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Surface Hardness Improvement of 3D Printed PLA Using Nickel Electroplating

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A R T I C L E I N F O

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A B S T R A C T

Electroplating is a process that uses electric current to deposit a layer of metal onto the surface of a conductive material, enhancing its properties such as corrosion resistance, electrical conductivity, and mechanical strength. This study investigates the process of nickel electroplating on 3D-printed polylactic acid (PLA) substrates, focusing on the efficiency and quality of the nickel coatings achieved through electroplating techniques. The methodology encompasses several stages, starting with the design and 3D printing of PLA specimens. Following this, the preparation of the electroplating setup is meticulously carried out, ensuring optimal conditions for the electroplating process. The quality of the nickel coating is then evaluated through a series of tests to assess its mechanical and electrical properties. The key findings from this research indicate that the electroplating process effectively deposits nickel onto the PLA substrates. This deposition significantly enhances the mechanical strength and electrical conductivity of the PLA specimens. The study's results suggest that nickel electroplating on PLA can be a viable method for improving the material properties of 3D-printed parts. This advancement not only contributes to the development of cost-effective and sustainable metal coating techniques for polymer-based materials but also has the potential to broaden the application scope of 3D-printed parts in various fields of engineering and technology. Such improvements could be particularly beneficial in industries requiring enhanced material performance, such as electronics, automotive, and aerospace sectors.

Introduction

Aside from metals and ceramics, one of the most significant categories of materials utilized in industry are polymer materials. Their low density, strong resistance to chemicals, and ease of producing goods with intricate geometries have led to the swift advancement of their uses. (polymer weakness)

To apply copper and nickel coatings on polymeric materials, the first electroplating baths were created in the 1950s, which marked the beginning of research into this field (Augustyn et al. 2021). Electroplating is commonly used to coat metals with a thin layer of another metal, such as silver or gold, to enhance their appearance and provide additional corrosion resistance (Arash et al. 2015). Electroplating can also be applied to PLA-coated metals, providing them with the same benefits of enhanced appearance and corrosion resistance (Baghery et al. 2010). This process involves immersing the PLA-coated metal in an electrolyte solution containing the desired metal ions while applying an electric current. This electric current causes the metal ions to be attracted to the PLA-coated surface, forming a thin layer of metal on top (Valko et al. 2021).

Metallizing plastic provides numerous benefits, including reflectivity, abrasion resistance, electrical conductivity, and various decorative finishes (Arai, Sato, and Endo 2011). It also enhances wear and corrosion resistance, offers electromagnetic shielding, improves formability, increases impact resistance and weatherproofing, lowers costs, and allows for more flexible part designs (Dechasit and Trakarnpruk 2011; Wang et al. 2011; Kim et al. 2007). Additionally, it reduces weight compared to metal alternatives (Di et al. 2011; Ma, Tan, and Kang 2000; Kulkarni, Elangovan, and Hemachandra 2013).

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Metallized plastics are valuable in various industries, including electronics, petroleum, national defense, toy manufacturing, automotive, and computers. They are used for electronic housing, wheel covers, lamp housing, ventilation and air conditioning parts, pipes, fittings, and more (Teixeira and Santini 2005; Bazzaoui et al. 2012; Skelly 2008).

This electroplated layer improves the look and feel of the PLA-coated metal and adds durability and wear resistance. Additionally, electroplating PLA-coated metals can potentially improve their chemical catalyst properties, increasing their utility in various applications (Carneiro et al. 2021). Overall, electroplating has a positive effect on PLA-coated metals by improving their appearance, durability, and corrosion resistance while potentially enhancing their chemical catalyst properties (Robson et al. 2014). Electroplating has a positive effect on PLA-coated metals as it improves their appearance, durability, and corrosion resistance while potentially enhancing their chemical catalyst properties (Raja et al. 2019).
There are some challenges in doing electroplating process of Polylactic Acid (PLA) such as controlling and dosing electrolytes, deposition, uniformity of metal layers and adhesion. the challenge is to be said as controlling and dosing electrolytes This is a key challenge in the operation of electroplating process chains. Electrolyte components are continuously degraded and dragged out during the production process. uniformity of metal layers, deposition, adhesion, and complexity of prints (Leiden et al. 2020). Deposition only takes place in direct contact between the metallization bath and the surface (Augustyn et al. 2021). Electrically deposited metal layers on conductive polymeric materials show discontinuity, considerable roughness and different layer thickness depending on the distance from the contact electrode (Augustyn et al. 2021). And lastly adhesion is the initial metallic coatings exhibited poor adhesion to the polymeric substrates (Augustyn et al. 2021).
The problem stated in this thesis is how to increase the hardness and toughness of the PLA resin mold in hot embossing applications. Since PLA is a brittle material, it could not stand a force from a hot embossing element for so many times, since it could become crack and unusable for the next experiment. The way to increase this by coating it with some metals that have a high resistance of heat and wear from environment, thus the electroplating could help with this issue by using the platting element to coat plastic object.
Based on the problem statement of the objectives of this study to find the optimum electroplating parameter, the optimum parameter would be found by using the experiment based and improving hardness and microstructure of PLA coated nickel

