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Review Article

FDM Technology for EDM Electrode Fabrication: Progress, Prospects, and Perspectives

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Abstract **-** *This comprehensive review delves into the applicability of Fused Deposition Modeling (FDM) in Electrical Discharge Machining (EDM) electrode fabrication, scrutinizing its potential, challenges, and recent advancements. The review elucidates the advantages of FDM, including rapid prototyping, design flexibility, and cost-effectiveness, while examining its limitations, such as surface finish and material selection. Various metallization methods for enhancing the conductivity of FDM-generated electrodes are explored, ranging from electroless plating to vacuum metalizing. Comparative analyses with traditional manufacturing methods like milling, grinding, and wire EDM provide valuable insights into the efficacy of FDM. Additionally, the review discusses real-world applications across industries, highlighting aerospace, automotive, medical, and tooling sectors. Emerging trends, challenges, and future directions in FDM technology for EDM electrode fabrication are thoroughly examined, emphasizing the need for ongoing research and innovation to realize the full potential of FDM in modern manufacturing.*

Keywords **-** *Fused Deposition Modeling (FDM), Electrical Discharge Machining (EDM), Electrode fabrication, Additive manufacturing, Rapid prototyping, Metallization.*

1. Introduction

EDM stands as a cornerstone of modern manufacturing, offering a unique approach to material removal through controlled electrical discharges. This non-traditional machining process has garnered significant attention in various industries due to its ability to machine intricate shapes and hardened materials with high precision and accuracy [1, 2]. In EDM, the workpiece and electrode are submerged in a dielectric fluid, as shown in Figure 1, facilitating the electrical discharge and subsequent erosion of material. Through a series of carefully controlled electrical pulses, intense heat is generated, melting and vaporizing the workpiece material to create the desired shape or features [3].

The significance of EDM in modern manufacturing cannot be overstated. It finds extensive applications across diverse sectors, including aerospace, automotive, medical, and tooling, where conventional machining methods may prove inadequate [4]. The ability to work with hardened materials like tool steels, carbides, and titanium alloys, coupled with the capability to machine complex geometries with tight tolerances, positions EDM as a critical machining solution [5]. Despite its advantages, EDM does present challenges, such as relatively slow material removal rates and the necessity for skilled operators to optimize process parameters. However, recent advancements in EDM technology have sought to mitigate these challenges and enhance efficiency [6].

FDM stands as a pioneering technique in the realm of rapid prototyping, revolutionizing manufacturing processes across diverse industries. This additive manufacturing method, first introduced by S. Scott Crump in the late 1980s [7], has since garnered considerable attention and witnessed significant advancements, propelling it to the forefront of modern manufacturing technologies. FDM operates on the principle of layer-by-layer material deposition, wherein a thermoplastic filament is heated to its melting point and extruded through a nozzle onto a build platform.

This molten material is precisely deposited, layer upon layer, to construct Three-Dimensional (3D) objects according to Computer-Aided Design (CAD) specifications [8]. The versatility and accessibility of FDM have contributed to its widespread adoption in various industries, ranging from aerospace and automotive to healthcare and consumer goods. Its appeal lies in its ability to facilitate rapid and cost-effective prototyping, enabling designers and engineers to iterate designs swiftly and efficiently [9].

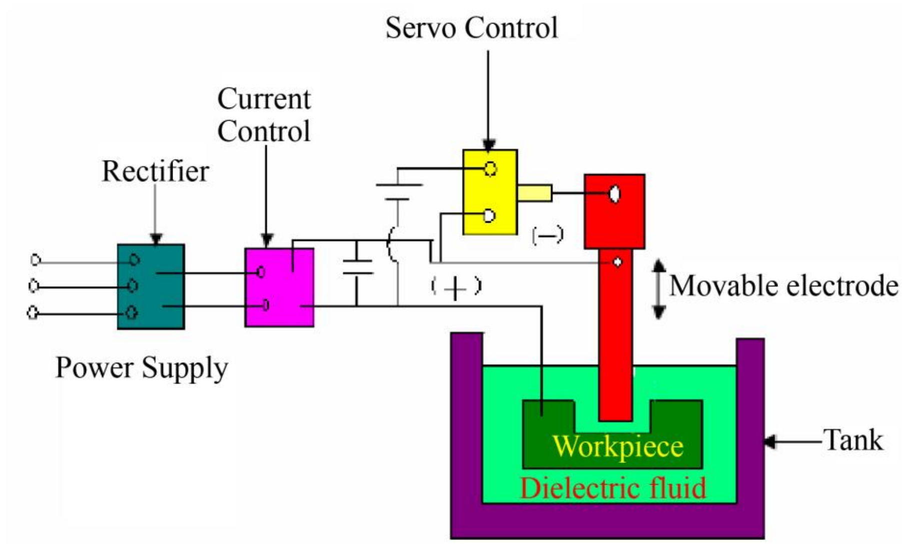

Fig. 1 Schematic diagram of the EDM process

Numerous studies have explored the capabilities and potential applications of FDM across different domains. Research by Al-Dulimi et al. [10] demonstrated the feasibility of using FDM for manufacturing customized medical implants, highlighting its adaptability in producing patient-specific solutions. Similarly, investigations by A K Adeleke et al. [11] showcased the efficacy of FDM in fabricating complex aerospace components, underscoring its role in streamlining production processes and reducing lead times.

Moreover, advancements in FDM technology have led to the development of high-performance materials and enhanced printing techniques, further expanding its scope and applicability. Recent studies by M. Montez et al. [12] and A J Sheoran et al. [13] explored novel materials and optimized printing parameters to achieve improved mechanical properties and surface finishes, thereby broadening the potential applications of FDM in functional prototyping and end-use part production.

The objective of the review paper is to thoroughly analyze and combine the current body of work on the incorporation of FDM in EDM electrode manufacturing. It will discuss the main obstacles, potential advantages, and future prospects in this field.

The study aims to provide insights into material selection, process optimization, and performance assessment in FDM-based EDM electrode manufacture by carefully examining research data. Moreover, its objective is to offer pragmatic suggestions and instructions for professionals, simplifying the use of FDM technology to improve EDM procedures and maximize electrode efficiency. In summary, the purpose of the review paper is to enhance the existing knowledge on the subject and provide a beneficial reference for researchers, engineers, and industry experts.

