On the use of Copper Tool developed by Atomic Diffusion Additive Manufacturing (ADAM) Process for Electrical Discharge Machining

Mohd Yunus Khan[1,*], *P. S.* Rao[1], and *B. S.* Pabla[1]

[1]National Institute of Technical Teachers' Training and Research, Chandigarh, India

Abstract. This paper highlights the review of work done in the area of 3D printed tools for the spark machining process. In recent times, additive manufacturing has gained wide popularity in different sectors. The additive manufacturing process or 3D printing, is a method for creating three-dimensional objects by layering material. Using the additive manufacturing technique of atomic diffusion, a tool for electrical discharge machining was developed. In this method, a mixture of metal and polymer that are formed into wire was employed and kept in a cartridge. The material mix is deposited in similar to extrusion process. A computer software does all the calculation, costing, weight analysis and printing time assessment. The procedure of the same is discussed. The scanning electron microscopic analysis of the same is done along with porosity measurement using ImageJ software. The surface characteristics of the printed tool was measured with Gwyddion software. Discussion on applicability of printed tool for electrical discharge machining process is done. words.

1 Introduction

Electrical discharge machining (EDM) is used to machine hard and difficult-to-machine materials. The material is expulsed from the workpiece through melting and vaporization when a spark occurs in a small gap between the work sample and the tool [1]. The accuracy of the machined component is greatly influenced by the shape and accuracy of the tool used since, the tool has a shape that corresponds to the intended profile to be formed on the workpiece. Commonly used tool materials include copper, graphite, brass, and graphite. EDM has applications in numerous fields: manufacturing of gear, mould and die making, automobile, aircraft, biotechnology, surgical sectors, etc. [2-4]. In the manufacture of dies and molds, the machining of tools makes up 25-40 % of the overall lead time and can cost up to 50 % of the entire machining cost [5]. A longer lead-time during the mold manufacturing process can delay the product's launch and have an impact on the market. To get the necessary cavities, complex features in die and molds require the use of several tools with precise geometry that are run sequentially. In recent years, the development of the EDM tool using additive manufacturing techniques has demonstrated remarkable possibilities for reducing lead times and lowering the number of tools needed for intricate cavity machining. Thus, the benefits of using 3D printing to manufacture EDM tools are process cost and time. A number of techniques of 3D printing are used for developing EDM tools. A summary of some research in the field of EDM tools is presented in Table 1.

The purpose of this paper is to review the work done in the area of 3D printed EDM tool. A novel technique of atomic diffusion atomic manufacturing to develop EDM tool has been discussed. Necessary steps involved in printing electrode are discussed. In the end, the framework for future research work has been presented.

2 Development of EDM Tool using ADAM Process

EDM tool was developed on Markforged Metal X 3D printer available at 4D Simulations (A Unit of Adroitec Information Systems Pvt. Ltd.), Noida. This technique is referred Atomic Diffusion Additive Manufacturing (ADAM). It employs a mixture of metal and polymer that are formed into the wire that are kept in a cartridge at the top of the printer. The material mix is deposited just like the extrusion process. Eiger software does all the mathematical calculations, part cost, weight, and printing time assessment. Materials that can be used in Metal X include stainless steel, Inconel, Copper, Titanium. Part printed in Metal X system goes to washing bath followed by the sintering process. In the washing bath, the green part is immersed in a specific solution that removes the primary binding substance. A medium-sized furnace converts brown parts into a final metallic form. The washing bath and sintering furnace are connected to Markforged software. No post processing is required [19]. Fig. 1 shows photograph of Metal X system.

