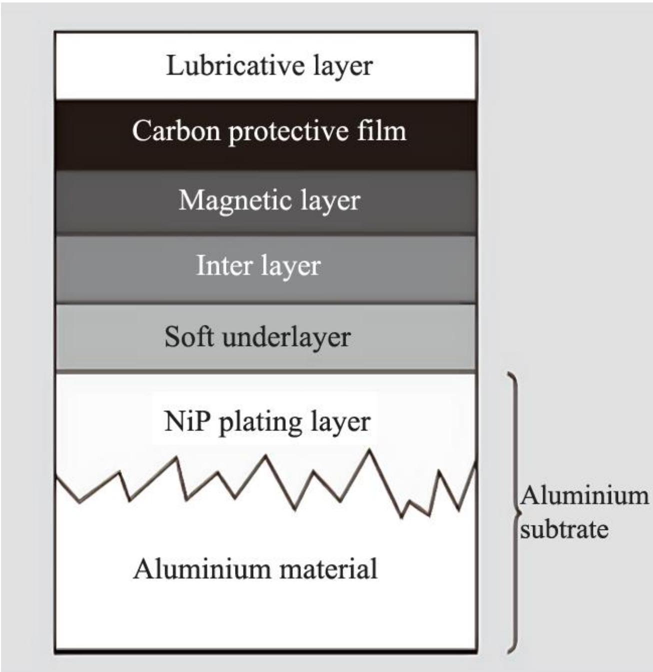

Figure 1.
Basic structure of magnetic recording media.

As mentioned earlier, recording densities are increasing year by year; hence, the development of Al substrate with the lowest number of surface defects is very crucial. The complete elimination of these defects is impossible, yet it is vital to meet and satisfy requirements that have become increasingly demanding year by year. The customers' demand for their specifications regarding the lowest number of surface defects depends on their user applications. With higher storage sizes, Al substrates with a lower number of surface defects are needed.

Producing Al substrate involves four main processes, starting with incoming raw material called Al blank. The Al blank is an aluminum alloy that is melted, cast, and rolled. Then it is stamped into a disk shape to form the Al blank. It is produced by the Al blank supplier. The overview of the manufacturing process for Al substrates is described in Figure 2:

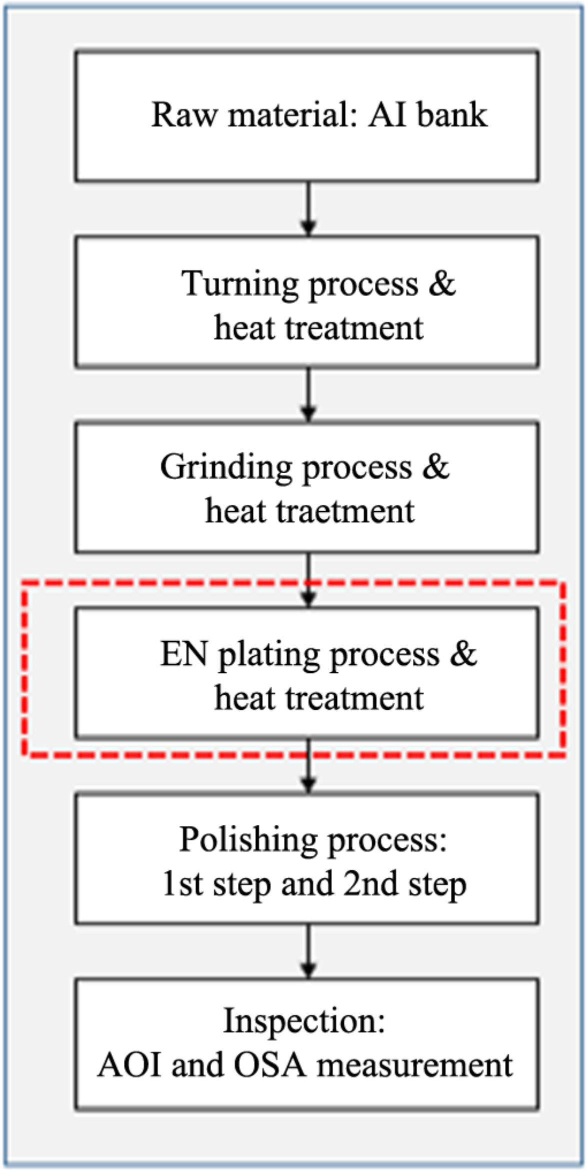

Figure 2.
Overview of Al substrate manufacturing process.
Source: (*www.showadenkohd.com.my*).

Described in Figure 2, the aluminum (Al) blank will go through turning and grinding processes. The turning process is specifically designed to cut the inner and outer surfaces of the Al blank following the production specifications, while the grinding process is intended to grind the Al surface to produce the grinding substrate (G sub). Both processes are very important to prepare a smooth and clean Al surface before it is ready for the EN plating process. The grinding process is constantly monitored because the composition and cleanliness of the grinding substrate can affect the defects and quality of the plating process. The heat treatment for both processes is to release stress in the Al surface.

In this study, the EN plating process is the central focus. Generally, the EN plating technique achieves several critical objectives: it fortifies corrosion resistance, augments surface hardness properties, ensures consistent and compact coating deposition, and generally maintains the pre-plated surface aesthetics [4]. In substrate industries, the EN plating process is used to develop a high-quality Ni-P layer between Al and magnetic bits.

The EN plating process involves a series of steps to produce a plating substrate. Depicted in Figure 3 are the steps in the EN plating process. In the initial process, EN plating involves the cleaning process and pre-plating or pre-treatment operation before the grinding substrate can be input into the Ni-P plating bath. The cleaning process uses a special salt detergent solution to remove organic contamination and eliminate solid impurities on the Al ground surface.

