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A Review on Additively Manufactured Electrodes for use in Electro-Discharge Process

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Abstract: - An electrode is regarded as the most critical component of an Electro discharge Machining (EDM) process. Previously, when selecting electrode materials for a specific purpose, researchers examined the electrical and thermal conductivity. However, problems such as excessive wear with green compacted tools, increase toughness with sintered electrodes, poor rigidity with additively manufactured electrodes remained the key challenges. To address these issues, researchers are now investigating surface modification via electrode erosion by designing an EDM electrode of their choice for a specific application. As a result, this Mini-review paper discusses research efforts related to the fabrication of electrodes for EDM applications using various techniques such as Casting and machining, Electrodeposition, powder metallurgy, and additive manufacturing. Furthermore, this mini review aimed to provide insight into EDM electrode manufacturing via additive manufacturing, specifically the FDM method, as well as its benefits and drawbacks. Finally, suggestions for future research work on how to improve fussed Deposition Modelling (FDM) manufactured EDM electrode performance were highlighted.

Keywords: EDM, Electrode, Additive Manufacturing, FDM.

I. INTRODUCTION

Electro-discharge machining (EDM) is an electro-thermal material erosion process that primarily employs electrical energy and converts it to thermal energy via a continuous cycle of discontinuous electrical discharges between the tool and workpiece submerged in a dielectric medium. At temperatures ranging from 8000°C to 20000°C and pressures of 20 MPa, the electric sparks create a plasma channel between the electrode and workpiece. During the machining process, the materials of the electrode and workpiece melt and solidify with the assistance of dielectric fluid. This fluid is specifically designed to meet the necessary criteria for cooling, insulation, and the removal of microscopic debris [1,2]. The EDM process possesses some advantages over the conventional machining approaches due to its capability to develop geometrically complex shapes and efficiently machine various materials, irrespective of their hardness, ductility, and brittleness [3]. There is no direct contact between the tool and workpiece, resulting in the absence of chips formation, interactive and vibrational stresses during the process [4].

EDM electrodes are made from solid, conductive metals such as titanium, copper, and tungsten, among others [5], [6]. Non-metals such as graphite and ABS were also reported to have been used as EDM electrode materials [7]. Researchers use various methods to fabricate EDM electrodes. These methods include conventional machining of metallic materials, casting, additive manufacturing, powder metallurgy, and electrodeposition. Additive manufacturing of electrode (AM) is a novel technique for fabricating part shape by deposition of successive layers of material [8]. The layer thickness is determined by the computer-aided design (CAD) model's tessellation together with the machine settings. AM enables production of intricate shapes within the shortest possible time with no need for special tooling or separate process plan [9]. The process chain is divided into five major stages. Generally, AM processes follow similar process chain [10]. The initial three steps are referred to as pre-processing, which are then followed by part fabrication and post-processing procedures.

Fused deposition modelling (FDM) is a widely used 3D printing technique that can be employed to produce electrodes for EDM. FDM involves melting a thermoplastic material and extruding it through a nozzle to layer by

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layer create a 3D object. To make EDM electrodes with FDM, a conductive material is mixed with the thermoplastic material to improve its electrical conductivity.

The following steps are typically involved for FDM production of EDM electrodes:

i. Design: Electrode is designed using computer-aided design (CAD) software.

ii. Material choice: The thermoplastic material is chosen because it works well with the conductive material and can handle the high temperatures and pressures of the EDM process. ABS, PLA, and nylon are all thermoplastics that are often used for FDM.

iii. The Conductive Material: The conductive material is selected based on how well it transfers electricity and how well it works with the thermoplastic material. Graphite, copper, and aluminium are all examples of common conductive materials.

iv. Material Preparation: To get the desired electrical conductivity, the conductive material is mixed with thermoplastic material in the right amount. The electrode is made by pushing the material that has been mixed through the FDM nozzle.

v. Post-processing: The electrode is taken out of the FDM machine and then post-processed to get the right surface finish and get rid of any flaws. This can be done by sanding, polishing, or putting a conductive material on the electrode.