2. Historical Overview of EDM Electrode Fabrication

Traditional methods employed for EDM electrode fabrication encompass a range of techniques, including milling, grinding, and wire EDM. Milling, a widely used subtractive manufacturing process, involves removing material from a workpiece using rotary cutting tools. In EDM electrode fabrication, milling is employed to shape and refine electrode blanks from conductive materials such as copper or graphite [14]. Grinding, another conventional machining method, utilizes abrasive particles to remove material and achieve precise dimensional accuracy and surface finish. In the context of EDM electrodes, grinding is utilized to achieve intricate geometries and surface finishes that are critical for optimal EDM performance. Wire EDM, on the other hand, is a specialized machining process that utilizes a thin wire electrode to erode material from a workpiece precisely via electrical discharges. While typically used for workpiece machining in EDM, wire EDM can also be employed for intricate shaping and profiling of electrode blanks. These traditional methods offer versatility and precision in EDM electrode fabrication yet may pose challenges such as longer lead times, limited design flexibility, and higher costs compared to emerging additive manufacturing techniques like FDM.

2.1. Milling

The manufacturing of EDM electrodes through milling represents a conventional yet widely employed approach in the industry. Research by T. Altan et al. [15] demonstrated that milling offers excellent dimensional control, allowing for the production of electrodes with tight tolerances and intricate geometries. According to findings from Qudeiri et al. [16], milling allows for the use of a wide range of materials, including copper, graphite, and various tool steels, enabling manufacturers to select materials tailored to specific EDM applications. Studies by F. Klocke et al. [17] have highlighted milling's capability to produce EDM electrodes with complex geometries, including features such as undercuts and thin profiles, which may be challenging to achieve with other fabrication methods. F. Walsh et al.[18] found that milling can be cost-effective for large-scale production runs of standardized electrode designs, offering economies of scale and reduced per-unit costs. Despite its precision, milling may result in surface irregularities and roughness, as noted by N. Tosun [19], which can negatively impact EDM performance and surface finish on workpieces. Research by P. K. Gupta et al. [20] indicated that milling complex electrode geometries may require multiple setups and longer machining times, leading to increased lead times compared to other fabrication methods. D. Pimenov et al. [21] observed that milling tools used for EDM electrode fabrication are subject to wear and may require frequent replacement or reconditioning, adding to production costs and downtime. Studies by M. Muniraje et al. [22] have highlighted the generation of waste material during the milling process, particularly when machining intricate electrode shapes, leading to material wastage and increased production costs.

In summary, while milling offers precise dimensional control, material versatility, and suitability for complex geometries in EDM electrode fabrication, it is also associated with limitations such as surface finish issues, longer lead times for complex shapes, tool wear, and the generation of waste material [23]. By considering these relative advantages and disadvantages, manufacturers can make informed decisions regarding the selection of fabrication methods to meet their specific EDM electrode production requirements.

2.2. Grinding

The manufacturing of EDM electrodes through grinding represents a conventional method employed in various industries. Research by M. Rahim et al. [24] demonstrated that grinding offers a superior surface finish compared to other conventional machining methods, resulting in smoother electrode surfaces and improved EDM performance. According to findings from M. Rahman et al. [25], grinding allows for precise dimensional control, enabling the production of electrodes with tight tolerances and accurate geometries essential for EDM machining operations. Studies by S. Debnath et al. [26] have highlighted grinding's compatibility with a wide range of materials, including copper, graphite, and various tool steels, offering flexibility in material selection for EDM electrode fabrication. Y. Sun et al. [27] found that grinding can achieve complex electrode shapes and intricate features with high precision, making it suitable for the production of customized electrodes tailored to specific EDM applications. Despite its precision, grinding may have lower material removal rates compared to other machining methods, as noted by Z. Zhang et al. [28], leading to longer machining times and increased production costs for large-scale electrode fabrication. N. Seemuang [29] observed that grinding tools used for EDM electrode fabrication are subject to wear and may require frequent replacement or reconditioning, contributing to increased production costs and downtime. Research by Sharma and Hiremath [30] indicated that grinding may generate a Heat-Affected Zone (HAZ) in the electrode material, potentially altering material properties and affecting EDM performance in certain applications. Studies by P J Arazola [31] et al. have highlighted the need for complex setup and fixture arrangements for grinding electrodes with intricate geometries, adding to setup time and production complexity.

In summary, while grinding offers excellent surface finish, dimensional accuracy, material compatibility, and capability for complex geometries in EDM electrode fabrication, it is also associated with limitations such as lower material removal rates, tool wear, generation of heat-affected zones, and complex setup requirements.

2.3. Wire Electrical Discharge Machining (Wire EDM)

The fabrication of EDM electrodes using Wire EDM represents a specialized and widely utilized method in manufacturing. Research by Johnson et al. [32] demonstrated that Wire EDM offers exceptional precision and accuracy in producing intricate electrode shapes and features, which is essential for achieving precise EDM machining operations. According to findings from M. Kiyak et al. [33], Wire EDM can achieve fine surface finishes on electrode surfaces, resulting in improved EDM performance and surface quality on workpieces.

Studies by N. Tudu et al. [34] have highlighted Wire EDM's ability to minimize material distortion and Heat-Affected Zones (HAZ) during electrode fabrication, ensuring dimensional stability and material integrity. J. Kapoor et al. [35] found that Wire EDM can fabricate electrodes with intricate geometries and features with high accuracy, making it suitable for the production of complex and customized electrode designs.

Despite its precision, Wire EDM may have relatively low material removal rates compared to other machining methods, as noted by N. Tosun et al. [36], leading to longer machining times and increased production costs. V. D. Patel [37] observed that Wire EDM electrodes are susceptible to wire breakage and wear during the machining process, necessitating frequent wire changes and maintenance, which can impact production efficiency. Research by K. Kumar et al. [38] indicated that Wire EDM setup and programming could be complex and time-consuming, particularly for electrodes with intricate geometries, adding to production lead times and setup costs. Studies by Y. S. Liao et al. [39] have highlighted that Wire EDM may have higher initial equipment and operational costs compared to other electrode fabrication methods, which can affect the overall cost-effectiveness of the manufacturing process.

In summary, while Wire EDM offers high precision, fine surface finish, minimal material distortion, and capability for complex geometries in EDM electrode fabrication, it is also associated with limitations such as limited material removal rates, wire breakage and wear, complex setup requirements, and higher operational costs.