* Corresponding author: yunus.mech19@nitttrchd.ac.in

Table 1. Literature review

S.No.	Authors (Year) [Ref. No.]	Workpiece and tool material	Investigation	Experimental Conditions	Conclusions
1.	Mohanty et al. (2017) [6]	**Workpiece material:** D2 steel **Tool material:** EOS Direct Metal 20	EDM performance using a Rapid Tooling route was observed.	Peak current (A): 8,10,12 Flushing pressure (kgf/cm^2): 0.3,0.6,0.9 Pulse duration (μs): 100,150,200 Pulse interval (μs): 10,20,30	• Reduced rate of tool wear, greater rate of material removal, and lower surface integrity were observed.
2.	Shamsudin and Lajis (2017) [7]	**Workpiece material:** Aluminium **Tool material:** Copper, Alumina, maltodextrin	A feasibility study on the manufacturing of MMC material for EDM tools utilizing the RP process was conducted.	Polarity: positive Pulse duration (μs): 86 Peak current (A): 5.4 Pulse interval (μs): 43 Voltage (V): 60 Machining time (s): 30	• The electrode with the maximum material removal and minimum tool wear was sintered at 977°C using a Cu-Al_2O_3 composite. • The electrode with Cu- Al_2O_3 composite sintered at 977 °C had a greater surface quality compared to the other electrodes.
3.	Padhi et al. (2018) [8]	**Workpiece material:** D2 Steel **Tool material:** Copper, Aluminum	EDM electrode efficiency of an RT electrode was evaluated.	Current i(A): 2, 3, 4 Duty cycle (%): 70, 75, 80 Pulse duration (μs): 50, 100, 150 Machining Time (min): 6 Open circuit voltage (V) :40 Flushing pressure (kPa): 350	• The electroplated ABS plastic EDM RT electrode showed better performance. • The RT electrode may be utilized for irregular cutting or a semi-finishing operation.
4.	Danade et al. (2019) [9]	**Workpiece material:** Ti-Al6-V4 **Tool material:** Copper	The machining efficiency of a copper-coated square-shaped ABS electrode.	Current (A):12, 16, 18 Gap voltage (V): 50, 60, 70 Pulse duration (μs): 100, 150, 200	• The efficiency of a coated RP electrode was found to be comparable to that of a solid electrode.
5.	Equbal et al. (2019) [10]	**Workpiece material**: mild steel **Tool material:** Copper	Experimental study on the possibility of EDM electrode manufacture using FDM	Current (A): 3, 6, 9 Pulse duration (ms): 90, 180, 270 Pulse interval (ms): 90, 120, 150	• The performance of the FDM electrode can be improved using MOGA for Pareto optimality.
6.	Sahu and Mahapatra (2019) [11]	**Workpiece material:** Titanium **Tool material:** RP, Graphite, Copper	EDM performance using different electrode materials.	Open circuit Voltage (V): 20, 25, 30 Duty cycle (%): 65, 75, 85 Peak current (A): 20, 25, 30 Pulse duration (μs): 100, 200, 300	• The tool type and discharge current are noteworthy factor effecting the performance measures. • Surface properties provided by RP tool were excellent. Graphite tool electrode provides improved material and tool wear values.

