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Review on Integrating Additive Manufacturing and Electrical Discharge Machining: Advances in Electrode Fabrication and Industrial Applications

D. Venkatasri [a], L. Sivasankar[b], P. Chandrika[c]

[a,b,c] *UG Scholars, Mechanical department, GMR Institute of Technology, Rajam, Andhra Pradesh, India*

A B S T R A C T

This study on the integration of additive manufacturing (AM) and rapid prototyping (RP) techniques in optimizing the production of EDM electrodes, improving machining performance, and reducing costs. ABS plastic, fabricated via Fused Deposition Modeling (FDM) and electroplated with copper, proves effective for rough and semi-finishing EDM, especially on D2 and mild steel. Al-Si-Mg alloys, produced using Selective Laser Sintering (SLS) and Selective Laser Melting (SLM), exhibit high material removal rates, reduced tool wear, and enhanced surface properties when machining titanium and high-strength steels. Pure copper electrodes manufactured through 3D printing and sintering, integrated with cryogenic cooling channels, enable precise machining and superior surface quality. Advanced materials like Ti6Al4V alloys and gypsum-based powders allow the fabrication of complex, textured electrodes, while aluminum electrodes mixed with CuO nano powder and bio diesel enhance surface finish and removal rates. This study also on EDM of AA4032-TiC using Direct Metal Laser Sintering (DMLS) and conventional copper electrodes reveals that DMLS electrodes achieve lower residual stress and surface roughness, while conventional electrodes offer higher material removal rates. Innovations such as Atomic Diffusion Additive Manufacturing (ADAM), which utilizes metal-polymer wire deposition. Furthermore, this research explores the parallels between AM and EDM in producing complex geometries and improving material properties, emphasizing hybrid approaches to enhance surface finish and mechanical strength. Techniques like Powder Sheets, Pneumatic Extruding Direct-Writing Deposition (PEDWD), and Fuzzy Logic systems underline advancements in metal AM, addressing challenges like production volume, post-processing, and quality standards. These developments underscore the transformative potential of AM and EDM, particularly in industries like aerospace, automotive, and medical devices, where precision and design flexibility are paramount.

Keywords: Additive manufacturing (AM), Rapid Prototyping (RP), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Atomic Diffusion Additive Manufacturing (ADAM), Metal Additive Manufacturing (MAM), Industrial Metal Printers, Learning Powder Sheets.

1. Introduction

Electrical discharge machining (EDM) is a precision machining technique uses controlled, repeated sparks to remove material from conductive workpiece materials. When the workpiece is fully submerged in an insulated working medium known as dielectrics, sparks are created between the tool (electrode) and the workpiece. Because the dielectric strength decreases at a particular voltage and a plasma channel forms between the electrode and the workpiece, concentrated sparks are created when power is applied. In sectors where high accuracy is required, electric discharge machining (EDM), is frequently utilized, especially for materials with complicated forms and high hardness. Additionally, machining intricately shaped dies, molds, and vital components for use in automotive, electronic, aerospace, and other industrial applications are among the several application fields. Solid conductive metals like brass, copper, bronze, and tungsten as well as non-metals like graphite have been used to make EDM electrodes [1]. EDM is also used primarily for machining hard and brittle materials like steel, titanium, tungsten, super-alloys, and ceramic that are utilized in the mold and die, electronic, and semi-conductor manufacturing industries. In the mold and die sectors, the design and fabrication of the electrode accounts for 50% of the EDM cost, whereas the EDM of the work piece accounts for 25–40% of the entire cost [3]. The automotive industry has advanced its use of Metal Matrix Composites (MMCs) with metals like copper, titanium, and aluminium reinforced with ceramics like TiC for better performance. Aluminium MMCs, especially AA4032 alloy with TiC, are valued for their high strength and corrosion resistance.

However, a significant portion of the time and cost of the EDM process is spent generating these electrodes, which is driving a shift toward more cost-effective and efficient electrode production methods. Copper is preferred for its high conductivity and simplicity of machining, while graphite and copper-graphite composites are also utilized for their durability. EDM electrode materials are selected based on their mechanical characteristics, melting points, and electrical and thermal conductivity.

Recent advancements in additive manufacturing (AM) have introduced new materials for EDM electrode production, improving performance, cost, and efficiency. Copper alloys with enhanced thermal conductivity, such as copper-tungsten and copper-chromium, offer better wear resistance and strength at elevated temperatures. Hybrid materials, such as copper-graphite composites, offer a balance of electrical conductivity and wear resistance, while cold spray technology (SP3D) accelerates metal powders to create dense, conductive electrodes without thermal melting. Metal Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) technologies allow for high-precision electrodes made from advanced metal powders, improving performance and geometry customization. Additive Manufacturing (AM) and Rapid Prototyping (RP) offer promising solutions for EDM electrode fabrication by allowing rapid production of complex geometries without extensive tooling. For EDM electrodes, alternative materials including ABS plastic, AlSi10Mg alloys, and aluminium-based metal matrix composites may be employed thanks to techniques like Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), and Selective Laser Melting (SLM). The conductivity required for EDM applications can be obtained by metalizing these AM produced electrodes with copper or aluminium coatings. Metal Additive Manufacturing (MAM) has revolutionized the production of complex metal components, offering unparalleled design flexibility, reduced material waste, and accelerated lead times. This innovative technology directly transforms CAD models into finished components, reducing production time and increasing design flexibility. AM's significance extends beyond prototyping, producing "form-fit-functional" parts that transform industries with efficient, rapid, and complex component production capabilities. Laser Powder Bed Fusion (LPBF), a Metal Additive Manufacturing (AM) technique, has transformed industries like aerospace, medical, defense, and automotive.

The study combined experimental and numerical simulations using L-shaped specimens with block-type supports, alongside numerical simulations of line, contour, and cone supports. Laser Powder Bed Fusion (LPBF) has revolutionized additive manufacturing (AM) by enabling the production of complex geometries with unparalleled precision. To address these limitations, this study explores Metal Additive manufacturing with Powder Sheets (MAPS), a novel LPBF technology utilizing powder sheets.

SLM-produced Ti6Al4V and AlSi10Mg electrodes are examples of advanced manufacturing processes. In order to improve EDM performance, researchers have investigated the use of biodegradable oils, oil emulsions, and conductive/non-conductive particles as dielectric mediums. As a result, variations in electrodes and dielectric modifications (such as adding powders or biodegradable oils) help reduce surface roughness and improve material removal rates (MRR) and tool wear rates (TWR). The SLM AlSi10Mg electrode is fabricated using titanium grade as the workpiece. In contrast to traditional copper-tungsten, metal-matrix composites such as TiB2-CuNi, Mo-CuNi, and ZrB2-CuNi are compatible with Selective Laser Sintering (SLS), a rapid prototyping technique that can create complex shapes, and provide benefits in terms of cost, lead time reduction, and performance. Additionally, compared to conventional machining techniques, the SLS-fabricated AlSi10Mg tool is beneficial for manufacturing complex EDM tool electrodes because it creates parts layer by layer utilizing a high-power laser to melt and fuse powder particles.