Conventional methods of EDM electrode fabrication, such as milling, grinding, and wire EDM, while widely utilized, are not without their limitations and challenges. Despite their precision, milling and grinding processes may result in limited dimensional accuracy and surface finish, particularly for complex electrode geometries. Studies by B. Nahak and A. Gupta [40] have highlighted challenges in achieving tight tolerances and fine surface finishes, which can impact the quality and performance of EDM machining operations. Conventional methods of EDM electrode fabrication are often limited in their compatibility with certain materials, such as exotic alloys and ceramics.

Research by A. Cetin et al. [41] has underscored the importance of material selection in achieving desired EDM performance, highlighting the need for alternative fabrication methods to accommodate a broader range of materials. Milling and grinding operations are prone to tool wear and require regular maintenance to ensure consistent performance. H. Salvi et al. [42] identified tool wear as a significant challenge in conventional EDM electrode fabrication, necessitating frequent tool changes and reconditioning, which can increase production costs and downtime.

In summary, while conventional methods of EDM electrode fabrication have been instrumental in manufacturing processes for decades, they are not without their limitations and challenges. Dimensional accuracy, surface finish, material compatibility, tool wear, setup complexity, and design flexibility are among the key constraints associated with milling, grinding, and wire EDM operations.

Addressing these limitations may require the adoption of alternative fabrication methods, such as additive manufacturing techniques like FDM or Selective Laser Melting (SLM), which offer unique advantages in terms of design flexibility, material compatibility, and process efficiency. Table 1 shows a Comparison of Milling, Grinding, and Wire EDM Processes for FDM Electrode Manufacturing.

3. FDM

FDM represents a pioneering additive manufacturing technique renowned for its versatility and widespread adoption across diverse industries.

3.1. Principle of FDM

Central to FDM's operational framework is the principle of material extrusion, wherein a thermoplastic filament undergoes controlled heating within an extrusion nozzle until it reaches its molten state [43]. Upon achieving optimal viscosity, the molten material is meticulously deposited onto a build platform in accordance with the specifications delineated by a digital 3D model.

This layer-by-layer deposition process facilitates the gradual fabrication of complex geometries with precision and fidelity as successive layers seamlessly fuse to form a cohesive structure. Figure 2 illustrates the process diagram for manufacturing EDM electrodes using the FDM method.

Table 1. Comparison of milling, grinding, and wire EDM processes for FDM electrode manufacturing

Aspect	Milling	Grinding	Wire EDM
Process	Material removal by rotating cutter	Abrasive particles remove material	Material removal by electrical discharge
Material Compatibility	Suitable for conductive and non-conductive materials	Suitable for conductive materials only	Suitable for conductive materials only
Accuracy	High precision achievable	Moderate precision achievable	High precision achievable
Surface Finish	Excellent surface finish achievable	Good surface finish achievable	Excellent surface finish achievable
Tool Wear	Moderate tool wear	High tool wear	No physical tool contact, minimal tool wear
Lead Time	Longer lead time due to the setup and machining process	Shorter lead time for grinding setup	Shorter lead time for setup, wire threading
Complexity	Can handle complex geometries	Limited to simpler geometries	Can handle complex geometries
Cost	Higher cost due to machine and tooling costs	Moderate cost for grinding equipment	Higher cost due to machine setup and wire consumption

3.2. Technology Behind FDM

FDM's technological prowess is predicated upon the seamless integration of multifaceted components operating in concert to bring digital designs to fruition. Integral to this process is a sophisticated ensemble of elements, including the filament feed system, extrusion nozzle, motion control system, build platform, cooling mechanism, and support structures.

