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ELECTRICAL DISCHARGE MACHINING (EDM)

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ABSTRACT

EDM is one of the most common and widely applied hard material machining techniques for complex geometries in modern machining. Aerospace, automotive, and mold making industries are able to offer the technique to succeed in their activities. Undoubtedly, the widest challenge in preparing the electrodes in EDM is the traditional preparation by CNC machining, casting, or metal injection molding techniques. The preparations involve significant lead times, complex geometries of tools, and high-cost materials. With the increasing demand for fast, low-cost, and personalized services, it becomes crucial that the advanced additive manufacturing techniques like SLS be used for achieving rapid tooling of EDM electrodes.

The purpose of this paper is to research whether this direct EDM electrode fabrication is possible using SLS technology, directly manufacturing EDM electrodes from a CAD model. SLS is an additive process. The technique uses the selective fusion of fine powder particles with a laser beam to form three-dimensional objects. This process offers the designer a lot of advantages, such as flexibility in design and form, lead times that are shorter than traditional machining processes, and the chance to produce complex geometries not possible with traditional machining processes. Within this work, the study will search for the achievement of mechanical properties, surface quality, electrical conductivity, and overall machining efficiency within a performance evaluation of EDM electrodes fabricated using SLS. This study relates to powder metallurgy of different materials: metallic powders, such as copper, tungsten, composite material designed for additive manufacturing. Material properties, like thermal conductivity, porosity, and wear resistance, are the important factors to assess the performance of powder in EDM applications. An important set of process parameters consisting of laser power, scan speed, layer thickness, and postprocessing were optimized to achieve electrodes that acquire the necessary properties for the effective working of EDM. This study discusses Laser Powder Bed Fusion (LPBF). It is one of the prominent additive manufacturing techniques where complex and high-performance parts can be produced. For the case of pure copper, the material is known to possess excellent electrical and thermal conductivity, but it is problematic to process because of the high reflectivity and good thermal conductivity. This gives the property of low absorption for lasers and high dissipation for thermal, which may prove problematic for the creation of a dense, high-quality part. The research works with optimization of process parameters, namely laser power, scanning speed, hatch spacing, and layer thickness for enhanced processability of pure copper powder. Advanced sources for laser were used, that include green and blue lasers having a wavelength better suited to being absorbed by copper rather than its reflectivity. In conclusion, the study evaluates how all these parameters affect the fabricated electrodes in terms of their density, surface finish, mechanical properties, and electrical performance. Significant observations were made about how it was seen that using the high-power, short-wavelength laser resulted in greater energy absorption and hence higher and uniform densification. Over 99% relative density with suitable material properties for application in electrodes was obtained in a certain parameter window. In the present study, the focus was on the importance of post-processing by annealing, relieving residual stresses, and further increasing conductivity for LPBF-processed copper parts. Overall, it demonstrates the capability of LPBF for the production of pure copper electrodes and delivers insights into overcoming material-specific challenges and opens pathways towards industrial applications in electronics, energy systems, and electrochemical processes.

Keywords: Rapid tooling, EDM electrodes, Selective Laser Sintering, additive manufacturing, electrical discharge machining, metal powders, copper, tungsten, composite materials, electrode fabrication, material properties, surface finish, electrical conductivity, process optimization, laser sintering, design flexibility, rapid prototyping, machining efficiency, techniques of additive manufacturing, post-processing, wear resistance, thermal conductivity, lead-time reduction, precision tooling, manufacturing efficiency, material selection, and the related manufacturing challenges with complex geometries.

