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Advancing Manufacturing Efficiency: Electroplating Nickel onto 3D-Printed Polymer

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Abstract

Traditionally, fabrication of die plates for injection molding involves time-consuming milling and hand polishing processes which are quite time taking to achieve the necessary smooth surfaces. One solution to fast fabrication of these die plates is to electrodeposit the metallic material onto a 3D printed polymer of the final geometry. However, electroplating, like other modern manufacturing processes such as laser-based additive manufacturing methods, involves various processing parameters that affect the microstructure and mechanical properties of the fabricated part. This study aims to determine the feasibility of using electroformed nickel on 3D-printed polymers by investigating the surface condition, microstructure and mechanical properties of the deposited part. Fused Deposition Modeling (FDM) with polylactic acid (PLA) filament were used to print test specimens, which were electroplated in a Watts-type bath with and without Saccharin, an organic additive. The results demonstrated that the nickel deposition mirrored the 3D-printed surface, significantly reducing the need for hand polishing. The use of Saccharin resulted in a smoother surface finish and fewer voids, enhancing the mechanical properties of the electroformed nickel. Hardness testing revealed that the nickel plated with saccharin achieved a hardness comparable to high-durability steels used in injection molds, implying a comparable tensile strength. This study concluded that the electroplating process can drastically reduce the production time and cost of metallic parts for various applications, including injection molding, making it a viable alternative to traditional methods.

Keywords: Electroplating; Watts bath; Nickel; 3D-printed materials; Injection molding

Introduction

In the realm of manufacturing, especially for rapid prototyping and small-scale production, the need for innovative techniques is paramount. One of the most critical components in this field is the injection mold die, which traditionally demands extensive time and cost to be produced. These dies, typically crafted from hard-to-machine steel, require weeks of milling and hand polishing to achieve the necessary smooth surfaces for effective injection molding [1]. This extended production time and associated costs create significant bottlenecks, particularly in an industry where speed and flexibility are crucial for competitive advantage and iterative product development.

Additive manufacturing (AM), *a.k.a.* 3D printing, has emerged as a transformative solution in various manufacturing processes due to its ability to create complex geometries with relative ease [2]. However, when it comes to injection mold dies, the main challenge of using metal AM parts is the surface condition of the as-printed part, which is typically far from acceptable for injection molding. To address this challenge, this research explores the potential of combining 3D printing with electroforming, a process that involves the electrodeposition of nickel onto a 3D-printed polymeric substrate. Electroforming, defined by ASTM B 832-93 as "the production or reproduction of articles by electrodeposition upon a mandrel or mold that is subsequently separated from the deposit," offers a promising method to enhance the strength and functionality of 3D-printed dies [3].

Nickel, as a material, brings additional benefits to the table. It not only has increased thermal conductivity over standard molds, thereby reducing part cooling time and enhancing manufacturing efficiency, but it also provides high corrosion resistance. This makes nickel an ideal candidate for creating durable and efficient molds for injection molding processes. Moreover, the versatility of this approach extends beyond injection molding, offering potential applications in various industries that rely on mass-produced discrete parts formed using dies and molds [4].

Given the significance of polymer materials in industrial applications, with plastic injection molding accounting for over 70% of components in many products, the development of faster and more cost-effective mold production methods is crucial [5]. This study aims to determine the feasibility of using electroformed nickel on 3D-printed polymeric parts by studying the surface condition, microstructure and mechanical properties of the electrodeposited nickel parts. Due to the large number of process parameters – such as bath temperature, electric current density, solution pH, agitation of the solution, electrolyte composition, etc. – the mechanical properties of the plated nickel vary with an adjustment in any process parameter [6]. This work focuses on a novel method of initial metallization of non-conductive 3D-printed parts and optimization of critical electrolyte bath parameters to enhance the mechanical properties, specifically hardness, of electroformed nickel.