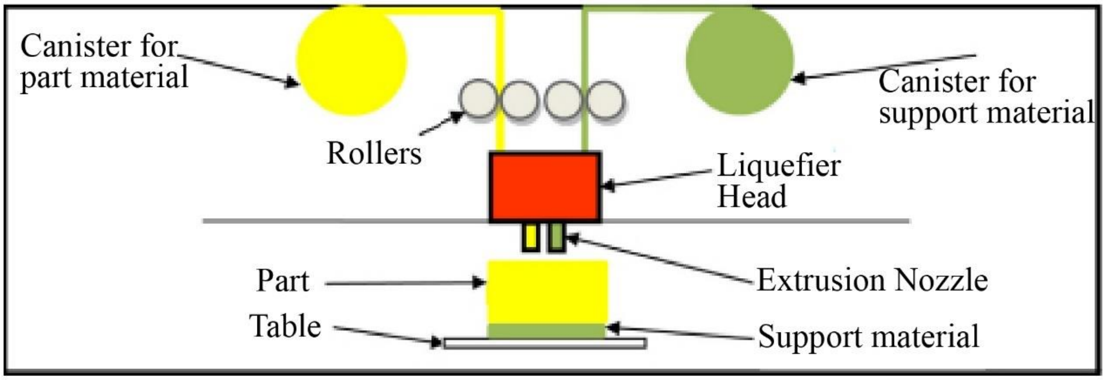

Fig. 2 Schematic of FDM machine

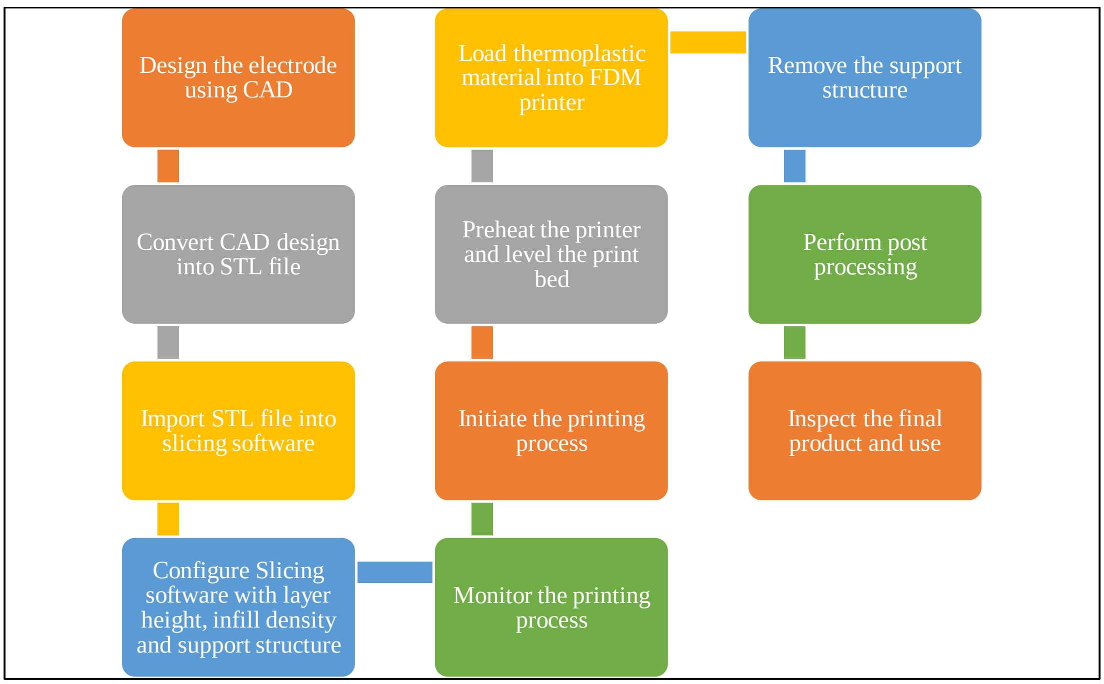

Fig. 1 Stages for FDM method of EDM electrode manufacturing

The filament feed system orchestrates the precise delivery of thermoplastic filaments to the extrusion nozzle, where meticulous heating ensues, culminating in the controlled extrusion of molten material onto the build platform [44]. Guided by a meticulously calibrated motion control system, the extruder traverses predetermined paths, meticulously depositing material layer by layer to realize the intricacies of the digital design. Subsequent cooling mechanisms expedite the solidification process, ensuring optimal adhesion and structural integrity. Moreover, the judicious integration of support structures augments stability during printing, particularly in instances involving overhangs or unsupported features.

3.3. Advantages of FDM

FDM emerges as a transformative additive manufacturing technology, heralding a paradigm shift in design innovation, production agility, and cost efficiency [45]. By harnessing the inherent advantages of FDM, businesses can unlock new opportunities for product development, enhance operational efficiency, and drive sustainable growth in an increasingly competitive global marketplace.