II. Literature On EDM Electrode

Materials used as electrodes in EDM could be machined or fabricated using a variety of manufacturing approaches. It is obvious that, the properties of the tool material have a direct impact on the machining process, surface tolerance, and surface roughness [11]. A hole with a square cross-section, for example, may become more elliptical in shape due to excessive electrode wear. Due to the impact of high-energy ions from the molten pool on the electrode, the first limitation in material selection is that the electrode should not undergo excessive wear. It should be noted that no single electrode material can meet all the requirements [6,7]. FDM for EDM electrode production has several advantages over traditional methods such as injection moulding or CNC machining, Powder metallurgy and electrodeposition. FDM enables the creation of complex shapes and geometries, as well as rapid prototyping and cost savings due to lower tooling and setup costs. Furthermore, when conductive thermoplastic materials are used, they can produce electrodes with superior electrical conductivity and performance when compared to traditional non-conductive materials. However, as depicted in Figure 1, the performance of an electrode depends on numerous variables.

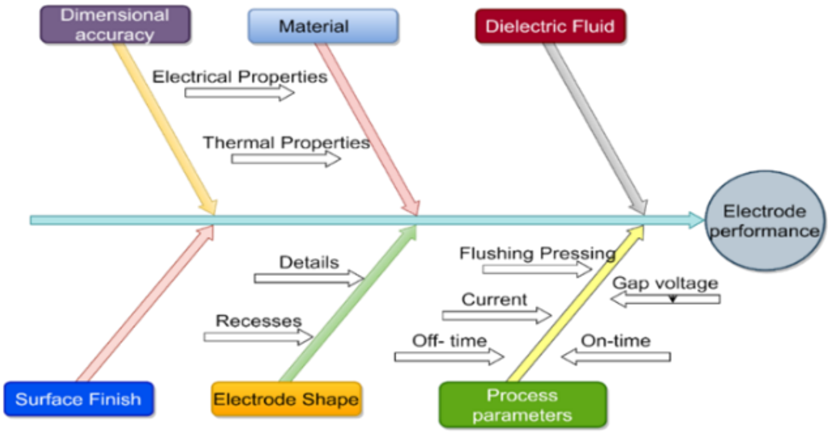

Figure 1: Factors Effecting Electrode Performance.

However, in general, an electrode material should possess the following properties, with the caveat that these requirements may vary based on the intended use of the electrode [8–10]. The electrode should not degrade too quickly despite being battered by the plasma's high-energy ions, and a rise in temperature shouldn't result in any melting or evaporation. The cutting effectiveness is enhanced by higher electrical conductivity (lower resistance). Otherwise, bulk heating occurs when cold admission electrons are unable to efficiently leave the electrode surface. Furthermore, when choosing tool properties, it is important to consider the melting point of the electrode. A higher melting point ensures a higher electrode wear ratio (electrode wear/workpiece erosion). Since EDM requires multiple tools, it is advisable to use cost-effective electrodes. Additionally, the electrode should possess high thermal conductivity to effectively absorb heat from the heated zone. High thermal conductivity reduces local temperature rise. This also benefits the electrode and improves the mechanical properties of electrode materials, including tensile strength and hardness. It is also critical that the electrode material should be easily machined. Electrodes Manufacturing would be difficult if the machinability of the Electrode material is poorIn die-sinker EDM, a rotary tool is utilized to create a negative replica of the tool geometry. It is essential for the tool to be compatible with standard machining methods in order to establish the desired form. Density plays a vital role in determining the performance of the electrode material. A higher density leads to reduced dimensional loss, which is crucial for achieving the desired results. The material's density also influences its surface tolerance. A higher density will result in a smaller dimensional loss for a given weight loss. Therefore, it is extremely important to minimize deviations in dimensional loss.

