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Performance Evaluation of Electrode Fabricated by using FDM in Die-Sinking EDM

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ABSTRACT

An electrode is a vital transmission tool of electrical charges that erodes a workpiece surface in die-sinking electrical discharge machining (EDM). However, the demanding requirements of the geometrical complexity and accuracy of an electrode significantly affected its manufacturing cost and time. Therefore, rapid tooling (RT) was attempted to improve electrode manufacturing. This research aims to verify the application of the FDM electrode in die-sinking EDM. Furthermore, the metallization and the machining performance of the FDM electrode were also studied. Fused Deposition Modelling (FDM) was utilized to fabricate a cylindrical electrode core made of Polyethylene Terephthalate Glycol (PETG). In primary metallization, the electrode core was immersed in copper paint. Next, the coated PETG substrate was electroplated in secondary metallization at a current density of 0.023 A cm^{-2} for 168 hours (7 days). The electrolyte consists of 80 g/ℓ copper (II) sulphate pentahydrate and 20 ml/ℓ sulphuric acid. The machining performance of FDM electrode such as material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR) was benchmarked with a copper electrode. Copper coating with an average thickness of 334 µm was successfully electroplated on the surface of the FDM electrode. Additionally, the FDM electrode was able to machine the mild steel workpiece with 1 mm infit at a peak current of 16 A and pulse-on time of 50 µs without suffering premature electrode failures such as edge failure, delamination, distortion and rupturing. Lastly, the machining performance of the FDM electrode was comparable to the copper electrode in terms of MRR, EWR and SR. The potential of the FDM electrode in EDM machining is proven successful and can be investigated further to enhance the performance of this electrode.

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1. Introduction

A tool electrode is an essential component in die-sinking Electrical Discharge Machining (EDM) used to transmit the sparks or electrical charges to erode the workpiece into the desired shape. Electrode manufacturing accounts for more than 50 % of the die-sinking EDM operation's cost and time [1]. The complexity and accuracy of geometry determine the time and cost of manufacturing the electrode. Therefore, rapid tooling (RT) was attempted for electrode manufacturing in die-sinking EDM. RT rapidly manufactures tools that serve as pattern, mold, and dies using additive manufacturing (AM) technologies [2].

RT can reduce the electrode manufacturing time because Computer-Aided Design (CAD) software was utilized to reduce the product development time for the electrode design. In addition, complex electrode profiles which were not feasible in conventional electrode manufacturing could be fabricated. Furthermore, RT also reduces the electrode manufacturing cost because it requires significantly less raw material than a conventional electrode. Hence, the weight of the FDM electrode was reduced, thereby improving the transportability and storage of the FDM electrodes [3]. Besides that, the FDM electrode has the potential for reusability after machining due to metallization [4].

Fused Deposition Modelling (FDM) was one of the popular additive manufacturing (AM) technology attempted for electrode manufacturing in die-sinking EDM in this study. It was categorized as indirect RT because it required a subsequent process, metallization. Crucially, copper was generally used as the metal coating material for metallization in most works because it satisfied the electrode requirements for die-sinking EDM by having good durability, affordability, electrical and thermal conductivity [5].

Metallization is a significant transitional process that coats the surface of the FDM electrode with a thin metal layer to ensure its proper functioning in die-sinking EDM [6]. Therefore, the metallization technique primarily influenced the quality of the copper coating on the surface of the FDM electrode. It was found that extensive data related to the quality of copper coating on the FDM electrode were not disclosed in many related works. Consequently, it caused uncertainty regarding the transparency of the metallization technique used to fabricate the FDM electrode. Thus, this research aims to study the quality of copper coating by analyzing the average thickness and surface morphology of the copper coating on the FDM electrode.

Many works have reported that the FDM electrode was feasible for die-sinking EDM because it had approximately similar machining performance compared to a conventional electrode. However, the supporting findings on the actual conditions and characteristics of the FDM electrode after machining in die-sinking EDM were inadequate. Hence, the validity of using the FDM electrode in die-sinking EDM was unreliable in related works. In this study, the application of the FDM electrode in die-sinking EDM was verified by examining the cross-section of the FDM electrode and the workpiece cavity after machining. Moreover, further verification was performed by evaluating and benchmarking the machining performance of the FDM electrode with a copper electrode in die-sinking EDM.

Acrylonitrile Butadiene Styrene (ABS) was commonly used as the electrode core material in most related studies due to its excellent metallization properties [7]. Unfortunately, the research trend revealed a limitation in testing different electrode core materials compatible with the FDM electrode. As a result, the related works exhibited an insufficient understanding of the effects of using different electrode core materials for the FDM electrode. This research attempted to use Polyethylene Terephthalate Glycol (PETG) as an alternative electrode core material for the FDM electrode due to several advantages compared to ABS. Firstly, PETG had higher durability than ABS because glycol compounds help retain its amorphous structure, thereby improving the machining stability of the

FDM electrode during the machining process [8]. In fact, the presence of glycol compounds enhanced the chemical resistance of PETG, making it suitable for metallization [9]. Furthermore, PETG was a safer printing material than ABS because it never released toxic fumes which contain volatile organic compounds (VOCs) such as styrene and 1,3-butadiene that potentially pose respiratory problems during printing [10]. Lastly, PETG had better printability than ABS due to low warping tendency and good bed adhesion during printing [11].