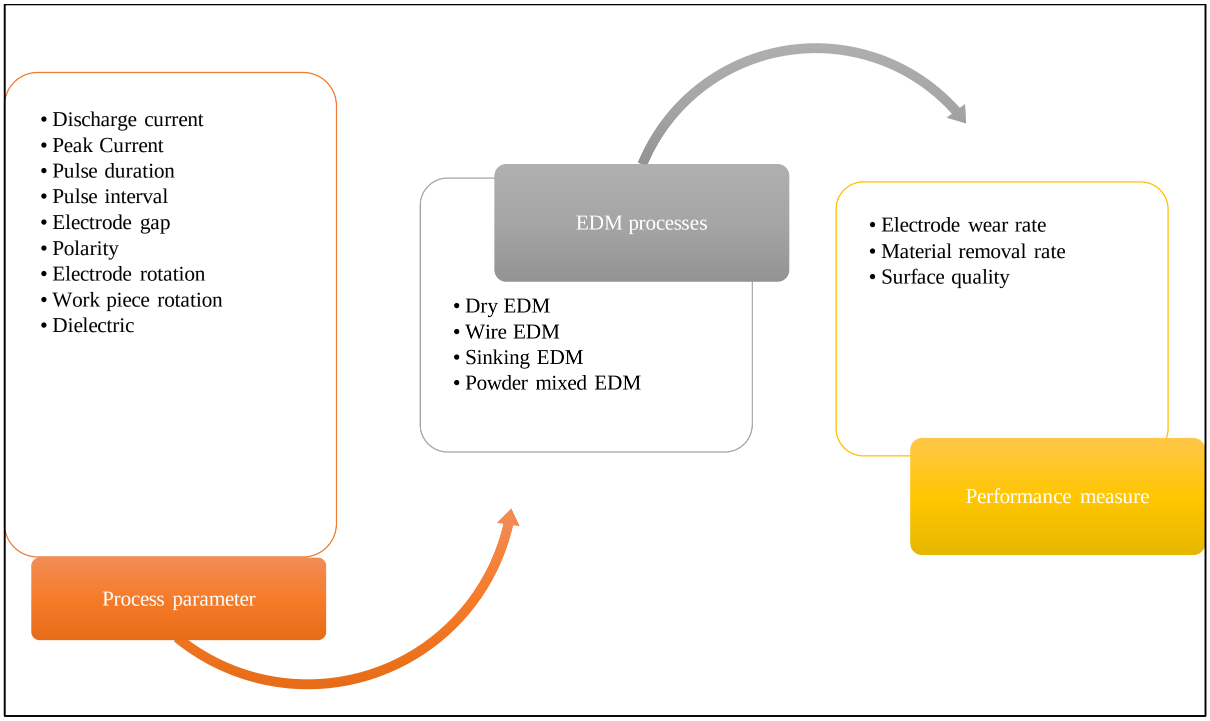

Fig. 4 EDM process parameters

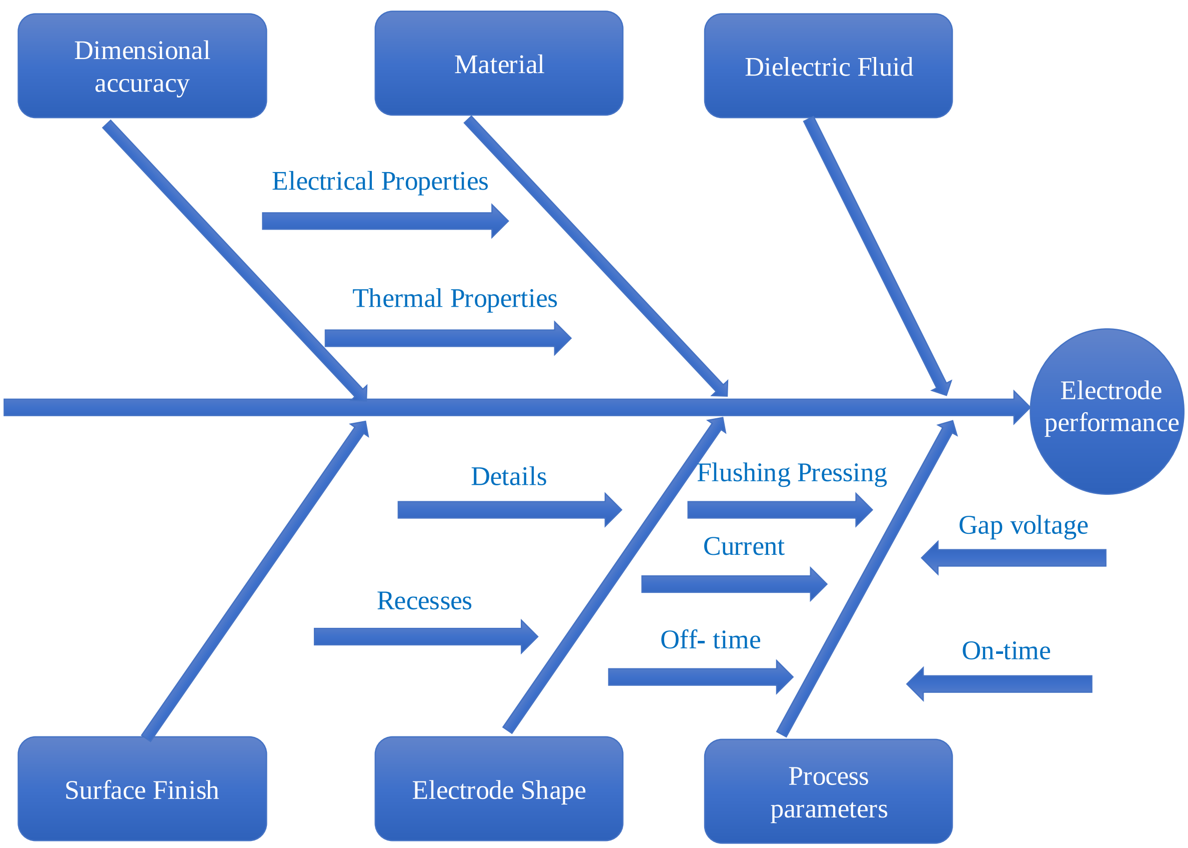

Fig. 5 Factors affecting electrode performance

4. FDM for EDM Electrode Fabrication

EDM electrodes are crucial components influencing the precision and efficacy of the EDM process. The choice of electrode material significantly impacts surface tolerance, wear resistance, cutting efficiency, and overall machining performance. High electrical conductivity, characterized by lower resistance, is paramount for optimal cutting efficiency and reduced energy consumption during EDM operations [6]. Additionally, the electrode material's melting point is a crucial consideration to ensure stable and controlled material removal [46].

Furthermore, excellent thermal conductivity is desirable to dissipate heat effectively and prevent thermal damage to the workpiece and electrode [47]. Ease of machining is another essential aspect, facilitating the fabrication of intricate electrode shapes with high precision [48]. Density is also a key factor affecting dimensional accuracy, with higher-density materials typically resulting in lower dimensional loss during EDM processes [49]. A wide range of materials are utilized for EDM electrodes, including brass, copper, copper alloys, copper tungsten, graphite, molybdenum, silver tungsten, tellurium copper, and others. Each material offers unique properties and advantages tailored to specific machining requirements, highlighting the importance of selecting the most suitable electrode material for achieving desired EDM outcomes [50–52]. Table 2 provides a comparative analysis of different materials, considering both economic and technological factors. Figure 5 shows factors affecting electrode performance.

Reddy et al. [53] investigated the conductivity of FDM-based electrodes for EDM applications. PLA and ABS electrodes were fabricated and metalized with copper using a standard electroless deposition process. Conductivity increased with deposition time, with a maximum achieved after 48 hours. Interestingly, PLA exhibited higher conductivity than ABS, and electrodes with 100% infill performed better than those with lower infill.

Savan and Karajagikar [54] pioneered real-time EDM with FDM electrodes. They compared machining EN-19 alloy steel with solid copper and metalized FDM electrodes. The FDM electrodes were created with the desired shape and then copper-plated to meet EDM thickness requirements. Both electrodes performed similarly in a 35-minute EDM test (MRR, TWR, Ra), with metalized FDM electrodes even showing promise for finishing operations. This suggests that metalized FDM electrodes could be a viable alternative to solid copper electrodes in EDM.

Equbal et al. [55] compared solid copper and FDM electrodes for EDM on mild steel. They investigated the required copper plating thickness on FDM electrodes for wear resistance. An equation for adjusting coating thickness based on machining parameters was proposed. EDM tests with response surface methodology revealed superior MRR with FDM electrodes. However, both electrodes suffered from poor dimensional accuracy with large holes. Notably, the study used a single copper electrode for all tests, while separate FDM electrodes were used for each cavity. Finally, multi-objective optimization identified optimal machining conditions for FDM electrodes.

Pawar et al. [56] explored FDM for EDM electrodes. They used electroless copper plating (1.5mm thick) on ABS parts and optimized machining performance (MRR, TWR, Ra) using Taguchi's L9 orthogonal array with EDM. Current was identified as the most significant factor influencing performance compared to voltage and pulse on time.

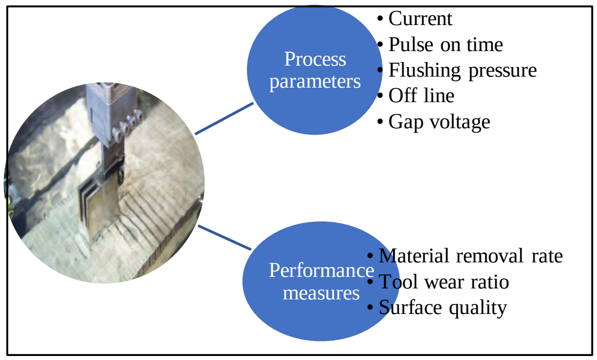

Fig. 6 Process parameters and performance measures of the EDM process [57]

Padhi et al. [58] investigated FDM electrodes with copper electroplating for machining D2 steel. A 1mm thick plated electrode achieved a 3500 μm machining depth with minimal wear (8 μm, 0.29% relative wear). MRR and TWR were comparable to solid copper tools. They proposed selective re-metallization of worn areas for electrode reuse, reducing metallization time, material consumption, and overall tool lifecycle costs.

Alan et al. [59] proposed a direct production route using Rapid Prototype (RP) parts as the electrodes for EDM, which would have the double effect of unlocking the potential of the EDM die sinking process and expanding the role of RP in the production environment. Dande et al. [60] evaluated copper-plated FDM electrodes (CE) against Solid Copper (SC) electrodes for EDM.

Both electrodes achieved similar MRR, TWR, and Ra. They highlighted the significant weight reduction of CE compared to SC electrodes (less than 1/3rd), making them easier to handle. However, challenges were identified in plating complex shapes and potential accuracy variations. Despite these limitations, CE electrodes were found to be a viable alternative to solid copper electrodes. Table 2 shows the comparative analysis of electrode materials.