Also this study investigates a novel approach for creating complex-shaped pure copper electrodes used in electric discharge machining (EDM) by combining 3D printing and pressure less loose sintering and The electrodes feature a cryogenic cooling channel and are tested on D2 steel work pieces. A comparative analysis was conducted on three electrode types: solid copper, 3D-printed without cryogenic cooling, and 3D-printed with cryogenic cooling [12]. This paper demonstrates how AM and RP processes may simplify the production of EDM electrodes, making them affordable substitutes that facilitate intricate component design, cut down on material waste, and provide flexible answers to contemporary machining problems.

2. Methodology

This review is mainly about research papers that have already been published and talk about the materials that are used to make the EDM electrode using various Additive Manufacturing technologies and Rapid Prototyping and also this study on metal additive manufacturing-industrial metal printers. The papers also show that academics are interested in the most important trends, influential works, and research directions for the future. Bulleted lists may be included and should look like this

2.1 Types of AM technologies:

1. Fused Deposition Modeling (FDM): It also known as Fused Filament Fabrication (FFF), this solid-based AM technology melts a thermoplastic filament and extrudes it layer-by-layer to form objects. It supports a range of materials, including thermoplastics, fiber composites, and metals. Key issues include anisotropy due to weak layer bonding and limited surface quality.

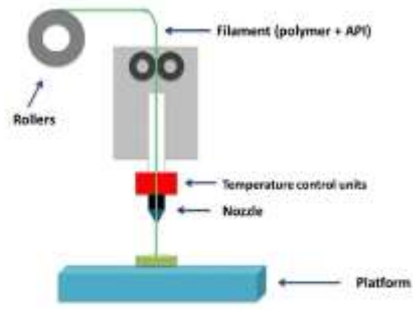

Fig 1: Fused deposition modeling (FDM) [39]

2. Laminated Object Manufacturing (LOM): It is a solid-based AM process that uses adhesive-coated films, which are cut and laminated layer by layer to form an object. It is versatile for different materials, particularly useful for long-fiber reinforcements in composites, but can suffer from anisotropic properties.

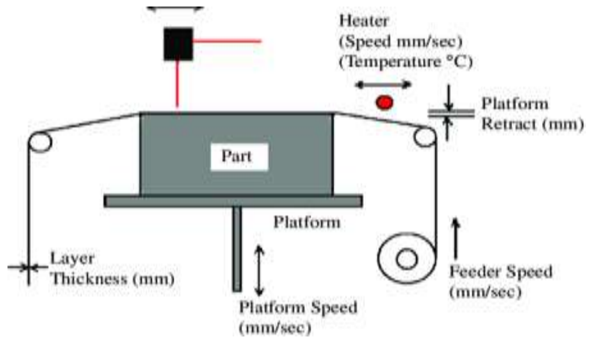

Fig 2: Laminated Object Manufacturing (LOM) [40]

3. Stereolithography (SLA): it is a liquid-based AM technology that used ultraviolet (UV) light to polymerize a liquid resin. It produces high-resolution, smooth-surface objects and is often used in applications requiring precision. SLA is limited to specific photoresins and has challenges in incorporating high-performance reinforcements.

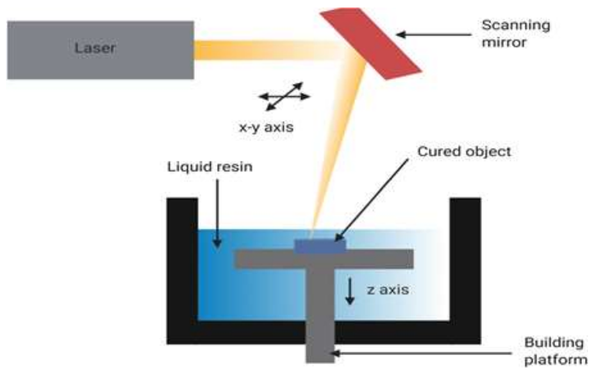

Fig 3: Stereolithography (SLA) [41]

4. Selective Laser Sintering (SLS): It is a powder-based technology that uses a laser to sinter powdered materials (such as polymers and metals) layer by layer. It produces high-quality parts without the need for support structures, however it has issues with surface polish and material switching.

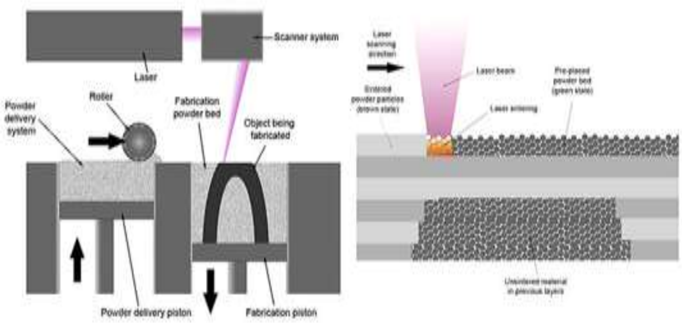

Fig 4: Selective Laser Sintering (SLS) [42]

5. Direct Metal Laser Sintering (DMLS): It is an additive manufacturing process that uses Powder Bed Fusion (PBF) to fabricate metal objects. It works by spreading a thin layer of metal powder that is selectively fused with a high-powered laser to form the desired geometry layer by layer. The technology enables the manufacturing of extremely complex and customized parts, such as those used in the aerospace and medical fields.

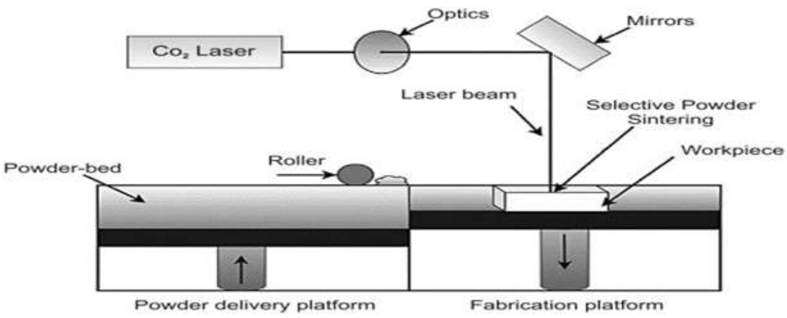

Fig 5: Direct Metal Laser Sintering [43]

2.2. Types of EDM Technology:

1. Wire electrical discharge machining: Wire Electrical Discharge Machining (WEDM) is an innovative manufacturing technique that uses electrical discharges to precisely cut materials, particularly those that are difficult to machine. WEDM operates by creating electrical discharges between a thin wire electrode and the surface of the workpiece. These discharges produce local melting and evaporation of the substance.

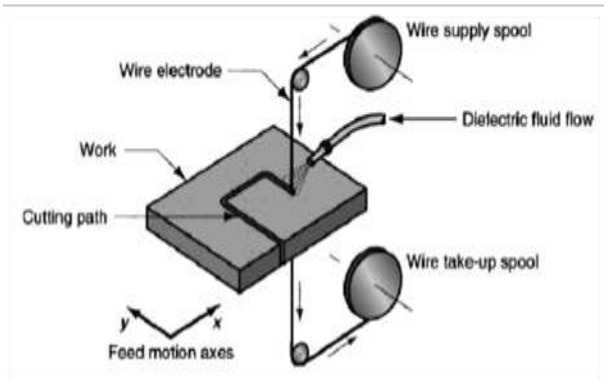

Figure 6. Wire electrical discharge machining [44]

2. Die-sink Electrical discharge machining: It is also known as sinker EDM. It is a specific type of EDM process that is primarily used for creating complex shapes and cavities in hard materials. The design of the electrode is crucial in die-sink EDM. The electrode is often customized to the wanted cavity or form to be created in the workpiece.