1. INTRODUCTION

Electrical Discharge Machining or EDM is a widely used, although not the least yet applied in precision machining in aerospace, automobile, and mold making industries where high accuracy and the ability to machine hard intricate materials becomes utmost important. The process is established with the idea of an electrode making controlled sparks that actually cause the erosion of material on the workpiece to enable even the most precise formation of complex shapes. The performance of the EDM process depends mainly on the quality and design of the electrode, so the fabrication phase holds a very crucial place in the entire machining workflow. In the past, it has traditionally been fashioned by techniques such as CNC machining, casting, or metal injection molding. Despite their long history, major drawbacks of these techniques include long lead times and heavy material costs, leading to design limitations that contribute to lower productivity, especially Rapidly AM technologies that are generally faster, more flexible, and less expensive have triggered a growing interest in tooling applications as well. Among several AM methods, SLS has found to be one of the most significant methods for direct CAD-based fabrication of high-accuracy components. SLS involves applying a laser to selectively sinter fine powders, such as metal, to form solid objects one layer at a time. It mainly offers major benefits such as the ability to make complicated geometry, less lead time, and elimination of the need for conventional tooling that is expensive and time-consuming. Despite the several promising potentials of SLS, its application in EDM electrode manufacturing was still at its preliminary stage. The biggest challenge remains to ensure that the electrodes produced by the SLS possess desirable mechanical properties and electrical conductivity, with good surface finish, to execute efficiently in the EDM process. Special EDM electrodes require high thermal conductivity and wear resistance, with minimal porosity as well; thus, these must be selected specifically with appropriate optimization of the SLS parameters. In addition, critical balance between electrode geometry, properties of material, and EDM performance should be ensured so that at least the same performance can be achieved with SLS-manufactured electrodes as with conventionally made electrodes. Laser powder bed fusion a type of Additive technology that, with the selective melting of metal powders via a laser beam, allows constructing parts layer by layer: LPBF. Provides abilities to fabricate geometrical structures with characteristics not accessible when using additive technologies. For example, copper has fantastic electrical and thermal conductivity values. Appropriate for application in production of the following parts: electrical components, electrodes, heat exchangers, and more. Pure copper has high reflectivity, reducing its absorption of lasers, making it challenging to melt effectively. Pure copper electrodes are therefore critical in industries like electrical discharge machining, welding, and power generation. High reflectivity to near-infrared laser wavelengths used in LPBF leads to considerable energy loss during melting, thus affecting the melting efficiency and part density. High Thermal Conductivity rapid heat dissipation in copper poses challenges in maintaining a stable melt pool, thus potential defects like porosity or incomplete fusion may be created. LPBF makes use of a high-energy laser beam that selectively melts and fuses metallic powders, building parts directly from 3D digital models. Among various metals, pure copper has been of great interest in LPBF due to its high thermal and electrical conductivity, which makes this material the best choice for crucial applications such as electrodes for electrical discharge machining (EDM), power systems, and thermal management devices.

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 laser sintering process. The papers also show that academics are interested in the most important trends, influential works, and research directions for the future.

2.1 Electrode by Selective Laser Sintering (SLS): This study investigates EDM tool electrodes manufactured using Selective Laser Sintering (SLS), with emphasis on their performance using X210Cr12 and C45 steel work materials. It observes that the higher the scan speed during fabrication, the higher the porosity of the electrode, which consequently leads to increased wear and lower MRR [5]. Bronze-nickel electrodes are very effective for finishing, while copper-bronze-nickel is very effective for rough machining, and Copper-coated nickel-based bronze gives improved wear resistance and conductivity, and steel-phosphate and polyester composites also show improved wear resistance with copper post-sintering, and other composites like TiB2-CuNi is very high in wear resistance, but Mo-CuNi is less effective [5]. Specific parameters on an EOSINT M-280 SLS machine have been used to produce AlSi10Mg EDM electrodes, which are mostly aluminum, silicon, and magnesium, with a diameter of 12 mm, according to SEM and EDX analysis [5].

