International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

A Review on Advancements in Additive Manufacturing for EDM Electrode Fabrication and Cutting Tool Applications

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ABSTRACT :

The use of Additive Manufacturing (AM) technologies into the production of electrodes for Electrical Discharge Machining (EDM) constitutes a significant step forward in modern manufacturing. This study examines the use of AM techniques such as Selective Laser Melting (SLM), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), and Atomic Diffusion Additive Manufacturing (ADAM) in EDM electrode production, emphasising their ability to create complex geometries, integrate flushing channels, and achieve higher material removal rates (MRR). These methods enable the creation of customised and complicated electrodes using sophisticated materials such as polymer-based composites containing carbon nanotubes, copper alloys, and ABS-based materials. The resulting electrodes outperform in EDM operations by increasing MRR, decreasing tool wear rates (TWR), and achieving improved surface roughness (SR). Furthermore, AM enables the optimisation of electrode designs to fit specific machining needs, resulting in functional electrodes capable of performing complicated EDM jobs with enhanced process stability and efficiency. The impact of critical process parameters such as pulse current, pulse-on time, and powder concentration in powder-mixed EDM (PM-EDM) on machining efficiency and surface quality is also addressed. AM methods enable the manufacture of nearly-fully dense copper electrodes by optimising laser scanning conditions, resulting in better EDM characteristics. AM reduces production time, material waste, and energy consumption, making it a cost-effective and sustainable solution for industries that require accurate and intricate equipment, such as aerospace, automotive, and medical applications. This study reveals AM's potential to improve the capabilities, efficiency, and accuracy of EDM procedures while broadening their application domains in advanced manufacturing.

Keywords: Selective Laser Melting (SLM), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), ABS- materials.

Introduction :

Electrical Discharge Machining (EDM) is a sophisticated electrothermal material removal method that uses controlled electrical discharges to manufacture difficult-to-cut materials. EDM allows for the exact sculpting of electrically conductive materials without requiring direct tool-to-workpiece contact by producing high-energy sparks in a dielectric medium. This procedure is especially useful for complex geometries and difficult-to-machine materials such as titanium alloys, superalloys, and electrically conductive ceramics. However, the limitations of EDM, such as poor material removal rates (MRR), surface quality problems, and expensive prices, need the development of novel ways to improve its performance and widen its uses. One notable innovation in EDM is the manufacture of electrodes, a vital component that has a direct impact on the machining process's efficiency and precision. Historically, electrodes were manufactured from materials such as copper and graphite using traditional production methods, which may be time-consuming and costly. Recent advancements in additive manufacturing (AM) techniques, including selective laser melting (SLM), fused deposition modelling (FDM), and powder metallurgy, have created new opportunities for making detailed and high-performance electrodes. These techniques enable rapid prototyping, customisation of complex geometries, and the use of sophisticated materials like as tungsten, titanium alloys, and copper, which are required for good electrical conductivity and endurance. Additional advances include the use of sophisticated EDM versions such as powder-mixed EDM (PM-EDM) and additive-mixed EDM (AM-EDM), which insert solid, liquid, or gaseous additives into the dielectric medium to improve machining results. These procedures improve material removal rates, surface cleanliness, and process efficiency. Micro-EDM, a miniature version of EDM, has emerged as a potential method for producing complicated components from hard materials, with extraordinary precision for use in aerospace, medical devices, and micro-electromechanical systems (MEMS). Additive manufacturing is used for more than just electrode creation; it also produces cutting tools for EDM. AM-based cutting tools produced from refractory metals such as tungsten are especially useful for machining hard materials, as they allow for great precision and excellent surface finishes. For example, AM techniques such as Atomic Diffusion Additive Manufacturing (ADAM) have demonstrated the potential to produce cost-effective and high-performance EDM electrodes by optimising parameters such as impulse time, current intensity, and capacitor levels to maximise material removal while minimising tool wear. As industries need more advanced machining capabilities, the combination of additive manufacturing and EDM offers a significant step forward. AM-driven advancements improve the adaptability, efficiency, and application breadth of EDM by solving issues such as tool wear, material homogeneity, and machining precision, transforming it into an important technology for high-performance manufacturing.

