

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 $334 \mu\text{m}$ 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 $50 \mu\text{s}$ 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 memesis 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
$\varnothing$	- 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 ₃ COOH	- Acetic Acid
CuSO ₄	- Copper (II) Sulphate
CuSO ₄ .5H ₂ O	- 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
EWI	- Electrode Wear Rate
FCCD	- Face Central Composite Design
FDM	- Fused Deposition Modelling
H ₂ CrO ₄	- Chromic Acid
H ₂ O ₂	- Hydrogen Peroxide
H ₂ SO ₄	- Sulphuric Acid
H ₃ PO ₄	- Phosphoric Acid
HAZ	- Heat-Affected Zone

HCl	- 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

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PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

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.

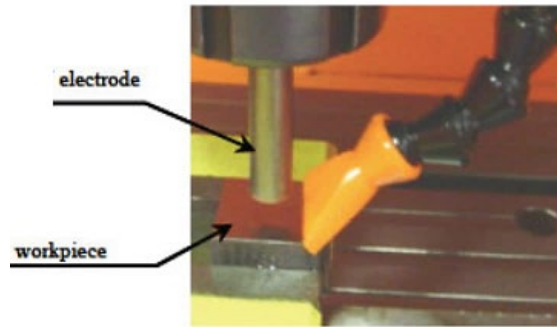


Figure 1.1: Electrode for die-sinking EDM (Amorim, Weingaertner & Bassani, 2010)

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).

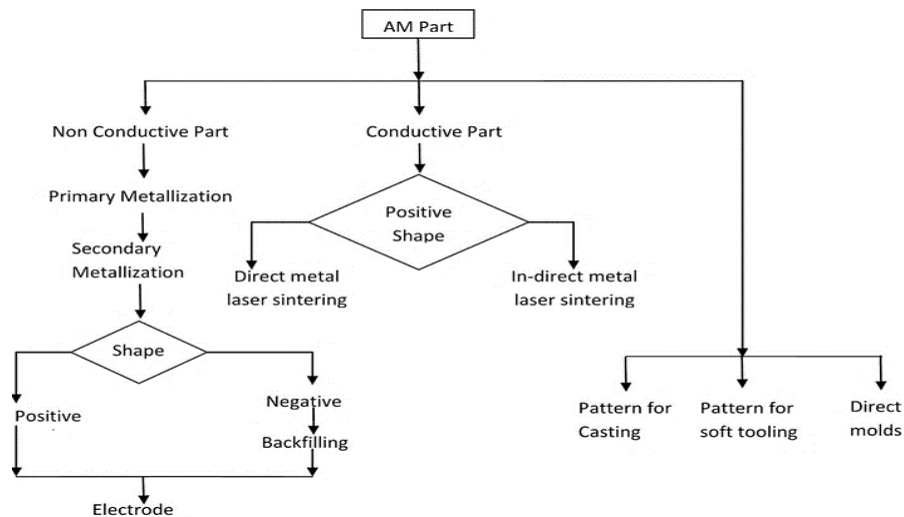


Figure 1.2: Manufacturing of RT electrodes in die-sinking EDM

(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.

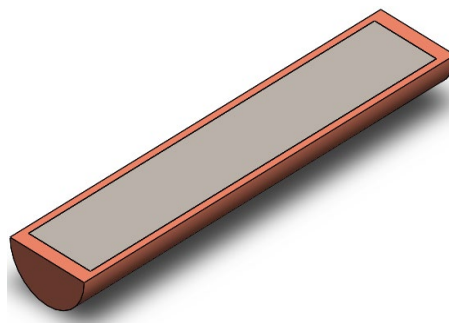


Figure 1.4: Vertical cross-section of the FDM electrode

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.