Many works have reported that the FDM electrode was feasible for die-sinking EDM because it had approximately similar machining performance compared to a conventional electrode. However, the supporting findings on the actual conditions and characteristics of the FDM electrode after machining in die-sinking EDM were inadequate. Hence, the validity of using the FDM electrode in die-sinking EDM was unreliable in related works. In this study, the application of the FDM electrode in die-sinking EDM was verified by examining the cross-section of the FDM electrode and the workpiece cavity after machining.

2. Methodology

2.1 Fabrication of Electrode Core

Since the FDM electrode must fit into the die-sinking EDM electrode tool holder of 10 mm diameter, thus electrode diameter must be smaller by approximately 2 mm tolerance to cater for the diameter expansion after metallization. Therefore, a cylindrical electrode core was designed in CAD software, Solidworks 2020 with a diameter and height of 8 mm and 18 mm respectively. After that, the drawing file was converted into STL format. A slicing software, IdeaMaker, was used to interpret and process the STL file into the G-code file. Next, the FDM 3D printer, Raise 3D N2 Plus, prints the electrode core. The printing parameters of the electrode core in the IdeaMaker were shown in Table 1.

Table 1
Printing parameters of electrode core in IdeaMaker

Printing Parameter	Numerical Value
Print Temperature (°C)	250
Bed Temperature (°C)	80
Print Speed (mm/s)	50
Infill Density (%)	100
Infill Pattern	Grid
Layer Height (mm)	0.1
Extruder retraction length (mm)	0.5
Extruder retraction speed (mm/s)	20

2.2 Metallization of Electrode Core

The electrode core cannot be used directly for machining purposes in die-sinking EDM due to the weak structural strength and insulative properties of PETG. Therefore, metallization was carried out to transform the PETG electrode core into a functional electrode for die-sinking EDM.

Metallization is a surface treatment process in which a thin layer of metal is coated onto a component or part to significantly improve the structural strength and electrical conductivity of the FDM electrode. Primary metallization aims to transform the insulative surface of the electrode core into electrically conductive, whereas secondary metallization thickens the coating layer.

In primary metallization, the electrode core was immersed in copper paint. After that, the coated PETG substrate was dried for 4 hours by hanging it on a retort stand. This coating technique was chosen for primary metallization because it has fewer processing steps and time than electroless plating.

Secondary metallization was carried out by electroplating the coated PETG substrate for 168 hours (7 days) at a current density of 0.023 A cm^{-2}. The electrolytes concentration used were copper (II) sulphate pentahydrate, $CuSO_4.5H_2O$ and sulphuric acid, H_2SO_4 at 80 g/ℓ and 20 ml/ℓ respectively. Figure 1 below shows the experimental set up of electroplating the FDM electrode with copper.

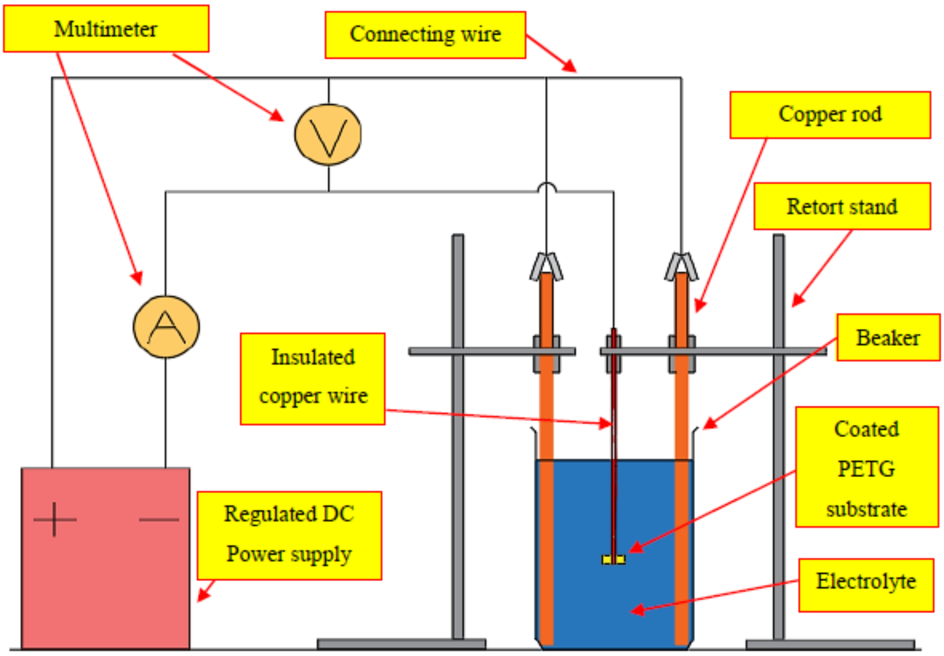


Fig. 1. Schematic diagram of an electroplating setup

2.3 Verification Experiment

A verification experiment was conducted to verify the application of FDM electrode to machine an infit of 1 mm on a mild steel workpiece in die-sinking EDM. The die-sinking EDM machining parameters such as the peak current and pulse-on time were tested at 16 A and 50 µs respectively. Subsequently, the vertical cross-section of FDM electrode was examined after the machining process to detect any physical changes in the electrode core. Furthermore, an inspection was performed on the cavity workpiece cavity machined by FDM and copper electrode on the mild steel workpiece to analyze the cavity surface's machining quality.