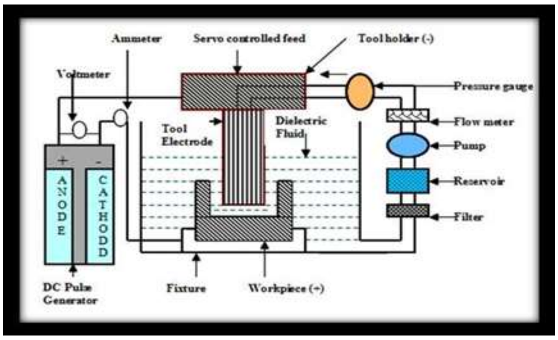

Fig 7: Die-sinking EDM [45]

3. Micro-Electrical discharge machining: Micro-Electrical Discharge Machining (Micro-EDM) is an advanced manufacturing methods that uses electrical discharges for removing material from the workpiece, enabling for the fabrication of complex and precise microstructures. The technology allows for the creation of micro holes with high aspect ratios, which is essential for many engineering applications [32].

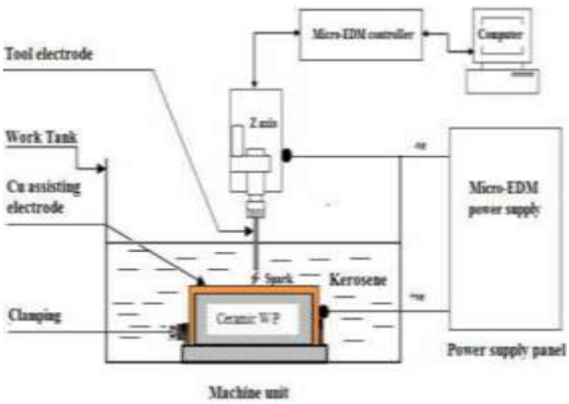

Fig 8: Micro electrical discharge machining [46]

4. Powder Mixed Electrical Discharge Machining: It is an advanced EDM technology that incorporates powder particles to the dielectric fluid to improve machining performance. The method is particularly useful for minimizing defects like recast layers and microcracks, improving surface properties like hardness and corrosion resistance.

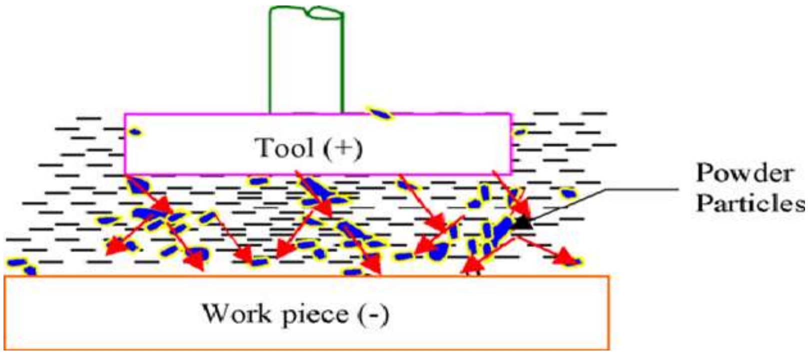

Fig 9: Powder Mixed Electrical Discharge Machining (PMEDM) [47]

2.3 Materials and Methods of Electrode Fabrication in EDM

1. Electrode by Fused Deposition Modeling (FDM)

In order to obtain accurate dimensional precision, better surface finish, and sufficient compressive strength for use in Electrical Discharge Machining (EDM), electrode production entails a number of crucial stages. In order to improve the compressive strength of the ABS core, the procedure starts with the manufacture of trial Fused Deposition Modeling (FDM) pieces, where the parameters are adjusted .After these parts are fabricated, metallization takes place in two steps: primary metallization gives the FDM parts conductivity, and secondary metallization thickens the metallic layer using techniques like copper electroless plating and subsequent electroplating in (figure10).

The thickness of the copper layer on the ABS core is determined by the equation is

$$T^2 = -5.3571t^2 + 101.09t - 154.94$$

where, t = operation time, T = thickness of copper

Fig 10: Metalized FDM electrodes [1]

With a strong correlation coefficient (R2 = 99.8%), the above equation determines the thickness of the copper layer. To account for the copper deposition, the starting FDM part diameter needs to be 6.06 mm for a final electrode diameter of 6.5 mm [1,3]. A variety of metallization methods are used, such as electroless plating with coatings seeded with aluminium, annealed chemically reduced silver colloidal solution, and conductive silver paint coating. To attain the required thickness, thick copper electroplating is carried out using a solution of copper sulfate and sulfuric acid, with the thickness of the electroplating layer growing over time.

The process of producing electrodes involves utilizing an FDM machine to fabricate cylindrical ABS pieces, then applying an aluminium-charcoal paste and electroplating copper. This two-step procedure maximizes electrical conductivity and structural integrity while guaranteeing the creation of viable electrodes for EDM applications. Two kinds of electrodes are made: a solid copper electrode that has been machined to specifications and an RP electrode made using FDM and electroless copper coating. The ultimate goal is to design efficient electrodes for EDM applications while maintaining electrical conductivity and structural integrity.

2. Electrode by Selective Laser Sintering (SLS)

Study examines EDM tool electrodes created via Selective Laser Sintering (SLS), focusing on their performance with X210Cr12 and C45 steel work materials. It finds that higher scan speeds in fabrication increase electrode porosity, leading to higher wear and reduced material removal rates (MRR) [5]. Bronze-nickel electrodes are effective for finishing, while copper-bronze-nickel performs well in rough machining and Copper-coated nickel-based bronze enhances wear resistance and conductivity, and steel-phosphate and polyester composites show improved wear resistance with copper post-sintering and additionally other composites like TiB2-CuNi has high wear resistance, while Mo-CuNi is less effective [6].

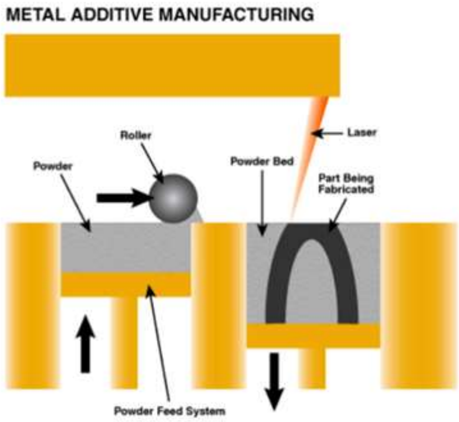

Fig 11: SLS process

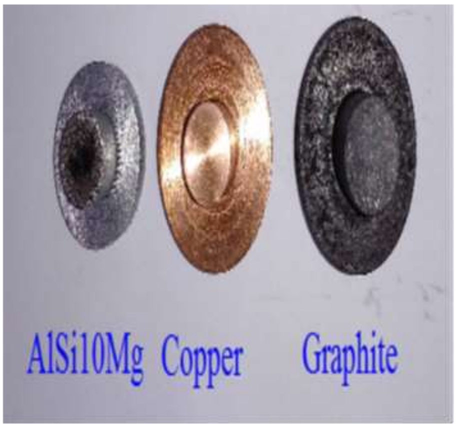

Fig 12: Tool electrodes [6]

AlSi10Mg EDM electrodes were produced on an EOSINT M-280 SLS machine with specific parameters, yielding 12 mm diameter electrodes composed mainly of aluminum, silicon, and magnesium, as verified by SEM and EDX analyses [6].