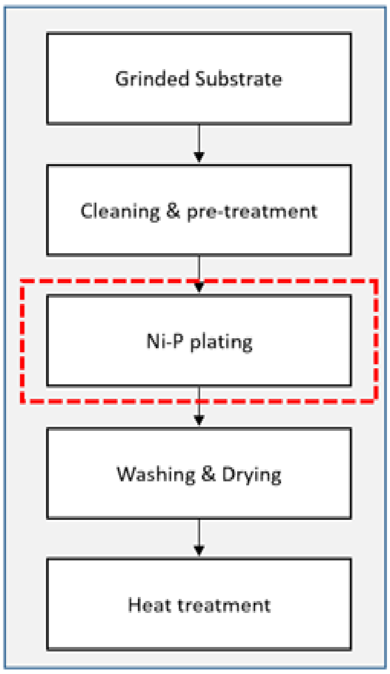

Figure 3.
Step in EN plating process.
Source: (*www.showadenkohd.com.my*)

Pre-plating or pre-treatment operations are to ensure the Al ground surface has a surface oxide coating, commonly using zincate coating. The amount of zincate deposited is very small, with the maximum thickness usually about 0.1 micron. This thickness is sufficient to smooth the aluminum surface [2]. Commercial aluminum surface preparation commonly employs the zincate technique, distinguished by its uncomplicated approach of immersing aluminum workpieces in zinc ion-containing alkaline solutions. During this process, the temperature of the zincate solution must be controlled below room temperature at 20°C. Zinc ions play a crucial role in safeguarding aluminum from re-oxidation, enabling it to be later coated with more noble metals. The quantity of zinc deposited during the pre-treatment phase greatly impacts the quality of the resulting zinc oxide layer. To ensure complete coverage and avoid exposing aluminum, a minimum pre-treatment duration of 120 seconds is essential. However, prolonging the pre-treatment time does not lead to a more uniform or thicker zinc oxide film [5].

The process is followed by the EN plating process. EN plating is different from traditional electrolytic coating or plating methods that rely on uniform deposition and the use of electricity; this approach allows for the application of conductive materials without electrical assistance [6]. EN plating requires elevated temperatures, typically exceeding 80°C, to facilitate the self-catalytic reaction necessary for the process [7] without electrodes, as in conventional electrolytic coating. EN plating was pioneered by Brenner and Riddell [8], who secured a patent for the process in 1950. This technique holds significant importance in the metal finishing industry and is extensively utilized for coating various metal substrates, including steel, copper, aluminum, and their respective alloys [9]. The EN plating solution commonly consists of several components, including an aqueous solution of nickel ions that will deposit onto the Al substrate, a reducing agent (NaH2PO2) that initiates the reaction, and a complexing agent for stabilizing metal ions. Conversely, the buffer agent will control pH fluctuations. The control of nickel content and pH during the plating process has a significant impact on the quality of the substrate surface. Nickel content and pH value will be automatically monitored by the plating controller. Then, the auto-adjustment of the plating solution will occur if both parameters are out of the set value. An elevated pH level in the plating solution can disrupt the plating rate, potentially resulting in issues such as surface roughness, pitting defects, or the formation of cloudy deposits [4]. On the other hand, poor nickel content in the plating solution will result in a slow plating rate, poor coverage, and dull deposits [6]. Moreover, the temperature of the plating bath must also be closely monitored for consistent high-quality deposits. Some factors also relate to dipping duration. The phosphorous (P) content cannot be monitored automatically. Instead, the P content will be measured by a technical person using the manual titration method, where the plating bath solution will be sampled two times per shift to measure the P content.

Next is the washing process after EN plating is completed. This is to remove any residue on Al substrate surface which then continued by drying process with 1% of hot ammonia solution. The Al substrate then will be rotated in the hot air to ensure the substrate are dry enough prior to heat treatment process. Heat treatment or annealing is a process that expose Al substrate to various temperature for different time period. This process is to release the stress on the Al substrate. Heat treatment significantly influences the corrosion resistance of EN plating, as studies consistently reveal that the as-deposited coatings exhibit superior corrosion resistance. This is attributed to their amorphous structure. However, heat treatment causes the amorphous phase to transition into a crystalline structure, altering its properties. Table 1 shows the properties of EN plating and Figure 4 demonstrates the major use of EN deposit referring to article by Sahoo and Das [10] and Kundu, et al. [6]:

Table 1.
Properties of electroless nickel coating.

Feature	Benefit
Excellent corrosion resistance	Good coating durability
High hardness value	Low wear characteristics
Low friction co-deposits available	Self-lubricating coating
Uniformity in deposit	Eliminates post-plate finish
Good brightness	Attractive finish
Fast plating rate	High production output
Good chemical resistance	Acts as a protective coating
Solderability/weldability/traceability	Functional in many applications
Non-magnetic/magnetic	Magnetic properties selectivity

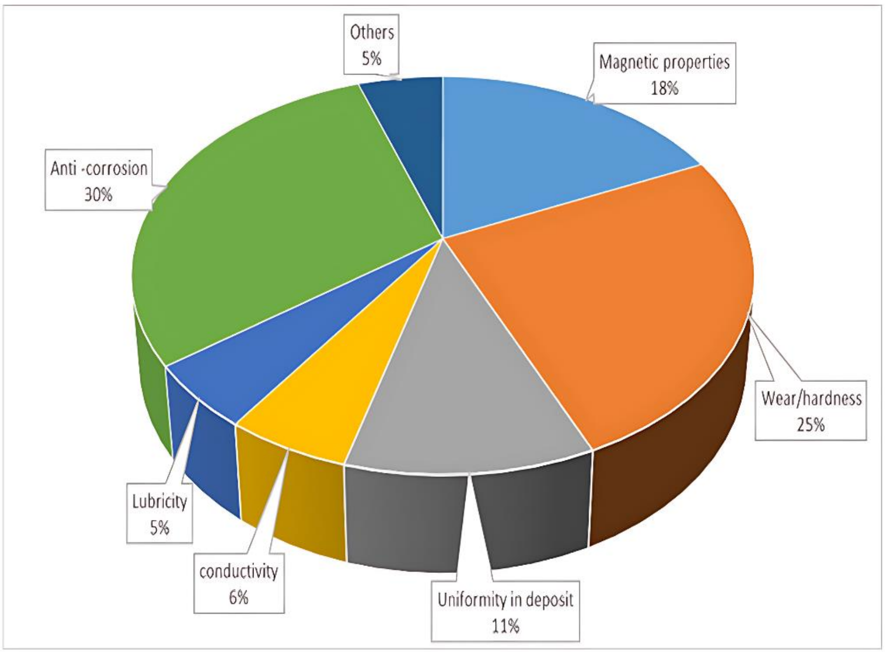

Figure 4.
Major use for electroless nickel deposit.