7.	Ilani and Khoshnevisan (2020) [12]	**Workpiece material:** Ti-6Al-4V **Tool material:** RP, Copper	The innovative electrode is compared to solid electrodes with and without powder.	Peak current (A): 15-25 Concentration of powder (g/l): 0-5 Spark time (µs): 50-70	• Proposed technique to the PM-EDM showed a 33%, 31%, and 77% improvement in material wear, tool wear, and surface roughness, respectively. • The surface integrity produced by the PM-EDM had been significantly enhanced.
8.	Klaric et al. (2020) [13]	**Workpiece material:** St 37-2 steel plate **Tool material:** Copper	Investigates the possibility of using the SP3D printing technology to produce EDM electrodes built-in cooling systems.	Polarity: positive Peak current (A): 5 Pulse interval (µs): 45 Pulse duration (µs): 110 Voltage (V): 55	• Possibility of using the SP3D printing technology to produce EDM electrodes built-in cooling systems, which could potentially reduce electrode wearing.
9.	Shaikh and Ahuja (2020) [14]	**Workpiece material:** P20 mold steel **Tool material:** Silver, nickel, Copper	Improving the performance of EDM tools for machining.	Electrode polarity: Positive Duty factor (%): 88 Peak current (A): 10 Spark time (ms): 200 Work time (s): 1 Machining time (min): 60 Gap voltage (V): 60 Retract distance (mm): 5	• Coatings combination and optimizing the parameters of the tool using fuzzy logic, improves the performance during machining.
10.	Shashank et al. (2021) [15]	**Workpiece material:** Stainless steel 316 L **Tool material:** Copper	Optimizing of EDM electrode by DMLS technique for SS316L material	Peak current (A): 10, 15, 20 Pulse time (µs): 5, 6, 7 Pause time (µs): 4, 5, 6	• Current is a significant factor, with greater current resulting in a superior surface finish, moderate material loss rate, and electrode wear rate. •
11.	Equbal et. al (2021) [16]	**Workpiece material:** Mild steel **Tool material:** Aluminum-charcoal, Copper	Examining the dimensional characters Precision of a Novel ABS P400 Polymer-Based EDM Electrode Prepared Cavity	Pulse duration (µs): 90, 120, 150 Peak current (A): 3, 6, 9 Pulse interval (µs): 90, 180, 270	• According to the findings, change in diameter and change in depth were lower when EDM was done using new electrodes.
12.	Equbal et al. (2023) [17]	**Workpiece material:** Mild steel **Tool material:** Acrylonitrile-butadiene- styrene (ABS)	Studied EDM performance using electrode developed by fused deposition modelling	Current (A): 3, 6, 9 Pulse time (µs): 90, 180, 270 Pause time (µs): 90, 120, 150	• SR was found to be significantly higher with ABS electrodes.
13.	Sahu et al. (2023) [18]	**Workpiece material:** D2 tool steel **Tool material:** RP tool, Copper, brass	Optimized EDM performance using RP tool	Duty cycle (%): 50, 75 Peak current (A): 10, 20, 30 Pulse time (µs): 100, 200, 300	• Performance of RT tool was found to be better than Copper and brass tools.

Fig. 1. Metal X system (Courtesy: 4D Simulation, Noida)

Specification of complete Metal X system is given in Table 2. The photograph of pure Cu EDM tool printed by this process is shown in Fig. 2.

Table 2. Specifications of Metal X system

Parameter	Specifications
Build volume	300 mm x 220 mm x 180 mm
Foot print	575 mm x 467 mm x 1432 mm
Z layer resolution	50 micron, 125 microns
Washing solution	Opteon SF79
Washing bath size	356 mm x 254 mm x 203 mm
Washing volume	18356 cm^3
Heating element	Kanthal
Sinter capacity	Cylindrical- 248mm ID x 406mm L
Sinter volume	19644 cm^3
Sinter gas	Inert gas
Peak temperature of furnace	1300°C

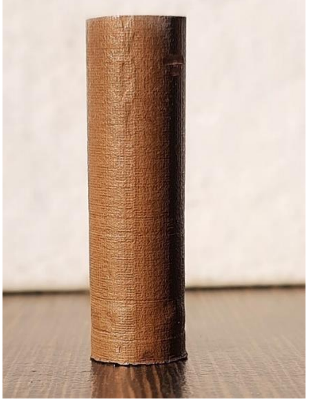

Fig. 2. EDM tool developed by ADAM process

3 Process of Printing

Below is a step-by-step description of ADAM's process:

1. The first stage is construct a digital model of the product to be developed. This is done using CAD software. Reverse engineering can also be employed to produce a digital model by using scanning methods.
2. CAD model is converted into a STL (stereolithography) file and a material is selected from available option. The Eiger software does the rest of the things. Software does all the mathematical calculation- from scaling up for sintering to calculating part cost, weight and printing time. Just upload STL, pick a metal, and press print.
3. Just like metal injection molding, as-printed items are "green" and scaled up to allow for shrinkage during sintering.
4. To get the binder off, green parts go through a washing stage. The metal powder is then sintered in a furnace, where it solidifies.
5. The final parts are ready for use. No CNC or Wire EDM is required for removal of part from the build plate or to remove the support. A simple wash and support removal needed to make the part usable. [20]