Materials and Methods

Fused Deposition Modeling (FDM) printing was used to print parts onto which the nickel was electroplated. The specific printer used was a Creality K1 Max printer. Test specimens were printed using white Polylactic Acid (PLA) filament, which can be seen in Figure 1. The samples were of cubic shape of 0.5 inches edge size with an added tab at the top to allow for better electrical connection to the power source. These sample dimensions were chosen based on their ability to allow observation of various spatial effects, such as cathode current density and "dog boning", during the electroforming process [7].

The issue of metallizing polymers is well-documented in specialized literature[8], [9], [10], [11]. Traditional polymeric materials are insulators and, therefore, cannot be electroplated. Technological advancements have focused on improving chemical and physical methods to address this challenge. However, the resulting methods are intricate, require specialized and expensive equipment, and often use chemicals that are harmful to the environment and human health, one such chemical being chromic acid [12], [13]. One of the most common methods for metalizing polymers is known as electroless plating. This process involves many steps with strong chemicals including cleaning or degreasing, etching, sensitization, and activation [8]. Another issue with using common methods such as electroless plating as the method for initial or primary metallization is the effect it has on the surface interface between the metal atoms and the polymer. The etching process in electroless deposition removes material from the polymer surface to allow for the infusion of metal ions. This process leads to an undesired highly textured surface that is unwanted in most types of injection molding dies.

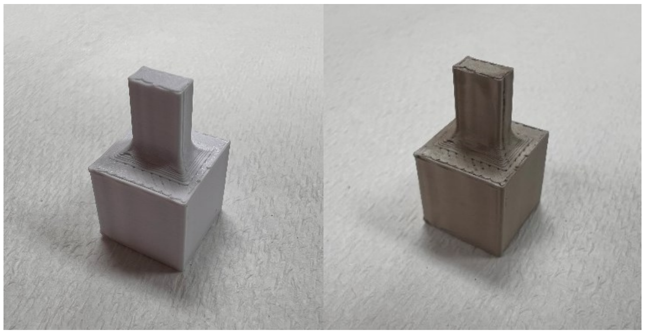

Figure 1-Polymeric cubes that were used as the base for Ni electroplating: before (left) and after (right) metallization

Equbal et. al. [13] attempted to solve this problem by using a mixture of aluminum-charcoal paste to achieve a primary conductive layer to electrodeposit onto. The surface resistivity of this aluminum-charcoal paste was compared to an electroless deposition process and was found to have a significantly lower surface resistivity. The lower surface resistance allows for easier and more efficient plating processes. Inspired by the process described in Equbal et al. [13], a silver conductive paint was used in this study to perform the primary metallization of the PLA parts. The resistivity comparison between electroless deposition, Al-Charcoal paste, and MG Chemicals silver paint can be seen in

Table 1. As can be seen in this table, the silver paint provides a much lower surface resistivity. Another advantage of using a coating as opposed to a deposition process on the polymeric material is that it prevents the need for etching, therefore avoids formation of undesired interior texture on the final deposited part. This method of using silver conductive paint solves both the problem of primary metallization and the need to mirror the polymer surface accurately.

Table 1-Surface resistivity of metallization processes

Primary Metallization Process	**Surface Resistivity (Ω)**
Chromic Acid Etching	920,000
Aluminum-Charcoal Paste	0.09
Silver Conductive Paint	0.015

The electrolyte composition is one of the most important factors in the resultant plated-nickel mechanical properties. This study focuses on using a Watts-type bath as the electrolyte due to its simplicity and cost. The Watts bath formulation is an aqueous solution containing three main ingredients: nickel sulfate, nickel chloride, and boric acid. After extensive literature review, two formulations were derived based on the most desired properties for a better surface condition. The main difference between the solutions is the addition of an additive manufactured by Caswell Inc., containing an organic additive called saccharin. The organic additive saccharin was chosen due to its ability to drastically increase the hardness of the plated nickel. Adding saccharin to a Watts-type bath has been found to increase the hardness of the electrodeposited Ni by up to 65% [14].

The Watts bath solution was prepared in a large, graduated cylinder on a hot plate with a magnetic stir bar. The required amount of distilled water was added and heated to approximately 40 °C. The ingredients were added one at a time and the solution was mixed continuously until each ingredient was fully dissolved. The composition of both solutions can be seen in Table 2 After the final ingredient was added for each formulation, the bath was stirred for an additional 10 minutes to ensure proper dissolution.