2.4 Experimental Machining Test

This study conducted an experimental machining test to evaluate the FDM electrode's machining performance in die-sinking EDM. Machining parameters such as peak current and pulse-on time were selected as the manipulating variables. Besides that, material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR) were the responding variables in the experiment. Table 2 and Table 3 show the die-sinking EDM machining parameters and the experimental machining test design layout respectively. An experimental run with a center point was included in determining the stability and linearity of data. Therefore, a total of five experimental runs were tested. Three FDM electrodes were fabricated in this experiment. Each electrode surface's side was machined in each experimental run.

A mild steel workpiece with dimensions of (L) 4.5 cm x (W) 4.5 cm x (H) 1.5 cm was chosen as the workpiece material for the experimental machining test. Besides that, a cylindrical copper electrode with a diameter of 9.5 mm and a height of 19 mm was used to benchmark the machining performance of the FDM electrode. The diameter of the copper electrode was acceptable because it did not exceed the diameter of the die-sinking EDM electrode holder fixed at 10 mm. Lastly, graphical plots of MRR, EWR and SR were analyzed to compare the machining performance of FDM and copper electrodes in die-sinking EDM.

Table 2
Machining parameters of die-sinking EDM in the experimental machining test

Machining Parameter	Unit	Low Level	High Level
Peak Current	A	8	16
Pulse-on Time	µs	50	100

Table 3
Design layout of the experimental machining test

Run Number	Peak Current (A)	Pulse-On Time (µs)	MRR (mg/min)	EWR (mg/min)	SR (Ra)
1	8	50			
2	8	100			
3	12	75			
4	16	50			
5	16	100			

2.5 Data Collection

Data collection was conducted on the machining performance of die-sinking EDM such as material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR). Besides that, the copper coating of the FDM electrode was also analyzed.

2.5.1 Material removal rate (MRR)

The material removal rate (MRR) is defined as the weight of workpiece material removed per unit time [4]. The following equation is used to determine the MRR [12]:

$$MRR = \frac{W_b - W_a}{t_m} \quad (1)$$

where W_b: Weight of workpiece before machining; W_a: Weight of workpiece after machining; t_m: Machining time.

2.5.2 Electrode wear rate (EWR)

The electrode wear rate (EWR) is the weight of electrode material removed per unit time from the electrode [1]. The following equation is used to determine the EWR:

$$EWR = \frac{E_b - E_a}{t_m} \quad (2)$$

where E_b: Weight of electrode before machining; E_a: Weight of electrode after machining; t_m: Machining time.

2.5.3 Surface roughness (SR)

The surface roughness (SR) evaluates the surface texture of the cavity machined by FDM and copper electrodes on the workpiece. Roughness Average (Ra) is the average of individual measurements of a surface's peaks and valleys. The surface roughness tester, Mitutoyo SJ-410 used to measure the SR.

2.5.4 Copper coating on FDM electrode

A coping saw and bench vise were used to slice the vertical cross-section of the FDM electrode. Furthermore, an optical microscope, Nikon Eclipse LV150NL was used to examine the FDM electrode's vertical cross-section to determine the copper coating's thickness. Lastly, the copper coating's surface morphology and element composition were analyzed by scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) respectively by using the SEM machine, Hitachi SU-1510.

3. Results

3.1 Metallization Results for FDM Electrode

The average thickness of the copper coating on the FDM electrode achieved was 334 µm after electroplating for 168 hours (7 days), as shown in Figure 2. The average thickness of the copper coating for the FDM electrode achieved more than 180 µm for EDM application, as suggested by Equbal *et al.,* [1].