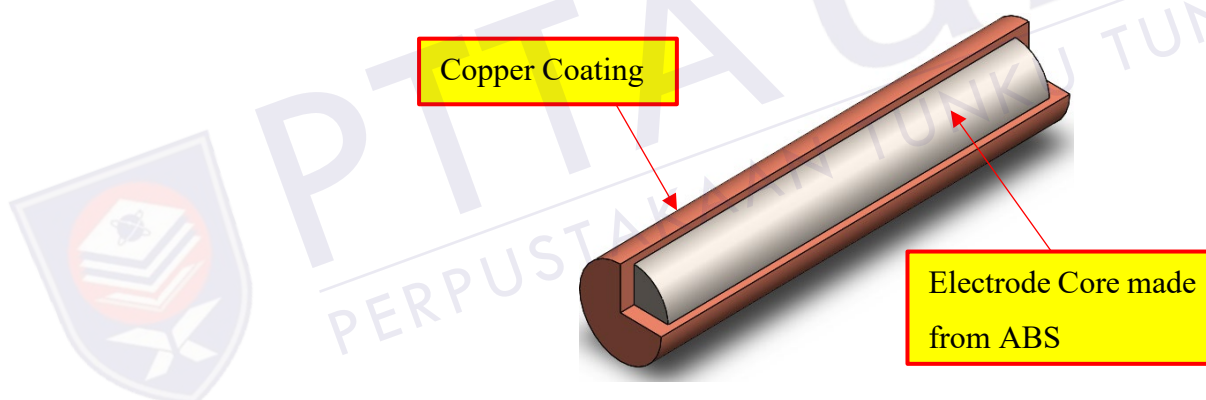


Figure 1.5: ABS as the electrode core in the FDM electrode

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

REFERENCE

- Airwolf. (2015). *3D Printing with PETG: Tips and Tricks*. Retrieved on January 6, 2021, from <https://airwolf3d.com/2015/12/05/3d-printing-with-petg-tips-and-tricks/>
- Alamro, T., Yunus, M., Alfattani, R., & Alnaser, I. A. (2021). Effect of a Rapid Tooling Technique in a 3D Printed Part for Developing an EDM Electrode. *International Journal of Polymer Science* 2021, 2021, 6616652.
- Amorim, F. L., Weingaertner, W. L., & Bassani, I. A. (2010). Aspects on the optimization of die-sinking EDM of tungsten carbide-cobalt. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 32(SPE), 496-502.
- Apmen. (2019). *EDM: Past, Present and Future*. Retrieved on November 16, 2020, from <https://www.equipment-news.com/edm-past-present-and-future/>
- Arthur, A., Dickens, P. M., & Cobb, R. C. (1996). Using rapid prototyping to produce electrical discharge machining electrodes. *Rapid Prototyping Journal*, 2(1), 4-12.
- Augustyn, A. (2020). *Electrolysis*. Retrieved on May 18, 2021, from <https://www.britannica.com/science/electrolysis>
- Azhar Equbal, M., Equbal, I., Sood, A. K., & Equbal, M. A. (2017). A Comparative Study on Electroplating of FDM Parts. *Mechanical Engineering*, 8(5), 930-938.
- Bokisa, G. S. (2013). *Method for Comparison of Leveling in Decorative Acid Copper Plating*. Retrieved on May 13, 2022, from <https://www.pfonline.com/articles/method-for-comparison-of-leveling-in-decorative-acid-copper-plating>
- Cambridge, U. o. (2020). *Sample Preparation*. Retrieved on January 8, 2021, from <https://www.doitpoms.ac.uk/tlplib/optical-microscopy/preparation.php>