The final process is polishing process, involving two steps of polishing activity. Typically, 1st polishing uses a slurry containing alumina abrasive powder step to remove grinding mark and waviness. Conversely, 2nd polishing uses a colloidal silica slurry to adjust micro-waviness and surface roughness [3].

1.1. Background of The Study

The ability to reduce the number of surface defects is challenging in the development of high-quality Al substrate for magnetic recording media. A high-quality surface of the Al substrate contributes to the consistency of the magnetic head flying at a height of several nanometers. This will make the recording and playback of information stable.

Demanding larger capacity recording storage for HDDs is becoming increasingly important, especially in the mass data storage of Near Line HDDs. Near Line HDDs are used in data centers to store both online and offline information. They require even smaller and more densely packed magnetic bits. Therefore, the surface efficiency of Al substrate is very important to produce high-quality media magnetic disks in HDDs [3].

The optimum combination of control factors and levels in the EN plating process will reduce the number of surface defects and produce a higher-quality Ni-P layer [1]. However, developing the optimum combination of control factors and levels requires a significant amount of time and cost to conduct a series of experiments. Hence, the Taguchi method (orthogonal array) is proposed in this study. The Taguchi method enables the determination of the influence of control factors on the response while also assessing the validity and reliability of these factors.

1.2. Research Objectives

Based on the above discussion, the objectives of this study are summarized as follows:

a) To identify the optimum control factors of analytical parameters, temperature bath, and dipping duration in the EN plating process to produce the Al substrate with high surface efficiency.
b) To predict and forecast the performance characteristics of surface efficiency on Al substrate using the Taguchi Method.

1.3. Research Question

This study is conducted to produce the Al substrate with high surface efficiency by reducing the number of surface defects. Hence, the selected control factor is controlled variance, which impacts the reduction of the number of surface defects. Analytical parameters, temperature, and dipping duration in the EN plating process are considered as control factors to achieve a low number of surface defects. Below is a list of research questions to be answered by this study:

a) What is the effect of the analytical parameter on the number of surface defects of the Al substrate?
b) What is the effect of the temperature bath on the number of surface defects of the Al substrate?
c) What is the effect of dipping duration on the number of surface defects of the Al substrate?

2. Literature Review

2.1. Surface Efficiency

Al substrate technology involves three major issues to overcome problem in surface efficiency: (1) smoothness, (2) end shape and (3) micro-defect and residue [3]. Smoothness refers to roughness and waviness of Al substrate surface, while end shape refers to roll-off value that is measured at outer edge of surface Al substrate and micro-defect is count as surface defect, detected on middle of Al substrate surface.

This study focuses on reducing the count of surface defects measured by AOI and OSA. By reducing the defects, good surface efficiency on Al substrate will be achieved. The quantity of defects on the Al substrate is extremely important because it directly impacts production performance yield, as mentioned earlier. The relative number of defects on the Al substrate surface must be reduced in order to support higher recording densities of magnetic recording media for HDD industries. Figure 5 shows studies by the company Fuji Electric in 2011, indicating that as storage size increases from 250 GB to 1 TB, the relative number of defects for 100nm class size measured by OSA must be reduced, as well as surface roughness, waviness, and roll-off issues.

	250 GB substrate	500 GB substrate	1 TB substrate
Surface roughness (AFM-R_a)	≤0.15 nm	≤0.14 nm	≤0.12 nm
Micro-waviness (W_q)	≤0.23 nm	≤0.14 nm	≤0.12 nm
Edge roll-off	≤15 nm	≤10 nm	≤7 nm
Relative number of defects*	100	70	30

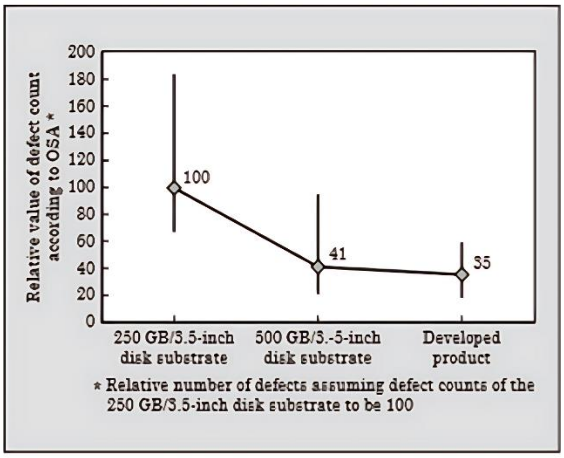

Figure 5.
Surface requirement and number of surface defect –Study by company Fuji Electric.
Source: Kainuma, et al. [3].

Other than roughness and waviness, uniformity of thickness Ni-P layer also contribute to the surface efficiency. In EN plating process, the uniformity of the surface charge across the part dictates the consistency of the deposition process. A perfectly even charge distribution ensures that the plating occurs at the same rate across every point of the surface [4]. Study by Kundu, et al. [6] and Sahoo and Das [10] also discover the EN plating can achieve consistent thickness across components, even on those with intricate geometries and complex shapes.

2.2. Dipping Duration

Dipping duration or plating time generally affects the electroplated layer thickness. The plating thickness increases with increasing of plating time [11]. The increasing of plating time will decrease the concentration of reactant gradually because the formation of plating consumes the metal and non-metal ions [12]. According to Gao, et al. [7] the optimum temperature and plating time produce dense, homogenous and crack free structure. Besides, increasing of plating time will improve the surface morphology [13] though finding by Oloruntoba [11] show that surface topography seemed to roughen with high plating time.