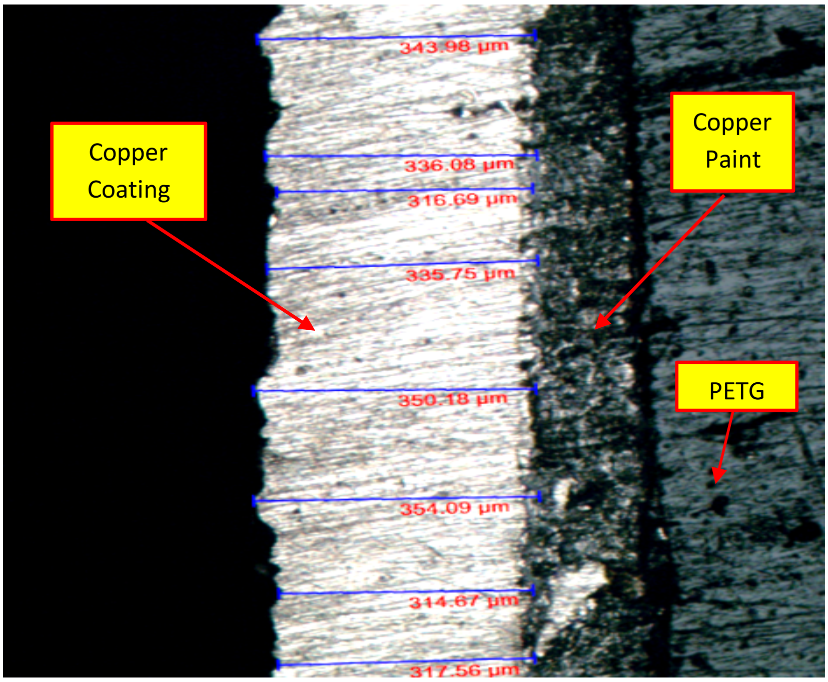


Fig. 2. The average thickness of copper coating for the FDM electrode

Based on Figure 3, the FDM electrodes had electroplating defects such as excess, dull and rough copper deposition. Excess copper deposits occurred because high current density accumulates at the edges. Therefore, high current density attracts more copper deposition at the corner than on a flat surface. Additionally, the absence of brightening and leveling agents in the electroplating bath could have caused rough copper deposition on the FDM electrode. Consequently, the FDM electrode cannot be directly used in die-sinking EDM. Therefore, the surface finishing of the FDM electrode surface was performed by lathing with a distance of 0.06 mm to ensure the surface of the copper coating. The FDM electrode in Figure 4 was ready to be used in die-sinking EDM after surface finishing.

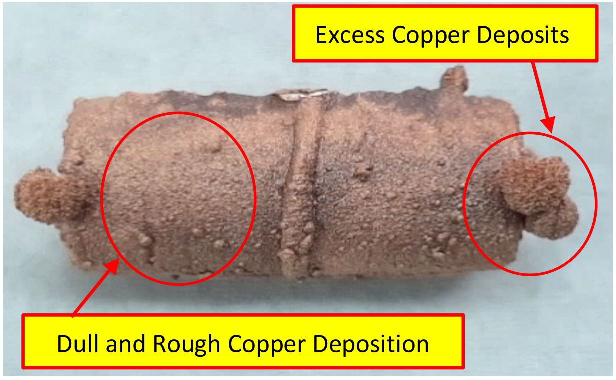
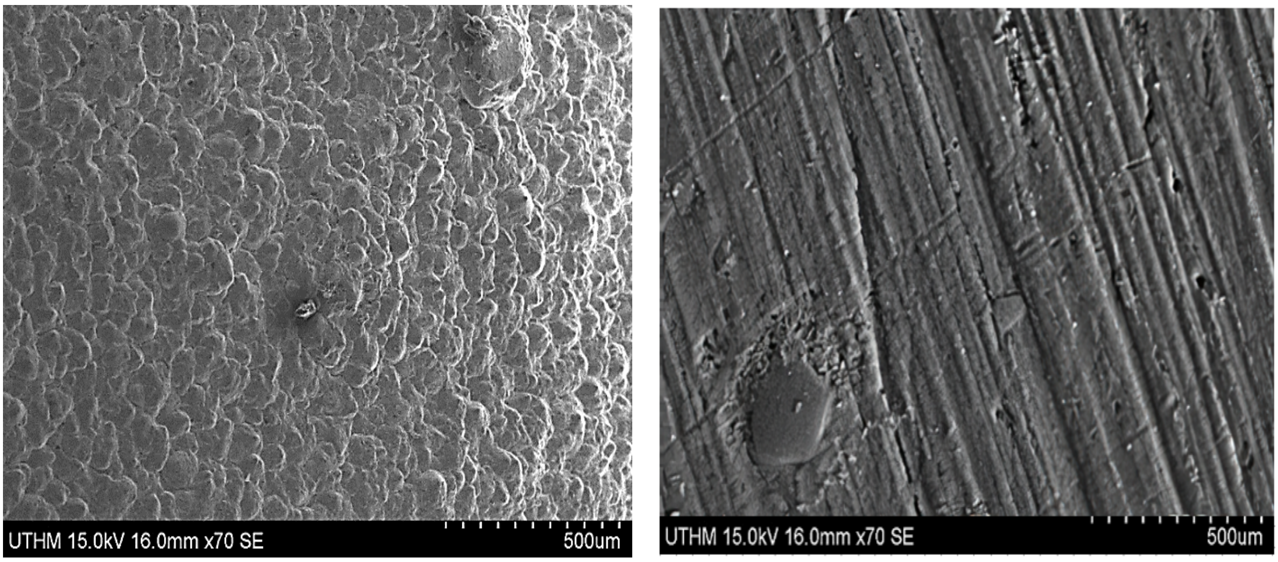


Fig. 3. Electroplating defects of the FDM electrode


Fig. 4. The FDM electrode after surface finishing

3.2 Surface Morphology of SEM and EDS on the Copper Coating

The SEM image in Figure 5 revealed that the surface of the copper coating was rough for the FDM electrode. Thus, the rough machining surface of the FDM electrode required surface finishing before its usage in die-sinking EDM. Besides that, the scoured surface of the copper electrode was smoother than the surface of the copper coating on the FDM electrode. However, microscopic scratches were present on the former surface due to the abrasion from sanding.



(a) (b)

Fig. 5. The SEM image of copper coating for (a) FDM electrode and (b) copper electrode

The elementary analysis of EDS spectra for the copper coating of FDM electrode in Figure 6 indicated that the copper coating only consisted of the copper element. The electroplating results in this research were valid because no contaminants or impurities were present in the copper coating. Impurities and contaminants can interfere with the adhesion between the copper deposits and the substrate's surface, which results in brittle copper deposition.

