PERFORMANCE EVALUATION OF ELECTRODE FABRICATED BY FUSED DEPOSITION MODELLING IN DIE-SINKING ELECTRICAL DISCHARGE MACHINING

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For my beloved family, relatives and friends

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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 sulphate 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 can 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.

ABSTRAK

Elektrod ialah alat penghantaran penting cas elektrik yang menghakis permukaan bahan kerja dalam acuan-tenggelam pemesinan nyahcas elektrik (EDM). Walau bagaimanapun, keperluan menuntut kerumitan geometri dan ketepatan elektrod mempengaruhi kos dan masa pembuatannya dengan ketara. Oleh itu, Penyepaduan Perkakasan Pantas (RT) telah dicuba untuk menambah baik pembuatan elektrod. Penyelidikan ini bertujuan untuk mengesahkan aplikasi elektrod FDM dalam acuan-tenggelam EDM. Tambahan pula, penyaduran dan prestasi pemesinan elektrod FDM turut dikaji. Pemodelan pemendapan pelakuran (FDM) telah digunakan untuk menghasilkan teras elektrod silinder yang diperbuat daripada *Polyethylene Terephthalate Glycol* (PETG). Dalam penyaduran primer, teras elektrod direndam dalam cat kuprum. Seterusnya, substrat PETG bersalut disadur dalam penyaduran sekunder pada ketumpatan arus 0.023 A cm^{-2} selama 168 jam (7 hari). Elektrolit terdiri daripada 80 g/ℓ kuprum sulfat dan 20 ml/ℓ asid sulfurik. Prestasi pemesinan elektrod FDM seperti kadar penghakisan bahan (MRR), kadar kehausan elektrod (EWR) dan kekasaran permukaan (SR) telah ditanda aras dengan elektrod kuprum. Salutan kuprum dengan ketebalan purata 334 μm berjaya disadur pada permukaan elektrod FDM. Selain itu, elektrod FDM boleh memesin bahan kerja keluli lembut dengan kedalaman sebanyak 1 mm pada 16 A arus puncak dan 50 μs kadar pengaliran cas elektrik tanpa mengalami kegagalan elektrod pramatang seperti kegagalan penepian, delaminasi, herotan dan pepecahan. Akhir sekali, prestasi pemesinan elektrod FDM adalah setanding dengan elektrod kuprum dari segi MRR, EWR dan SR.

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LIST OF SYMBOLS & ABBREVIATIONS

A	-	Ampere
A	-	Surface Area
CE	-	Current Efficiency
cm	-	Centimeter
F	-	Faraday Constant = 96485 C/mol
h	-	Height
Hz	-	Frequency
I	-	Current
I_p	-	Peak Current
J	-	Current Density
J	-	Joule
kg	-	Kilogram
L	-	Length
ℓ	-	Litre
m	-	Mass
M	-	Molar mass
mg	-	Milligram
min	-	Minute
ml	-	Milliliter
mm	-	Millimeter
n	-	Number of Electrons Involved in the Deposition Reaction
Ø	-	Diameter
Pa	-	Pascal
Q	-	Electrical Charge
r	-	Radius
Ra	-	Roughness Average

s	-	Second
t	-	Time
T_{off}	-	Pulse-off Time
T_{on}	-	Pulse-on Time
V	-	Voltage
wt %	-	Weight Percentage
ρ	-	Density
τ	-	Duty Cycle
Ω	-	Ohm
%	-	Percentage
°C	-	Degree Celcius
µm	-	Micrometer
µs	-	Microsecond
ANOVA	-	Analysis of Variance
BBD	-	Box-Behnken Design
CAD	-	Computer-Aided Design
CH_3COOH	-	Acetic Acid
$CuSO_4$	-	Copper (II) Sulphate
$CuSO_4.5H_2O$	-	Copper (II) Sulphate Pentahydrate
DA	-	Dimensional Accuracy
DC	-	Direct Current
DMLS	-	Direct Metal Laser Sintering
DOE	-	Design of Experiments
EDM	-	Electrical Discharge Machining
EDS	-	X-Ray Spectroscopy
EWR	-	Electrode Wear Rate
FCCD	-	Face Central Composite Design
FDM	-	Fused Deposition Modelling
H_2CrO_4	-	Chromic Acid
H_2O_2	-	Hydrogen Peroxide
H_2SO_4	-	Sulphuric Acid
H_3PO_4	-	Phosphoric Acid
HAZ	-	Heat-Affected Zone