Factors Affecting FDM Manufacturing Method

FDM is a widely used manufacturing technique that utilizes a 3D printer to produce a part in a layered manner. This process involves melting and extruding a thermoplastic material through a nozzle. Various factors influence the effectiveness and quality of FDM manufacturing. These factors include material properties, nozzle diameter and height, temperature and bed levelling, support structures, speed and acceleration, and environmental conditions. The properties of the thermoplastic material are particularly important for achieving a high-quality final product. The solidification temperature, viscosity, and tensile strength are key factors that determine the success of the FDM procedure.

Furthermore, the size and height of the nozzle utilized in FDM can impact the precision and resolution of the final output. A smaller nozzle diameter enables more intricate details and enhances resolution, whereas a larger diameter can accelerate the manufacturing process. The thickness of each layer deposited also plays a role in the overall product quality. A thinner layer height can yield a smoother surface finish, although it may extend the production time.

Lastly, precise temperature control and proper bed levelling are essential for successful FDM manufacturing. Inconsistent temperature or an unlevelled bed can lead to improper adhesion between layers, resulting in a flawed print. The overall quality of the final product in the FDM process can be influenced by the speed and acceleration parameters. While higher velocities can decrease production time, they may also result in lower quality prints. Depending on the complexity of the printed component, support structures may be necessary to prevent collapse during printing. The design and placement of these support structures can have an impact on the final product's quality and may require additional post-processing. In addition, environmental conditions such as temperature and humidity can affect the effectiveness of the FDM process. Elevated temperatures or humidity levels can cause thermoplastic materials to distort or deform, leading to unsuccessful prints. Figure 2 below illustrates the process diagram for the FDM EDM electrode manufacturing method. The specific details may vary depending on the type of FDM printer and software used, as well as the material and electrode design being employed.

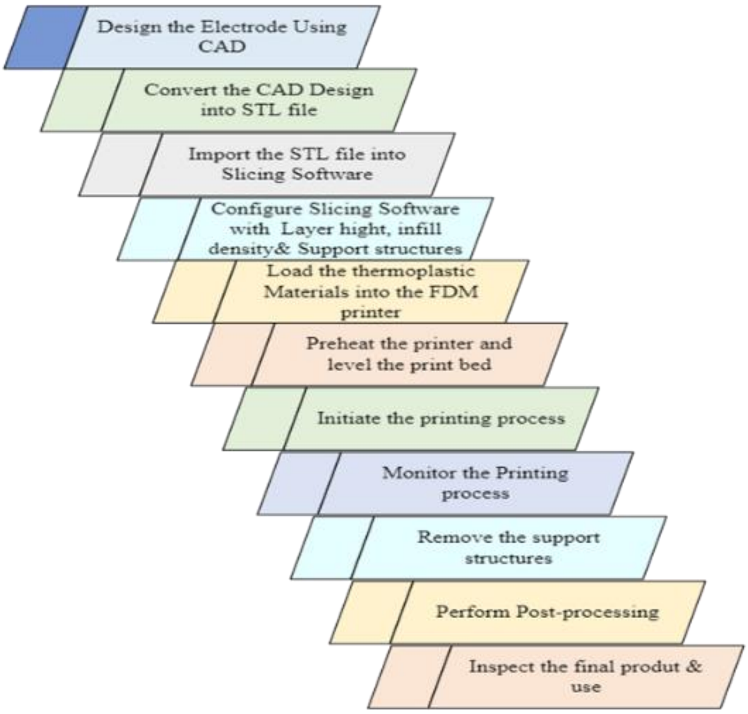

Figure 2: Stages for FDM EDM Electrode Manufacturing Method

III. RESULTS

Based on the literature review, it has been determined that researchers have utilized a range of methodologies for the fabrication of EDM electrodes. These methodologies include conventional machining of metallic materials, casting, additive manufacturing, powder metallurgy (PM), and electrodeposition methods. This section provides an in-depth analysis of the methodologies employed in previous studies for the production of EDM electrodes.