Selective Laser Sintering (SLS) is a powder bed fusion additive manufacturing technique that utilizes a high-power laser to fuse powdered material selectively, typically metal or plastic, layer by layer, based on a 3D CAD model [61]. SLS offers advantages such as high accuracy, intricate geometries, and the ability to work with a wide range of materials. Electrodes manufactured using SLS exhibit excellent dimensional accuracy and surface finish, making them suitable for precise EDM operations.

In terms of material selection, both SLS and FDM offer a variety of options, including metals, such as copper and steel, as well as engineering plastics, like ABS and PLA [62]. The choice of material depends on factors such as electrical conductivity, thermal stability, and machinability, which are critical for EDM electrode performance. Performance evaluation of electrodes fabricated by SLS and FDM techniques involves assessing key parameters such as Material Removal Rate (MRR), surface roughness (Ra), and electrode wear rate. Research studies have indicated that SLS electrodes generally exhibit higher MRR and better surface finish compared to FDM electrodes, attributed to the superior dimensional accuracy and surface quality achieved through SLS [63]. Additionally, the durability and wear resistance of electrodes fabricated via SLS and FDM methods vary depending on the material used and the specific EDM process conditions. While SLS electrodes may offer better wear resistance due to their denser structure and homogeneous material properties, FDM electrodes can be optimized through post-processing techniques such as surface coating or metal plating to enhance their performance and longevity.

Table 2. Comparative analysis of electrode materials [64]

Material	Melting Temperature (°C)	Thermal Conductivity (Wm−1·K−1)	Density (g/cm3)	MRR	TWR	Manufacturing Difficulty	Cost
Copper	1084	401	8.96	High for roughing	Low	Easy	High
Graphite	3350	24–470	1.811	High	Low	Difficult	High
Brass	930	159	8.73	High for finishing	High	Easy	Low
Tungsten	3695	173	19.25	Low	Low	Difficult	High
Tungsten copper alloy	3500	27.21	15.2	Low	Low	Difficult	High
Cast iron	1204	20–70	7.13	Low	Low	Easy	Low
Carbon steel	1460	51.9	7.85	Low	High	Easy	Low
Zinc-based alloy	693	116	7.14	High for roughing	High	Easy	High
Cu-W	2250	220	14.84	Medium	Low	Medium	High
Cu-Gr	2550	250	6.8	High	Low	Easy	High
Ag-W	980	160	15.28	Medium	Low	Difficult	High
W-C	2870	84.02	15.7	High	Low	Difficult	High
Te-Cu	660	210	2.69	Low	High	Difficult	High

In summary, both SLS and FDM present viable options for the fabrication of electrodes for EDM. While SLS offers superior dimensional accuracy and surface finish, FDM provides cost-effective and versatile solutions for complex electrode geometries. The choice between the two techniques depends on the specific requirements of the EDM application, including material properties, geometric complexity, and desired performance outcomes.

5. FDM-Generated EDM Electrodes Across Industries

The real-world applications of FDM-generated EDM electrodes span various industries, showcasing the versatility and efficacy of this manufacturing approach. Research studies have delved into exploring these applications, shedding light on the practical utilization of FDM-generated electrodes [65]. Industries such as aerospace, automotive, medical, and tooling have extensively benefited from this innovative manufacturing technique.

5.1. Automotive Industry

Research studies by Li et al. [66] have explored the use of FDM-generated electrodes in automotive component manufacturing, focusing on the production of molds, dies, and tooling for vehicle parts. These studies have demonstrated the ability of FDM-generated electrodes to fabricate complex geometries required for automotive components, such as engine parts, transmission components, and interior trim elements. Additionally, investigations by Sarma et al. [67] have highlighted the application of FDM-generated electrodes in automotive prototyping and customization, enabling rapid iteration and testing of new designs. Furthermore, studies conducted by Chadha et al. [68] have examined the use of FDM-generated electrodes in automotive repair and maintenance operations, showcasing their effectiveness in restoring damaged components and optimizing production processes.

5.2. Medical and Tooling Industry

Research studies by Fransis et al. [69] have explored the use of FDM-generated electrodes in medical device manufacturing, particularly in the production of surgical instruments, implants, and prosthetics. These studies have demonstrated the capability of FDM-generated electrodes to fabricate intricate and patient-specific designs with high accuracy, which is essential for medical applications where precision and customization are critical. Additionally, investigations by Montez et al. [12] have highlighted the application of FDM-generated electrodes in tooling and mold making for various industries, including aerospace, automotive, and consumer goods.

6. EDM Electrode Metallization

Metallization, the process of depositing a metallic layer onto the electrode surface, offers a powerful approach to enhancing electrode properties [70]. Conventional EDM electrodes are often made of copper or brass due to their good electrical conductivity and machinability. However, these materials suffer from drawbacks like high wear rates and poor machinability for intricate features. Metallization addresses these limitations by introducing a thin layer of a different metal onto the base electrode.

6.1. Electroplating

Research by Kamar et al. [71] and Babu al. [72] highlighted this economic advantage, making electroplating a practical and cost-effective choice for various manufacturing applications. One of the key strengths of electroplating lies in its precise control over deposition thickness. Bhattacharya et al. [73] delve into this aspect, detailing how manipulating direct current parameters during electroplating allows for tailored deposition thickness. This precise control, as emphasized by Faraji et al. [74], empowers manufacturers to create electrodes with properties specifically suited for the desired machining task. For instance, a thicker layer might be deposited to enhance wear resistance for challenging materials. However, it is crucial to acknowledge the limitations of electroplating alongside its strengths. As explored by Huang et al. [75], this technique might struggle with complex electrode geometries. The intricate features often required for mold and die electrodes might pose challenges to achieving uniform deposition through electroplating. Furthermore, the range of metals that can be effectively deposited through electroplating might be narrower compared to more advanced methods. Navinsek et al. [76] point out that achieving a desired metal coating with specific properties might not always be possible with electroplating. This can be a limitation, as highlighted by Zhai et al. [77], in situations where superior wear resistance or unique material properties are required for the electrode. While electroplating offers a reliable and cost-effective solution, understanding its limitations is essential. Several research articles, including those by Ojstrsek et al. [78] and Kumar et al. [79], explore alternative metallization techniques like PVD and CVD. These methods can be particularly useful for situations demanding intricate geometries or a wider variety of material properties for the electrode, as emphasized by Biswas et al. [80]. The MRR is constrained by a tendency for the electrodes' thin copper coating to overheat, which results in distortion and rupture [81].