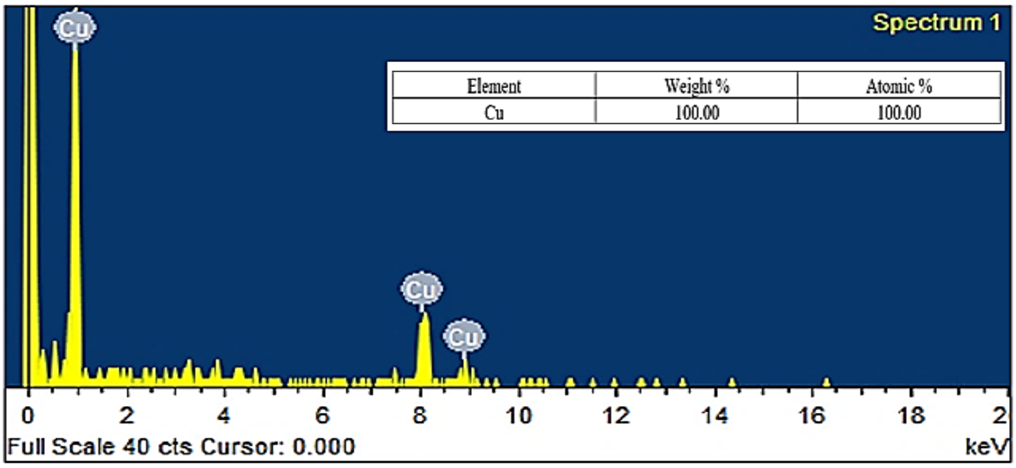


Fig. 6. EDS spectra for copper coating of FDM electrode

3.3 Analysis of FDM Electrode after the Verification Experiment

The FDM electrode successfully machined the mild steel workpiece with an infit of 1 mm when machining parameters such as the peak current and pulse-on time were tested at 16 A and 50 µs respectively. The vertical cross-section of FDM electrode as shown in Figure 7 was obtained to examine its physical changes after machining.

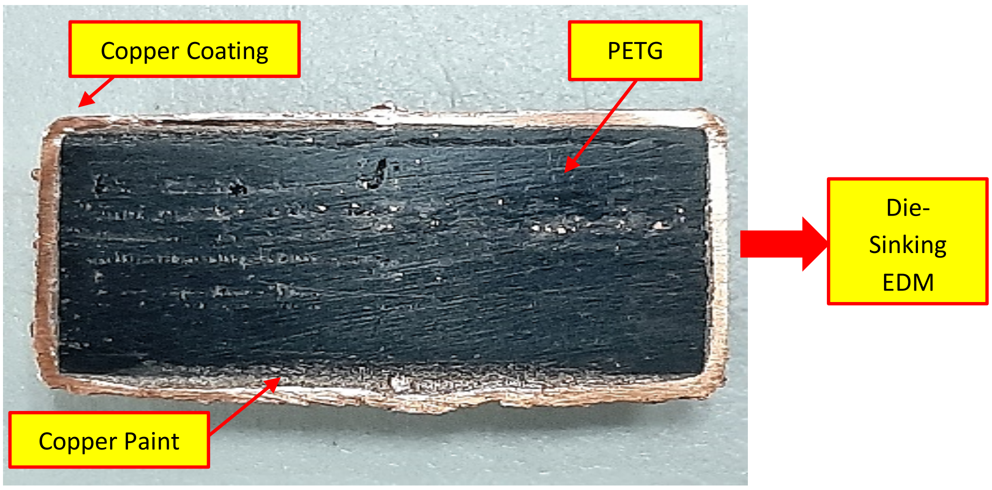


Fig. 7. Vertical cross-section of the FDM electrode after machining

Based on Figure 6, the electrode core and the copper coating of FDM electrode remained intact after machining in die-sinking EDM. Hence, it was evident that PETG was a suitable electrode core material besides ABS because the thermal decomposition of PETG did not happen during the machining process. In addition, this positive outcome dismissed the claim made by Alamro *et al.,* [13] that the FDM electrode was unsuitable for roughing machining operation due to extreme sparking temperature which could melt the electrode core.

Besides that, this verification experiment demonstrated the capability of the FDM electrode for roughing machining operations when a high peak current of 16 A was tested. This capability was also verified by Danade *et al.,* [3] and Ilani and Khoshnevisan [14] when they applied a minimum peak current of 12 A and 15 A in their work respectively. Moreover, the FDM electrode did not suffer any premature failures highlighted by Equbal and Sood [15] in their review, such as distortion, delamination, edge failure, peppering and rupturing of the copper coating. Lastly, the verification experiment showed that the FDM electrode possessed sufficient structural integrity to endure thermal stress during die-sinking EDM [5].

3.4 Analysis of Workpiece Cavity after Machining in Die-Sinking EDM

The workpiece cavity machined by FDM and copper electrode with 1 mm infit on mild steel workpiece was shown in Figure 8. The geometrical shape of the workpiece cavity for the FDM electrode was irregular compared to that of the copper electrode due to rough copper deposition at the edges. Furthermore, the surface finish of the workpiece cavity machined by the FDM electrode was generally rougher than that of the copper electrode. Additionally, some bumps were found on the workpiece cavity of the FDM electrode because several voids or crevices were present on the lathed surface of the FDM electrode due to uneven copper deposition during electroplating. This analysis demonstrated that the electroplating defects on the FDM electrode fundamentally affect the machining quality of the workpiece cavity.