The review also details the SLS manufacturing process for EDM tool electrodes, utilizing a high-power laser to sinter AlSi10Mg powder under controlled conditions [6]. The EOSINT M-280 machine is used, with specific parameters such as a 30μm layer thickness, 400 W laser power, and a 200°C argon environment [7]. The resulting stepped cylindrical electrode has a diameter of 12 mm. For comparative analysis, copper and graphite electrodes of the same size are produced through conventional turning, and their performance is evaluated in EDM operations on a titanium work piece [7].

Additionally, this review explores study explores the use of Selective Laser Sintering (SLS) to directly produce EDM electrodes, focusing on optimizing key parameters like layer thickness, laser scan speed, and scan line spacing to improve densification, porosity, and surface morphology. The performance of electrodes made with these optimized settings was tested in EDM experiments, comparing them to solid copper and copper powder electrodes. The materials used included a Cu-Ni matrix with reinforcements like ZrB2, TiB2, and Mo, which were processed under controlled SLS conditions. The results demonstrated that SLS-manufactured electrodes with composite materials could be effective for EDM, showing potential advantages over traditional electrodes.

3. Electrode by Selective Laser Melting (SLM):

The study utilized a Realizer SLM-50 laser machine to fabricate electrode tools (ETs) under controlled conditions, maintaining an argon atmosphere at 8 mbar pressure. A 50 W fiber laser with a wavelength of 680 nm was employed to sinter Ti6Al4V titanium powder onto a titanium substrate, achieving a layer thickness of 30μm. To enhance the EDM process, the fabrication occurred in transformer oil [9].Two distinct ET shapes were designed: a square ET with sides measuring 19 mm and a cylindrical ET with a 19 mm diameter in figure-4. Both designs featured a grid of square cells (2 mm) and partitions (1 mm), creating a textured surface height of 3 mm. The modeling process for SLM manufacturing involved using Siemens NX v.11, Materialize Magics, and ANSYS Additive. The steps included defining the working space in CAD software, arranging the parts on the platform, constructing necessary supports, simulating the manufacturing process in ANSYS Additive, and making adjustments to the model before proceeding with construction [9].

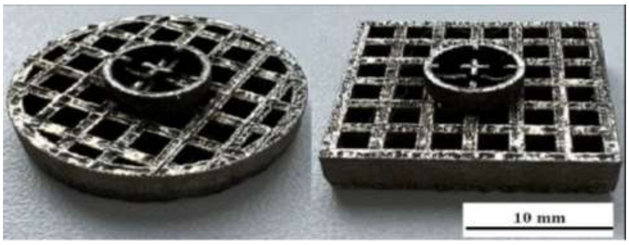

Fig 13:. Electrode Tool (ET) via SLM process [8]

Additionally, this study explores manufacture AlSi10Mg electrodes by Selective Laser Melting (SLM), for Electrical Discharge Machining (EDM). It emphasizes the advantages of using 3D-printed materials, particularly in precision applications, due to their ability to create intricate shapes and designs. The AlSi10Mg alloy is selected for its favourable electrical and thermal properties, as well as its lightweight and cost-effective nature compared to traditional materials like copper and graphite [10]. The integration of a novel dielectric fluid composed of lemon peel biodiesel mixed with CuO nanopowder enhances the performance of the 3D-printed aluminium electrodes during the machining process [10]. This innovative approach showcases the potential of 3D printing technology to improve machining efficiency and support environmentally friendly practices in EDM, representing a significant advancement in the manufacturing and application of electrodes in this field [9].

4. Electrode by Rapid Prototyping (RP):

This study explores the use of Rapid Prototyping (RP) with gypsum-based powder for constructing EDM electrodes featuring complex geometries. The design process employs Pro/E software, with the resulting models converted to STL format to ensure compatibility with the Zcorp Z402 RP system [11]. The resulting gypsum electrodes are porous, water-soluble, and mechanically weak, despite the fact that RP makes production quick, economical, and material-efficient then the electrodes are sealed with epoxy resin to optimize their performance due this, this process creates a protective covering around the electrode that keeps moisture damage at bay and preserves dimensional precision for EDM applications [11]. Here the electrode is manufactured through RP with investment casting in the production of EDM electrodes. Initially, an RP-created resin-sealed prototype serves as a master mold for creating a silicon mold [11]. This silicon mold is then used to produce wax patterns necessary for the investment casting process. The role of RP is critical in creating the initial complex geometries with precision, which are later replicated in wax for casting. This approach allows for the rapid and cost-effective creation of high-quality brass electrodes, with RP contributing significantly to design accuracy and the quick turnaround required for investment casting setups in EDM electrode fabrication [11].

In this also study involves fabricating cryogenically cooled copper electrodes using a rapid manufacturing process in figure5. It begins with designing a CAD model in Solid Works, converting it to an STL file, and slicing it for 3D printing using castable resin [12,14]. After printing, the polymer model is utilized to create a mold, which is subsequently heated to remove the polymer [12,14]. The fabrication process culminates in filling the mold with copper powder and subjecting it to a sintering process optimized for achieving high density and electrical conductivity [12].

Fig 14: EDM electrode Fabricated by RP [14]

5. Electrode by Direct Metal Laser Sintering (DMLS):

This study also explores the use of Direct Metal Laser Sintering (DMLS) to produce copper electrodes for Electrical Discharge Machining (EDM) of Metal Matrix Composites (MMCs), specifically the AA 4032 aluminium alloy reinforced with 6% TiC for added hardness [15,16]. The DMLS fabrication process includes designing in Pro-E software, converting to STL format, and processing with an EOS M280 DMLS machine, where multiple parameters are optimized for EDM application. The study then evaluates both DMLS and conventional copper electrodes by analyzing Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR), microstructure, and residual stress, with machining conditions varied using a Die-Sinking EDM and an L27 orthogonal array [15,16].