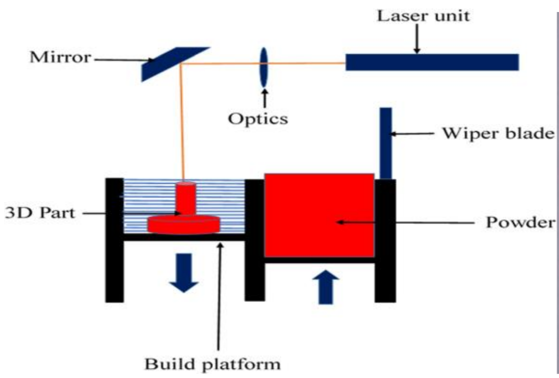

Figure1. SLS process [5]

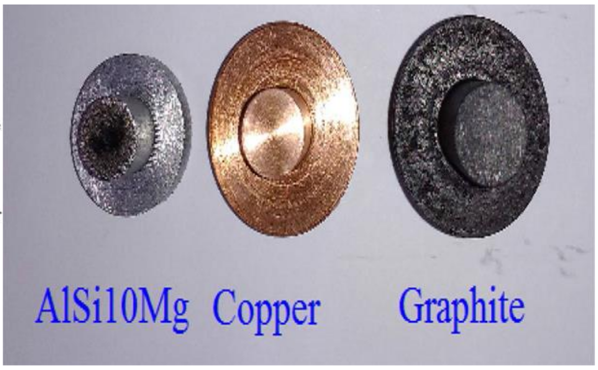

figure2. Tool electrodes [6]

The manufacturing process of SLS EDM tool electrodes is also provided in the review, where high-power laser sintering of AlSi10Mg powder is done at controlled conditions [6]. This process is carried out in EOSINT M-280, having certain parameters such as 30 μm layer thickness, laser power of 400 W, and an argon environment with 200°C [6]. The stepped cylindrical electrode diameter is 12 mm. For comparison, copper and graphite electrodes of equal sizes were made by conventional turning and then studied in EDM operations on a titanium work piece 6.

This review further elaborates on study which has explored the direct production of EDM electrodes by using Selective Laser Sintering (SLS). The paper tries to optimize the critical parameters such as layer thickness, laser scan speed, and scan line spacing for densification, porosity, and surface morphology. Performance of these optimized settings-made electrodes were tested in EDM experiments compared with solid copper and copper powder electrodes. In materials used, a Cu-Ni matrix with the presence of reinforcements of ZrB2, TiB2, and Mo was subjected to controlled SLS conditions [22, 23]. The result showed that composite material can be efficient electrodes in EDM manufactured using the SLS process. They can serve as potentially good alternatives against traditional electrodes.

2.2 Manufacturing of EDM electrodes by laser sintering process

Emergence of Additive Manufacturing: AM is termed revolutionary technology since the 1980s that permits layer-by-layer three-dimensional construction of complex parts directly from digital data files. This method is much advantageous than traditional manufacturing processes with its flexibility, lower waste, and lesser costs [1].

Diverse Applications: The applications of AM are diverse ranging from aerospace and mechanical engineering to medical sciences. This technology is particularly useful when creating complicated parts that demand a high degree of accuracy [1].

Direct Metal Optical Laser Sintering (DMLS): DMLS is noted as one of the most significant laser-based AM technologies that can help produce almost fully dense metal parts. It employs a laser to sinter or melt metal powders in the formation of highly complicated geometries and mechanical properties [1] [2].

Importances of Parameters: Some process parameters have a serious influence upon the DMLS process in terms of the quality of components produced through the technology: These process parameters include laser power, scan speed, and layer thickness. Optimizing these parameters will see to it that high-quality outputs are produced [2][3].

Comparative Study of EDM and SLS: From the paper, it was shown that there is a need to compare the performance of EDM with SLS techniques. Both have distinct benefits, and their efficiencies regarding material removal rates as well as wear volumes must be realized for selecting the appropriate method in specific applications [4].

Focus should be on Multi-Objective Performance Measures: Focus in the prior work has been mainly on multi-objective performance measures that are tool wear rate (TWR), material removal rate (MRR), and surface roughness. Further study of the hybrid method that happens in this case, the Taguchi method might improve the analysis made on the performance metrics [1].

Pilot Studies and Experimental Design: The literature also signifies the importance of pilot studies in refining experimental designs as well as for the reliability of the results obtained. These studies help in the selection of appropriate process parameters for EDM and SLS [5].