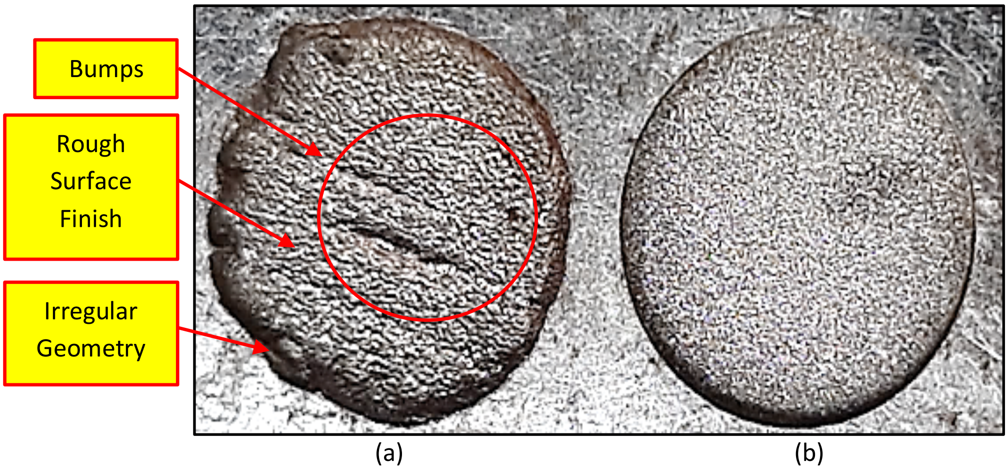


Fig. 8. Workpiece cavity machined by (a) FDM electrode and (b) copper electrode with 1 mm infit on mild steel workpiece

On the positive aspect of the FDM electrode, it can still functionally machine the mild steel workpiece at 1 mm infit without any premature electrode failures although the electroplating defects on the FDM electrode indicated that the electroplating setup in this research had yet to achieve the industrial electroplating standard. Hence, the surface quality of the workpiece cavity machined by the FDM electrode could be similar to or even better than the copper electrode when electroplating defects were sufficiently reduced in future works.

3.5 Evaluation of Machining Performance for FDM Electrode in Die-Sinking EDM

The copper electrode was used to benchmark the machining performance of the FDM electrode. Therefore, the machining performance of die-sinking EDM such as MRR, EWR and SR were analyzed and compared graphically between FDM and copper electrodes. The cavities machined by both electrodes were illustrated in Figure 9 after the five experimental runs.