- Carausu, C., Mazurchevici, A., Ciofu, C., & Mazurchevici, S. (2018). The 3D printing modelling of biodegradable material. *IOP Conf. Ser. Mater. Sci. Eng.* Constanta: IOP Publishing Ltd. pp. 042008.
- Carlota. (2019). *All you need to know about PETG for 3D printing*. Retrieved on January 6, 2021, from <https://www.3dnatives.com/en/petg-3d-printing-guide-181220194/#!>
- Caswell. (2022). *Caswell Copper Conductive Paint - 4oz*. Retrieved on November 26, 2022, from <https://caswellplating.com/copper-conductive-paint-4oz.html>
- Chakraborty, S., Dey, V., & Ghosh, S. (2015). A review on the use of dielectric fluids and their effects in electrical discharge machining characteristics. *Precision Engineering*, 40, 1-6.
- Chakravorty, D. (2019). *STL File Format (3D Printing) – Simply Explained*. Retrieved on November 16, 2020, from <https://all3dp.com/what-is-stl-file-format-extension-3d-printing/#pointone>
- Chandramohan, D., & Marimuthu, K. (2011). Rapid prototyping/rapid tooling—a over view and its applications in orthopaedics. *Int J Adv Eng Tech*, 2(4), 435-448.
- Chen, B., Wang, A., Wu, S., & Wang, L. (2016). Polyquaternium-2: a new levelling agent for copper electroplating from acidic sulphate bath. *Electrochemistry*, 84(6), 414-419.
- Choudhary, S. K., & Jadoun, R. (2014). Current advanced research development of electric discharge machining (EDM): a review. *International Journal of Research in Advent Technology*, 2(3), 273-297.
- Clark, E. (2020). *18 3D Printer Filament Types And Uses Comparison Guide*. Retrieved on December 22, 2020, from <https://www.allthat3d.com/3d-printer-filament/>
- Connor, N. (2021). *Mild Steel*. Retrieved on May 30, 2022, from <https://material-properties.org/mild-steel-density-strength-hardness-melting-point/>
- Corrosionpedia. (2017). *Decomposition Potential*. Retrieved on May 17, 2021, from <https://www.corrosionpedia.com/definition/2071/decomposition-potential>
- Corrosionpedia. (2019). *Current Efficiency*. Retrieved on May 18, 2021, from <https://www.corrosionpedia.com/definition/355/current-efficiency>
- Czelusniak, T., Higa, C. F., Torres, R. D., Laurindo, C. A. H., de Paiva Júnior, J. M. F., Lohrengel, A., & Amorim, F. L. (2019). Materials used for sinking EDM

- electrodes: a review. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 41(1), 14.
- Danade, U. A., Londhe, S. D., & Metkar, R. M. (2019). Machining performance of 3D-printed ABS electrode coated with copper in EDM. *Rapid Prototyping Journal*, 25(7), 1224-1231.
- Develve. (2020). *Center Point*. Retrieved on May 30, 2022, from <https://develve.net/Center%20point.html>
- Dey, A., & Yodo, N. (2019). A systematic survey of FDM process parameter optimization and their influence on part characteristics. *Journal of Manufacturing and Materials Processing*, 3(3), 64.
- Dhatrak, H., & Kamble, N. (2020). A Review on to Study the Performance of Fused Deposition Modelling Electrode for EDM Process with EN8 Material. *International Journal of Research in Engineering, Science and Management*, 3(2), 654-657.
- Ehl, R. G., & Ihde, A. J. (1954). Faraday's electrochemical laws and the determination of equivalent weights. *Journal of Chemical Education*, 31(5), 226.
- Equbal, A., & Sood, A. K. (2013). Problems and Challenges in EDM Electrode Fabrication using RP: A Critical Review. *World Applied Sciences Journal*, 28(8), 1127-1133.
- Equbal, A., Equbal, A., & Sood, A. (2014). Metallization on FDM processed parts using electroless procedure. *Procedia materials science*, 6, 1197-1206.
- Equbal, A., Sood, A. K., & Shamim, M. (2015). Rapid tooling: A major shift in tooling practice. *Manufacturing and Industrial Engineering*, 14(3-4).
- Equbal, A., Sood, A. K., Ansari, A. R., & Equbal, A. (2017). Optimization of process parameters of FDM part for minimizing its dimensional inaccuracy. *International Journal of Mechanical and Production Engineering Research and Development*, 7(2), 57-66.
- Equbal, A., Equbal, M. I., & Sood, A. K. (2019). An investigation on the feasibility of fused deposition modelling process in EDM electrode manufacturing. *CIRP Journal of Manufacturing Science and Technology*, 26, 10-25.
- Equbal, A., Equbal, M. I., Equbal, M. A., & Sood, A. K. (2019). An Insight on Current and Imminent Research Issues in EDM. *Non-Conventional Machining in Modern Manufacturing Systems*. India: IGI Global. pp. 33-54.