HCI	-	Hydrochloric Acid
HDPE	-	High-Density Poly Ethylene
HF	-	Hydrofluoric Acid
HIPS	-	High Impact Polystyrene
HNO_3	-	Nitric Acid
IMLS	-	Indirect Metal Laser Sintering
KCA	-	Potassium Cyanide
LCD	-	Liquid Colour Display
LOM	-	Laminated Object Manufacturing
MRR	-	Material Removal Rate
Pd	-	Palladium
PET	-	Polyethylene Terephthalate
PETG	-	Polyethylene Terephthalate Glycol
pH	-	Potential of Hydrogen
PLA	-	Polylactic Acid
PPE	-	Personal Protective Equipment
PVA	-	Polyvinyl Alcohol
PVC	-	Polyvinyl Chloride
RP	-	Rapid Prototyping
RSM	-	Response Surface Methodology
RT	-	Rapid Tooling
SD	-	Secure Digital
SEM	-	Scanning Electron Microscope
SLS	-	Selective Laser Sintering
SR	-	Surface Roughness
STL	-	Stereolithography
Ti-Al6-V4	-	Titanium Alloy Grade 5
TPE	-	Thermoplastic Elastomer
USB	-	Universal Serial Bus
UV	-	Ultraviolet
VOCs	-	Volatile Organic Compounds

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Exploring new advanced materials in the past centuries, such as metal composites, ceramics, superalloys, and others, led to a safer and better quality of components and products in many applications (Shrivastava & Sarathe, 2014). However, most advanced materials are considered difficult-to-machine materials due to their stronger material properties than regular steel. The use of conventional machining such as grinding, milling, lathing, drilling and others has led to higher tool wear rate, machining and maintenance cost, and the inability to machine complex shapes.

Scientists and researchers invented Electrical Discharge Machining (EDM) in 1770 to reduce the maintenance and machining cost of high-hardness materials. EDM has been used to machine electrically conductive metals with high hardness regardless of their shape or geometry until today due to its high precision, better surface finish, good machining efficiency and lower machining cost. Die-sinking EDM is one of the popular variants of EDM used in many applications.

A tool electrode is essential for die-sinking EDM, as shown in Figure 1.1. An electrode's function was to transmit the sparks or electrical charges to erode the workpiece into the desired shape.

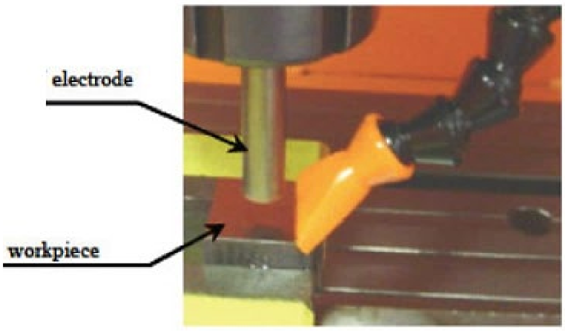

Figure 1.1: Electrode for die-sinking EDM (Amorim, Weingaertner & Bassani, 2010)

Electrode manufacturing accounts for more than 50 % of the die-sinking EDM operation's cost and time (Equbal, Equbal & Sood, 2019). The complexity and accuracy of geometry determine the time and cost of manufacturing the electrode. Therefore, researchers investigated alternatives to manufacture electrodes for die-sinking EDM.

Additive manufacturing (AM) has provided the possibility to improve electrode manufacturing's cost and time for die-sinking EDM. Since 1991, researchers have applied the rapid tooling (RT) concept for electrode manufacturing.

According to Equbal, Equbal, Equbal, *et al.* (2019), there were three methods of applying RT in electrode manufacturing as shown in Figure 1.2. AM parts fabricated by AM technologies such as Direct Metal Laser Sintering (DMLS) and Indirect Metal Laser Sintering (IMLS) were categorized as the electrically conductive route. Therefore, they can be used directly as functional electrodes in EDM due to the sintering of fine metallic powder. However, AM parts fabricated by AM technologies such as Fused Deposition Modelling (FDM) and Stereolithography (SLA) were categorized as the non-electrically conductive route because of the insulating base materials such as thermoplastic and resin. Hence, they require an intermediate step, metallization, to fulfill EDM's conductivity and durability requirements.

Besides that, the AM part fabricated by AM technologies was also used as the mold for the production of electrodes in the electrode manufacturing industry (Kechagias *et al.*, 2008).