2.3. Temperature Bath

The main elements of an EN plating bath are nickel ions and a reducing agent, with the immersion substrate maintained at a temperature around 90 °C. To ensure a smooth and consistent plating process, certain organic complexing agents are introduced into the bath, complexing with the nickel ions and maintaining a stable reaction [6]. Described by Gao, et al. [7], high temperature contributes to the smoothness of the surface Ni-P coating; however, overheating in the EN process can crack the Ni-P coating, which is attributed to the excessive hydrogen evolution. Thus, at high temperatures, the EN plating process has a sufficient deposition rate to produce a coating layer. Nonetheless, high temperatures require high energy, which increases costs, while a decrease in temperature results in a low deposition rate. Accordingly, the stability of the deposition rate should be improved. Genova, et al. [14] specified that in a pure electroless plating process, deposition starts at a temperature of 65 °C; however, it yields poor results, as the deposition rate is < 2 μm per hour. Therefore, this led to the selection of 70 °C as the lower temperature in their investigation. The research also emphasized that the reactivity of the reducing agent is significantly impacted by the bath temperature. When the temperature surpasses a certain threshold, the deposition rate continues to rise; however, this comes at the cost of deteriorating surface morphology.

2.4. Analytical Parameter

Described by Hu, et al. [15] and supported by Kundu, et al. [6] the plating process is heavily influenced by several key factors, including the composition of the plating bath, operational conditions such as pH and temperature, and the bath loading factor, which is the ratio of the substrate's surface area to the solution volume. Additionally, the inherent characteristics of the substrate itself play a significant role in determining the outcome of the coating process. Accordingly, analytical parameter in this study refers to bath composition which consist of combination parameters: pH value, nickel content and phosphorous content for EN plating solution. All parameters are combined as one set control factor because as these parameters have interconnected between each parameter.

2.5. Nickel Content

Nickel (Ni) salt is the main element in the electroless Ni-P plating process, and commonly, Nickel Sulfate is widely used as a primary resource. Among all metals that can be electroless plated, Ni and its alloys dominate the industrial landscape of this plating technique, accounting for a staggering 95% of all applications. At the heart of this process, hypophosphite reigns supreme as the reducing agent of choice [16]. The nickel-phosphorus coating has attracted special attention due to its great corrosion resistance and the uniformity of Ni-P layers. The findings revealed a notable enhancement in micro-hardness, adhesion, and corrosion resistance of the deposits. This suggests that the consumption of nickel salt and the reducing agent hypophosphite significantly impacts the buildup of SO4-2, which in turn affects the quality of the coating [15].

2.6. Phosphorous Content

Phosphorous (P) is important element consist in reducing agent, sodium hypophosphite (NaH2PO2). Hypophosphite reigns supreme in commercial electroless nickel baths, prized for its ability to deliver faster deposition rates, enhanced stability, and simplified bath management [10]. The characteristics of nickel-phosphorous (Ni-P) coatings are heavily influenced by the phosphorous content within the alloy. According to Gawrilov [17] there are three main classes of NiP coating: (1) Low phosphorous coating (1-5 wt% P) which give very good mechanical properties at the expenses limited corrosion resistant, (2) Medium phosphorous coating (6-9 wt% P) which offer a good mechanical properties and corrosion resistance, and (3) Coatings with high phosphorous content (10-14 wt% P) demonstrate exceptional corrosion resistance but tend to have weaker mechanical properties. The phosphorous content plays a crucial role in determining the microstructure and overall characteristics of the coating. At low to medium phosphorous levels, electroless nickel (EN) coatings consist of a combination of amorphous and microcrystalline structures. In contrast, when the phosphorous content is high, the structure becomes entirely amorphous.

The study by Lin and Chou [18] highlights that the phosphorous content significantly impacts both the microstructure and the specific capacitance of electroless Ni-P coatings deposited from acidic and alkaline baths. At lower phosphorous levels, the coating tends to form a porous, ridge-like structure with pores in the micrometer range when etched. Therefore, it is suggested that increasing the phosphorous content reduces the pore size to nanometer size.

2.7. pH Value

The phosphorus content decreases almost linearly with the increase of bath pH from 3 to 5.5 and maintains a constant level for both Ni-P and Ni-P-Re [19]. The Re element is an additional metallic ion in the EN plating process. However, Re does not affect any significant changes in phosphorus content. On the other hand, nickel content decreases along with the addition of other metallic ions.

Accordingly, as the pH of the solution rises, the plating rate accelerates, while simultaneously, the phosphorus content of the deposit diminishes [6]. Within the confines of this system, electroless deposition thrives within a pH window of 3.0 to 6.0. Beyond this upper limit, specifically above 6.5, insoluble by-products begin to form, likely nickel hydroxide, disrupting the plating process. Conversely, the deposition process did not start in a solution with a pH below 3 [19]. Consequently, the plating rate exhibited an almost linear increase as the pH rose within the range of 4 to 12. This clearly indicates that the pH level in the bath plays a crucial role in influencing the plating rate [15].

3. Methodology

This study employs the robust Taguchi method, a powerful experimental design originally conceived by Japanese engineer Genichi Taguchi to revolutionize manufacturing quality. While initially focused on production processes, its versatility has since propelled its application into diverse fields, spanning biotechnology, marketing, and even advertising [20-23]. Professional statisticians have widely appreciated the advancements and objectives introduced by Taguchi methods, especially Taguchi's innovative approach to designing experiments that analyze variation. These methods employ orthogonal arrays, enabling researchers to explore the entire parameter space efficiently with a significantly reduced number of experiments.

The Taguchi method is built on the concept of fundamental functionality, offering a consistent and universal goal that remains applicable across various scenarios. This approach provides a reliable standard for handling dynamic and frequently shifting conditions. Additionally, the Taguchi Method aligns well with emerging human-centric quality evaluation techniques, making it highly adaptable to modern quality assessment practices.

3.1. Research Approach

This research employs a quantitative methodology, utilizing the Design of Experiments (DOE) to optimize each factor level. Specifically, the Taguchi method, with its characteristic orthogonal arrays, provides a statistically robust framework for efficient experimentation. This approach allows for the development of an optimized model while minimizing the required number of experimental runs. The generated Taguchi orthogonal arrays serve as the core structure of the experimental design.

Through the Taguchi method, the signal-to-noise (S/N) ratio was calculated to determine the validity and reliability of the parameter involved as emphasized by Kumar and Simha TP [24]. Depending on desired output quality characteristics, three categories of signal-to-noise are available: -

Smaller the better

• Used when the objective of the experiment is to minimize the response.