- Fan, H. (2017). *What is electroplating? How does the electroplating process work?* Retrieved on January 8, 2021, from <https://insights.vecoprecision.com/what-is-electroplating-how-does-the-electroplating-process-work>
- Fefar Savan, D., & Karajagikar, M. J. (2014). Study and Analysis of Metallized electrode fabricated with FDM Rapid Prototyping technique for Electro discharge machining (EDM). *AIMTDRC*. India: IIT Guwahati.
- Gordeev, E., Degtyareva, E., & Ananikov, V. (2016). Analysis of 3D printing possibilities for the development of practical applications in synthetic organic chemistry. *Russian Chemical Bulletin*, 65(6), 1637-1643.
- Gostimirovic, M., Kovac, P., Sekulic, M., & Skoric, B. (2012). Influence of discharge energy on machining characteristics in EDM. *Journal of mechanical science and technology*, 26(1), 173-179.
- Hang, O. (2022a). *H1 Leveling Agent 2 Mercaptothiazoline / 2 Thiazoline 2 Thiol For Acid Copper Baths*. Retrieved on May 14, 2022, from <https://www.acidcopperplatingbrighteners.com/sale-11775627-h1-leveling-agent-2-mercaptothiazoline-2-thiazoline-2-thiol-for-acid-copper-baths.html>
- Hang, O. (2022b). *Acid Copper Plating Brighteners*. Retrieved on May 15, 2022, from <https://www.acidcopperplatingbrighteners.com/supplier-342731-acid-copper-plating-brighteners>
- Haq, R. H. A. (2009). *Performance Evaluation of Different Types of Graphite Electrodes on Titanium (Ti-6Al-4V)*. Universiti Teknologi Malaysia, Malaysia.
- Harrison. (2020). *Ra & RMS: Calculating Surface Roughness*. Retrieved on January 19, 2021, from <http://www.harrisonep.com/electropolishing-ra.html>
- Ilani, M. A., & Khoshnevisan, M. (2020). Powder mixed-electrical discharge machining (EDM) with the electrode is made by fused deposition modeling (FDM) at Ti-6Al-4V machining procedure. *Multiscale and Multidisciplinary Modeling, Experiments and Design*, 3(3), 173-186.
- Jeevamalar, J., & Ramabalan, S. (2015). A Review on EDM Process Parameters. *International Journal of Applied Engineering Research*, 10(51), 2015.
- Jetguy, T. (2020). *RAISE3D N2 PLUS*. Retrieved on May 30, 2022, from <https://www.pebblereka.com/product-page/raise3d-n2-plus>

- Joo, M. W., Lee, Y.-S., Chung, Y.-G., & Lee, H. K. (2022). Sarcomas in Teachers Using Three-Dimensional Printers: A Report of Three Patients and Literature Review. *Clinics in Orthopedic Surgery*, 14(2), 310.
- Kabra, S. (2015). *What is conventional machining process?* Retrieved on November 16, 2020, from <https://www.quora.com/What-is-conventional-machining-process>
- Kechagias, J., Iakovakis, V., Katsanos, M., & Maropoulos, S. (2008). EDM electrode manufacture using rapid tooling: a review. *Journal of Materials Science*, 43(8), 2522-2535.
- Khan, A. A., Ndaliman, M. B., Ali, M. Y., Lawal, S. A., Sulong, N. F. B., & Mohamad, U. A. K. B. (2013). Effect of Electrical Parameters on Performance of Cu-TiC Mixed Ceramic Compact Electrode in EDM Process. *ICMAAE*. Kuala Lumpur.
- Khan, I., & Shaikh, D. A. (2014). A Review of FDM Based Parts to Act as Rapid Tooling. *International Journal Of Modern Engineering Research ISSN*, 2249-6645.
- Khan, M. Y., Rao, P. S., & Pabla, B. (2020). Investigations on the feasibility of Jatropha curcas oil based biodiesel for sustainable dielectric fluid in EDM process. *Materials Today: Proceedings*, 26, 335-340.
- Kolli, M., & Kumar, A. (2015). Effect of dielectric fluid with surfactant and graphite powder on Electrical Discharge Machining of titanium alloy using Taguchi method. *Engineering Science and Technology, an International Journal*, 18(4), 524-535.
- Kondo, H. (2019). *PETG vs ABS: The Differences – Simply Explained*. Retrieved on January 19, 2021, from <https://all3dp.com/2/petg-vs-abs-3d-printing-filaments-compared/>
- Lima, F., Mescheder, U., & Reinecke, H. (2012). Simulation of current density for electroplating on silicon using a Hull cell. *solar cells*, 6, 7.
- Lobovsky, M. (2022). *Guide to Rapid Tooling*. Retrieved on May 28, 2022, from <https://formlabs.com/asia/blog/rapid-tooling/>
- Locker, A. (2020). *2020 PETG Filament Buyer's Guide*. Retrieved on January 6, 2021, from <https://all3dp.com/1/petg-filament-3d-printing/>
- Lowenheim, F. A. (1942). *Modern Electroplating*: John Wiley & Sons.