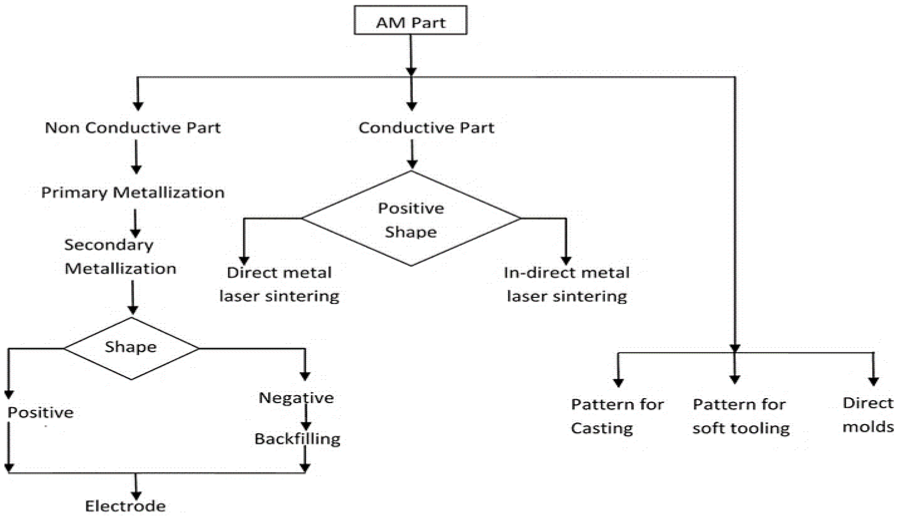

Figure 1.2: Manufacturing of RT electrodes in die-sinking EDM
(Equbal, Equbal, Equbal, *et al.*, 2019)

One of the most attractive types of AM, FDM was used for electrode manufacturing in die-sinking EDM, as shown in Figure 1.3. FDM was the cheapest among the types of AM in terms of raw materials and printer cost. The electrode manufacturing by FDM was categorized as indirect RT because it required a subsequent process, metallization.

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 (Czelusniak *et al.*, 2019).

Researchers speculated that FDM's electrode manufacturing could reduce its 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 (Danade, Londhe & Metkar, 2019). Besides that, the FDM electrode has the potential for reusability after machining due to metallization (Padhi *et al.*, 2018).

Figure 1.3: Electrode fabricated by FDM (Equbal *et al.*, 2017)

The electrode manufacturing time was greatly reduced 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.

1.2 Background of Research Gap

Few research gaps have been identified after reviewing the related works from Fefar Savan & Karajagikar (2014), Pawar *et al.* (2016), Padhi, Mahappatra & Das (2017), Danade *et al.* (2019), Saxena & Metkar (2019) and Equbal, Equbal & Sood (2019).

Many related works lacked comprehensive information on metallization techniques. Most research did not reveal and elaborate on the metallization techniques to fabricate the FDM electrode. Furthermore, the quality of metallization was also not reported in most research. Hence, the authenticity of the metallization techniques used in related works was disputable.

Most research did not report or explain the conditions of FDM electrodes after machining. Hence, the actual conditions and characteristics of the electrode core in the FDM electrode are unknown. The vertical cross-section of the FDM electrode after machining as shown in Figure 1.4 was not illustrated in any related works. Therefore, due to this case study's absence, most related works cannot fully justify whether the FDM electrode functions as intended.

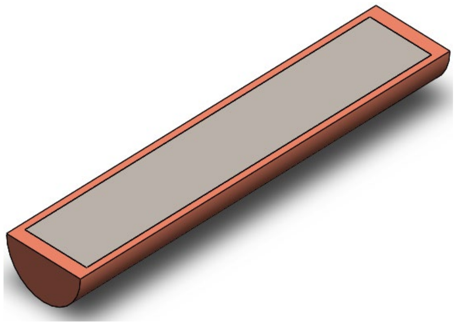

Figure 1.4: Vertical cross-section of the FDM electrode

Over the past years, new FDM filaments such as nylon, wood, metal, ceramic, composite, water-soluble, conductive, carbon fiber, magnetic, and others have been developed for different applications (Plica, 2020). However, previous research typically only investigated the Acrylonitrile Butadiene Styrene (ABS) as the material for the electrode core, as shown in Figure 1.5. It showed a lack of studies on the variety of electrode core materials in the FDM electrode.

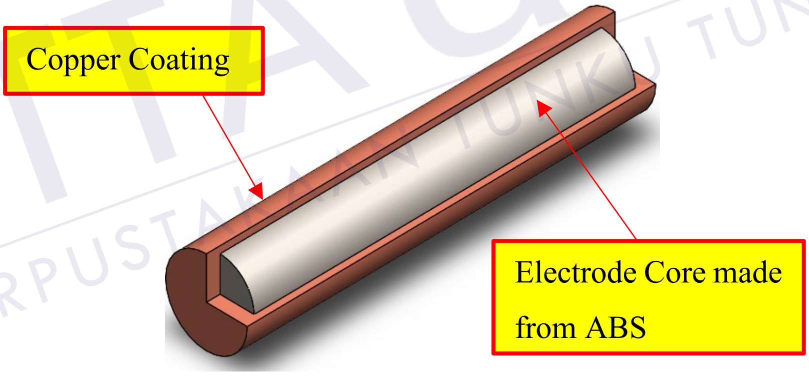

Figure 1.5: ABS as the electrode core in the FDM electrode

1.3 Problem Statement

Metallization is a crucial transitional process that coats the surface of the FDM electrode with a thin metal layer to ensure its proper functioning in die-sinking EDM (Kechagias *et al.*, 2008). 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 disclosed in many related works. Consequently, it has caused uncertainty regarding

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