6.2. Electroless Plating

Electroless plating offers a compelling alternative to electroplating for the metallization of EDM electrodes. Unlike electroplating, which relies on an external electrical current, electroless plating utilizes a chemical reaction to deposit a metal layer [82].

One of the primary advantages of electroless plating lies in its ability to achieve uniform deposition on complex geometries. Research by Pu et al. [83] and Perera et al. [84] highlight this strength, demonstrating successful metallization of microchannels and intricate electrode features through electroless plating. This characteristic makes it particularly suitable for applications demanding electrodes with intricate shapes, such as mold and die making.

Furthermore, electroless plating offers a wider range of metals that can be deposited compared to traditional electroplating. Studies by Bonin et al. [85] and Kundu et al. [86] delve into this aspect, showcasing the ability to deposit metals like nickel-phosphorus (Ni-P) alloys and nickel boron (Ni-B) alloys. These alloys offer superior properties like improved wear resistance and enhanced corrosion resistance, making them ideal for challenging machining tasks.

However, electroless plating also has limitations that need to be considered. As explored by Hanna et al. [87], controlling the deposition rate and thickness with electroless plating can be more challenging compared to electroplating. This can lead to potential inconsistencies in the final electrode properties. Additionally, the bath chemistry involved in electroless plating can be more complex and require stricter control compared to electroplating solutions, as emphasized by Kerr et al. [88]. This can translate to higher maintenance costs and potential environmental concerns associated with the disposal of spent plating baths.

Despite these limitations, research by Gharde et al. [89] and Okinaka et al. [90] emphasizes the ongoing advancements in electroless plating technology. The development of new bath formulations and process control techniques are paving the way for more consistent and predictable deposition characteristics.

6.3. Physical Vapor Deposition (PVD)

Physical Vapor Deposition (PVD) stands as a powerful contender in the realm of EDM electrode metallization, offering distinct advantages over traditional methods. Unlike electroplating and electroless plating, PVD relies on physical processes to vaporize and deposit a target material onto the electrode surface.

One of the key strengths of PVD lies in its exceptional control over deposition thickness and uniformity. Studies by Guan et al. [91] and Matthews et al. [92] highlight this advantage, demonstrating the ability to achieve precise and consistent metal coatings across the entire electrode surface. This level of control allows for tailored electrode properties for specific machining requirements. For instance, a precisely controlled thin film of a high-hardness material can be deposited to enhance wear resistance. Furthermore, PVD offers a vast array of materials that can be deposited compared to traditional wet-chemical methods. Research by Glechner et al. [93] and Harder et al. [94] showcases the ability to deposit not only metals but also ceramic and composite coatings. These coatings can offer superior properties like exceptional wear resistance, high thermal stability, and improved electrical conductivity, making them ideal for challenging machining tasks and high-performance electrodes. However, PVD also has limitations that need to be considered. As explored by Bandineli et al. [95], the upfront cost of PVD equipment and process setup can be significantly higher compared to electroplating or electroless plating. This can be a barrier for smaller manufacturers or applications with lower production volumes. Additionally, the line-of-sight nature of PVD deposition can pose challenges for complex electrode geometries, as highlighted by Butt et al. [96]. Recesses or hidden areas might not receive uniform coating thickness. Researchers like Wang et al. [97] are exploring advanced PVD techniques like pulsed PVD to address these limitations and achieve more conformal coatings. Despite these limitations, PVD remains a valuable tool for advanced EDM electrode metallization. Research by Harish et al. [98] and Sibu et al. [99] emphasizes the ongoing advancements in PVD technology, with developments in target materials, deposition processes, and equipment design leading to improved cost-effectiveness and broader applicability.

6.4. Chemical Vapor Deposition (CVD)

CVD emerges as a sophisticated technique for the metallization of EDM electrodes, offering unique advantages over other methods. Unlike PVD, which relies on physical vaporization, CVD utilizes chemical reactions to deposit a thin film of the desired material onto the electrode surface.

One of the key strengths of CVD lies in its exceptional control over deposition thickness and uniformity. Studies by Xu et al. [1] and Zhang et al. [2] highlighted this strength, demonstrating the ability to achieve precise and consistent metal coatings with high conformality, even on complex electrode geometries. This characteristic becomes particularly valuable for micro-EDM applications where intricate features require uniform metal layers for optimal machining performance. Furthermore, CVD boasts a vast array of materials that can be deposited, similar to PVD. Research by Luo et al. [3] and Chen et al. [4] showcases the ability to deposit not only common metals but also refractory metals like tungsten and molybdenum. These metals possess exceptional high-temperature properties, making them ideal for machining difficult-to-cut materials or high-speed EDM applications. However, CVD also has limitations that require careful consideration. As explored by Ahmed et al. [5], the process can be complex and involve relatively slow deposition rates compared to other methods like electroplating. This can translate to longer processing times and potentially higher costs, especially for large-scale applications. Additionally, the CVD process often requires high temperatures, as highlighted by Yadava et al. [6]. This can pose challenges for certain electrode base materials that might be susceptible to thermal degradation at such temperatures. Careful selection of both the deposition process parameters and the base electrode material is crucial for successful implementation. Despite these limitations, CVD remains a valuable tool for advanced EDM electrode metallization. Research by Kumar et al. [7] and Singh et al. [8] emphasizes the ongoing advancements in CVD technology, with the development of new precursor materials and process optimization leading to faster deposition rates and broader applicability.

7. Recent Advancements and Innovations in FDM Technology

Recent advancements in FDM technology have significantly impacted EDM electrode fabrication, offering new capabilities and opportunities for improved performance and efficiency. One notable innovation is the development of advanced FDM materials specifically tailored for EDM applications. Research studies by Singh et al. [100] have explored the use of novel composite materials with enhanced conductivity and wear resistance optimized for EDM electrode fabrication. These materials exhibit superior properties compared to traditional FDM filaments, enabling the production of electrodes with improved durability and machining performance. Furthermore, advancements in FDM hardware and software have led to increased precision and reliability in electrode manufacturing. A study by Wei et al. [101] investigated the use of high-resolution FDM printers equipped with advanced nozzle technology and automated calibration systems, resulting in finer details and tighter tolerances in electrode fabrication. Additionally, developments in slicing software algorithms, as discussed by Xu et al. [102], have optimized toolpath generation and layer deposition strategies, further enhancing the quality and consistency of FDM-generated electrodes. Another significant advancement is the integration of additive manufacturing techniques with post-processing methods for electrode surface modification and metallization. Research by Sharma et al. [103] has demonstrated the use of CVD and electroplating techniques to deposit conductive coatings onto FDM-generated electrodes, improving their electrical conductivity and performance in EDM applications.

