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Performance Evaluation of Different Types of Additive Manufacturing Electrodes Fabricated by Fused Deposition Modelling (FDM) on Machining Mild Steel

Nicolas Ng Yang Zu, Reazul Haq Abdul Haq^{1*}

¹Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA

*Corresponding Author Designation

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Abstract: The manufacturing of an electrode accounts for more than 50% of the total cost and time of a sinker Electrical Discharge Machining (EDM) operation. This study aims to study indirect Rapid Tooling (RT) electrode production to reduce fabrication costs and time. Polyethylene Terephthalate Glycol (PETG) and electrically conductive Polylactic Acid (PLA) were chosen as the electrode core material. In addition, the feasibility of metallization on the Fused Deposition Modelling (FDM) electrodes was investigated. Furthermore, the machining performance and characterization of the EDM electrodes were evaluated. For primary metallization, the dipping and hanging of the cylindrical sample with copper conductive paint produced a better coating than the aluminium paste method. Even though both methods have their drawbacks, nearly the entire cylindrical sample was coated when it was dipped into the paint. However, unfilled sections and uneven coating were formed when the aluminium paste method was tested. Therefore, future studies should attempt new methods to improve the primary metallization's initial coating quality and fabrication time.

Keywords: Additive Manufacturing, Electrical Discharge Machining, Electrode, Electroplating, Fused Deposition Modelling, Metallization, Rapid Tooling

1. Introduction

Sinker Electrical Discharge Machining (EDM) was invented to overcome the inevitable problems of conventional machining high tool wear rate, tool failure, machining and maintenance cost, and the inability to machine complex shapes. It is a non-conventional machining process that utilizes thermal energy to erode or machine electrically conductive parts of any shape or geometry ranging from high to extreme hardness [1]. The mechanical stress, vibrations and chattering are eliminated in EDM because there is no direct contact between the workpiece and electrode during the machining process

*Corresponding author: reazul@uthm.edu.my

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[2]. EDM is mainly used to machine intricately shaped mold and die in aerospace, automobile, electronics, and other industrial applications [3].

An electrode is a crucial tool in sinker EDM. It acts as a connector to transmit the spark discharge between the sinker EDM machine and the workpiece. However, the manufacturing of an electrode accounts for more than 50% of the total cost and time of a sinker EDM operation [1]. In addition, the greater complexity of the electrode's geometry and shape would lead to higher electrode production's time and cost. Therefore, scientists and researchers attempted to utilize rapid tooling (RT) to improve the electrode production for sinker EDM. Rapid tooling (RT) utilizes additive manufacturing (AM) to fabricate a tool quickly. AM or rapid prototyping (RP) is an innovative additive technique that fabricates physical models and functional prototypes from the Computer-Aided Design (CAD) model.

The RT of electrode production consists of direct and indirect routes. The electrode core is fabricated by selective metal sintering (SLS) or direct metal laser sintering (DMLS) for the direct route. Thus, the printed electrode core can be directly used for sinker EDM machining after its fabrication. However, for the indirect route, the printed electrode core fabricated by Fused Deposition Modelling (FDM) or Stereolithography (SLA) must undergo metallization before sinker EDM machining. Metallization converts the non-conductive electrode core into conductive while strengthening its structural strength.

Several research gaps were identified in previous research related to the indirect RT route for FDM electrodes. Firstly, the research trend showed a lack of a variety of electrode core materials being studied. Acrylonitrile Butadiene Styrene (ABS) was extensively used as the electrode core material in related research. Secondly, the feasibility of metallization was not thoroughly investigated and discussed. Lastly, the actual conditions and characterizations of the FDM electrode after machining were also not examined comprehensively.

This study aims to overcome the research gap mentioned above. Firstly, different materials such as Polyethylene Terephthalate Glycol (PETG) and electrically conductive Polylactic Acid (PLA) were used to fabricate the electrode core. Furthermore, the feasibility of the metallization of the electrode core was investigated. Additionally, the machining performance of FDM electrodes were evaluated and compared. Lastly, the characterizations of the FDM electrodes were studied after machining.