Methods

The method of choice in this experiment would be using electroplating or electrodeposition techniques, the specimen would be a 3D printed Polylactic Acid (PLA). That would be experimented with the weight composition, thickness composition, hardness difference and lastly the hardness test. These tests would be performed based on the electroplating parameters that are given on each of the specimens.

1. **3D Printing Process**

The specimen design is made using SOLIDOWORKS as the tool to make the specimen. There are two types of 3D designs here, one is the electroplating specimen for the electroplating procedure. The specimen design is made of square boxed; this leads to a manufacture using 3D print. The design would also come with a square notch to make the wire go through it and make the plating much easier, the placement of the notch does not need to be in a precise position thus it could be put anywhere in the specimen dimension. An example of the specimen is shown in Figure 1.

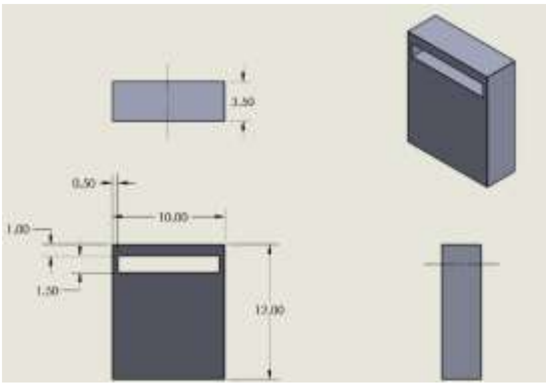


Figure 1. Square Notch Design Specimen

The 3D specimen was then printed using the Fused Deposition Modelling (FDM) 3D Printer (Anycubic Mega) and a 3D modeling tool named Ultimaker Cura. The printing parameters of the 3D design will be stated in the following Table 1.

Table 1. 3D Printing Parameters

E0 Temperature	205 °C
Bed Temperature	60 °C
Infill Density	10 %
Infill Pattern	Zig Zag
Fan Speed	100 %
Printing Speed	50 mm/s
Layer Height	0.2 mm

Wall Thickness	1.2 mm
Top Layer Thickness	1.3 mm
Bottom Layer Thickness	1.3 mm
Retraction Distance	6.0 mm
Retraction Speed	30.0 mm/s

2. Metallization

The initial step of electroplating is coating the material with the conductive paint to make the PLA have a conductive area. The conductive area is only painted on one side of the specimen, this is to ensure that the timing needed for the electroplating is lessened and has a better result since the area needed to be plated is less.

3. Electroplating Process

This would be the last step for making the specimen a metal coat. These steps utilize metal electro deposition by using the electrolysis method, the schematic diagram would be presented in Figure 2 and Figure 3.