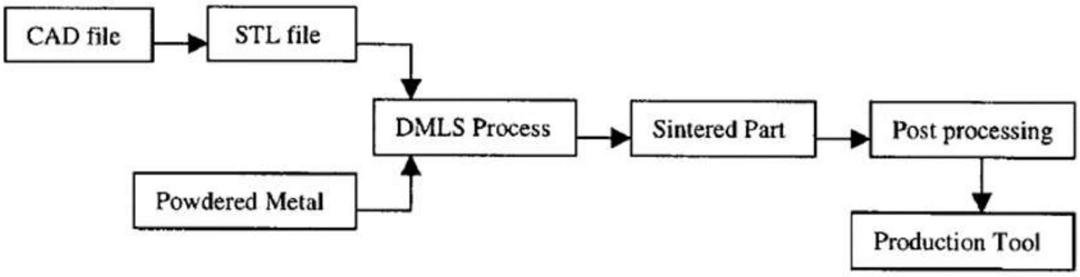

Fig 15. Flowchart of DLMS process [16]

By computing the Signal-to-Noise (S/N) ratio, deviance sequence, Grey Relational Coefficient (GRC), and the final Grey Relational Grade (GRG), multi-response optimization utilizing Grey Relational Analysis (GRA) aids in determining the optimal EDM settings. This investigation aims to enhance EDM performance and efficiency while optimizing machining conditions for DMLS electrodes as an alternative to conventional copper options.

6. Electrode by Atomic Diffusion Additive Manufacturing (ADAM):

The EDM tool was fabricated using the Markforged Metal X 3D printer with the Atomic Diffusion Additive Manufacturing (ADAM) process at 4D Simulations, Noida. This process involves a metal-polymer mixture in wire form, which is deposited layer by layer, similar to extrusion [17]. The Eiger software handles calculations for part cost, weight, and printing time, and automates the overall process. Available materials for this technique include stainless steel, Inconel, copper, and titanium.

The process begins by creating a digital model of the tool using CAD or reverse engineering. This model is converted into an STL file for printing. The material, in the form of a metal-polymer wire, is fed into the printer, where it is deposited layer by layer. The resulting "green" part, which is fragile due to the binder material, then undergoes a washing process to remove the binder before being sintered in a furnace. This step solidifies the metal powder and removes any remaining polymer, resulting in a strong, dense metallic structure.

After sintering, the tool is fully metalized and ready for use. No additional post-processing, such as CNC machining or Wire EDM, is necessary. Only a simple wash and support removal are required to prepare the part. This method allows the creation of complex EDM tools directly from digital designs, reducing production times and costs while ensuring high material strength and functionality for electrical discharge machining.

Fig 16 : EDM tool developed by ADAM process [17]

2.4 Metal additive manufacturing techniques

1. Metal additive manufacturing powder sheets:

Powder sheet manufacturing: creating powder sheets mixed with polymer binder or solvents, sheets with controlled thickness. The diagram illustrates the Metal Additive Manufacturing using Powder Sheets (MAPS) process. In this process, a thin layer of metal powder is spread onto a substrate using a roller system. A laser beam, controlled by a scan head, selectively melts the powder particles according to the desired component's cross-sectional geometry. As the laser scans, the melted powder particles fuse together, forming a solid layer. The process repeats layer by layer, with the build platform lowering incrementally after each layer is completed, until the entire 3D component is built. Once finished, the component is removed from the platform, and any excess powder is recycled. This method eliminates the need for loose powder often associated with other laser-based additive manufacturing technique

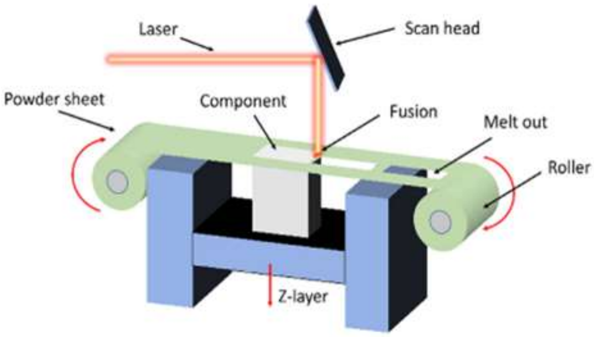

Fig 17: Raphical schematic of the MAPS [15]

2. Pneumatic extruding direct-writing deposition (PEDWD):

A schematic of the Pneumatic Extruding Direct-Writing Deposition (PEDWD) system is shown in **Fig19**. The system features a custom-designed nozzle with a heat preservation jacket, mounted at the bottom of **Chamber B**. To prevent nozzle blockage due to impurities, a stainless-steel filter screen is placed in **Chamber A**, where the raw metal material is initially loaded and surrounded by the filter screen.

The metal material is heated in **Chamber A** until it melts, at which point the molten metal flows through the filter into **Chamber B**. Heat is supplied by band heaters constructed with nichrome resistance wire, mica plates, and stainless-steel shells, which are clamped around both chambers. Temperatures are monitored using **K-thermocouples** embedded at the chamber bases and controlled by **REX-C100 temperature controllers**.

The deposition substrate moves in the horizontal (X-Y) plane, while the nozzle moves only along the vertical (Z) direction. The motion of all stages is driven by servo motors and coordinated using a **Lead shine DMC-2410 3-Axis controller board**, which also controls the gas paths via pressure and valve controllers. A **U-type water manometer** ensures precise working pressure measurement.

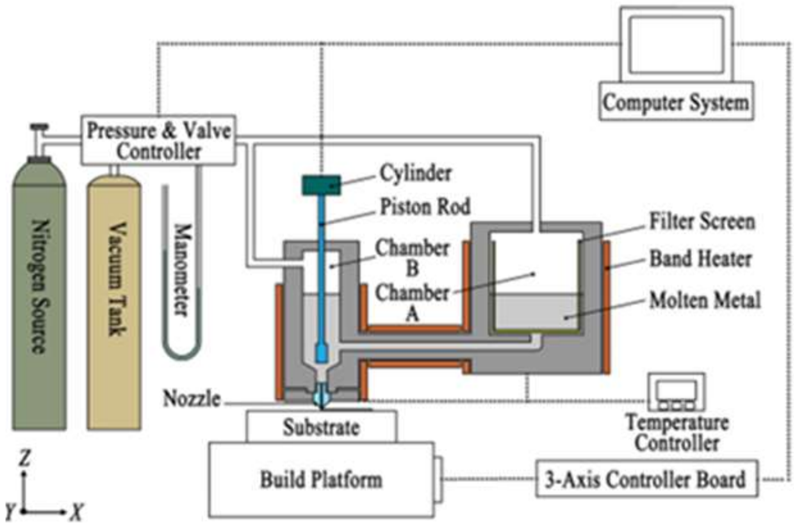

Fig 18: Schematic diagram of the PEDWD system.

3. Parameters influencing on AM:

Layer thickness (LT): LT affects interfacial bonding strength in 3D - printed items. Thicker layers can reduce thermal stresses and improve strength.

Printing speed (PS): it is influences the material's bonding strength and overall integrity. Low printing speeds can help heal cracks but may introduce residual stresses.

Infill density (ID): Higher infill density (ID) enhances strength and stiffness of printed objects.

Post processing: Post-processing in 3D printing improves the quality, functionality, and appearance of printed parts.

4. Parameters influencing on EDM:

EDM machining characteristics are primarily assessed using SR, MRR, and TWR, which are dependent on the processing parameters. The machine operation characteristics are:

Pulsed on time: The duration of each electrical pulse determines the amount of energy transferred to the workpiece, which directly affects the amount of material removal and the quality of the surface to be machined, making it critical for balancing speed and accuracy.