2. Methodology

The research workflow consists of progressive phases such as the three-dimensional (3D) printing of electrode core, metallization, machining of FDM in sinker EDM, data collection, and data analysis. The flowchart of the research is shown in Figure 1.

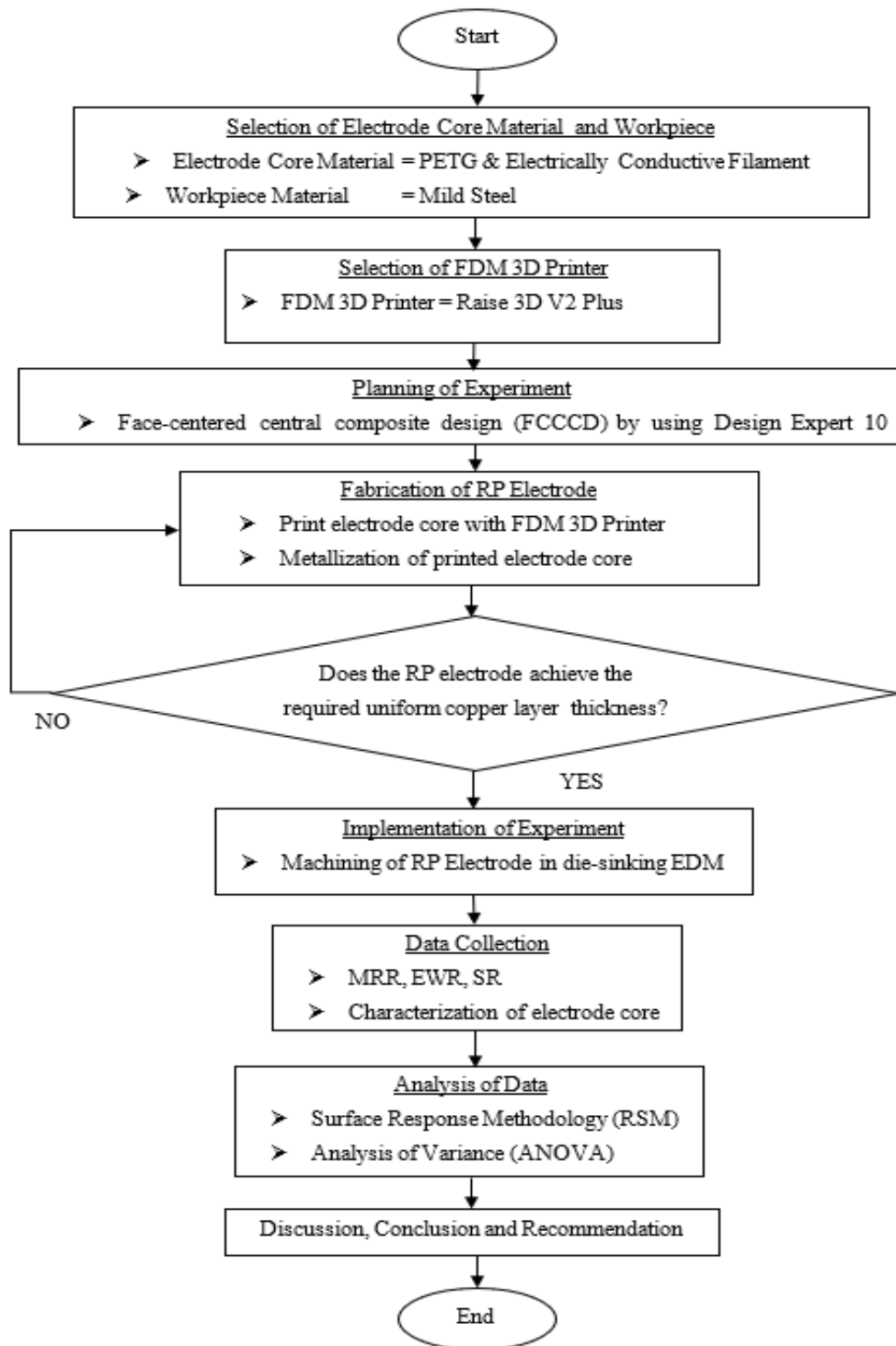


Figure 1: Research flowchart

A cylindrically shaped electrode of 17 mm length and 7 mm diameter was designed in Computer-Aided Design (CAD) software, Solidworks. Next, FDM 3D Printer, Raise 3D V2 Plus was used to print the electrode core.

2.1 Metallization

This research fabricates the FDM electrode by indirect RT electrode production. Therefore, metallization is a crucial step to produce the FDM electrode that satisfies the EDM requirements. The flowchart for the metallization of the printed electrode core is shown in Figure 2.