• S/N = - 10 *log (Σ(Y2)/n))

Larger the better

• Used when the objective of the experiment is to maximize the response

• S/N = - 10 *log (Σ(1/Y2)/n)

Nominal the best

• It will select the most suitable response of the variable.

• S/N = 10 *log (Y2/ σ2)

Y = mean; n = number of response in factor level combination

The expected output of this study is to reduce the number of defects on the surface of the Al substrate. Therefore, the 'smaller the better' function will be used. At the manufacturing level, reducing the number of surface defects will directly increase production yield and throughput.

3.2. Research Design

Manipulating input factors and parameters is crucial for process optimization, ultimately leading to enhanced outputs. This optimization translates to improvements in system performance across key metrics, including quality, cost-effectiveness, and efficiency. Implementing Taguchi methodology will help to identify the validity, significance, and reliability of the experimental results based on selected parameters. Figure 6 shows the flow process in the Taguchi Method that will be carried out in this study.

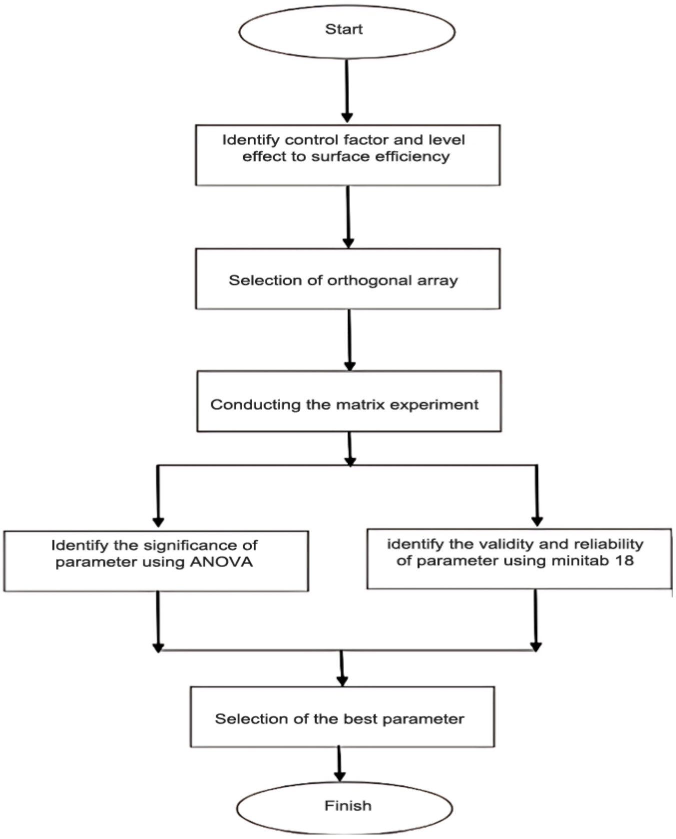

Figure 6.
Research Methodology process.

3.3. Control Factor and Level

The factors influencing the surface efficiency of the Al substrate will be defined in this section. Surface in this study refers to the monolayer nickel phosphorus (Ni-P) that forms on the aluminum disk during the process of Electroless Nickel (EN) plating. The selection of factors and their respective levels was determined by establishing the minimum and maximum ranges within which the sample remained stable. Subsequently, optimal levels for each factor, exhibiting the greatest influence on the experimental outcome, were identified. Control factors for each parameter were carefully considered, based on an evaluation of potential root causes contributing to surface defects on the Al substrate, with a specific focus on pit and nodule formation.

Based on previous studies, controlling analytical parameters (nickel content, phosphorous content, pH value), bath temperature, and dipping duration are the main factors in producing quality Al substrate. The high quality of Al substrate means the minimum number of defects encountered. The electroless nickel (EN) plating process demands precise regulation of critical parameters, including plating bath temperature, nickel concentration, and pH level. Optimal outcomes are attainable through meticulous control and maintenance of these factors, ensuring high-quality and consistent results. A good balance of nickel and phosphorous content with a suitable pH value will contribute to a good nickel deposition rate, producing a smooth Ni-P monolayer. A long dipping duration in the EN plating bath will contribute to a more stable Ni-P layer due to the production of more layers. However, a long dipping duration will increase the usage of chemicals and time, which will decrease the production output. Meanwhile, optimization of dipping duration will create a good surface substrate and maintain or increase the production output. Conversely, previous studies also show a relationship between temperature and nickel content on the thickness of the Ni-P layer. In the production process, the thickness of the Ni-P layer is required to be in the range of 10.5 µm to 12.5 µm. This may differ from other production processes in different companies. Besides, a thicker layer could leave a wavy or rough surface that might require refinishing, while a thinner layer can cause the Al substrate to not meet product specifications. For that reason, the selection of temperature levels has taken into account the desired thickness in this process.

Described earlier, the thickness will form within the range. Thus, all parameter plays important role in contributing to surface efficiency in producing Al substrate. Hence, a series of experiments will be conducted in this study to evaluate the best parameter. The selection level for every factor for this study is shown in Table 2. On the other hand, analytical parameter is the combination of nickel content, phosphorous content and pH value. Table 3 describes the setting value of nickel content, phosphorous content and pH value for level Low, Medium, High.

Table 2.
Factor and level experiment.

FACTORS		LEVELS		
		1	**2**	**3**
1	Dipping duration (min)	100	110	120
2	Temperature bath (°C)	92.5	93.0	93.5
3	Analytical parameter	Low	Medium	High

Table 3.
Factor levels of analytical parameter.

Analytical parameter	**Low**	**Medium**	**High**
Nickel content (g/L)	5.75	5.80	5.85
Phosphorous content (g/L)	37.5	37.0	36.5
Ph	4.48	4.50	4.52

3.4. Selection Orthogonal Array (OA)

Orthogonal array testing represents a systematic and statistically grounded black-box testing methodology in software testing. This technique facilitates the examination of all possible combinations of control factors and their respective levels within an experiment.

Table 4.
Orthogonal Array (OA) L9.