Methodology :

The study begins with a thorough analysis of current literature to identify important materials utilised in the production of EDM electrodes, with an emphasis on various additive manufacturing and rapid prototyping techniques. This theoretical research provides a foundational grasp of the most important trends, key works, and upcoming directions in this discipline. Building on this foundation, experimental validation is carried out to determine the feasibility and performance of AM-produced cutting tools in sophisticated machining techniques. This includes selecting appropriate materials, using AM technologies to create EDM electrodes, and evaluating their machining performance under controlled conditions.

Additive manufacturing cutting tools techniques :

3.1 Selective laser melting (SLM)

The breakthrough technology for producing tool electrodes, notably in the context of EDM, because to its capacity to construct complicated geometries, optimise material properties, and improve overall machining performance. The SLM method entails optimising several parameters, including the volume energy density (E V), which has a substantial impact on the material's density and toughness. For example, various levels of EV were tested to balance the cobalt content, which influences the mechanical qualities of the finished product. A lower cobalt level can diminish toughness, whereas a higher cobalt concentration increases material toughness. The primary purpose is to create an electrode for EDM applications.

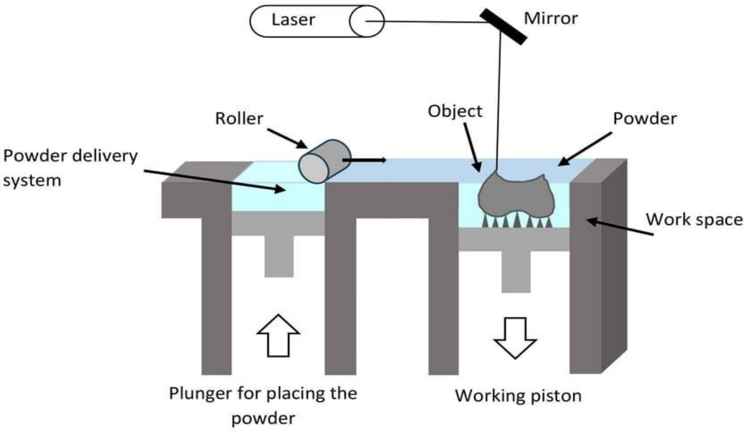


Fig 1: Selective laser melting [32]

3.2 Selective Laser Sintering (SLS)

SLS was used to fabricate EDM tool electrodes from a bronze-nickel powder combination. They discovered that greater scan speeds resulted in increased porosity, which reduced material removal rate (MRR) and increased electrode wear, particularly on X210Cr12 steel compared to C45 steel. Infiltrating copper into SLS-manufactured steel electrodes (steel-polyester-phosphate) resulted in reduced tool wear while increasing discharge current and pulse-on-time due to ferrous carbide development. Combining AM procedures (such as SLS or DMLS) with post-processing techniques (e.g., infiltration and electroforming) may result in ideal electrode properties.