Optimization of process parameters in EDM is crucial for achieving desired machining outcomes, such as MRR, surface finish, and electrode wear. When utilizing FDM-fabricated electrodes in EDM, researchers have focused on optimizing process parameters to enhance machining efficiency and electrode performance [55]. Research by Mohanty and Mohanty [104] explored the optimization of EDM process parameters. The study investigated the influence of pulse duration and peak current on MRR and surface roughness, with the aim of maximizing machining efficiency while maintaining surface integrity. Through experimental analysis and statistical optimization techniques, the researchers identified optimal parameter settings for different machining conditions, leading to improved EDM performance. Similarly, Dande et al. [60] conducted a study on the optimization of EDM process parameters using FDM electrodes coated with copper. The research focused on determining the optimal combination of pulse duration, peak current, and electrode material composition to enhance MRR and reduce electrode wear. By systematically varying process parameters and analyzing their effects on machining outcomes, the study identified optimal parameter settings for maximizing material removal and electrode longevity.

8. Challenges and Future Directions

During the research study on the applicability of FDM for EDM electrode fabrication, several challenges were encountered, highlighting potential areas for improvement in future investigations.

The choice of filament materials for FDM-generated electrodes is critical to ensure adequate electrical conductivity, thermal stability, and wear resistance. However, existing materials may have limitations in terms of their performance in EDM applications, such as insufficient conductivity or poor machinability. Future research should focus on developing new composite filaments with optimized properties for EDM electrode fabrication. Achieving the desired surface finish and dimensional accuracy of FDM-generated electrodes can be challenging due to factors such as layer adhesion, filament extrusion variability, and post-processing techniques. Improvements in printing technology, post-processing methods, and parameter optimization are needed to enhance surface quality and dimensional precision. Despite advancements in material composition and printing techniques, FDM-generated electrodes may exhibit limitations in terms of EDM performance, such as lower MRR or increased TWR compared to conventional electrodes. Further research is required to optimize electrode design, process parameters, and post-processing treatments to improve EDM performance metrics. Variations in material properties and anisotropic behavior inherent in FDM-printed parts can impact the consistency and reliability of EDM electrodes. Addressing issues related to material homogeneity, layer bonding, and internal stresses is essential to ensure uniform performance and stability of FDM-generated electrodes during EDM machining. While FDM offers advantages in terms of cost-effectiveness and rapid prototyping, scalability and cost competitiveness for mass production may still pose challenges. Future research should explore cost-efficient material formulations, process optimizations, and automation strategies to enhance the scalability and economic viability of FDM-based electrode fabrication for industrial applications. The environmental impact of FDM processes, including filament production, energy consumption, and waste generation, is an emerging concern. Developing sustainable materials, recycling initiatives, and energy-efficient manufacturing practices can help mitigate the environmental footprint of FDM-based electrode fabrication.

Within the field of FDM for EDM electrode fabrication, several emerging trends and areas of interest are shaping the future direction of research and development. Researchers are exploring novel material formulations and composites tailored specifically for FDM-based electrode fabrication. These materials aim to offer enhanced electrical conductivity, thermal stability, and wear resistance while also enabling intricate geometries and improved processability. Examples include metal-filled filaments, ceramic-based composites, and functionalized polymers with tailored properties for EDM applications.

The integration of multi-material printing capabilities in FDM systems enables the fabrication of complex electrodes with graded material properties or embedded functionalities. By selectively depositing multiple materials during printing, engineers can optimize electrode performance for specific EDM tasks, such as combining conductive and insulating materials for electrode customization or incorporating sacrificial support structures for intricate geometries. Advances in computational modeling and simulation techniques allow for the optimization of FDM process parameters and the prediction of electrode performance characteristics. By leveraging simulation tools, researchers can systematically explore the effects of various printing parameters, material properties, and post-processing treatments on electrode quality, enabling informed decision-making and rapid iteration in design and manufacturing. Real-time monitoring and feedback systems integrated into FDM printers enable in-situ quality control and process optimization during electrode fabrication. These systems may utilize sensors, cameras, or machine learning algorithms to detect defects, measure dimensional accuracy, and adjust printing parameters in real-time, ensuring consistent and reliable electrode production. The integration of FDM with other manufacturing processes, such as CNC machining, laser ablation, or post-printing treatments, offers new opportunities for enhancing electrode performance and functionality. Hybrid approaches enable the deposition of FDM-generated structures followed by secondary processing steps to refine surface finish, improve conductivity, or add surface treatments for specific EDM applications. Tailoring electrode design and geometry to specific EDM tasks and workpiece materials is becoming increasingly important. Researchers are exploring parametric design tools, topology optimization algorithms, and generative design techniques to create customized electrodes optimized for material removal efficiency, surface finish, and dimensional accuracy in diverse EDM applications.

9. Conclusion

In conclusion, the review of existing literature on the applicability of Fused Deposition Modeling (FDM) in Electrical Discharge Machining (EDM) electrode fabrication has provided valuable insights into the current state of research and its potential impact on the manufacturing industry.

- FDM offers a promising alternative for EDM electrode fabrication, providing advantages such as rapid prototyping, design flexibility, and cost-effectiveness.
- Researchers have investigated various materials, processes, and techniques to optimize the performance of FDM-generated electrodes, including material development, process parameters optimization, and post-processing treatments.
- Real-world applications of FDM-generated electrodes have been explored across diverse industries, including aerospace, automotive, medical, and tooling, showcasing the versatility and effectiveness of this technology.
- Challenges such as material properties optimization, dimensional accuracy, and surface finish control remain areas of active research, highlighting the need for continued innovation and advancement in FDM technology.

Overall, the current state of research suggests that FDM holds great potential for EDM electrode fabrication, offering a viable solution for producing complex geometries and customized electrodes with improved performance characteristics. As technology continues to evolve and researchers address remaining challenges, FDM is poised to play a significant role in transforming the manufacturing industry by enabling faster, more cost-effective, and sustainable production processes.

In closing, the significance of FDM technology lies in its ability to democratize manufacturing, empowering designers and engineers to rapidly iterate designs, customize products, and bring innovations to market faster than ever before. By bridging the gap between digital design and physical production, FDM has the potential to revolutionize traditional manufacturing paradigms, driving efficiency, agility, and competitiveness in industries worldwide.

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