2.3 LPBF Experimental Setup

Preparation of Laser Beam:

Produce a laser beam from the source laser. Send the laser to the collimator to make the laser beam parallel and thus have uniform intensity. Send this laser beam to a galvanometer that controls its direction.

Beam Focusing:

The galvanometer allows a beam to pass through an F-theta lens. This implies that the F- theta lens focuses the laser beam at such a point size for excellent melting at a micro-spots size on the platform during building.

Shielding Gas Chamber:

A laser beam with shielding gas goes through the laser transmission window where the laser beam transmits over chamber. The shielding gas, normally argon or nitrogen, prevents oxidation of the molten metal and stabilizes the laser interaction with the materials

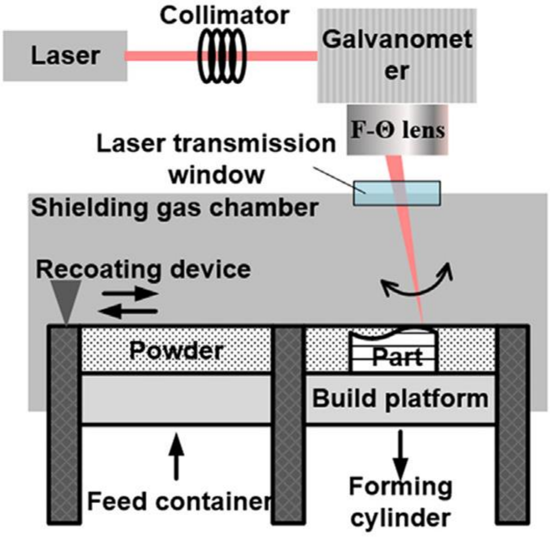

Figure3. LPBF Experimental Setup

2.4 microwave sintered composite tool for electro discharge machining of Titanium alloys

A blend of advanced sintering techniques with material selection and precise manufacturing processes is used in order to create a microwave-sintered composite tool for EDM of titanium alloys. composite tools and applying them effectively in EDM operation. Material Selection for the Composite Tool In order to fabricate a composite tool that is optimized for Electrical Discharge Machining (EDM) applications, particularly for challenging materials such as titanium alloys, the following materials are frequently selected:

1.Matrix Material: Copper (Cu): This is the principal matrix material used in EDM tools because it has better thermal conductivity and an excellent electrical conductivity characteristic. Copper Alloys, such as Cu-W: Tungsten-copper composites are widely used since these materials impart excellent thermal and electrical conductivity along with outstanding wear resistance. Graphite: This is used in combination with other materials primarily because of its excellent thermal stability and passable wear resistance. Cobalt-Based Alloys or Tungsten Carbide (WC): These are used to build wear resistance. They retain hardness and strength even at a high temperature. Reinforcement Material: Ceramic Particles: Silicon carbide (SiC), aluminum oxide (Al_2O_3) or titanium carbide (TiC) particles are added for improvement of abradability, hardness and thermal stability. Graphene: In advanced certain formulations, graphene might be added to improve the electric conductivity, wear resistance along with structural integrity up at high temperatures. Other Additives: Binder A good binder can be either of a polymer or ceramic type, whereby composite materials retain their structural form even before sintering occurs. Conductive Elements This composite tool should retain the electrical conductivity during the process of EDM; therefore a conductive matrix, perhaps of copper or one of its alloys is used. 2. Composite Powder Fabrication The preparation of the composite powder is an important second stage: Powder Mixing: Homogeneous Mixing: The selected matrix and reinforcement powders are mechanically blended or using the ball milling technique, so that reinforcements are distributed well within the matrix.

Particle Size Control: This process requires strict control over the particle size distribution to enable efficient sintering and to avoid defects such as poor sinterability or excessive porosity. Binder Addition: A binder is added if the powder requires a binder to aid in the forming process. The choice of the binder depends on the required sintering temperature and the final properties of the tool. 3. Microwave Sintering Technique Another advanced and progressive technique to fabricate tools is microwave sintering. Microwave sintering uses microwave energy to raise the temperature of the composite powder so that solid and structurally sound tools can be formed.