Pulse off time: The interval between successive pulses allows the dielectric fluid to cool and flush out debris, preventing overheating, maintaining stable discharge, and reducing the risk of short circuits or machining errors.

Discharge current: The magnitude of current flowing during a discharge determines the energy of the spark; higher currents accelerate material removal but can lead to increased tool wear and a rougher surface finish.

Discharge voltage: The potential for electricity between the conducting electrode and the workpiece influences spark energy and plasma channel development, hence affecting material removal efficiency and machining quality.

Flushing pressure: The pressure of the dielectric fluid is crucial for eliminating debris from the machining gap, ensuring uniform sparking, and minimizing defects such as re-deposits or gap blockages.

Reciprocating speed: Back and forth movement of the tool or workpiece helps distribute the machining load, improve flushing effectiveness, and maintain uniform material removal across the surface.

Working time: The total time the machine is actively engaged in the machining process affects overall productivity, and careful scheduling ensures optimal use of resources and minimal downtime

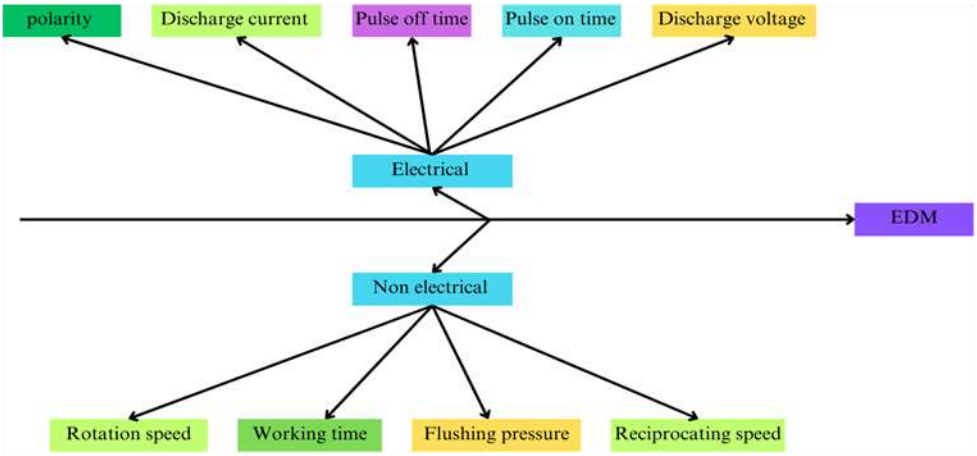

Fig 19. EDM Parameters

5. Performance Measures:

The study evaluates several performance indicators for Electrical Discharge Machining (EDM) using various electrodes, focusing on material removal rate (MRR), tool wear rate (TWR), surface roughness (Ra), surface crack density (SCD), white layer thickness (WLT), and micro-hardness (MH) of the WLT.

1. Material Removal Rate (MRR)

MRR has preference in the process of EDM, which is related to the manufacturing rate[31]. This can be determined based on the volume of the weight of the material removed during the process of machining in relation to machining time given in equation[31].

$$\text{Material removal rate} = \frac{\text{Amount of workpiece material remove}}{\text{machining time}}$$

2. Tool Wear Rate (MRR)

TWR is another measurement that must be kept to a minimum in order to increase machining efficiency. On the other hand, increased tool wear raises tool costs, reduces geometric precision, and leads to higher manufacturing costs [31]. TWR is the ratio of the amount of tool material worn out to the machining time, as shown in equation [31].

$$\text{TWR} = \frac{\text{Amount of tool material eroded}}{\text{Machining time}}$$

3. Surface Roughness (Ra)

The average surface roughness of the machined work piece is measured using a Taylor-Hobson roughness tester, with multiple readings taken from different locations to compute an average.

4. Surface Crack Density (SCD)

SCD assesses the formation of cracks during machining, calculated as the total crack length observed in scanning electron microscope (SEM) images divided by the area of the SEM image. Measurements are averaged from multiple images.

5. White Layer Thickness (WLT)

WLT refers to the re-solidified layer on the machined surface, measured using SEM imaging. The thickness is averaged over several measurements to assess the impact of machining parameters.

6. Micro-Hardness (MH)

Micro-hardness of the white layer is evaluated using a Vickers micro-hardness tester, with indentations made at three different locations to ensure accuracy in the average reading.

3. Similarities between EDM and AM:

Both technologies despite their differences in operation but processes share several similarities in terms of customization, material manipulation, and the precision with which they work.

1. Layer-by-Layer Material Manipulation :

Both AM and EDM processes can be used to add or remove material in a layer-by-layer manner, enabling the manufacturing of complex parts that are otherwise difficult to achieve through conventinal manufacturing. For instance, AM builds objects layer-by-layer using materials like thermoplastics, resins, and powders [29]. Similarly, EDM can add material to the workpiece through the Electrical Discharge Coating (EDC) process, which enhances the surface properties by depositing thin layers of material on the workpiece surface [31].

2. High Precision and Surface Quality :

Both AM and EDM are known for achieving high levels of precision and surface quality, which are essential for applications in industries like aerospace, medical, and automotive. AM processes such as Stereolithography (SLA) provide highest resolution and excellent surface finish due to precise control over UV polymerization [29]. In EDM, surface quality is carefully controlled through dielectric fluid, which cools and flushes the material, resulting in enhanced surface smoothness [31].

3. Customization of Material Properties :

Both processes allow customization of material properties by introducing additives or adjusting parameters to achieve specific mechanical or thermal characteristics. In AM, materials like nanofillers (e.g., graphene oxide and carbon nanotubes) are incorporated to enhance strength and thermal stability [29]. In EDM, various powders like silicon carbide or titanium can be added to the dielectric fluid, which improves microhardness and surface characteristics of the workpiece [31].

4. Use of Composite Materials :

AM and EDM processes can both work with composite materials. Parts from composites, including particle-reinforced and nanofiller-enhanced composites, are manufactured using additive manufacturing methods such as fused deposition modeling and selective laser sintering [29]. Similarly, EDM processes can machine conductive ceramic composites, particularly when aided by doping with conductive phases, making it possible to work with traditionally non-conductive materials [30].

5. Material Flexibility :

Both AM and EDM are flexible in the range of materials they can handle. AM accommodates various materials like thermoplastics, metals, ceramics, and composites depending on the process used [29]. In EDM, different types of powders (e.g., graphite, aluminum, and chromium) can be mixed in dielectric fluids to enhance material removal and improve surface quality [31].

6. Experimental Optimization for Enhanced Performance:

AM and EDM processes both benefit from experimental optimization to achieve desirable outcomes. In AM, optimization techniques like Response Surface Methodology (RSM) and statistical modeling (e.g., ANOVA) are used to determine optimal sintering parameters for improved density and conductivity [33]. Similarly, EDM performance is influenced by parameters like pulse duration and current, which are carefully adjusted to balance factors like Material Removal Rate and Tool Wear Rate [31].

7. Adaptability for Advanced and Customized Shapes :

Both technologies are capable of creating intricate and customized shapes, which are often required in high-tech industries. AM uses additive layering to build complex geometries directly from CAD models [33], while EDM can machine complex shapes by controlling the discharge pattern to remove material precisely, even in hard-to-reach areas [31].