Table 2- Compositions of the two solutions used for electroplating

Solution	**1**	**2**
Nickel Sulfate (g/L)	240	240
Nickel Chloride (g/L)	50	50
Boric Acid (g/L)	45	45
Caswell Brightener (saccharin, (g/L))	----	40

Table 3-Electrodeposition process parameters

Parameters	**Both solution 1 and 2**
Temperature	≈ 40°C
pH	4.0 to 5.0
Agitation	Mechanical
Anode type	Nickel
Current Density	6.7 A/dm^2

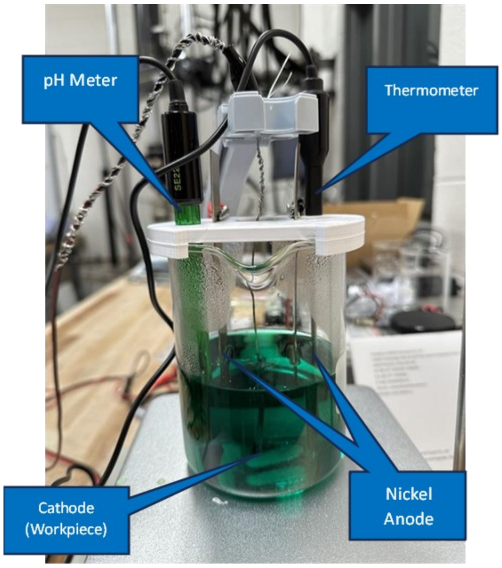

Figure 2-Electrodeposition setup

The sample plating processes in the solution was started after the samples were carefully painted with the silver conductive paint. The process starts with adding the required volume of solution to a graduated cylinder that has been de-greased. The solution is then brought to a temperature of approximately 40 °C while stirring. Alligator clips were connected from the positive terminal of the power supply to the anodes, and from the negative terminal to the work piece or cathode. A DC power supply was used throughout this experiment. Once the proper electrical connections have been made, the sample cube is then submersed in the solution with two of the cube's faces parallel to the anodes. The test setup can be seen in Figure 2 along with the operating conditions in Table 3.

Samples were plated for 1, 1.5, 2, 5, and 10.5 hrs. in both solutions. Additionally, two samples from each solution were plated for 2 hrs. with 100 mL and 62 mL of solution. An additional sample was plated for 18 hrs. with Solution 2 to study the deposition rate. After the samples were plated for the required time, they were removed from the solution and rinsed with distilled water to remove any excess electrolyte. The samples were then prepared for hardness testing. This preparation involves cutting the samples in half and mounting them in a Buehler metallography mounting machine. Once the samples have been mounted, they were sanded up to 2000 grit sandpaper to provide a smooth surface for hardness testing. These mounted samples can be seen in Figure 3. Some of the sample halves were also taken and heated to remove the PLA material. Once the PLA material was removed, a visual inspection was performed to determine if the coating had accurately mirrored the FDM parts.

Figure 3-Cut and mounted samples deposited with (left) and without (right) Caswell

The hardness testing was performed on a Shimadzu microhardness testing machine. Multiple hardness tests were performed on each side of the sample cubes to better characterize the deposition condition. The positions for hardness testing can be seen in Figure 4, where the number and placement of tests are represented by the black diamonds. The number of hardness tests was reduced on samples plated for less than or equal 2 hrs. due to the thinner deposition.

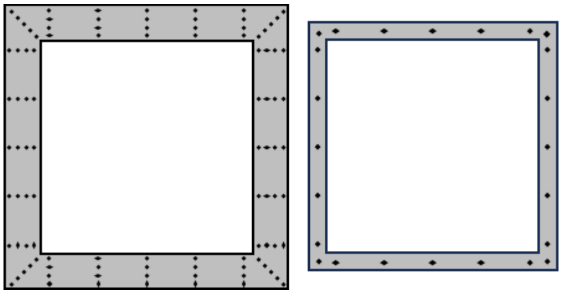

Figure 4-Positions of Vickers hardness measurements on samples with longer (left) and shorter (right) than two hours of deposition.