Experiment No.	**L_9 (3^3) Orthogonal array**		
	Control Factors		
	1	**2**	**3**
Experiment # 1	1	1	1
Experiment # 2	1	2	2
Experiment # 3	1	3	3
Experiment # 4	2	1	3
Experiment # 5	2	2	1
Experiment # 6	2	3	2
Experiment # 7	3	1	2
Experiment # 8	3	2	3
Experiment # 9	3	3	1

The choice of an appropriate orthogonal array is contingent upon the number of control factors and their associated levels. A full factorial design, on the other hand, encompasses every possible combination of all levels for each control factor under consideration [25]. This design allows the study in the combination of control factors on the response to be performed. Described in Table 4, the OA used in this study is L9 (3 parameters with 3 level design). L9 OA, consists of nine set of experiment is carried out in this study.

3.5. Conducting the Matrix Experiment

In accordance with the above OA, a total of 9 sets of experiments were conducted. Each of the above 9 experiments was conducted 3 times to account for the variations that may occur. Al grinded substrate (3.5-inch diameter) that is loaded into the EN plating bath is placed on a plating carrier known as a carousel. The quantity for every sample is 1800 pieces of Al grinded substrate. This quantity refers to the EN plating bath capacity. All the setting values for each parameter are set at the EN plating control panel. After completing the EN plating process, all samples undergo a heat treatment process under the same conditions and a polishing process in the same machine line under the same conditions. Then, the count of surface defects for all samples is measured by two types of equipment: 1) Automated Optical Inspection (AOI); 2) Optical Spectrum Analyzer (OSA).

AOI measures every single piece of Al substrate. The number of defects encountered is calculated through the quantity of Al substrate entering the AOI machine. The end results then appear as a percentage value. For OSA, only 4 pieces of Al substrate from every sample are measured, where the results appear in units of cps (counts per surface). The end results are an average of the number of defects encountered for the 4 pieces measured. Both equipment measures the number of defects with different sizes of defects. AOI laser is where the detection of defect size in micrometers is performed, whereas OSA laser detects defect size in nanometers. In simple terms, AOI measures defects with larger sizes compared to OSA.

AOI measures 100% of Al substrate. AOI results are calculated based on the quantity of rejected Al substrate, which means the Al substrate that encounters a number of surface defects greater than the allowable limit (8 pass, 7 fail), then divided by the total quantity input of Al substrate. From the percentage of surface defects, the yield of the product can be calculated. Table 5 shows the experimental layout with the selected values of the factors, and below is an example of AOI calculation:

Quantity input: 1800 pieces Al substrate; Quantity rejected: 100 pieces

$$\% \text{ Rejected} = 100/1800 \times 100\% \approx 5.6\%$$

$$\% \text{ Yield} = 100\% - 5.6\% = 94.4\%$$

Table 5.
OA with Control Factor.

Experiment	1	2	3
1	Low	92.5	100
2	Low	93.0	110
3	Low	93.5	120
4	Medium	92.5	110
5	Medium	93.0	120
6	Medium	93.5	100
7	High	92.5	120
4	High	93.0	100
9	High	93.5	110

3.6. Identify Significance of the Control Factors

Analysis of Variance (ANOVA) is employed to determine the statistical significance of the control factors in relation to the response variable. This method allows for a precise assessment of how each factor influences the outcome, ensuring a robust understanding of their impact within the experimental framework [26]. It allows us to determine which control factors have the highest impact on the response. Additionally, the calculation of the P-value in the software Minitab 18 enables the identification of control factors that are significant toward the response.

3.7. Identify Validity and Reliability of the Control Factors

The Signal to Noise (S/N) ratio for each experiment is calculated using Minitab 18 software. As previously highlighted, this ratio is essential for assessing the validity and reliability of the control factors at play. Given that the objective function in this study follows a "smaller is better" criterion, the appropriate control function type has been employed [27]. From the S/N ratio value calculated in the software, average S/N ratio for each factor is determined.

3.8. Selection of the Optimum Control Factors

The selection of the optimum controls factors is based on function used in calculating the S/N ratio [28]. Since the objective function in this study is smaller the better, the factor and level with highest S/N ratio are chosen as the optimum control factors.

3.9. Research Framework

The research framework of this study are established through rigorous review of literature on reducing the number of surface defect on Aluminium substrate for HDD application, focusing on EN plating process [29]. There are various control factors including plating loading, plating solution composition, concentration of reducing agent and temperature as control factor [30]. After consideration of all these factors, following research framework is established.

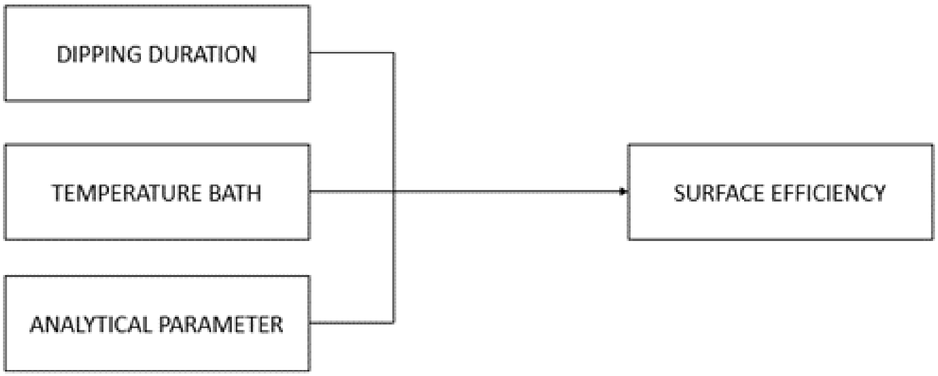

Figure 7.
Research Framework.

To obtain a good Ni-P layer on an Al substrate during the EN process, three control factors described in Figure 7 were studied. In view of reducing the number of surface defects, which will increase production throughput, the attained results through the analysis performed are explained and discussed.

4. Results and Discussion

The results obtained from applying the methodology process described earlier are presented. This section is divided into three sections: data collection from the measurement of surface defects after conducting nine experiments, data analysis for the Taguchi approach, and lastly, the confirmation experiment for optimizing control factors and levels.