3 Analysis and Discussion

The dimensions and weight measurements are shown in Fig. 3 while the values of dimensions, weight and, obtained density of developed tool are given in Table 3. The density of tool was calculated using simple equation of density based on weight and volume of the tool. The density of solid copper is nearly 8.9 gm/cm^3. It can be noted that the EDM tool manufactured by ADAM process has some specific properties one of such property is low density and thus more wear during its use in EDM process. This shows that the printed tool has a good potential to be used in electrical discharge coating process. Number of tool of various density of same material can be printed and tested in EDM under straight and reverse polarity condition.

Table 3. Dimensions, weight, and density of tool developed

Diameter (mm)	Length (mm)	Volume (mm^3)	Weight (gm)	Density (gm/cm^3)
10.03	38.51	3041.20	22.2519	7.316

Different analysis of the printed EDM tool were conducted to study surface characteristics and porosity of the tool. The scanning electron microscopy was carried to study the topological features of the surface. A scanning electron microscope of make Joel JSM-IT 100 (available at NITTTR, Chandigarh) was used for this purpose. SEM imaging takes place by scanning the specimen with a high energy beam of electrons. When these electrons strike the specimen they develop secondary electrons, characteristic X-rays, and

* Corresponding author: yunus.mech19@nitttrchd.ac.in

backscattered electrons. The detectors are employed to collect these signals and form images that can be seen on a computer screen.

SEM image of the printed tool at higher magnification (X100) is shown in Fig. 4. It can be noted that the layers of parent material are clearly visible on the surface. Also, there is significant distance (gap) between the layers which means the porosity of the printed tool is expected to be higher than solid copper tool. It can already have been established that the density of tool is less than solid copper. These properties will result in higher tool wearing with printed tool and hence, bright chances of use in surface coating.

Fig. 3. Dimensions and weight of the developed EDM tool (Courtesy: NITTTR, Chandigarh)

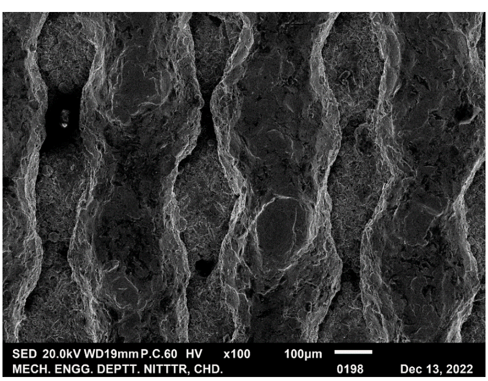

Fig. 4. SEM image of the developed EDM tool

The surface texture, waviness, and surface roughness of the printed EDM tool was determined using Gwyddion software. Data processing and statistical analysis of the sampled data obtained through SEM image can be conducted easily by user friendly and open source Gwyddion software. The variation of surface texture is shown in Fig. 5. Lay, surface roughness, and waviness are three properties that together define a surface's texture. It consists of the tiny, local surface imperfections that deviate from the ideal of a flat surface. It aids in differentiating different items and surfaces, modifies light, and affects size, but it can also convey a specific design style.

Surface roughness i*s* defined as the irregularities which are inherent in the manufacturing process. It is measured by how far an actual surface deviates from its ideal form in the direction of the normal vector. If these variances are considerable, the surface will be rougher and if they are minimal, the surface will be smoother. The variation of surface roughness and waviness is depicted in Fig. 6 and 7 respectively. Surface waviness is the measurement of the more widely spaced portion of surface texture. It is a broader view of roughness because it is more precisely defined as the irregularities with spacing is greater than the roughness sampling length. The value of average roughness and waviness were found to be 4.727 µm and 19.98 µm respectively. While the maximum height of the roughness was recorded to be 95.81 µm, the maximum height of the waviness was detected to be 136.4 µm.