Moulds encompassing the composite powder are subjected to compression to achieve the requisite morphology of an Electrical Discharge Machining (EDM) tool, for example, an electrode or a tool insert.

Green Body Formation. The mold is compressed to produce a so-called "green body", which is the tool structure without reaching full density. The intermediary product can be removed through low-temperature thermal treatment cycle known as debinding. The material displays microwave energy absorption, which causes localized heating and accelerates sintering in the composite. The use of microwave energy allows for a faster thermal rise compared to conventional sintering techniques, thus improving cycle time and energy efficiency. Cooling and Post-Sintering: Controlled Cooling: After the sintering, the composite tool is cooled slowly in a controlled environment to minimize the formation of thermal stresses, thus minimizing the fracture possibility. Post-Sintering Treatment: Sometimes, further thermal treatment is given to the tool to improve its mechanical properties, which may include hardness or wear resistance. Tool Preparation after EDM Process: After sintering, the composite tool needs preparation to make it ready for use in operation. Shaping and Finishing: Surface Grinding: In general, the tool is subjected to surface grinding for the production of high-quality surface finish while retaining uniform geometry and dimensions that are necessary for the EDM process. Tool Activation: Shaping of Electrodes: If the tool is to be used as an EDM electrode, then it is cleaned very carefully and activated for the proper discharge of electrical impulses during the EDM process. The EDM process comprises the following: Tool Sintering: The microwave-sintered composite tool is installed in the EDM equipment; some EDM equipment is mounted on an inactive electrode, while other ones make use of rotating or reciprocating actions, depending on the available EDM device. Some of the widely recognized types of EDM equipment are wire EDM and die-sinking EDM. Workpiece: A titanium alloy is processed inside the machine, and a gap is formed between the electrode and the workpiece. EDM Process Parameters: Electrical Parameters: The EDM machine parameters are optimized specifically for the titanium alloy material and composite tool in terms of discharge energy, pulse duration, and frequency. Dielectric Fluid: The used dielectric fluid is normally deionized water or oil, which enables the formation and interruption of electrical discharges, which also help to cool down both the tool and the workpiece in the process of machining. Material Removal Process: Spark Erosion: The hybrid tool will produce electrical sparks that lead to erosion of the titanium material of the workpiece so that material is removed precisely. Tool wear: The hybrid tool, however, suffers from material erosion due to electrical discharges. The EDM parameters along with the optimized material composition also govern the wear rate experienced by the tool.