4.1. Data Collection

A total of nine experiments were conducted with each factor level setting by L9 orthogonal array. Each of experiment was conducted three times (27 experiments in all). As discussed, two types of results from 2 different equipment AOI and OSA were collected. Table 6 shows AOI results while Table 7 shows OSA results.

Table 6.
Results AOI measurement.

Experiment	AOI surface defect Results (%)			
	1	2	3	Mean
1	2.0%	1.8%	2.1%	2.0%
2	1.9%	1.6%	1.8%	1.8%
3	1.9%	1.6%	1.8%	1.8%
4	2.0%	1.7%	1.9%	1.9%
5	0.5%	0.9%	0.4%	0.6%
6	1.2%	1.1%	1.3%	1.2%
7	1.0%	0.8%	0.9%	0.9%
8	0.6%	0.7%	0.5%	0.6%
9	3.7%	3.1%	3.6%	3.5%

Table 7.
Results OSA measurement.

Experiment	OSA surface defect Results (cps)			
	1	2	3	Mean
1	30	45	40	38.3
2	45	33	28	35.3
3	32	33	23	29.3
4	41	39	42	40.7
5	51	55	31	45.7
6	34	29	25	29.3
7	40	33	38	37.0
4	39	50	41	43.3
9	44	38	49	43.7

4.2. Data Analysis

P-value of control factor is to identify the significance of the control factor towards the response. Table 8 shows P-value for each control factor towards response, AOI and OSA.

Table 8.
P-value towards AOI and OSA.

Response variable	AOI	OSA
Control Factor	**P-Value**	**P-Value**
Dipping Duration	0.039	0.607
Temperature Bath	0.019	0.449
Analytical parameter	0.024	0.935

The results show that the P-value for AOI has met the significance value below 0.05 in each control factor. Thus, it can be comprehended that all control factors are significant towards the response and have a greater influence on the experiment. However, the OSA P-value of all control factors is higher than the significance value of 0.05. This is possible due to other factors that contribute to surface defects at the nanometre scale. This is supported by the prior discussion, as the OSA measurement is intended to account for the number of defects at the nanometre scale. Other factors that may be involved include bath loading factor, Al grinded cleanliness, pre-treatment performance, and DI water quality, which contribute to Al substrate quality.

4.3. S/N Ratio Analysis

The S/N ratio of all experiment is calculated in software Minitab 18 using smaller the better formula. This formula is selected as accordance to the objective of this study, to minimize the response with is the number of surface defect (AOI, OSA). Table 9 designates the S/N ratio data.

Table 9.
S/N ratios.

Experiment	S/N Ratio
1	-28.6612
2	-27.9534
3	-26.3369
4	-29.1745
5	-30.1817
6	-26.3369
7	-28.3537
8	-29.7261
9	-29.1745

The parameter with the highest S/N ratio value is chosen as the optimum parameter to achieve the highest efficiency. Figures 8, 9, and 10 demonstrate the graft of S/N ratio for each control factor and level. Figure 8 demonstrates the graft of S/N ratio for control factor dipping duration where the optimum level for this factor is 100 minutes. Figure 9 on the other hand illustrates the graft of S/N ratio for the control factor of the temperature bath, with optimum level at 93.5 °C.

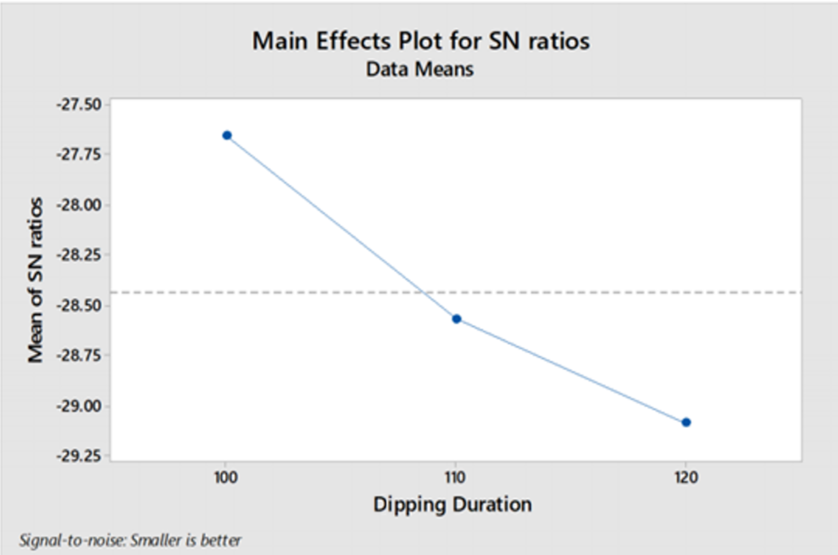

Figure 8.
S/N for Dipping Duration.

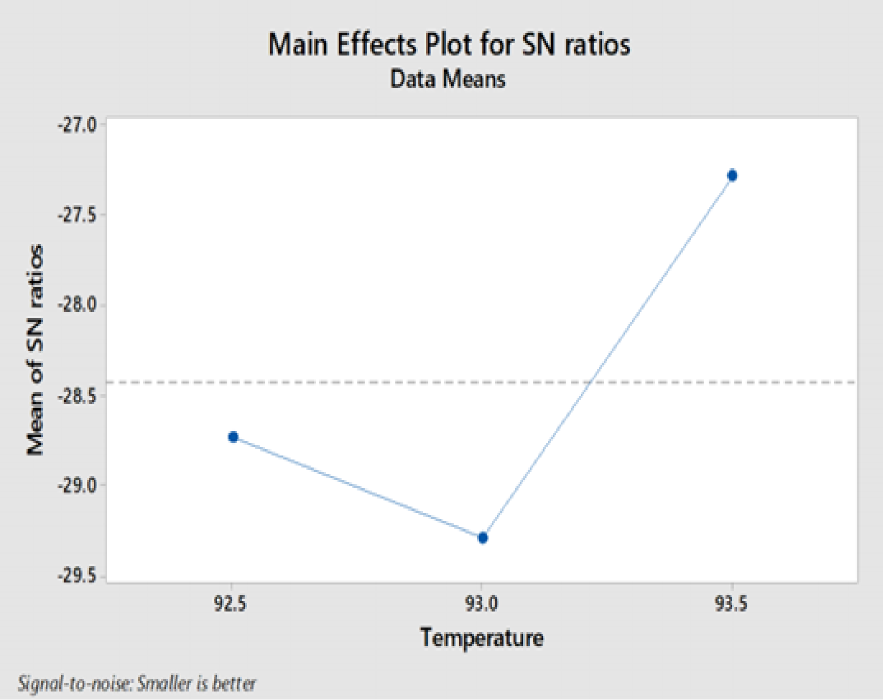

Figure 9.
S/N ratio for Temperature

Figure 10 shows the graft of S/N ratio for the analytical parameter. The optimum level for this factor is at a low level. By using the smaller the better formula, it can be decided that the lowest S/N ratio value for each control factor is selected to optimize the condition.