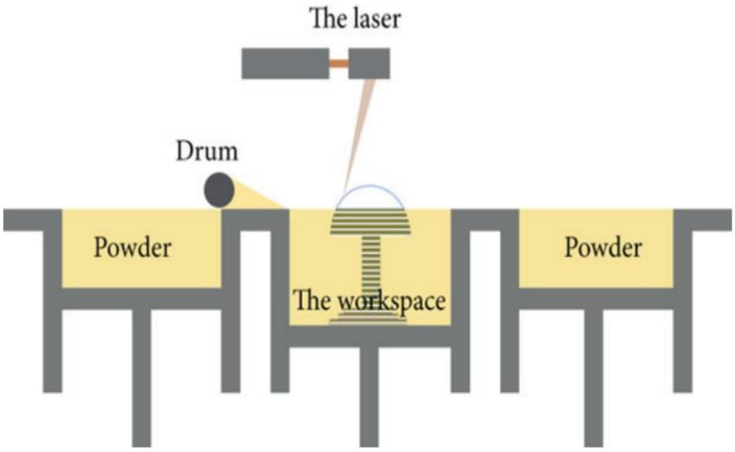


Fig 2: Selective Laser Sintering

3.3 Fusion Deposition Modelling (FDM):

FDM is known for its capacity to produce complicated and customised shapes, which is very useful in the mould and die business. According to the article, EDM methods account for a considerable percentage of cycle time in electrode manufacturing, and FDM can assist minimise this time while preserving the requisite precision and surface properties. The use of FDM in the electrode manufacturing process not only simplifies production but also improves machining performance. The study explores several EDM settings and their effects on material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR), with the goal of determining the effectiveness of FDM-fabricated electrodes in actual applications.

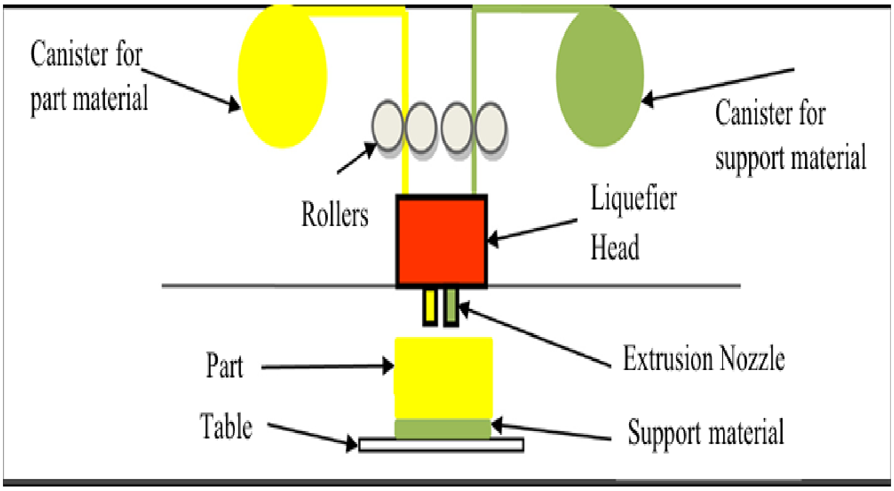


Fig 3: Fusion Deposition Modelling

3.4 Electron Beam Melting:

Electron beam melting (EBM) is an additive manufacturing process that selectively melts metal powder layer by layer using a high-power electron beam in a vacuum environment. This method is particularly suitable for materials like tungsten, which have high melting points and are prone to oxidation. The EBM process begins with the preparation of tungsten powder, which is then spread in a thin layer on a build platform. The Arcam EBM A2X machine, used in this study, operates at a vacuum pressure of 10^-4 to 10^-5 mbar, ensuring a clean environment that is crucial for processing tungsten due to its high oxygen affinity. The findings demonstrate the potential of EBM for producing high-density, crack-free tungsten components, making it a promising technique for advanced manufacturing applications in the field of fusion technology.

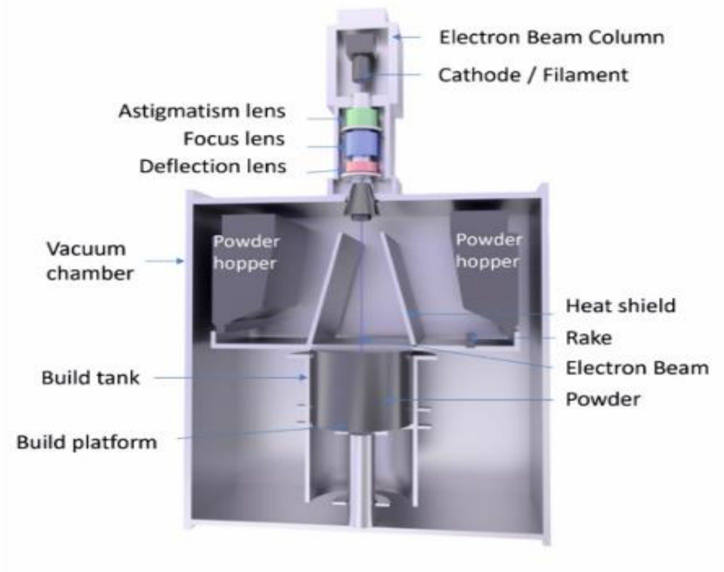


Fig 4: Electron beam melting

4.Measurements

4.1 Material Removal Rate (MRR): For AM applications, the Material Removal Rate (MRR) is crucial to determine how efficiently material is removed from the workpiece. The calculation of MRR is as follows:

MRR = Material removed from work piece / (Machining time * Density)

4.2 Tool Wear Rate (TWR): Tool Wear Rate (TWR) is used to gauge the degradation of AM electrodes under electrical discharge, calculated as:

TWR =Material removed from electrode / (Machining time * Density)

4.3 Electrode Wear Ratio (EWR): The Electrode Wear Ratio (EWR) compares the TWR to the MRR, showing the relationship between tool wear and workpiece removal. EWR is calculated as:

EWR = (TWR /MRR) *100

4.4 Specific Energy Consumption (SEC): Specific Energy Consumption (SEC) assesses the energy efficiency of the EDM process with AM electrodes by calculating the energy needed per volume of material removed. The formula is:

SEC =Energy Consumed /Volume of removed material

4.5 Surface Roughness (Ra): Surface roughness, Ra, is a measure of the machined surface's finish. Given the small diameter of machined holes (e.g., 3 mm), a non-contact BRUKER ContourGT-K surface roughness tester is used to measure Ra in five distinct areas on the workpiece. The average roughness from these measurements provides an overall Ra value. AM electrodes can sometimes produce smoother surfaces, enhancing surface finish quality in EDM applications.

4.6 Radial Overcut (ROC): Radial Overcut (ROC) is critical for accuracy in EDM, especially with AM electrodes where high precision is required.

ROC = (Machined hole diameter) – (Electrode diameter)/2

5. The EDM Parameters

The study evaluates several performance indicators for Electrical Discharge Machining (EDM) using various electrodes, focusing on Open circuit voltage, Peak current, Pulse duration, Duty cycle, Tool material.

5.1 Open circuit voltage

It represents the potential differential between the tool electrodes and the workpiece. It refers to the voltage that exists across the electrodes when the circuit is not completed by the workpiece. The voltage is applied between the electrode and the workpiece, but there is no direct electrical contact.

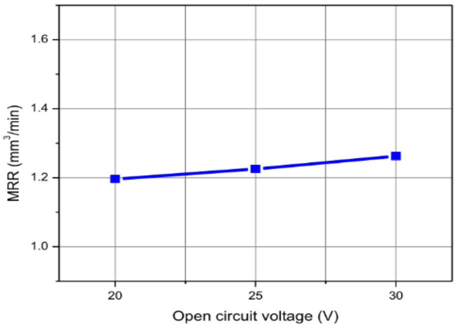
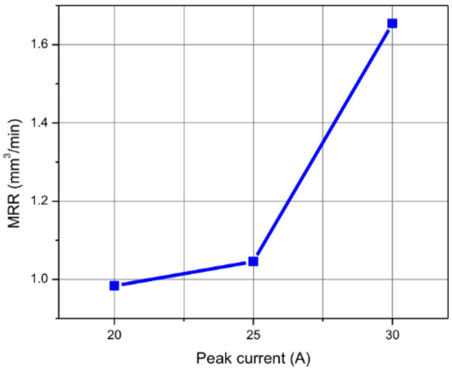


Fig 5: V vs MRR

5.2 Peak current:

The maximum current available each pulse from the power supply/generator. Average current is the average amperage in the spark gap measured throughout a whole cycle. Throughout the machining operation, the EDM machine ammeter measures the average current. It is critical in determining the material removal rate, the depth of the spark craters, and the overall efficiency of the machining process.

Fig 6: Ip vs MRR



5.3 Pulse duration:

Electrical discharge machining refers to the time during a cycle when current is allowed to flow. It's sometimes referred to as the pulse on time. In EDM, one of the most essential electrical pulse parameters is pulse duration, which is followed by discharge current.