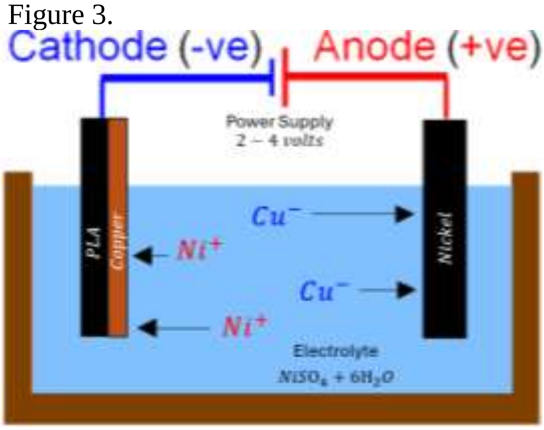


Figure 2. Electroplating Schematic Diagram

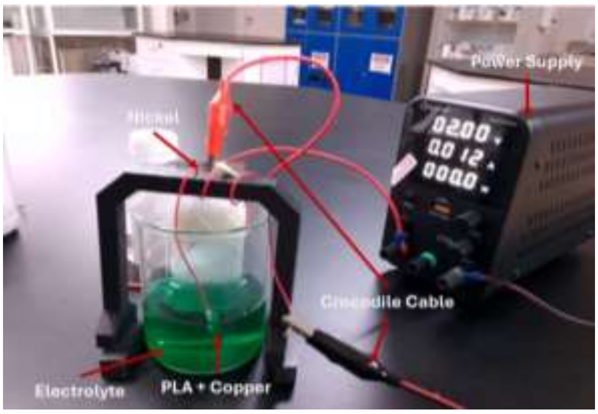


Figure 3. Real Application of Schematic Diagram

There is another equation regarding the electrolysis reaction in the electroplating the reaction equation would be shown in the equation tab below here:

$$2Ni^{+} + 2e^{-} \rightarrow 2Ni_{(M)}\ (At\ the\ Cathode)$$

$$2Cu^{-} - 2e^{-} \rightarrow Cu_{2(g)}\ (At\ the\ Anode)$$

$$2Ni^{+}Cu^{-}_{(l)} \rightarrow 2Ni_{(s)} + Cu_{2(g)}\ (Overal\ Reaction)$$

The parameters variable is only in the current while other values are the same, such in this experiment the time needed is 2 hours for each of the specimen while the voltage starts from 3 volts until 4 volts thus it only produces 3 different specimen voltage for each current. The parameters would be shown in the Table 3 – 5

Table 1. Electroplating Parameters for 0.024 Current

No	Specimen	Voltage (V)	Current (I)
1	1A	3.00	0.024
2	2A	3.50	
3	3A	4.00	
4	1B	3.00	0.05
5	2B	3.50	
6	3B	4.00	
7	1C	3.00	0.065
8	2C	3.50	
9	3C	4.00	

4. Quantitative Analysis

Weight

In an electrolytic cell, the electron flow inside the cell is opposite to that in the external circuit. At the cathode, electrons from an external source cause reduction, while at the anode, oxidation occurs as electrons return to the external source (Al-Bat'hi 2015). Here is the equation that governs the electroplating process.

And it could be combined using the weight of the deposit metal equation for the deposition. The equation is listed below

Equation 1. Weight Composition Equation (1)

$$w = \frac{(I)(t)(A)}{(n)(F)} \quad (2)$$

Where, w (g) is the weight of deposit metal, I (C/s) is the current, t (s) is the time, A $(g \cdot mol^{-1})$ is the atomic weight, n $(equivalents \cdot mol^{-1})$ is the valence of the dissolved metal in solution and F is Faraday's constant (96,485.309 $C/equivalent$)

5. Qualitative Analysis

Weight

Specimen	Voltage (V)	Current (I)	A (mg)	T (mg)

1A	3.00	0.024	412.5	439.1
2A	3.50		408.9	441
3A	4.00		409.6	450.4
1B	3.00	0.05	433.7	532.6
2B	3.50		485.2	555.2
3B	4.00		451.4	557.1
1C	3.00	0.065	476.4	600
2C	3.50		481	591.8
3C	4.00		491.4	594.6

A = Actual Value
T = Theoretical

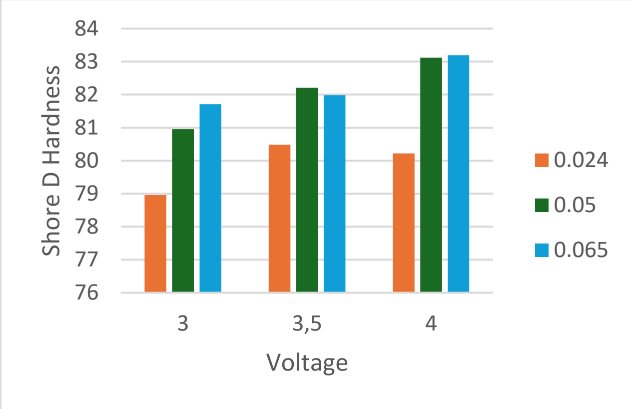


Figure 5. Hardness Value

Results and Discussions

Quantitative Assessment

Weight Overview

Based on the results above the value could be compromised, which is increasing and decreasing at the same time. From current 0.05A and 0.065A it has an increasing effect on the plating specimen, however there is a decrease in the voltage 4 at current 0.05A, in which the value is less than the voltage 3. While the current 0.024 has a decreasing effect on the plating specimen. Based on the result the specimen result is going into a constant rate rather than a fluctuation on some of the specimens, the only thing that happened here is the decreasing of voltage 4 current 0.05A. The result is based on an experiment from another paper that utilizes the current density over the weight difference, where the weight and current is increasing constantly (Supriyatna et al. 2021; Supriadi and Fadlil 2013).