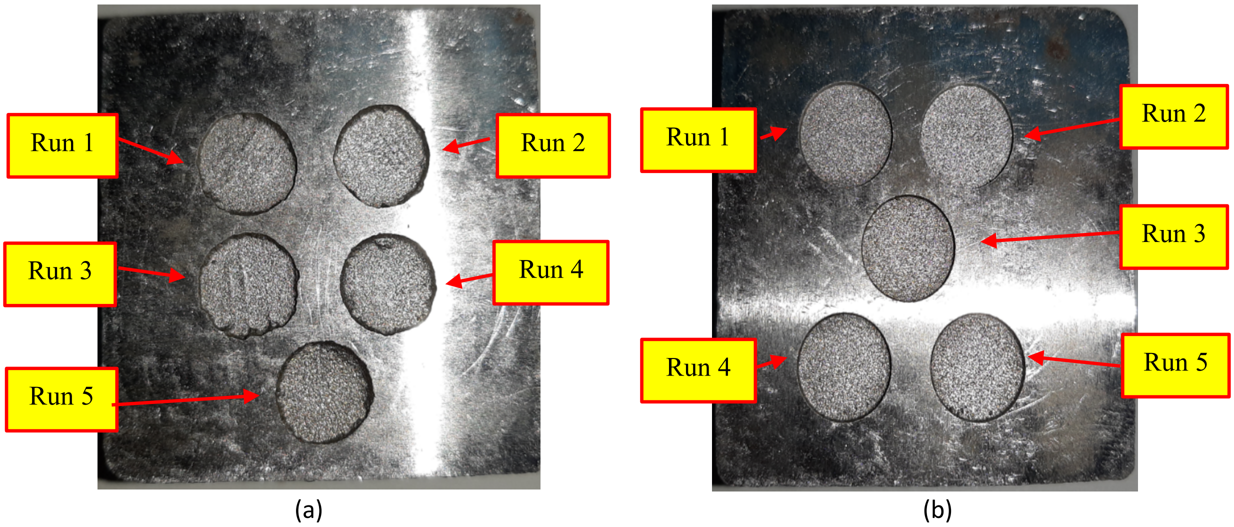


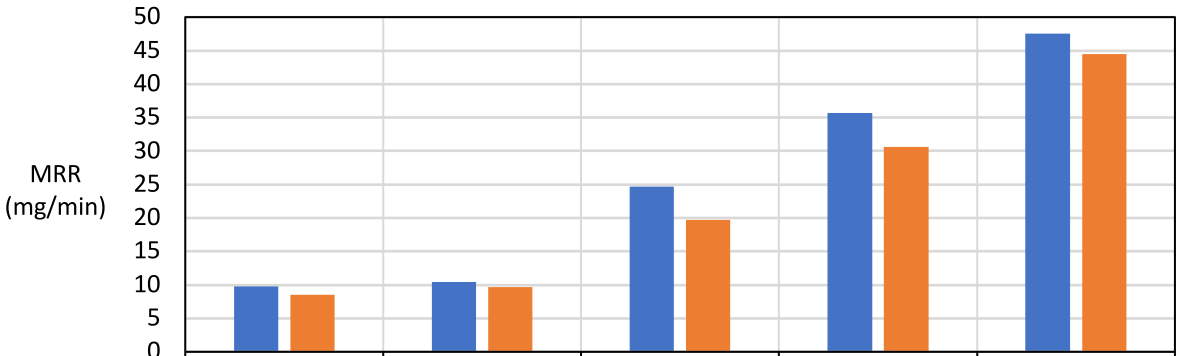
Fig. 9. Cavities on the mild steel workpiece machined by (a) FDM and (b) copper electrode after five experimental runs

3.5.1 Graphical analysis of results for MRR

Based on Figure 10, the MRR for both electrodes increased steadily when the peak current increased from 8 A to 16 A. A high peak current leads to high discharge energy, generating high thermal energy in the discharge zone [15]. A large volume of workpiece material was melted and vaporized by the high thermal energy, resulting in higher MRR.

When the pulse-on time for both electrodes was increased from 50 µs to 100 µs, the increased sparking duration hastened the machining time while increasing the MRR minimally. It showed that the peak current was more significant than the pulse-on time in influencing the MRR.

The FDM electrode had a marginally lower MRR than the copper electrode. The Void formation and irregular geometrical shape of the FDM electrode decreased the machining surface area. Therefore, the current flow from the machining surface of the FDM electrode was less effective than that of the copper electrode.



	Ip = 8 A Ton = 50 µs 1	Ip = 8 A Ton = 100 µs 2	Ip = 12 A Ton = 75 µs 3	Ip = 16 A Ton = 50 µs 4	Ip = 16 A Ton = 100 µs 5
Copper Electrode	9.743	10.48	24.69	35.64	47.51
FDM Electrode	8.523	9.708	19.74	30.60	44.52

Run Number

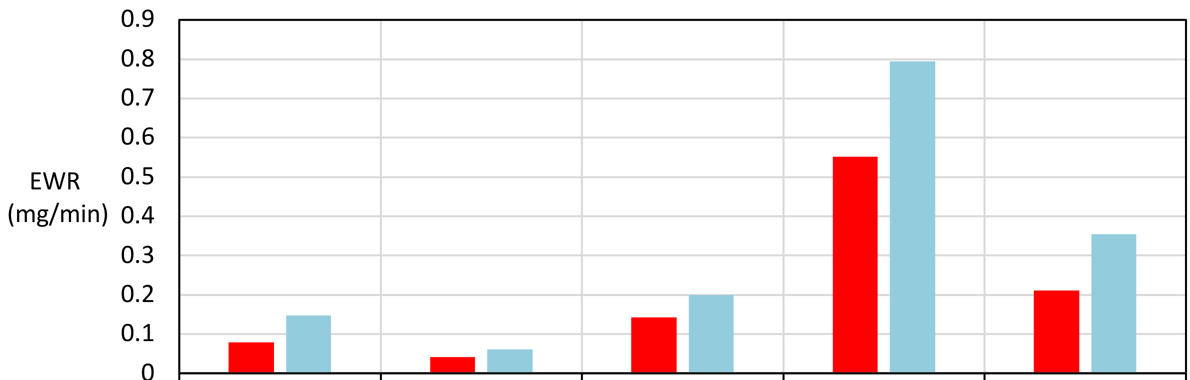
Fig. 10. Graph of MRR for FDM and copper electrodes

3.5.2 Graphical analysis of results for EWR

According to Figure 11, the EWR of both electrodes decreased when the pulse-on time was increased from 50 µs to 100 µs. The increase in the pulse-on time allowed the width of the plasma channel to widen. Therefore, the excessive heat generated at the electrode surface was spread evenly to a large area [14]. The distributed heat energy lowered the local temperature of the electrode surface. Additionally, the excess heat was dissipated at the electrode surface because the widened plasma channel increased the heat transfer from the electrode to the workpiece [1]. Thus, the EWR decreases when less heat erodes the electrode surface.

The EWR of both electrodes drastically increased when the peak current was increased from 8 A to 16 A. The peak current had a more significant impact than the pulse-on time in affecting the increment of EWR. A higher peak current increased the discharge energy at the spark gap tremendously, eroding more electrode material [16,17].

The EWR for the FDM electrode was noticeably higher than that of the copper electrode due to several factors. Firstly, the FDM electrode had a lower copper volume than the copper electrode. The low copper volume of the FDM electrode could not absorb and distribute the excess heat effectively from the machining surface to its body. Hence, the EWR increases because the excess heat quickly erodes the machining surface of the FDM electrode. Other than that, the poor electroplating quality compromised the uniformity of copper deposition on the machining surface of the FDM electrode. Therefore, the EWR of the FDM electrode increases due to low copper volume at its machining surface, which was caused by the existence of voids and the irregular formation of copper deposits [18].