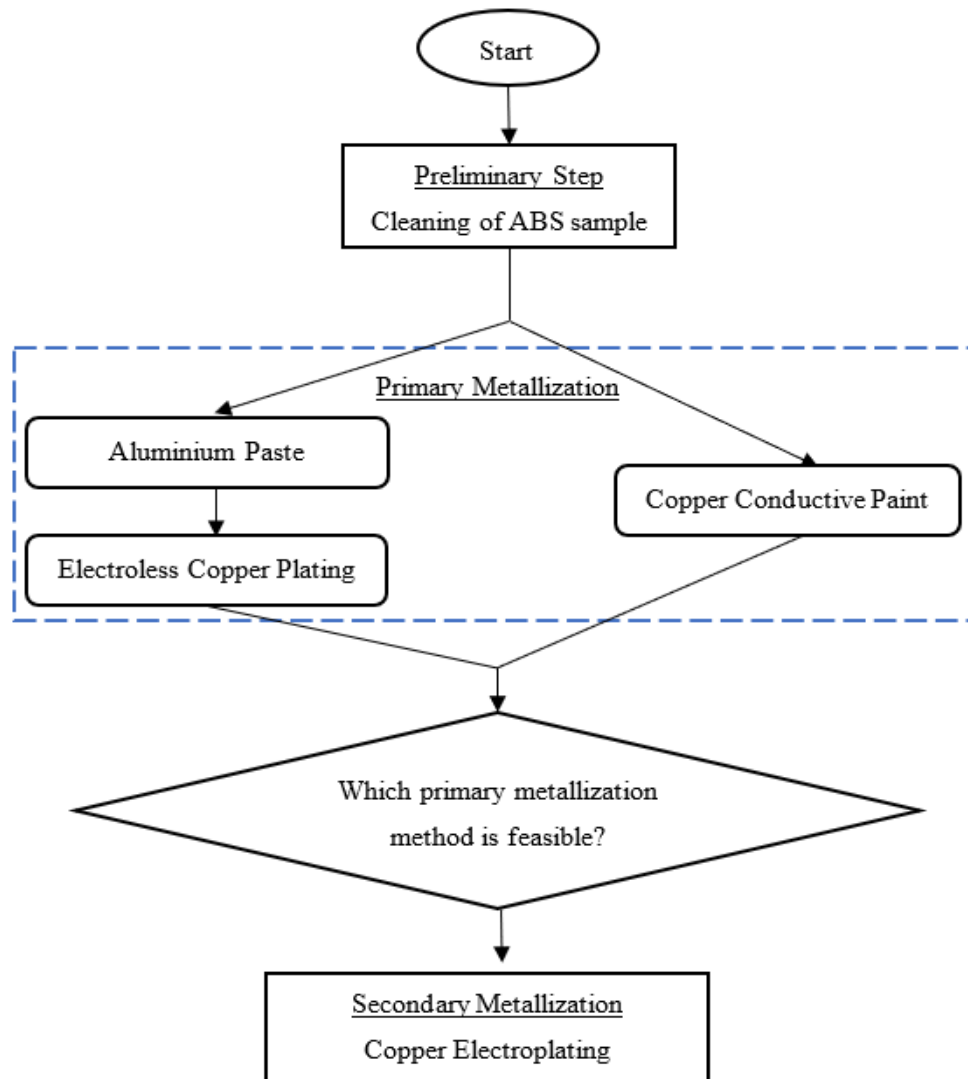


Figure 2: Metallization of the printed electrode core

Prior to primary metallization, the cylindrical samples were cleaned and sanded with 320-grit sandpaper. Two different methods for primary metallization were tested, aluminium paste and conductive copper paint. The aluminium paste method was referred directly from Sahoo, Sahu & Mahapatra [4]. The aluminium powder, enamel paint, carbon powder and distilled water with a ratio of 40:36:3:21 were mixed and stirred vigorously with a magnetic stirrer to prepare the aluminium paste. Then, the paste was applied entirely to the sample. After drying in the oven for 45 minutes, the sample was immersed in an aqueous solution containing 30 mL of 15 wt% copper sulphate, Cu_2SO_4 and 30 mL of 5 wt% sulphuric acid, H_2SO_4 for 72 hours. The other alternative for primary metallization was applying the conductive copper paint by dipping and hanging. First, the sample was tied and hung on the retort stand with copper wire. Next, the sample was dipped into the copper conductive paint. Finally, excess paint was wiped away at the sample's bottom to ensure uniformity of coated paint.

Copper electroplating was conducted for secondary metallization. The setup for copper electroplating is shown in Figure 3. The electrolyte consists of 160 g/L copper sulphate pentahydrate and 20 ml/L of sulphuric acid. This research aims to achieve 2 mm of copper layer thickness.