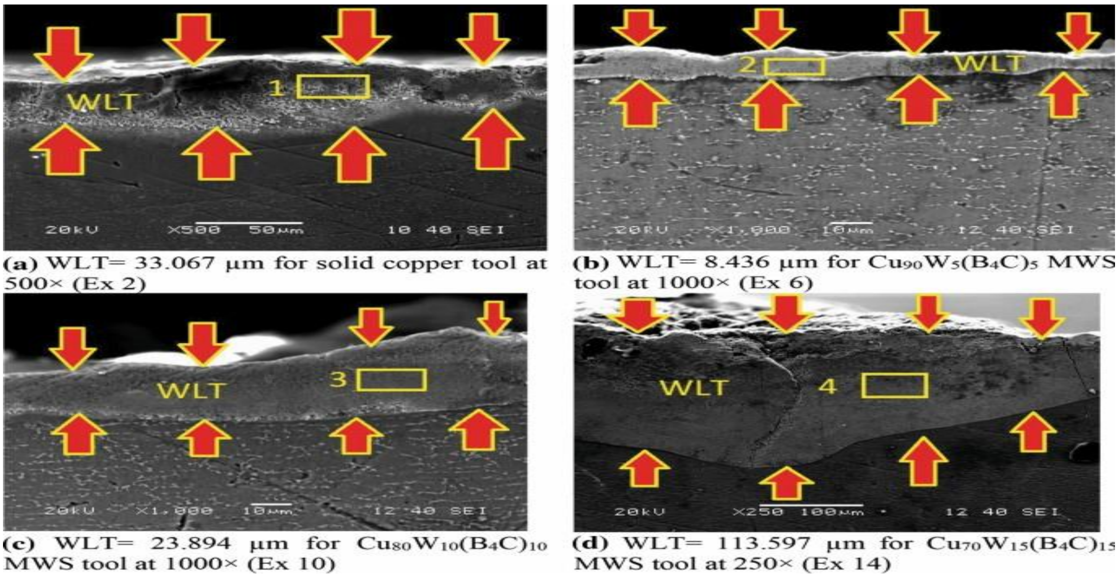

Figure4.Composite tools for EDM

3. RESULTS AND DISCUSIONS

The use of Selective Laser Sintering (SLS) in the manufacturing of EDM electrodes is an innovative approach that exploits the flexibility and fast production of additive manufacturing to enhance the productivity of processes in EDM tooling. This aspect of EDM electrodes is highly crucial when trying to make elaborate molds, dies, or components and especially in those geometries or materials with complex geometry that is otherwise challenging in terms of machining. There is therefore, tremendous scope for cost-effective customized, and rapidly producible EDM electrodes in applying the SLS technology.

3.1 Material selection for EDM electrodes

The selection of the material to be used in the fabrication of EDM electrodes is critical because it has a direct impact on machining efficiency, the rate at which the electrodes degrade, and the general performance. Traditionally, the electrodes used in the fabrication process were made of copper, graphite, or copper alloy; however, these materials have high costs and require preparation times for long periods to put them in the machines and are vulnerable to increased wear during EDM.

Materials Used in SLS-based EDM Electrodes: Materials like stainless steel, copper, and tungsten are widely used as metal powders in EDM electrodes due to their excellent thermal and electrical conductivity along with excellent wear resistance. Composite Materials: Metal-polymer composites and conductive polymers have been introduced in SLS, which offer an excellent combination of mechanical properties and processing benefits. Graphite Powders: Graphite is one of the most commonly used electrode materials in EDM, mainly due to its excellent thermal conductivity and low wear rate. In SLS applications, the sintering process is usually complex and problematic when high graphite content is used and particle bonding is optimal.

The stainless steel and copper powder-processed SLS electrodes displayed adequate electrical conductivity and could withstand the necessary conditions for EDM processing; however, their wear rates were slightly increased compared to conventional copper electrodes. Though the composites showed promise, the optimization of laser parameters was critical in order to attain uniformity and satisfactory electrical conductivity.

3.2 Surface Quality of SLS Fabricated EDM Electrodes

The quality of the surface of the electrode is a critical determining factor for material removal rates, machining precision, and the rate of wear of an electrode during the machining process; thus, surface quality stands out as a dominant aspect in EDM operations. Normally, the SLS method results in a coarser finish than conventional machining; thus, it affects the performance of EDM processes.

Factors Affecting Surface Roughness Laser Power and Scan Speed: High laser power can cause over-melting with spattering that creates a highly rough surface. Low laser power may lead to insufficient sintering resulting in products of insufficient density, which is not adequate for good conductivity.

Layer Thickness: The surface of the electrodes tends to look relatively rough, and layer lines are much more pronounced because the layers are thicker. This means that even though the construction time is a bit longer for thicker layers, it ends up yielding better resolution.

Generally, SLS electrodes have a surface roughness in the range of Ra 50–150 µm depending on the laser parameters used. This roughness is therefore higher as compared to copper or graphite EDM electrodes, which typically range at Ra between 20–50 µm. Impact of EDM Performance: The high surface roughness of the SLS electrodes does not significantly affect the overall performance of EDM, especially on the roughing operation where, in most cases, much material is removed at larger rates. However, during precision machining operations, surface treatment may sometimes be required after EDM.

Electrode Wear: The surface roughness of the EDM may increase wear rates, but in the SLS-produced electrodes, wear rates were of the order as found commonly with widely used conventional graphite electrodes for most applications. Surface roughness and associated wear are reduced as part of the process can be optimized through control of scan pattern and layer thickness.