The physical property of porosity is crucial in determining the texture and material quality. A porous material has a small amount of empty space between it and the surrounding material. The porosity of the developed EDM tool was determined by using ImageJ software. The value of porosity was found to be 60.67 %. This shows that the EDM tool developed by ADAM process has high porosity. A relationship between the tool wearing rate and porosity need to be established to study the impact of porous tool on surface deposition using reverse sparking machining. The image obtained by ImageJ software for measurement of porosity in shown in Fig. 8.

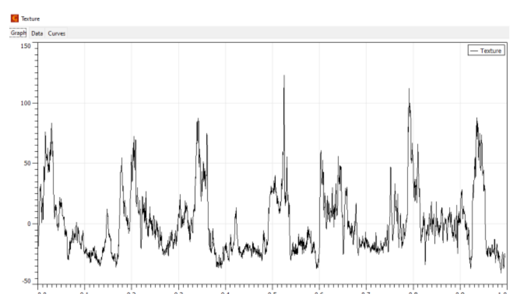

Fig. 5. Surface texture of the developed EDM tool

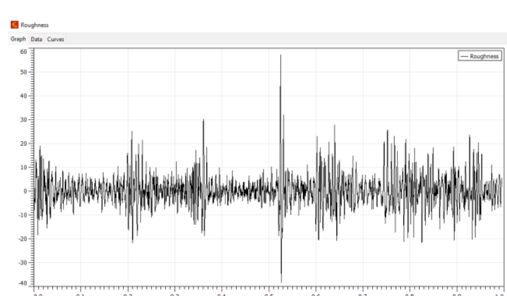

Fig. 6. Surface roughness profile of the developed EDM tool

https://doi.org/10.1051/e3sconf/202345502014

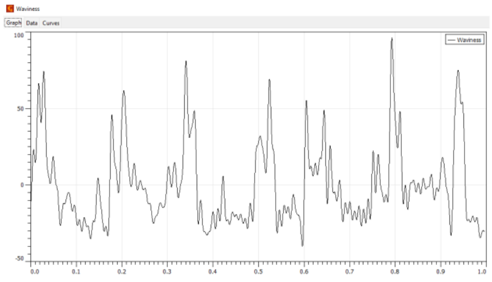

Fig. 7. Surface waviness of the developed EDM tool

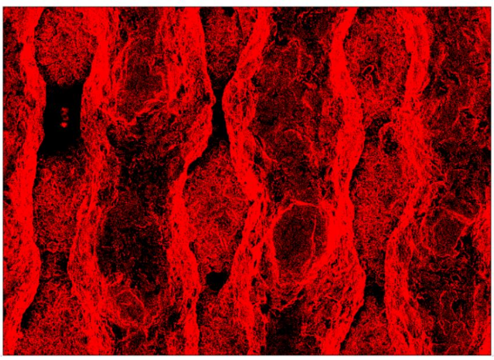

Fig. 8. Image used for determining tool porosity

3 Conclusions

In the recent times, the 3-D printing has gained wide popularity because of its applicability in various sectors of the industries. The process of 3D printing can be employed for developing tool for EDM process too. Through 3D printing, it is possible to develop tool of different shapes, materials, and properties. The review of literature in the area of 3D printed tool for discharge machining has been presented and the summary of results are highlighted in the tabular form. In this paper, the procedure to develop EDM tool using atomic diffusion additive manufacturing process has been discussed. It was observed that the density of developed EDM tool has low density. The surface characteristics of the printed tool were also determined using Gwyddion software. The results are analysed and discussed. The scanning electron microscopy was conducted to know the surface topography. It was observed that the developed tool has high porosity. The low density and high porosity means that the chances of tool wearing with this tool will be higher. Thus, it has a great potential to be used as tool for electrical discharge coating.