The methods used in the studies are alienated into categories based on the materials and applications. Additive manufacturing method was used to manufacture EDM electrode using ABS (copper) and other materials. This method has the advantages that can be used to produce intricate shapes [16]– [25]. It also shortens the production time. However, the downside of this method includes its high cost and limited number of materials can be used and most disturbing, it involves two stages of production (printing and metallization) [26]– [33]. The AM method is further discussed in this section.

Powder Metallurgy was used by many researchers more than any other method. It was used to produce EDM electrode for virtually all materials [34]– [36]. Powder metallurgy (PM) offers several advantages over conventional manufacturing methods, such as enhanced material property control, improved performance, and reduced costs [37]– [46]. and this method can be utilized to modify the surface by depositing the electrode properties onto the workpiece through electrode erosion. However, one drawback of this approach is the presence of high porosity and tool wear in the green compact, while the tool wear is lower in the sintered tool [11], [47]– [56]. Additionally, Electrodeposition is the process of depositing metal ions onto a conductive substrate using an electrolytic cell. The electrodeposition process is used to grow a metal coating onto a conductive mandrel or substrate that has been shaped to the desired electrode geometry in the case of EDM electrodes. electrodeposition was used for electrode production for EDM applications. This method can be used on all conductive materials and has the advantage of having control over the properties of the tool [10]. Moreover, it can be used for both machining and surface modifications. However, researchers have reported high tool wear in this method [57]– [60]. Furthermore, conventional machining/casting has been used for EDM electrode manufacturing. This method can be used on any conductive material, as it is simple, inexpensive, and straightforward [6], [61], [62]. Disadvantages include the lack of control over electrode properties and surface defects. However, this type of instrument cannot be used for surface modification; it can only be used for machining [63]–[72].

The process of producing EDM using the powder metallurgy method involves the following steps:

Material selection: To ensure the best results, it is crucial to choose the right materials for the EDM electrode. These materials should have excellent electrical conductivity, a high melting point, and good thermal conductivity. Copper, tungsten, and graphite are commonly used as electrode materials. Subsequently, the chosen materials are meticulously pulverized into a fine powder. Milling or atomization techniques are frequently employed to accomplish this powder preparation process.

Blending: The powders are carefully blended to achieve the desired composition and properties. This step is of utmost significance as the properties of the final product depend heavily on the uniformity of the mixture.

Pressing: Using a hydraulic press, the blended powder is meticulously compressed into the designated shape and size. To ensure a densely packed configuration of the powder particles, the pressing operation is carried out under substantial pressure.

Sintering: Sintering takes place when the pressed parts are subjected to high-temperature sintering in a furnace. This process involves the bonding of powder particles, leading to the formation of a solid and compact material. The specific sintering temperature and duration depend on the type of material and the desired properties.

Machining: CNC machines are used to shape and size the sintered parts with precision. The surface finish and dimensional accuracy of the EDM electrode play a vital role in ensuring optimal performance during EDM.

Polishing and Coating: The final step involves polishing and coating the electrode to improve its surface finish and protect it from oxidation.

This section provides detailed descriptions of relevant research on using Additive Manufacturing to create EDM electrodes with both conductive and nonconductive materials. Durr et al. [73] were the first to report the use of direct metal laser sintering (DMLS) in the production of EDM electrodes regarding conductive materials. The machining rate was adequate, but there was significant tool wear and unacceptable surface roughness (Ra). Tay and Hyder [74] also utilized DMLS for the fabrication of EDM electrodes. However, the inconsistency in the copper coating thickness throughout the entire component rendered the electrodes unsuitable for industrial applications. Fred et al. [75] conducted a study on the selective laser sintering (SLS) method for producing EDM electrodes. They used the following powders: pure Cu powder, steel alloy DS20 powder, bronze-nickel (Br-Ni) alloy powder, and a powder consisting of 50% pure copper and 50% standard bronze-nickel alloy. In their comparative analysis, they found that the steel alloy and bronze-nickel alloy exhibited the highest densification and the lowest porosity. Tiago et al. [26] conducted a study to compare the densification behaviour and porosity of Cu powder, Cu-Ni, and ZrB2 electrodes during fast electrode fabrication, in contrast to solid copper (SC) electrodes. While CuNi-ZrB2 electrodes outperformed Cu-powder electrodes, they were still inferior to SC electrodes.