Discussion: The finishing techniques used to SLS-fabricated electrodes are mainly polishing, grinding, and electrochemical finishing. These are applied with the objective of reducing the surface roughness and maximizing the accuracy of EDM machining processes using the electrodes.

3.3 Mechanical and Thermal Properties

The primary attributes of mechanical and thermal properties of Electrical Discharge Machining (EDM) electrodes, which are critical for performance under elevated temperatures during the EDM process, encompass key characteristics such as thermal conductivity, electrical conductivity, hardness, and wear resistance.

Results concerning Mechanical Properties: Density: The density of electrodes manufactured through Selective Laser Sintering (SLS) varies from 90 to 98% of the theoretical density, depending on the selected material and process parameters. High-density electrodes are often associated with better mechanical properties along with high wear resistance. Hardness: This parameter depends on the powder type and the sintering process parameters. The hardness of SLS electrodes is found to be comparable to electrodes fabricated through conventional processes, although showing a slightly increased brittleness. Thermal Conductivity: The SLS-fabricated electrodes, comprising of metals like copper or stainless steel, showed excellent thermal conductivity; however, these were inferior to the traditionally machined copper electrodes. Such a difference may affect the heat dissipation process in EDM, thus causing localized heating, which could enhance wear rates over a longer operational period.

Wear Resistance: The SLS electrodes demonstrated acceptable wear resistance when used in traditional EDM applications, but were poorer than in traditional EDM materials. For improving electrode life specifically for certain applications, composite SLS materials, like those containing copper infiltration, are superior to other materials regarding wear resistance. Materials Optimization: Hybrid materials, such as copper-graphene or metal-carbon composites, added to the SLS electrodes will greatly improve their mechanical and thermal properties. Indeed, there is a greater capability to control powder characteristics and sintering conditions that could lead to improved conductivity and wear resistance.

Thermal Management: The poor thermal conductivity of some SLS electrodes creates an issue in precision EDM, where thermal sensitivity takes priority. Adding materials with high thermal conductivity, such as copper or copper composites, would well eliminate this issue.

	AISI M42	A6082
Melting point (solidus) [ºC]	>1500	555
Hardness	65 HRC	40 HB
Specific heat capacity [J/kg/K]	420	894
Thermal conductivity [W/m.K]	180	160
Density [g/cm^3]	8.0	2.7
Machinability [%]	40	190

Figure5. Typical properties of materials under EDM Testing

4. CONCLUSION

This work obviously shows huge scope for the process of SLS to be utilized to rapidly tool EDM electrodes in order not to depend on the conventional manufacturing techniques such as CNC machining and casting. Results further indicate that SLS can manufacture EDM electrodes with high geometrical complexity and design customization through technologies impossible overy difficult to realize with traditional techniques. There is the advantage of reduced lead times and design flexibility, with SLS thus presenting attractive benefits for applications that require fast prototyping and production of electrodes.

The results of experiments demonstrated that the electrodes produced with SLS are particularly suitable for comparable performance by a conventional EDM electrode if optimized in material properties as well as in process parameters, especially concerning material removal rate and electrode wear. In the study, porosity issues related to material shrinkage, and post-processing for surface finish and conductivity surface before wider industrial adoption also follow. The study identifies the crucial selection of proper material into the right level of thermal conductivity, strength, and wear resistance through experimentation with different metal powders like copper, tungsten, or a composite material required to ensure effective EDM machining.

Although SLS technology in the production of EDM electrodes is in its infancy, this study implies that material development, process optimization, and post-processing techniques will pave the way for breaking the above-mentioned limitations. For overcoming these issues, future research work should attempt to optimize the process of SLS in order to improve electrode quality, reduce material costs, and extend the number of materials that would be feasible to use for EDM applications.

Finally, it can be stated that the research confirms that SLS has the potential to make some great differences in EDM electrode manufacturing; thus, it promises a bright solution for rapid cost-effective customized tooling in high-precision industries. The addition of EDM electrode production into additive manufacturing actually corresponds to the growing need for lead times decrease, increasing freedom and flexibility in design, and lowering the production costs within the rapidly evolving manufacturing landscape.

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