8. Complex Geometry Production :

AM technologies allow for quick manufacture of complicated geometries without the requirement for specialized tools [37]. This aligns with EDM's ability to handle intricate shapes, particularly through customized electrodes that can achieve detailed machining on hard-to-machine materials [37].

9. Customization of Tooling Materials and Processes :

Both processes have research focusing on expanding material options to enhance performance. In AM, various polymers, metals, and composites are used, with ABS, polycarbonate, and conductive materials being notable examples [37]. Similarly, EDM research investigates materials like copper, steel, and advanced composites for electrode development [37].

10. Surface Finishing Requirements :

Both AM and EDM components often require post-processing to improve surface quality and dimensional accuracy. For AM, techniques like laser or chemical polishing are applied to refine surface roughness [36]. In EDM, post-fabrication processes like electroplating are employed to improve conductivity and surface properties [37].

11. Importance of Dimensional Accuracy :

Both methods aim for high dimensional accuracy, though challenges remain. In AM, shrinkage and surface deviations are common issues that affect final part dimensions, especially for complex geometries [38]. Similarly, EDM electrodes face dimensional inaccuracy due to factors like thermal expansion and uneven electroplating thickness [37].

12. Optimization for Process Efficiency :

Both technologies benefit from optimization of parameters to improve efficiency and product quality. For AM, laser polishing and print settings are fine-tuned to balance strength, surface roughness, and speed [36]. In EDM, parameters such as pulse duration and material composition are modified to enhance tool wear and material removal rates [37].

AM and EDM both involve precise manufacturing techniques that emphasize complex geometries, surface quality, dimensional accuracy, and continuous process optimization. Their shared characteristics make them valuable technologies for producing parts that require intricate details and high-quality finishes.

13. Parameter Dependency :

Both processes are highly sensitive to operational parameters **In EDM** Pulse time, discharge current, and voltage significantly influence the final surface roughness and precision. Multiple finishing cuts can enhance surface quality, although they increase processing time [35]. **In AM** Parameters such as laser power, scan speed, and layer thickness greatly impact the dimensional accuracy and geometric stability of parts. Minor changes in these parameters can affect the size and quality of manufactured features [38].

14. Surface Integrity Improvement :

The recommended finishing process significantly improves surface roughness by reducing the balling effect, un melted particles, and microcracks [35]. In laser-based AM, process parameters like as laser power and scan speed influence melt-pool shape, which frequently requires EDM for additional refinement [38].

4. Results and Discussions for further Research:

This study provides a comprehensive evaluation of 3D-printed and conventional copper electrodes in Electrical Discharge Machining (EDM), examining various EDM parameters and electrode properties to optimize machining performance. Key EDM parameters—current, pulse-on time (Ton), and pulse-off time (Toff)—are analyzed for their effects on performance indicators, namely material removal rate (MRR), tool wear rate (TWR), surface roughness (SR), and dimensional accuracy.

1. Material Removal Rate (MRR)

Effect of Parameters: Higher current and pulse-on time enhance MRR by increasing discharge energy, which expedites material melting and vaporization. However, a longer pulse-off time reduces MRR, allowing re-solidification of melted material, thus decreasing material removed per pulse.

Electrode Comparison: Copper electrodes yield higher MRR compared to rapid prototyping (RP) electrodes due to better conductivity. Graphite electrodes have the highest MRR, while RP electrodes perform the lowest.

Optimization: Nanopowder additives (e.g., CuO in lemon peel biodiesel) and critical stirring velocity improve MRR by enhancing spark distribution and heat dissipation. Excessive powder concentration, however, causes arc instability and reduces MRR.

2. Tool Wear Rate (TWR)

Effect of Parameters: Increasing current intensifies TWR by eroding the electrode's surface. For metalized FDM electrodes, a higher pulse-off time reduces TWR by aiding in dielectric re-establishment between discharges. Lower TWR is observed with copper electrodes, while RP electrodes have the highest TWR due to lower melting points.

Optimization: Cryogenically cooled RMECC electrodes demonstrate a significant reduction in TWR due to improved thermal conductivity and minimized heat accumulation, effectively prolonging electrode life.

3. Surface Roughness (SR)

Effect of Parameters: Higher current and pulse-on time increase SR by creating larger, deeper craters from intense discharges. Longer pulse-off time improves surface finish by enabling better flushing between discharges, reducing debris buildup.

Electrode Performance: RP electrodes yield smoother surfaces compared to graphite electrodes, which produce the roughest finishes due to intense spark energy. Nanopowder-mixed dielectrics improve SR by enhancing thermal conductivity, reducing melting, and creating smaller craters.

4. White Layer Thickness (WLT)

Effect of Parameters: WLT increases with pulse-on time and current, with graphite electrodes producing the thickest WLT due to high unflushed material levels. Cryogenically cooled electrodes exhibit thinner WLT and fewer surface cracks, attributed to lower residual stress. RP electrodes show the thinnest WLT and the most uniform recast layer, enhancing surface integrity.

Optimization: Use of nanopowder in dielectrics reduces crack formation by improving heat dissipation, reducing thermal energy in each discharge.

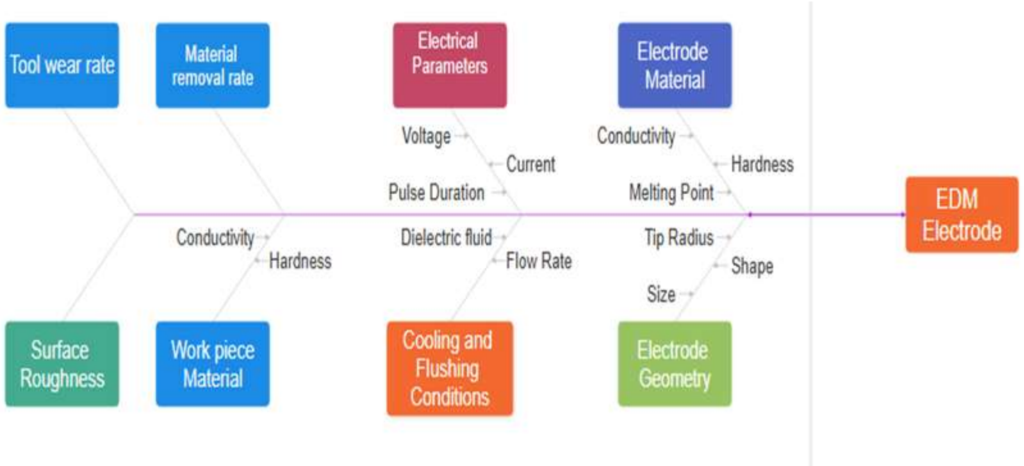

Fig 20: Factors effecting on EDM Electrode

5. Dimensional Accuracy (DA)

Electrode Comparison: The novel electrode exhibits superior dimensional accuracy (smaller deviations in cavity diameter ΔD) than the solid copper (SC)and metalized FDM electrodes. FDM-EM electrodes have variable accuracy, often requiring post-machining to meet precise dimensions.