In order to make non-conductive components conductive, the surface of the AM component is cleaned before the primary metallization process. Secondary metallization is then applied over the initial metallized layer to increase the coating thickness, in order to meet EDM requirements. Authur et al. [17] fabricated EDM electrode using stereolithography (SLA). Although satisfactory results were obtained, it was discovered that, the electrodes were insufficient for the roughing phase. In addition, the dispersion of heat in SLA electrodes has been studiedShear stress was discovered at the interfaces due to the different linear expansion of the inner plastic core and the outer metallized layer. Gillot et al. [76] examined the precision of CE electrodes (copper electroplated). Their research indicated that.

CE electrodes were deemed unsuitable for industrial purposes because of their lack of dimensional accuracy. In a study conducted by Dickens et al. [77], research was carried out on the application of spray metal deposition on SLA components. It was found that electroplating and electroforming outperformed spraying in terms of metallization. Soar et al. [14] also investigated the spray metal deposition method on stereolithography manufactured EDM electrode. They also claimed that the strength of the finished electrode is insufficient. SLA Manufactured EDM was electroformed by Yang et al [20]. However, metallization homogeneity was not achieved. Arthur et al [28] used electroforming and backfilling negative AM model to create electrodes. Hsu et al [16] employed gypsum powders (ZP100) in a Zcorp 402 3DP rapid prototyping machine for their research. Following nickel electroless plating, copper electroforming was used (ELP). Sreenathbabu et al. [78] investigated the hybrid adaptive AM approach and discovered that, while precise tools could be produced, their composition and tool life were poor. According to AM research for manufacturing EDM electrode particularly, using FDM to create electrodes can successfully develop electrodes that meet EDM criteria while overcoming the limitations of traditional AM approaches. Dhatrak et al. [79] conducted a study on the electrical conductivity of FDM-produced ABS and PLA-based EDM electrodes. They found that conductivity increased with deposition time and reached its peak at 48 hours. However, it is important to note that no real-time machining was performed, and the results were not independently verified.

On the other hand, Savan and Karajagikar [80] conducted the first real-time EDM using an FDM electrode. They compared the machineability of En-19 alloy steel with pure copper using a metalized FDM electrode. The authors found that the machining performance of the metalized FDM electrode was similar to that of the solid copper electrode when subjected to similar machining conditions. Equbal et al. [31] conducted a similar experimental investigation in this area. They used solid copper and FDM electrodes for machining mild steel in their study. The experiment showed that the FDM-produced electrodes performed better than the solid copper electrodes. However, it was also found that both types of electrodes resulted in significant dimensional inaccuracies, with large holes being produced.

Mohsen and Mohammad [27] investigated the feasibility of using FDM electrodes for Ti-6Al-4V alloy EDM. EDM was performed in two ways: with and without aluminium powder mixed into the dielectric. FDM electrodes have great potential for cutting complex structures in powder mixed EDM. This is in contrast to cutting without the powder in the dielectric. Padhi et al. [18] assessed the effectiveness of a tool electrode made from FDM samples by employing copper electroplating. Dande et al. [30] examined the machining performance of an FDM printed ABS part that was electroplated with copper to be used as an EDM electrode. Their findings indicated that copper electroplated electrodes are significantly lighter than solid electrodes.

However, SLS-EDM electrodes are highly effective in removing light materials. Nevertheless, they tend to experience greater wear and result in lower surface quality [81]. Researchers who have developed and manufactured FDMEDM electrodes assert that these electrodes exhibit comparable or superior performance to solid copper electrodes. The aforementioned study indicates that, despite numerous advantages, AM technologies have inherent limitations concerning part quality. The EDM electrode must possess precise dimensions, a refined surface finish, and sufficient strength to endure the rigorous machining conditions inherent in the machining process. Given that FDM is the most prevalent AM method, it is imperative to comprehend its deficiencies before endorsing it for industrial application.