- Lužanin, O., Movrin, D., & Plančak, M. (2013). Experimental investigation of extrusion speed and temperature effects on arithmetic mean surface roughness in FDM built specimens. *Journal for Technology of Plasticity*, 38(2), 179-190.
- Magma. (2020). *Magma PETG* Retrieved on December 23, 2020, from <http://magma3dp.com/100-magma-petg>
- Mandaloi, G., Singh, S., Kumar, P., & Pal, K. (2016). Effect on crystalline structure of AISI M2 steel using tungsten–thorium electrode through MRR, EWR, and surface finish. *Measurement*, 90, 74-84.
- Matta, A., Raju, D. R., & Suman, K. (2015). The integration of CAD/CAM and rapid prototyping in product development: a review. *Materials Today: Proceedings*, 2(4-5), 3438-3445.
- Mittal, V. (2020). *Electroplating*. Retrieved on May 16, 2021, from <https://chem.libretexts.org/@go/page/272>
- Mohamed, O. A., Masood, S. H., & Bhowmik, J. L. (2015). Optimization of fused deposition modeling process parameters: a review of current research and future prospects. *Advances in Manufacturing*, 3(1), 42-53.
- Mohanty, S. D., Mohanty, R. C., & Mahapatra, S. S. (2017). Study on performance of EDM electrodes produced through rapid tooling route. *Journal of Advanced Manufacturing Systems*, 16(04), 357-374.
- Niamat, M., Sarfraz, S., Ahmad, W., Shehab, E., & Salonitis, K. (2019). Parametric modelling and multi-objective optimization of electro discharge machining process parameters for sustainable production. *Energies*, 13(1), 38.
- Nouri, H. (2022). MBFA algorithm based optimization of tungsten carbide alloy wire cut machining process. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1-23.
- Ogino, Y., Hirata, Y., Kihana, S., & Nitta, N. (2018). Numerical simulation of free-flight transfer by a 3D metal transfer model. *QJ Jpn Weld Soc*, 36(1), 94-103.
- Padhi, S. K., Mahapatra, S., & Das, H. C. (2017). Performance of a Copper Electroplated Plastic Electrical Discharge Machining Electrode Compared to a Copper Electrode. *International Journal of Pure and Applied Mathematics*, 114(7), 459-469.
- Padhi, S. K., Mahapatra, S., Padhi, R., & Das, H. C. (2018). Performance analysis of a thick copper-electroplated FDM ABS plastic rapid tool EDM electrode. *Advances in Manufacturing*, 6(4), 442-456.

- Pandey, P. M. (2012). On the Rapid Prototyping Technologies and Applications in Product Design and Manufacturing. *Materials Science Forum*. Switzerland: Trans Tech Publications Ltd. pp. 101-109.
- Pawar, P., Anasane, S., Ballav, R., & Kumar, A. (2016). Experimental study of electroless copper coated on ABS material used for tooling in EDM machining process. *J. Prod. Eng*, 19(2), 27-32.
- Petrov, P., Agzamova, D., Pustovalov, V., Zhikhareva, E., Saprykin, B., Chmutin, I., & Shmakova, N. (2021). Research into the effect of the 3D-printing mode on changing the properties of PETG transparent plastic. *4th International Conference on Material Forming*. Belgium: University of Liège.
- Phull, G. S., Kumar, S., Walia, R. S., & Singh, H. (2020). Copper Electroforming Optimization for Fused Deposition Modeling Produced ABS Components for Indirect Tooling Applications. *Journal of Advanced Manufacturing Systems*, 19(01), 15-29.
- Plating, S. (2017). *Electroplating Defects and Issues*. Retrieved on May 21, 2022, from <https://www.sharrettsplating.com/blog/electroplating-defects-issues/>
- Plica, M. (2020). *2020 3D Printer Filament Buyer's Guide*. Retrieved on November 18, 2020, from <https://all3dp.com/1/3d-printer-filament-types-3d-printing-3d-filament/>
- Rajesh, R., & Anand, M. D. (2012). The optimization of the electro-discharge machining process using response surface methodology and genetic algorithms. *Procedia Engineering*, 38, 3941-3950.
- Raveendran, B. (2021). *What is Electroplating?* Retrieved on January 8, 2021, from <https://byjus.com/chemistry/electroplating-process/>
- Reddy, L., Krishna, L., Kumar, S., & Reddy, P. (2018). Estimation of electrical conductivity of ABS and PLA based EDM electrode fabricated by using FDM 3D-Printing process. *Int. J. Mod. Eng. Res. Technol*, 5, 332-338.
- Sahoo, S. K., Sahu, A. K., & Mahapatra, S. S. (2017). Environmental friendly electroless copper metallization on FDM build ABS parts. *International Journal of Plastics Technology*, 21(2), 297-312.
- Sahu, A. K., & Mahapatra, S. S. (2020). Performance analysis of tool electrode prepared through laser sintering process during electrical discharge machining of titanium. *The International Journal of Advanced Manufacturing Technology*, 106(3-4), 1017-1041.