	Ip = 8 A Ton = 50 µs 1	Ip = 8 A Ton = 100 µs 2	Ip = 12 A Ton = 75 µs 3	Ip = 16 A Ton= 50 µs 4	Ip = 16 A Ton = 100 µs 5
Copper Electrode	0.07837	0.04147	0.1427	0.5509	0.2101
FDM Electrode	0.1470	0.06156	0.1999	0.7945	0.3544

Run Number

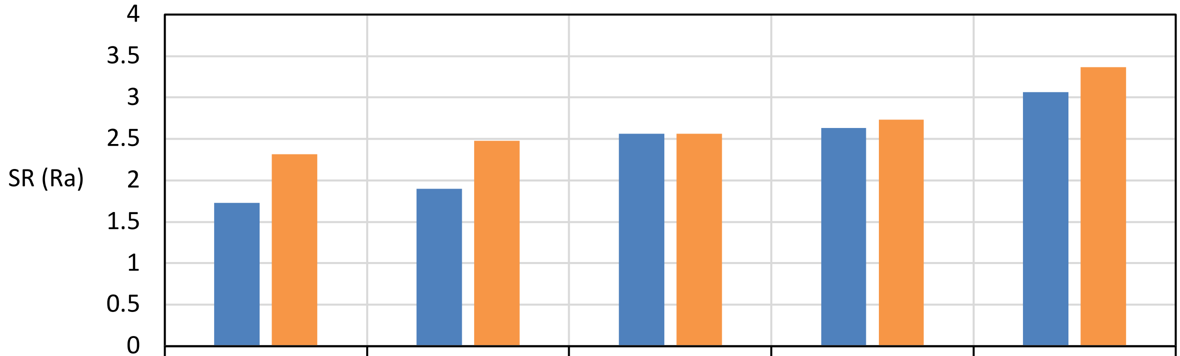
Fig. 11. Graph of EWR for FDM and copper electrodes

3.5.3 Graphical analysis of results for SR

In die-sinking EDM, the workpiece's thermal erosion naturally causes craters on the workpiece. In Figure 12, the SR of the cavity machined by both electrodes increased moderately when the peak current increased from 8 A to 16 A. The high peak current generated greater discharge energy, amplifying the size and formation of craters. Hence, the high discharge energy produced large craters on the workpiece surface [19]. Therefore, the SR of the cavity increased due to the irregular topography caused by these large craters.

A minimal increment in SR of the cavity was observed when the pulse-on time increased from 50 µs to 100 µs. This is because a long pulse-on time increases the duration of sparking, thereby intensifying the spark during machining. The generated high spark intensity widens and deepens the melting boundary on the cavity surface, which cause the craters to overlap [20]. Thus, the overlapping of craters contributes to a slight increase in the SR of the cavity.

The SR of the cavity machined by the FDM electrode was higher than that of the copper electrode due to the poor surface finish of the FDM electrode surface. The electroplating defects such as voids and irregular copper deposition affect the surface finish of the FDM electrode.



	Ip = 8 A Ton = 50 µs 1	Ip = 8 A Ton = 100 µs 2	Ip = 12 A Ton = 75 µs 3	Ip = 16 A Ton = 50 µs 4	Ip = 16 A Ton = 100 µs 5
Copper Electrode	1.725	1.902	2.565	2.630	3.068
FDM Electrode	2.318	2.478	2.566	2.732	3.368

Run Number

Fig. 12. Graph of SR for FDM and copper electrodes

4. Conclusions

This study incorporates FDM and metallization to fabricate an electrode for the die-sinking EDM. 334 µm average copper coating on the FDM electrode was achieved after 168 hours (7 days) of electroplating. However, the FDM electrode had electroplating defects such as excess, dull and rough copper deposition.

The FDM electrode successfully machined the mild steel workpiece at 1 mm infit in the verification experiment. It demonstrated that the FDM electrode could sustain under roughing machining conditions at a high peak current of 16 A and pulse-on time of 50 µs. Additionally, no electrode failures were observed after machining the mild steel in die-sinking EDM using the FDM electrode. Hence, it showed that PETG was a suitable electrode core material for the FDM electrode.

SEM analysis displayed the rough surface of copper coating on the FDM electrode due to irregular copper deposition. Furthermore, the scoured surface of the copper electrode was smoother than the surface of the copper coating on the FDM electrode. However, abrasion from sanding causes microscopic scratches on the former surface. Other than that, only the copper element was detected in the elementary analysis of EDS spectra for the copper coating of the FDM electrode. It proved that no contaminants or impurities were present in the copper coating.

The FDM electrode was comparable to the copper electrode based on the graphical analysis of MRR, EWR and SR. The MRR for both electrodes increased steadily when the peak current increased from 8 A to 16 A. The EWR of both electrodes drastically increased when the peak current was increased from 8 A to 16 A. SR of the cavity machined by both electrodes increased moderately when the peak current increased from 8 A to 16 A. However, the workpiece cavity machined by the FDM electrode had bumps, irregular geometry and rough surface finish due to electroplating defects. Thus, the quality of metallization significantly affects the machining performance of the FDM electrode.

For future research, the complex geometry of the FDM electrode should be investigated to unlock the potential of RT. Furthermore, a study on the relationship between the thickness of the metal coating and the FDM electrode's maximum infit should be carried out to determine its machining limitations in die-sinking EDM. Lastly, Different filament materials of FDM such as PLA and polycarbonate should be utilized to study their compatibility in fabricating the electrode core.

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