Table 1 presents an overview of the challenges associated with additive manufacturing (AM) techniques employed in electrode manufacturing. On the other hand, Table 2 provides a comprehensive assessment of the advantages and disadvantages specifically pertaining to the Fused Deposition Modelling (FDM) method.

Table 1: Comparison of additive manufacturing methods used for electrode manufacturing, as reported in the literature.

Method Used	Advantages	Disadvantages	Remarks
FDM	Flexibility of materials and cost-effectiveness.	Suitable only for small sizes, with unstable quality.	More than one stage of production is required.
DMLS	Design freedom, smoothness, and material reusability.	Post-processing of porous parts.	This could be an alternative method for producing EDM electrodes.
SLM	Highly complex geometries can be produced, resulting in the creation of strong and durable parts.	The high cost of machines and materials is a significant factor to consider. Another important consideration is the high temperature gradient, which can compromise the structural integrity.	A reliable approach for EDM electrode
SLA	A variety of materials can be printed	Curing is required after printing and large parts cannot be printed.	This method is not suitable for EDM electrodes.

Table 2: FDM method of electrode manufacturing

Electrode Application	Advantages	Disadvantages	Conclusion
The optimization of performance was achieved for an electrode created by electroless coating on an ABS component. [82].	A satisfactory result was obtained by utilizing a basic electroless technique to achieve a 1.5 mm metallized thickness on parts produced through FDM fabrication.	Machining was carried out based solely on the L9 array, and the machining was limited to a maximum value of 6A. To establish the effectiveness of the prepared electrode, it is necessary to perform testing using higher currents.	The performance analysis indicated that current is the dominant factor when compared to voltage and pulse on time. The optimal parameter settings for the prepared electrode were determined using the main effect plot.
The study was conducted to assess the effectiveness of tool electrodes produced through copper electroplating on FDM samples. Two cylindrical electrodes with stepped levels were created, and D2 steel plate was utilized for machining purposes [18].	Once the metallized layer on the electrode is worn out, it can be selectively and accurately re-metallized for reuse. This demonstrated process results in reduced metallization time and material usage, as well as a decrease in cycle time and tool cost.	Despite having numerous benefits, the machining process still falls short in terms of achieving precise dimensional accuracy for drilled holes.	Upon comparison to the solid copper tool, the results demonstrated that the copper electroplated electrode had higher MRR and TWR values than the solid copper tool
The study examined the machinability of an FDM component that had been copper electroplated. The performance of a CE electrode was compared to that of a SC electrode with the same outer dimension [30].	Their conclusion is that the weight of the copper electroplated electrode is considerably less than that of a solid electrode (less than one-third of the weight of a solid electrode), making plated electrodes more convenient to use. Additionally, they proposed that additive manufacturing techniques are a superior alternative for producing intricate shapes that are challenging to create using conventional machining techniques.	The plating process for complex electrode profiles can be challenging, and the accuracy of the plated electrode may differ.	Regarding each performance metric examined, the conductivity of the copper electroplated electrode was equivalent to that of a solid electrode.