Results

Samples fabricated using Watts bath formulations were able to mirror the surface of the print. However, the samples deposited with the electrolyte containing Caswell exhibited a superior structure layer after layer. This is caused by the ingredients in the Caswell to produce better leveling effects which resemble a Layer or Frank-van der Merwe growth pattern as opposed to the mix of Island or Island-Layer growth pattern that resulted from Solution 1[15]. These growth patterns are shown in Figure 5. The growth pattern of Solution 1 also caused an increase in possible nucleation sites for hydrogen causing hydrogen entrapment leading to a porous and pitted final structure, which can be seen in Figure 6.

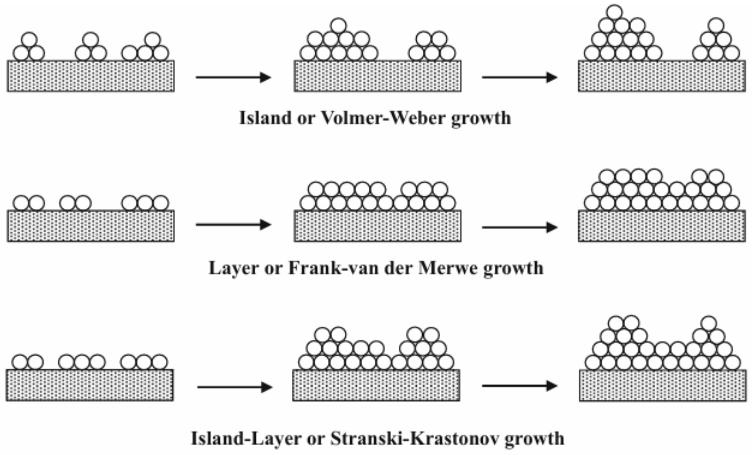

Figure 5-Growth characterization of electrodeposition [15]

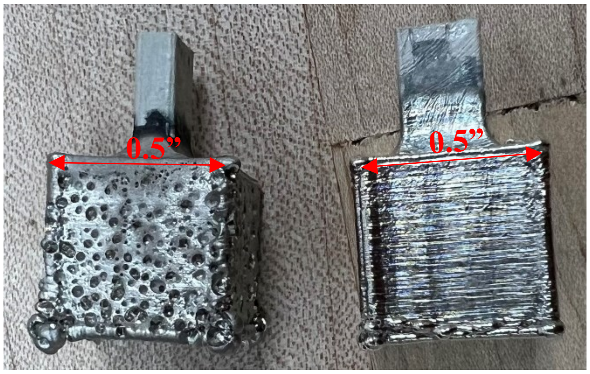

Figure 6-Comparison of exterior surface of plated samples. Left: plated without Caswell, right: plated with Caswell.

Saccharin works by adsorbing onto high points of the substrate surface, where the electric field intensity is higher. This adsorption inhibits nickel deposition at these high points, reducing the growth rate of nickel in these areas. Conversely, in the lower areas or valleys, where saccharin is less likely to adsorb, nickel ions can deposit more readily, effectively filling in the valleys. This differential deposition results in a smoother, more uniform nickel layer, reducing surface roughness and imperfections. Additionally, saccharin promotes micro-leveling, leading to finer smoothing of imperfections, and contributes to a brighter, more reflective finish while reducing internal stresses within the nickel coating [16].

Figure 7 shows the comparison between the interior surface of electrodeposited nickel from Solution 2 on two FDM sheets: one was sanded before deposition while the other one with as-printed surface finish. This figure clearly shows that the nickel deposition, using silver paint as the primary metallization, accurately mirrors the 3D-printed material's surface condition on the internal surface of the deposited part. This surface condition would be more suitable for applications such as injection molding die plates and this process also removes the need for extensive hand polishing. The surface condition almost perfectly mirrors the surface of the 3D-printed substrate part. Therefore, the final surface condition can be easily improved by changing printing settings or printing method, such as switching to more inherently smooth prints like stereolithography (SLA).