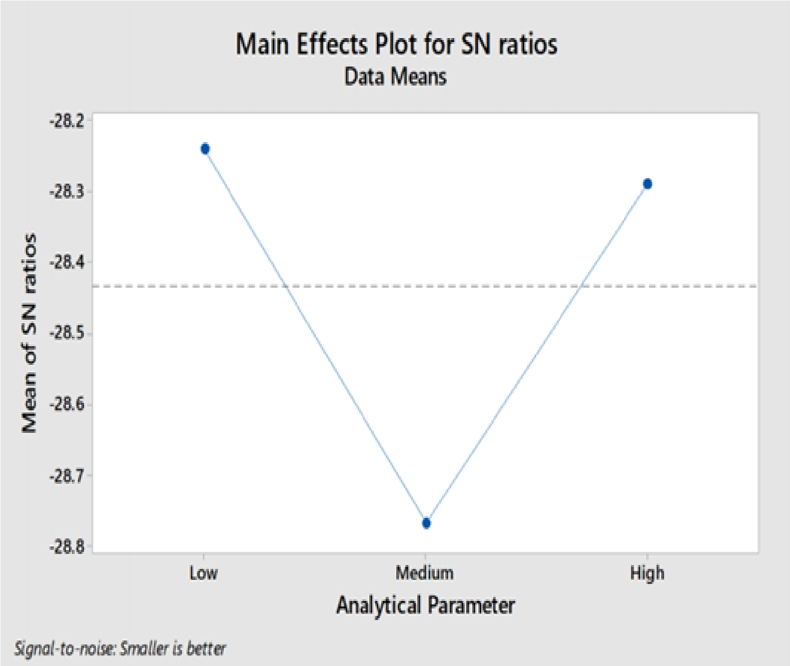

Figure 10.
S/N ratio for Analytical Parameter.

4.4. Selection Optimum Level

Based on the linear graph, the optimum values of the factors and their levels are as given in Table 10.

Table 10.
Optimum values of factors and their levels.

Control Factor	Optimum Level
Dipping Duration	100 minutes
Temperature	93.5 °C
Analytical parameter	Low

From the above results, it is proven that the combination of dipping duration, temperature bath, and analytical parameters of the EN plating process are major factors in achieving good surface efficiency of the Al substrate. The results support previous findings that an increase in temperature bath will increase the deposition rate of the Ni-P coating. However, overheating will increase the deposition rate, though it does not improve the quality of the Ni-P layer. The optimization of bath composition or analytical parameters is very important. Having lower nickel content and higher phosphorus content at a suitable pH value results in the lowest number of surface defects. The results also confirm that a low coating duration or dipping duration yields better results. Apart from reducing the number of surface defects, a lower dipping duration in the plating process increases total production output by at least 20% in a month.

Through adapting the Taguchi method, it utilizes quantity measurement levels and allocation procedures to promote high reliability of the outcomes as well as better generalizability of results. This method is significantly useful in eliminating wasted time by conducting a number of experiments. By implementing the optimum control factors and levels, it benefits the company in increasing productivity and achieving monthly targets.

Implementing the Taguchi methods in this study is based on the control factor and level. This method assists in investigating the validity and reliability of control factor. This experiment discovers the suitable control factor and level toward the response in order to achieve the desired target and ultimately helps company to save cost and time.

4.5. Confirmation Experiment

The following table (Table 11) indicates AOI and OSA results for the confirmation run conducted using optimized conditions, with a dipping duration of 100 minutes at a bath temperature of 93.5 °C and analytical parameters at a low level. A total of three sets of experiments were conducted. Referring to the obtained results in Table 11, it can be concluded that the results are lower and consistent. The AOI result can be reduced to below 1%. This directly increases the total yield to 99%. Conversely, the result of OSA demonstrates that the number of surface defects can be reduced to below 50 counts per surface (cps), which is the desired target from the industries.

Table 11.
Confirmation Experiment.

Experiment	**Number of surface defect**	
	AOI	**OSA**
1	0.9%	33
2	0.7%	40
3	1.0%	38

5. Conclusion

The optimum level of control factor to produce high quality of Al substrate is summarized in Table 12 as follow:

Table 12.
Optimum control factor and level.

Dipping duration	100 minutes
Temperature bath	93.5 °C
Analytical parameter	Low (Nickel content: 5.75g/L; Phosphorous content: 37.5g/L; pH: 4.48)

From the confirmation run of results, the lower number of surface defects is encountered. For the above analysis findings, the results of this study are answered as follows:

Table 13.
Research Question Results

No.	**Research Question**	**Results**
1	Effect of dipping duration on the number of surface defects of Al substrate.	Optimum dipping duration helps to develop a good Ni-P layer that directly contributes to lower surface defects.
2	Effect of temperature bath on the number of surface defects of Al substrate.	Using the high-temperature bath effect to achieve an excellent monolayer surface on the Al substrate.
3	Effect of analytical parameters on the number of surface defects of Al substrate.	The factor consists of three elements: nickel content, phosphorous content, and pH value, which affect the reduction of the number of surface defects. A combination of low nickel content and high phosphorous content yields good OSA and AOI results. A low pH setting also contributes to the reduction of surface defects.

As described in Table 13, it can be concluded that optimizing and utilizing the Taguchi method in this study has enabled it to predict and forecast the performance characteristics of surface efficiency on Al substrate. Consequently, there are benefits in achieving the desired results.

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