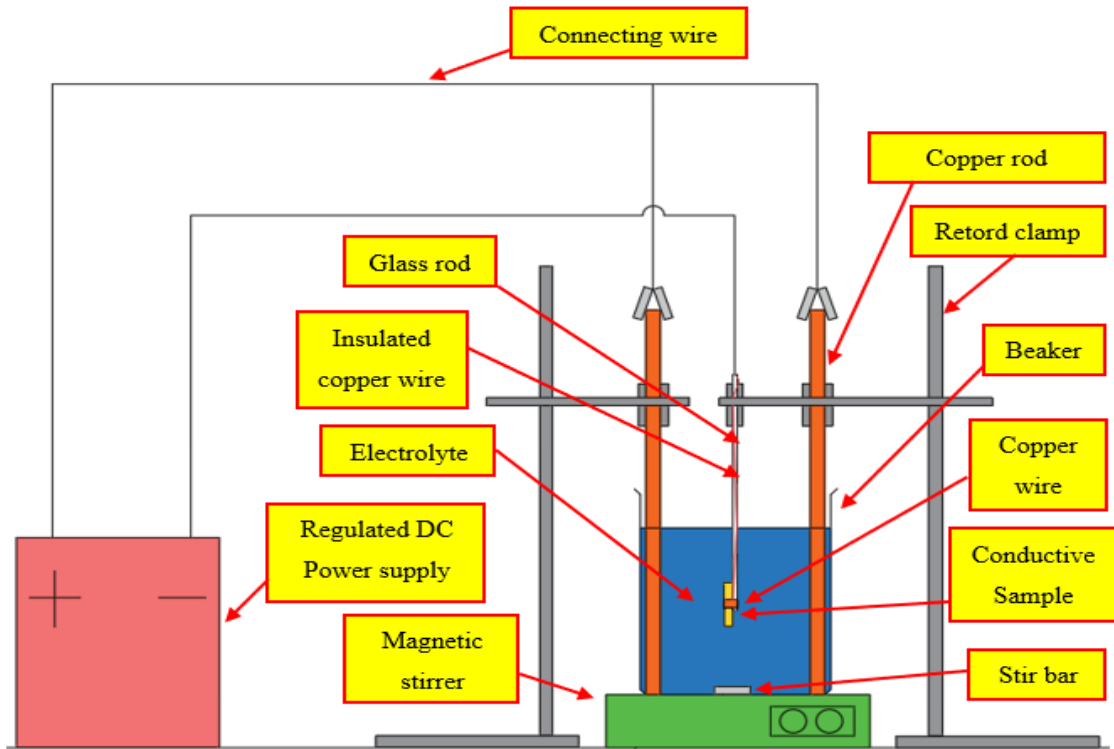


Figure 3: Setup for copper electroplating

Faraday's Law of Electrolysis was used to predict the electroplating time (Eq. 1) and mass of metal coating (Eq. 2) for a predetermined coating thickness in ideal conditions [5][6]. The equations used in this research are as shown below:

$$t = \frac{\rho AzFx}{MI} \quad \text{Eq. 1}$$

where t = Electroplating time (s)

M = Molar mass of material (g/mol)

I = Current obtained from the decomposition potential experiment (A)

ρ = Density of substance (g/cm³)

A = Surface area of substrate (cm²)

x = Plating thickness (μm)

F = Faraday constant (96485 C/mol)

z = Number of electrons involved in the deposition reaction

$$m = \frac{EIt}{F} \quad \text{Eq. 2}$$

where m = Mass of metal coating (g)

t = Electroplating time (s)

I = Current obtained from the decomposition potential experiment (A)

- ρ = Density of substance (g/cm³)
- F = Faraday constant (96485 C/mol)
- E = Equivalent mass of substance (g)

2.2 Design of Experiments

Three-level response surface methodology, face-centred central composite design (FCCCD) in Design Expert 10 software was used to optimize the required number of experiments. Table 1 shows the machining parameters used for FCCCD. Furthermore, it is used to study the relationship between several independent input variables and responses.

Table 1: Machining parameters in FCCCD