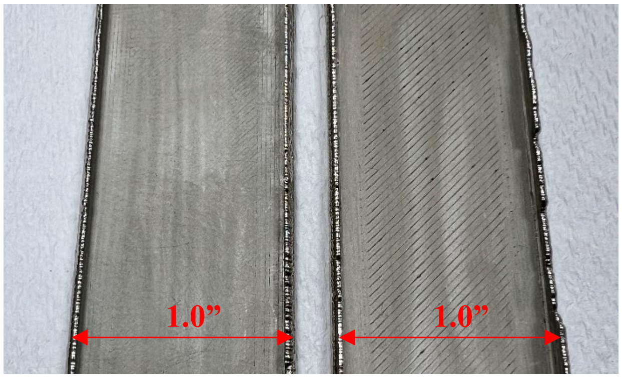

Figure 7-Comparison of interior surface of electrodeposited nickel (left was sanded before electrodeposition, right was not)

Table 4-Hardness for various plating times and volumes of electrolyte.

Plating Time (h)	Solution 1 (HV)	Solution 2 (HV)
2	258	529
2 (100 mL)	205	525
2 (62 mL)	271	561
5	258	562
10.5	270	527
18	NA	512

The hardness measurements of both solutions were linearly interpolated between the measured points using Python creating an array, which were then formed into a surface plot using Veusz [17]. Two of these surface plots are shown in Figure 8, for a plating time of 10.5 hrs. It is clear by these plots that Solution 2 has much higher hardness and greater uniformity. The average hardness of the 10.5 hrs. plating time in Solution 1 was 270 HV whereas that for deposition in Solution 2 was 527 HV, almost double. Since the hardness of a material can be correlated with the strength of it, the value of the hardness with Solution 2 is interesting when compared to the hardness of widely used die plate metals. P-20 steel is one of the most used steels for injection mold making. This steel has a hardness between 300 to 310 HV. Injection molds made of P-20 steel last up to 500,000 cycles [1]. A more durable steel for higher cycle injection molds is H-13 steel which has a hardness between 510 to 550 HV. The average hardness for all samples electrodeposited with

Solution 2 was 536 HV, based on Table 4. The plated nickel appears to easily match the hardness of typic injection molds. It should be noted that for accurate reliable durability analysis, other mechanical testing should be conducted, which will be the subject of our future works. However, such a high hardness for electrodeposition in Solution 2, implying high strength, may indicate enough longevity of the deposited material for applications such as injection molding.

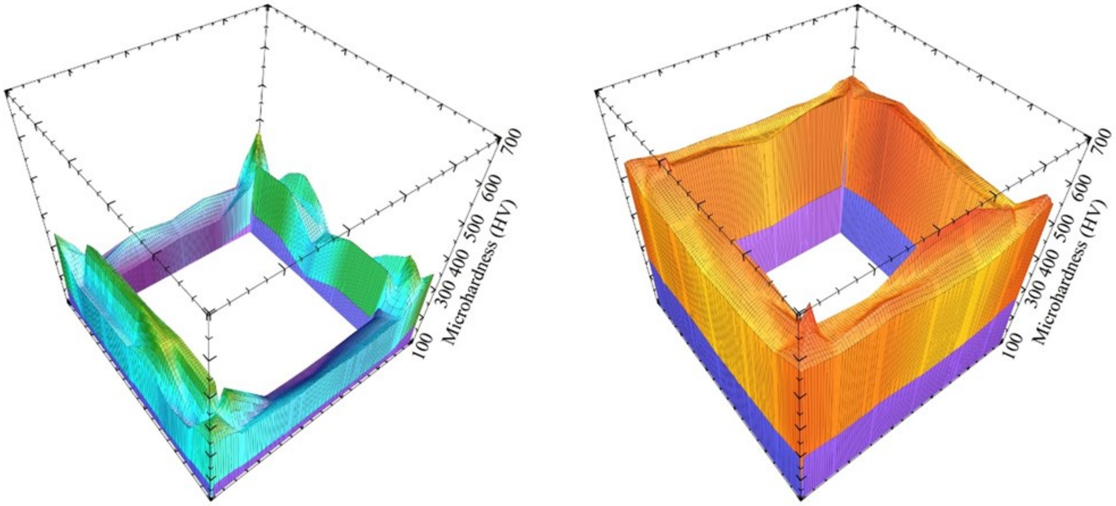

Figure 8-Surface hardness plots for nickel plated for 10.5 hrs. with Caswell (right) and without Caswell (left)