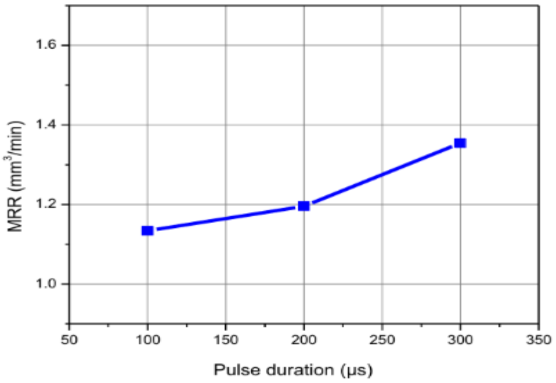


Fig 7: Ton vs MRR

5.4 Duty cycle

A proportion of on-time compared to overall cycle time. In general, larger duty cycles result in better cutting efficiency. The duty cycle is computed by dividing on-time by total cycle time (on-time plus off-time).

$$\tau = \frac{T_{on}}{T_{on} + T_{off}}$$

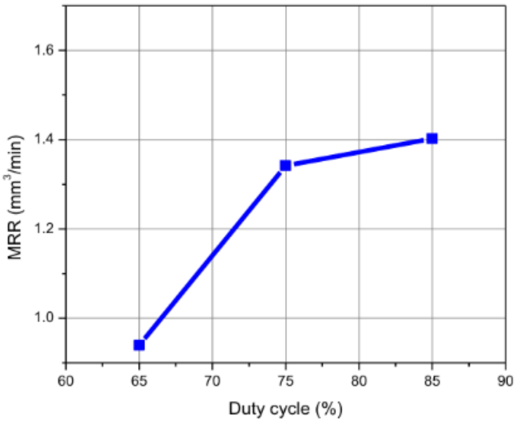


Fig 8: τ vs MRR

6.Results and Discussion :

6.1 Surface Roughness:

Machining Haynes 25 with a graphite electrode produced the highest material removal rate (MRR), which can be attributed to graphite's high melting temperature. However, this electrode produced higher Ra values due to the erosion of bigger particles from the surface, resulting in a rougher surface. The AM CuCr1Zr electrode had a lower Ra than copper or graphite. The fine dispersion of Cr precipitates in the AM material structure, as proposed by Jahns et al., increases hardness and reduces the size of eroded particles, resulting in a smoother machine surface. Copper electrodes had higher surface roughness values than AM CuCr1Zr but comparable to graphite due to larger particle erosion caused by high spark energy during EDM, which influenced surface texture.

6.2 Microhardness Results:

The AM CuCr1Zr electrode showed a balance of high MRR and increased microhardness (MH) on machined surfaces, most likely due to the fine microstructure and stability of Cr dispersions. This electrode created tougher surfaces on Haynes 25, making it more suited for applications needing great wear resistance. Graphite increased MRR and reduced specific energy consumption (SEC), but did not considerably improve microhardness. Copper electrodes demonstrated moderate hardness, owing to their lower melting point and rapid energy dissipation during EDM.

6.3 Specific Energy Consumption (SEC):

Graphite used the least specific energy during EDM due to its high MRR and thermal stability, making it extremely efficient. Both AM CuCr1Zr and copper electrodes have identical SEC values, implying equivalent energy efficiency. The inverse relationship between MRR and SEC was validated, with increased MRR resulting in lower SEC for all electrodes, graphite being the most energy-efficient electrode and AM CuCr1Zr providing a competitive balance of efficiency and surface quality.