The EDM tool of same material but of different densities can be developed using ADAM process. The influence of tool density as one of the input variable on machining characteristics of EDM can be conducted. The optimal value of tool density for machining as well as coating can be found out. It is also possible to develop too of same density but of different materials. The comparative study of the EDM performance using these tools can be conducted.

References

1. M. Y. Khan, P. S. Rao, Int J of Innov Tech & Explor Engg **8(11)**, 1696-1701 (2019).
2. C. Guo, S. Di, D. Wei, Mater & Manufac Proc **31(14)**, 1865-1871 (2016).
3. M.Y. Khan, P. S. Rao, B. S. Pabla, Adv in Mat & Process Technol **8(S4)**, 2204-2230 (2022).
4. Kunal, P. S. Rao, M .Y. Khan, K. Saidaiah, Mat Tod: Proc **62(6)**, 3707-3712 (2022).
5. G. Semon, *A practical guide to electro-discharge machining 2nd ed.* (Atelier De Charmilles, Geneva,1975).
6. S. D. Mohanty, R. C. Mohanty, S. S. Mahapatra, J of Adv Manufac Sys **16(04)**, 357-374 (2017).
7. S. Shamsudin, M. A. Lajis, Feasibility study on production of metal matrix composite (MMC) material for electrical discharge machining (EDM) tools using rapid prototyping (RP) technique. In: 8th Int Conf on Mechanical and Manufacturing Engineering (MATEC Web of Conferences) **135**, 00011 (2017).
8. S. K. Padhi, S. S. Mahapatra, R. Padhi, H. C. Das, Adv in Manufac **6(4)**, 442-456 (2018).
9. U. A. Danade, S. D. Londhe, R. M. Metkar, Rapid Prototyping J **25(7)**, 1224-1231 (2019).
10. A. Equbal, M. I. Equbal, A. K. Sood, CIRP J of Manufac Sc & Technol **26**, 10-25 (2019).
11. A. K. Sahu, S. S. Mahapatra, The Int J of Adv Manufac Technol **106(3)**, 1017-1041 (2020).
12. M. A. Ilani, M. Khoshnevisan, Multiscale and Multidisciplinary Modeling, Exp & Des **3(3)**, 173-186 (2020).
13. S. Klaric, Z. Botak, D. J. Hill, M. Harbidge, R. Murray, Tehnički Glasnik **14(1)**, 27-31 (2020).
14. M. S. N. M. Shaikh, B. B. Ahuja, Mat Tod: Proc **41 (4)**, 874-885 (2021).
15. S. Shashank, T. Pinto, C. G. Ramachandra, M. J. Raghavendra, Mat Sc & Engg **1013(1)**, 012002 (2021).
16. A. Equbal, A. Equbal, Z. A. Khan, I. A. Badruddin, M. B. A. Bashir, H. Alrobei, Polymers **13(23)**, 4109 (2021).
17. A. Equbal, S. Ahmad, I. A. Badruddin, Z.A. Khan, S. Kamangar, S. Javed, Proceedings of the Institution of Mech Engineers, Part B: J of Engg Manufacture **09544054221151093** (2023).
18. A. K. Sahu, S.S. Mahapatra, J. Thomas, A.E. Patterson, M. Leite, S. Goel, J of the Brazilian Soc of Mech Scs & Engg **45(9)**, 470 (2023).
19. M. Y. Khan, P. S. Rao, B. S. Pabla, Arch. of Metallur. & Mat.**68(4)**, 1225-1232 (2023).

20. M. Y. Khan, P. S. Rao, B. S. Pabla, 3-D printing technology: Inclusive study and applicability in different sectors. In: C. Pandey, V. Goyat, S. Goel, editors, *Lecture Notes in Mechanical Engineering-Advances in Materials and Mechanical Engineering,* Springer, Singapore 357-366 (2021).