Electrode Application	Advantages	Disadvantages	Conclusion
A comparison was made between the performance of pure copper and copper metallized FDM electrodes in machining En-19 alloy steel.[21]	By employing a straightforward electroless technique, it was possible to achieve a thickness of 700 mm on FDM produced components. The effectiveness of metallized FDM electrodes was like that of copper metal electrodes.	The process of fabrication was not completed in a single stage, as there was no rough machining and only superficial machining was carried out, which lasted for a short duration of 35 minutes.	FDM-manufactured EDM electrodes are more appropriate for final machining procedures and can be employed as replacements for intricate metal electrodes that have become worn out.
During the machining process, a comparison was made between the metallized FDM electrodes and SC electrodes in terms of their material removal rate (MRR), tool wear rate (TWR), surface roughness (Ra), and dimensional accuracy [32].	Basic metallization methods such as electroless and electroplating were employed, and a controlling equation to manage coating thickness in electroplating was suggested. In addition, the metallized FDM fabricated electrode exhibited quicker wear than the solid copper electrode.	Various metallized electrodes were used to machine various holes. A single electrode's full machining capability was not investigated. It requires more than on stage of fabrication	During rough, semi-finish, and finishing machining procedures, it was observed that metallized FDM fabricated electrodes were less suitable than solid copper electrodes. Additionally, recommendations for optimizing machining conditions to enhance efficiency were put forward.
A comparison was made between the machining capabilities of FDM electrodes and solid copper electrodes. [24]	The electroless process was an economical and uncomplicated method. When intricate-profiled electrodes became worn out, they needed to be speedily duplicated using FDM electrodes.	The absence of established literature and incomplete machining dimensions suggest that the machining was hastily performed.	In every way, the FDM electrode doesn't match the machining performance of a conventional copper electrode.
The practicality of using FDM electrodes for EDM on Ti-6Al-4V alloy was explored. Two different EDM techniques were utilized: [27].	The use of FDM electrodes showed significant promise for powder mixed EDM, particularly when it comes to creating intricate shapes. when aluminium powder was mixed with dielectric during machining, the average surface quality improved significantly.	The technique employed for coating was not revealed, and the machining dimensions were incomplete or absent.	The combination of Powder mixed EDM with both FDM and CNC electrodes has shown enhancements in MRR, TWR, and Ra. Nonetheless, this technique is restricted in terms of the types of materials it can work with

IV. Direction For Future Research

While FDM has a few benefits for EDM electrode production, it also has several drawbacks and limitations. Dimensional accuracy, surface finish, material limitations, electrode wear, and process limitations are examples of these restrictions. Despite these limitations, FDM-produced electrodes have shown promise in achieving comparable performance to traditionally produced electrodes while being less expensive and quicker to produce. To address these limitations and determine the full potential of FDM for EDM electrode production, additional research is required.

Dimensional precision: FDM-produced electrodes may have a lower degree of dimensional precision than those manufactured using conventional techniques. This can result in inaccuracies in the electrode shape and potentially impact the precision and accuracy of the EDM process. To achieve the desired surface finish, FDM-produced electrodes may require additional post-processing. The surface finish of the electrode is crucial to the EDM process because it affects the precision and quality of the machined parts.

Conductivity requirements may restrict the material options available for FDM-produced electrodes. Conductive thermoplastic materials may not be compatible with all EDM processes, necessitating additional testing to ensure compatibility.

Electrode wear may be greater for FDM-produced electrodes compared to traditionally produced electrodes. This can shorten the lifespan of electrodes and necessitate their replacement more frequently. FDM-produced electrodes may not be suitable for all EDM processes due to process limitations. The properties of the electrode material may impact the performance and precision of the EDM process, and additional testing may be necessary to determine the suitability of FDM-produced electrodes fora particular applications.

V. Conclusion

In conclusion, the Fused Deposition Modelling (FDM) method of Electrical Discharge Machining (EDM) electrode production offers several benefits over conventional manufacturing techniques. The FDM method offers greater design flexibility, permitting the production of complex geometries and custom shapes. This method also enables faster and more efficient EDM electrode production, resulting in reduced lead times and lower production costs. In addition, the FDM technique permits the use of a greater variety of materials, such as plastics, composites, and metals. This allows manufacturers to select the optimal material for their application, leading to enhanced performance and durability of EDM electrodes.

However, the FDM method has some limitations, including a lower level of precision and surface finish than conventional manufacturing techniques. In addition, the FDM method is unable to produce large EDM electrodes since the maximum build size of FDM printers is typically smaller than the size required for some EDM applications. Overall, the FDM method for EDM electrode production shows great promise as a technology that provides several advantages over conventional manufacturing. By utilising the benefits of FDM, manufacturers can produce high-quality EDM electrodes that meet application specifications while reducing costs and lead times.

Conflict Of Interest

The authors have declared no conflicts of interest.

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