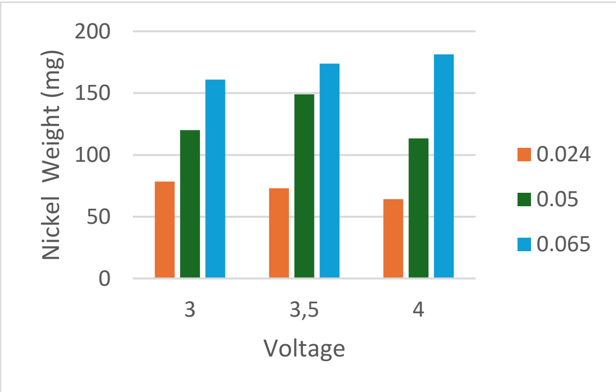


Figure 4. Weight Composition Difference

Hardness Overview

Based on the result above, the value could be compromised which all of them are increasing constantly from voltage 3 until voltage 4, and there is no fluctuation around the specimen from the beginning, only a steady increase in hardness value

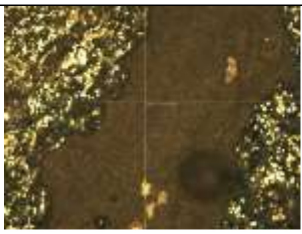
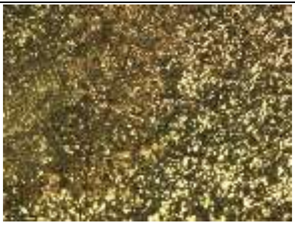
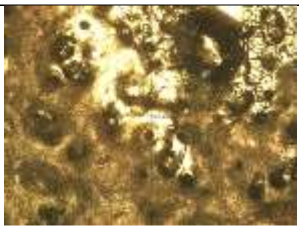
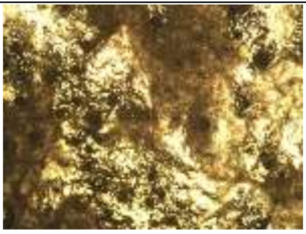
Based on figure 5, the lowest result could compromise which is specimen #8 while the highest are between specimen #2, #15, and #20. These results show also downward trendline for the result of PLA and PLA + Cu + Ni, these could occur due to the inconsistency of 3D specimen since, each 3D specimen has a tolerance of thickness thus making the data have a rather random parts in each specimen.

Qualitative Assessment

The Uniformity test is a test to determine where the deposition of each metal is uniformly spread across the area of the specimen, and it would be done by using the microscope that has been stated in the 3.6. procedure, by using the procedure the uniformity of each specimen could be found by pointing the microscope to the desired location. The location is preferably the defective one to find which one is the best result of each specimen. The electroplated sample specimen is available in table 6.

Table 2. Electroplated Sample Specimen

No	Microstructure	Macrostructure
1A		

2A		
3A		
1B		
2B		
3B		
1C		
2C		
3C		

Results are the main part of scientific articles, containing: net results without data analysis process, results of hypothesis testing. The results can be presented with a table or graph, to clarify the results verbally.

Discussion is the most important part of the entire content of a scientific article. The purpose of the discussion is: Answering the research problem, interpreting the findings, integrating the findings from the research into the existing body of knowledge and compiling a new theory or modifying the existing theory.

Conclusions

The research into electroplating PLA (polylactic acid) has demonstrated its feasibility, revealing that various parameters significantly influence the quality and characteristics of the final plated product. Key factors such as temperature, current density, and electrolyte composition were identified as crucial for achieving high-quality electroplated layers. However, challenges related to surface quality, including roughness and the presence of pores, were observed. These issues indicate a need for further optimization of pre-treatment and plating processes to improve the surface finish. The study also found that electroplated PLA exhibited enhanced mechanical properties compared to untreated PLA, suggesting its potential for a wider range of industrial applications. Additionally, the research highlighted the importance of considering environmental factors and the need for sustainable practices within the electroplating process. This underscores the potential for both technological advancements and environmental responsibility in the development of electroplated PLA.

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For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Conflicts of Interest
Declare conflicts of interest or state "The authors declare no conflict of interest." Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. Any role of the funders in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results must be declared in this section. If there is no role, please state "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results".

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