Factor	Machining Parameters	Units	Low Level	Medium Level	High Level
A	Current	A	2	4	6
B	Pulse-on Time	μs	50	100	150
C	Duty Cycle	%	75	80	85

2.3 Data Collection

The machining performance of sinker EDM in terms of material removal rate (MRR) (Eq. 3) and electrode wear rate (EWR) (Eq. 4) was determined by the following equations below [7]:

$$MRR = \frac{W_b - W_a}{t_m} \quad Eq. 3$$

where MRR = Material Removal Rate

W_b = Weight of workpiece before machining (g)

W_a = Weight of workpiece after machining (g)

t_m = Machining time (min)

$$EWR = \frac{E_b - E_a}{t_m} \quad Eq. 4$$

where EWR = Electrode Wear Rate

E_b = Weight of electrode before machining (g)

E_a = Weight of electrode after machining (g)

t_m = Machining time (min)

An optical microscope was used to examine the copper layer thickness at a magnification of 5X. In addition, the surface roughness of the machined workpiece was obtained with a surface roughness tester.

The analysis of variance (ANOVA) was utilized to study the significance between machining parameters and responses. Furthermore, the Design Expert 10 software generated a response surface plot to predict the behavior between the machining parameters and responses.

The vertical half of the sample sliced with a linear precision saw was examined with an optical microscope and scanning electron microscope (SEM) to reveal its characteristics after machining.