6.4 Electrode Wear Ratio (EWR):

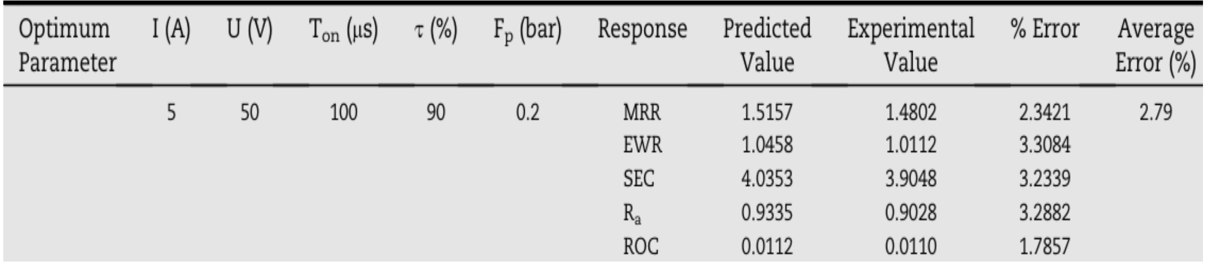
Graphite Electrode: Graphite exhibited the lowest EWR because its high melting temperature and robust structure prevented electrode deterioration during machining.

AM CuCr1Zr Electrode: AM CuCr1Zr displayed lower EWR than copper due to its increased hardness and structural stability, making it a long-term alternative for Haynes 25 EDM.

Copper Electrode: Copper has the highest wear rate, resulting in more frequent replacements and potentially greater expenses.

6.5 Radial Overcut (ROC):

The AM CuCr1Zr electrode generated a lower ROC than graphite and copper, which had bigger dimensional deviations due to larger spark-induced material evaporation. The AM electrode's fine-grained structure allows for more controlled material removal, resulting in tighter tolerances in EDM machining.



Optimum Parameter	I (A)	U (V)	T_{on} (μs)	τ (%)	F_p (bar)	Response	Predicted Value	Experimental Value	% Error	Average Error (%)
	5	50	100	90	0.2	MRR	1.5157	1.4802	2.3421	2.79
						EWR	1.0458	1.0112	3.3084	
						SEC	4.0353	3.9048	3.2339	
						R_a	0.9335	0.9028	3.2882	
						ROC	0.0112	0.0110	1.7857	

Fig 9: Optimum level of parameters along with confirmative with test results

Conclusion :

This review investigates the use of various Additive Manufacturing (AM) techniques for producing EDM (Electrical Discharge Machining) electrodes. It evaluates the machining performance of these AM-produced electrodes compared to traditional solid copper and other metal-based electrodes. The study also explores the application of AM technologies in fabricating cutting tools for EDM.

1.Additive manufacturing (AM) has emerged as a game-changing option for producing electrodes in Electrical Discharge Machining (EDM), providing improved precision, efficiency, and cost-effectiveness. AM techniques, such as Atomic Diffusion Additive Manufacturing (ADAM), successfully produce functional electrodes with comparable or superior performance to traditional copper-based tools, especially for difficult-to-machine materials like superalloys and advanced composites. These electrodes have high material removal rates (MRR), improved surface roughness, and low radial overcut (ROC), making them ideal for precision-driven industries including aerospace and medical technology. However, issues like as increased electrode wear due to porosity highlight the need for additional refinement in AM methods to improve durability.

2.According to research, optimising EDM process parameters such as peak current, pulse-on duration, and powder concentration in the dielectric fluid is critical for achieving excellent machining results. Advanced optimisation methods, like as Taguchi and TLBO, let AM electrodes manage many performance targets, increasing production while reducing energy consumption. Furthermore, AM's ability to create complicated geometries and incorporate sophisticated materials like nanofluids or graphene coatings improves surface integrity by decreasing flaws, making these electrodes especially useful for specialised applications like orthopaedic implants.

3.Despite these advances, existing EDM models have limits in reproducing surface roughness and material morphology due to the intricacies of plasma-channel creation and crater modelling. A comprehensive method that includes real-time tool wear, plasma-material interaction, and fluid dynamics is required to address these issues. Furthermore, the transition to environmentally friendly EDM methods, such as dry processing and the use of biodegradable fluids, is consistent with the industry 5.0 framework and represents a viable field for future research.

4.In conclusion, AM technology has the potential to revolutionise EDM by allowing for quick prototyping and manufacture of high-performance electrodes. Continuous developments in AM processes, together with optimised EDM parameter management and ecologically sustainable practices, will further enhance the utility of AM electrodes in high-precision, high-performance production applications, opening the way for novel solutions to modern machining.

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