- Satyanarayana, B., & Prakash, K. J. (2015). Component replication using 3D printing technology. *Procedia Materials Science*, 10, 263-269.
- Saxena, P., & Metkar, R. (2019). Development of electrical discharge machining (EDM) electrode using fused deposition modeling (FDM). *3D Printing and Additive Manufacturing Technologies*. Singapore: Springer. pp. 257-268.
- Schlesinger, M., Paunovic, M., & Society, E. (2000). *Modern Electroplating*: Wiley.
- Shrivastava, S. M., & Sarathe, A. (2014). Influence of process parameters and electrode shape configuration on material removal rate, surface roughness and electrode wear in die sinking EDM: a review. *International Journal of Emerging Technology and Advanced Engineering*, 4(4), 138-145.
- Singh, A. K., Mahajan, R., Tiwari, A., Kumar, D., & Ghadai, R. (2018). Effect of dielectric on electrical discharge machining: a review. *J Mater Sci Eng*, 377, 012184.
- Sood, A. K., & Equbal, A. (2020). Feasibility of FDM-electroplating process for EDM electrode fabrication. *Materials Today: Proceedings*, 28, 1154-1157.
- Sturges, S. (2020). *ABS vs PETG: Which is Best For 3D Printing?* Retrieved on January 19, 2021, from <https://3dsourced.com/3d-printer-materials/abs-vs-petg/>
- Sultan, T., Kumar, A., & Gupta, R. D. (2014). Material removal rate, electrode wear rate, and surface roughness evaluation in die sinking EDM with hollow tool through response surface methodology. *International Journal of Manufacturing Engineering* 2014, 259129.
- Taher, B. Y. (2016). *Which chemicals removes the copper oxide (black)layer effectively ?* Retrieved on May 19, 2021, from <https://www.researchgate.net/post/Which-chemicals-removes-the-copper-oxide-blacklayer-effectively>
- Thakur, A. (2020). *Which chemicals removes the copper oxide (black)layer effectively ?* Retrieved on May 19, 2021, from <https://www.researchgate.net/post/Which-chemicals-removes-the-copper-oxide-blacklayer-effectively>
- Ubaid, A. M., Dweiri, F. T., Aghdeab, S. H., & Abdullah Al-Juboori, L. (2018). Optimization of electro discharge machining process parameters with fuzzy logic for stainless steel 304 (ASTM A240). *Journal of Manufacturing Science and Engineering*, 140(1).

- Velling, A. (2020). *Mild Steel – All You Need to Know*. Retrieved on August 2, 2022, from <https://fractory.com/what-is-mild-steel/>
- Wei, L. (2016). *Copper Electroplating Fundamentals*. Retrieved on May 15, 2022, from <https://www.dupont.com/electronic-materials/blogs/knowledge/copper-electroplating-fundamentals.html>
- Wire, A. (2020). *Early History of Wire EDM*. Retrieved on November 16, 2020, from <https://prototype-shortrun.com/american-wire-edm/history-of-edm-machining/>
- Wu, Q.-X., Wu, M.-C., Hu, C.-C., Hsu, C.-Y., Chang, T.-L., & Tsao, C.-C. (2020). Study on the fabricated feasibility of electrodes in EDM using rapid prototyping (RP) and investment casting technology. *The International Journal of Advanced Manufacturing Technology*, 109(1), 377-384.