Scaling this electroplating process to achieve any thickness over any surface area needed for any injection mold geometry should not be an issue due to the plating process deposition occurring in a linear fashion as seen in Figure 9. This figure shows the deposition rate for a few samples plated for varying times. The samples weight was measured before and after deposition revealing the total mass of the deposited nickel. It also shows that the deposition rate is not dependent on the addition of the Caswell additive. This means that for more complex geometries the composition of the electrolyte can be altered to achieve better surface detail and the deposition rate will remain constant.

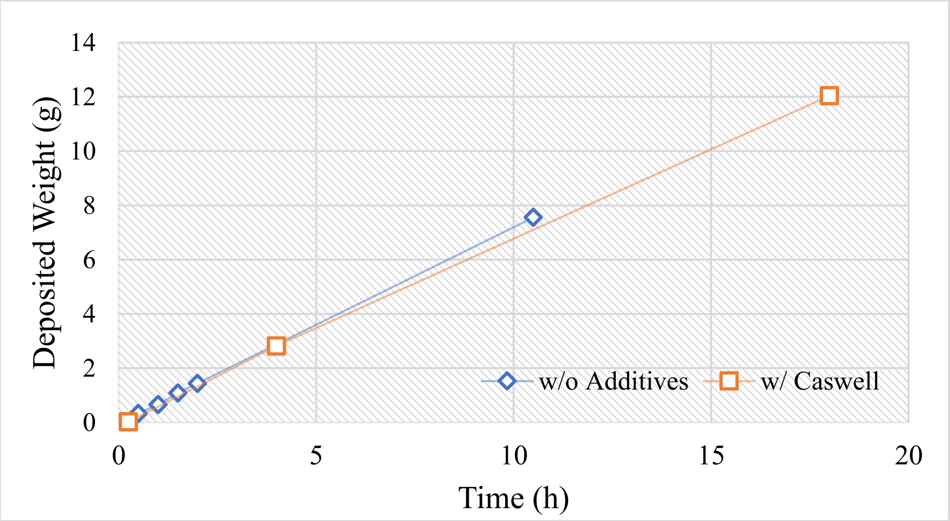

Figure 9-Deposition rate with and without Caswell

Summary and Conclusion

The comparison between traditional injection mold manufacturing and the electroplating process explored in this study reveals significant differences in both time and cost. Traditional manufacturing of injection mold die-plates, which involves extensive milling and hand polishing, typically takes over a month to achieve the necessary smooth surfaces required for effective injection molding. This process is labor-intensive and costly, often exceeding tens of thousands of dollars for most dies.

Electroplating can be an effective method for fabrication of parts for various applications. By electroforming nickel onto 3D-printed materials, the production time for die plates can be drastically reduced from over a month to just a couple of days. This method bypasses the need for milling and hand polishing, as the electroformed nickel layer mirrors the surface of the 3D-printed substrate. Therefore, in this work, evaluation of the surface condition and hardness of electroplated nickel parts, deposited on an FDM-printed substrate were studied. Based on the experimental results of this word, the following conclusions can be made:

- The use of a silver conductive paint for primary metallization enables electrodeposition of nickel on polymer. Moreover, it significantly enhances the internal surface finish of the nickel coating to accurately replicate the smooth surface of the 3D-printed polymer substrate.
- The solution used in Watts bath can greatly affect the surface condition and defect formation of the deposited part. In this study, using Solution 2, benefiting from saccharin, resulted in a significantly smoother surface finish and much less voids.
- The rate of deposition appeared to be independent of the solution and followed a linear trend as a function of the deposition time.

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