Microscopic and Phase Analysis: SEM and XRD analysis reveal that optimized EDM parameters with cryogenic cooling or nanopowder additives produce finer microstructures, reduce carbon deposition, and enhance dimensional accuracy through improved dielectric cooling.

6. Sintering Characteristics and Microstructure Analysis

Effect of Sintering Parameters: Sintering temperature and soaking time influence density, shrinkage, and electrical conductivity of electrodes. Higher temperatures increase density and conductivity by reducing porosity. Optimal conditions minimize volumetric shrinkage while maximizing material bonding and density.

7. Carbon Doping and Yield Strength:

Increased carbon content (C: 0.78–0.85% wt) during powder deposition (PD) is attributed to enhanced polymer vapor exposure to the melt pool. Carbon doping improves yield strength through interstitial solid solution strengthening and Orowan mechanisms, while maintaining good ductility.

8. Nozzle and Substrate Dynamics in PEDWD:

A throttle channel reduces molten metal velocity by 28–31%, confirmed experimentally and theoretically. Substrate velocity (Vs) affects metal flow; higher Vs reduces aggregation and improves flow consistency, Optimal range 40–60 mm/s. Nozzle-to-substrate gap affects deposition quality; smaller gaps restrict flow, while larger gaps weaken bonding.

9. Powder Sheet Fabrication and Heat Transfer:

Powder sheets exhibit distinct “metal particle” and “polymer binder” sides due to top-down drying and capillary forces. Positioning the metal particle side against the build plate enhances gas evaporation and thermal efficiency.

10. Material and Powder Analysis:

Thermal decomposition of polymer binders analyzed via TGA with SS304/In718/HEA powders in nitrogen. Spherical powders with fine particles show improved flowability and lower profile void volume. Optimal powder spreading: 80 mm/s velocity, 50 µm layer thickness.

11. Surface Roughness Challenges:

Surface roughness in L-PBF arises from the stair-stepping effect and partial melting. Polishing techniques like laser re-melting and electrochemical methods enhance smoothness, essential for aerospace and biomedical applications.

Overall, this study highlights that EDM performance is significantly influenced by electrode type and machining parameters. Conventional copper electrodes and 3D-printed metalized electrodes perform similarly in MRR, TWR, and SR, but the novel electrode type offers improved dimensional accuracy, particularly with pulse-off time adjustments and nanopowder additives. Cryogenically cooled RMECC electrodes also show promise in achieving better wear resistance, accuracy, and surface quality, marking a potential advancement in EDM electrode manufacturing and applications. This study also highlights the performance of metal additive manufacturing 3d printers in industries, highlights thatIncreased carbon content during powder deposition improves yield strength through solid solution and Orowan strengthening mechanisms while maintaining good ductility. Optimal processing conditions, such as substrate velocity (40–60 mm/s) and nozzle-to-substrate gap, significantly enhance deposition quality by reducing metal flow issues and ensuring strong interlayer bonding. Surface roughness in L-PBF remains a challenge due to partial melting and stair-stepping effects, but techniques like laser re-melting and electrochemical polishing effectively improve smoothness for critical applications.

5. Conclusions:

This review explores that the use of different Additive Manufacturing techniques and Rapid prototyping methods to produce EDM electrodes and examines their machining performance relative to traditional solid copper and other metal-based electrodes and also This study explores advancements in Additive Manufacturing (AM), focusing on the Metal Additive Powder Sheet (MAPS) process and support structure optimization in Laser Powder Bed Fusion (LPBF).

1. This study confirms that FDM-based electrodes, particularly those metalized with techniques such as acid copper electroplating or aluminum-charcoal (Al–C) paste, can be effectively used in EDM applications. However, these electrodes display challenges in achieving exact dimensions and uniform metal coating, especially at sharp corners. While FDM-electrodes perform similarly to solid copper in terms of Material Removal Rate (MRR), Tool Wear Rate (TWR), and surface finish, their dimensional accuracy lags behind solid copper electrodes due to the limitations in STL conversion, FDM fabrication accuracy, and metallization processes.

2. Dimensional Accuracy and Machining Depth: Machining accuracy varies between electrode types, with solid copper consistently achieving closer tolerances. The study finds that the dimensional deviation (ΔD) and depth deviation (ΔH) are minimized with novel electrodes but not completely eliminated. Variations in electrode wear and non-uniform erosion cause dimensional inaccuracies in the machined cavities. Furthermore, it highlights that current (I) is the most significant factor influencing both ΔD and ΔH, while pulse-on and pulse-off times also play essential roles in the machining process.

3. Impact of EDM Process Parameters: Current significantly affects all performance measures. Increased current leads to higher MRR but also results in higher TWR, SR, and dimensional inaccuracy. Extended pulse-on time enhances MRR and surface roughness, while a longer pulse-off time reduces MRR, TWR, and SR, as it allows the dielectric fluid to re-establish between discharges. Optimizing these parameters is essential to balance machining efficiency with dimensional accuracy and surface integrity.

4. This study also evaluates alternative electrode materials, such as graphite, which provides high MRR and low TWR, and is preferable for rough machining, while copper is favored for its balance between efficiency and surface finish. Rapid Prototyping (RP) methods, including Selective Laser Sintering (SLS) and Selective Laser Melting (SLM), show promise for creating complex electrode geometries with enhanced surface characteristics but come with high wear rates.

5. Sustainability and Optimization: This study also supports using a sustainable EDM approach by combining biodiesel-based dielectrics with CuO nanopowder, which improves MRR, SR, and dielectric stability at optimal stirring speeds and powder concentrations. Additionally, response surface methodology (RSM) and genetic algorithm-based multi-objective optimization help refine manufacturing conditions for electrodes fabricated through indirect rapid manufacturing methods like pressureless sintering.

6. MAPS Technology for Multi-Material Printing**:** MAPS eliminates the need for loose powder beds by using composite powder sheets made of metallic powder and polymer. This technique enhances feedstock handling safety, switchover efficiency, and material control while preventing cross-contamination. The process enables high-density (99.8%) prints without post-sintering, producing defect-free bonds and precise chemical transitions in multi-material components, such as SS304-In718-CoCrFeMnNi HEA.

7. Enhanced Material Properties**:** The incorporation of polymers introduces carbon, which enhances grain nucleation and improves strength through the Hall-Petch effect. MAPS-printed materials demonstrated a 1.6x higher yield strength than LPBF counterparts, with hardness values reaching 430±37 HV1. These properties make MAPS suitable for applications like functionally graded materials and coatings.
8. Support Structure and Optimization**:** LPBF support structures, including blocks, lines, contours, and cones, were evaluated for cost-efficiency, minimal material use, and optimal stress relief. Simulations and experimental testing identified configurations that reduce deformation and support volume. Regular optimization tests are recommended for new printers, involving statistical analyses to refine parameters like density, surface roughness, and hardness.
9. Powder Flow and Bed Topography**:** Powders with finer particles and smoother morphology exhibit better flowability, while highly spherical powders with satellites show reduced flow due to interlocking. Optimizing layer thickness and spreader velocity significantly improves powder bed profile height, critical for high-flowability powders.

Overall, this study highlights the potential of MAPS for producing stronger, more versatile materials and underscores the importance of optimizing support structures and process parameters for enhanced AM performance.

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