3. Results and Discussion

The primary metallization by applying the aluminium paste method was not satisfactory. The aluminium paste as shown in Figure 4 cannot be achieved the texture of a paste because it is too viscous. Thus, the texture felt like 'hard dough'. Furthermore, the stir bar in the magnetic stirrer was unable to stir the mixture because it tends to stick on the sticky mixture. Brushing the aluminium mixture with a paintbrush was also not favorable due to its viscous and hard texture. Therefore, the mixture was manually applied to the sample by using both hands. Sahoo *et al.* [4] did not provide insight on the preparation of the aluminium paste. Since the aluminium mixture was manually applied by hand in Figure 5, the coated aluminium mixture on the sample as shown in Figure 6 was not uniformly coated. Some sections of the sample are also not completely coated. Electroless copper plating will be redundant because these uncoated sections will not be plated with a thin layer of copper metal. These exposed sections would cause premature electrode failure during machining. Additionally, it was not possible to control the dimensional tolerance of the coated aluminium mixture. It proved that this method proposed by Sahoo *et al.* [4] was not suitable for primary metallization due to the uncontrollable dimensional tolerance, uneven and incomplete coating.



Figure 4: Aluminium mixture



Figure 5: Coating of the aluminium mixture by hand



Figure 6: Incomplete and uneven aluminium mixture coating on the samples

The dipping and hanging of cylindrical samples with copper conductive paint as shown in Figure 6 achieved a better result than the aluminium paste method. The sample was fully coated with the copper conductive paint, thus fulfilling the EDM electrode requirements. Other than that, this method obtained an average coated paint thickness of 53.7 μm . However, the coated paint thickness at the bottom part of the sample was higher than the top part as shown in Figure 7. This is because when the dipped sample is hung, the paint will flow downwards due to gravity. Thus, a greater amount of paint was deposited at the bottom part of the sample. Furthermore, the hung sample will tend to tilt or slant on one side due to the condition of the tying position as shown in Figure 7. Therefore, it leads to a slanted coating effect whereby the downward side of the sample will have more paint coating than the upward side. Therefore, a uniform coating of paint cannot be achieved because of the slanted coating effect and high coating at the bottom of the sample. Another drawback of the paint was the formation of air bubbles during dipping as shown in Figure 8. The top section of the sample has a high probability of air bubbles formation due to the faster flow rate of paint dripping downwards after dipping. The trapping of some air during the fast flow rate of the dripping paint was the factor for forming air bubbles. These air bubbles would lead to some unfilled sections of the sample, compromising the overall uniformity of the coated paint. Therefore, an extra step was taken by recoating these unfilled sections to ensure the sample was completely coated.



Figure 6: Dipping and hanging of cylindrical samples with copper conductive paint

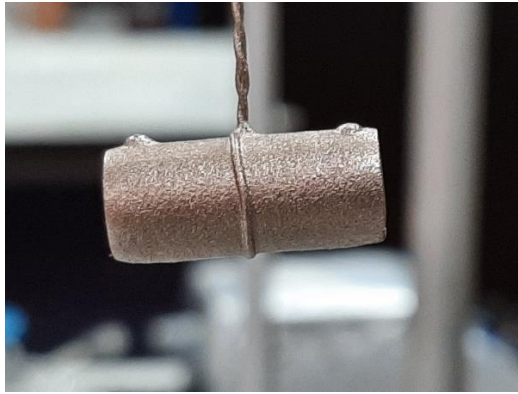


Figure 7: Slanted position and thicker paint deposited at the bottom of the sample



Figure 8: Formation of air bubbles after dipping the paint

4. Conclusion

In conclusion, the dipping and hanging of the cylindrical sample with copper conductive paint were preferred as the primary metallization even though it has several inevitable drawbacks. It was better than the aluminium paste method because it coats the sample almost entirely with the paint. Besides that, the time taken to complete the primary metallization for dipping and hanging of the cylindrical sample with copper conductive paint was also significantly shorter than the aluminium paste method. An average paint coating thickness of 53.7 μm was achieved when using the copper conductive paint. The research also proved that the aluminium paste method was not successful as proposed by Sahoo *et al.* [4].

In future studies, new techniques for primary metallization should be attempted to improve the initial coating quality and fabrication time.

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