Fabrication and Application of Composite Electrodes in Electrical Discharge Machining-A Review

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ABSTRACT
Electrical discharge machining (EDM) is a non conventional machining process extensively used in the machining of hard to machine materials and in die manufacturing industry. The major cost component in EDM is the cost of the electrode. The conventionally used electrode material like Copper and Graphite has very low wear resistance and wear out fast. There is continual process of finding electrode materials which have optimum value of electrical conductivity, thermal conductivity and wear resistance. Different composites of various combinations of material have been used in search of alternative tool material. This paper presents a review of different materials used for the manufacturing of composite electrodes for EDM and their fabrication techniques. It has been observed that among the different electrode fabrication techniques available, powder metallurgy has shown very good results.

Keywords
Electrical discharge machining, Material removal rate, Powder metallurgy, Rapid prototyping, Tool wear rate

1. INTRODUCTION
There is a perception in metal working to use right tool for the job. Choosing the correct cutting tool material for a particular machining operation is the beginning step in generating the most productive process plan for manufacturing a part. The selection of cutting tool material depends on the work material and the operation to be performed. Often, there are possible choices of tool materials that will produce the parts successfully but not cost-effectively [1]. Electrical discharge machining (EDM) is one of the most assuring and broadly used nonconventional machining process. In EDM, as soon as a suitable voltage is applied across two electrodes which are separated by a dielectric, the electrons break from cathode and move towards the anode due to the presence of field forces. These electrons collide with the molecules of dielectric and ionize the dielectric molecules. The electrons generated due to primary collisions are again accelerated, undergoes collision, leads to the establishment of plasma channel. Then there is avalanche motion of electrons towards the workpiece. The workpiece continuously impinged by the high energy electrons. The kinetic energy of the electrons converts into thermal energy resulting in the temperature as high as 10000°C-12000°C. There will be localized melting and vaporization resulting in material removal [2, 3]. The concept and discharge phenomenon of EDM is shown in figure 1.

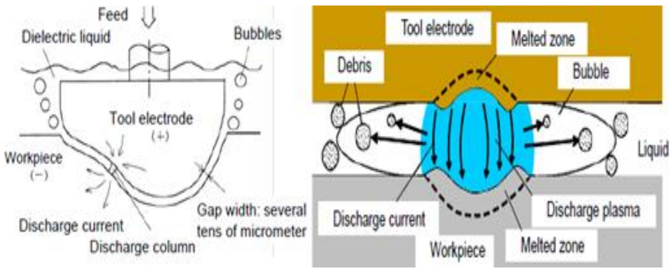

Fig 1: Concept of EDM [4]

The EDM has been a widely acknowledged process for manufacturing of dies in forging and extrusion industries. The machining of super alloys, metal matrix composites, advanced ceramics, etc., with close precision and surface finish can be done by EDM acceptably where the traditional machining fails. In EDM, the work-piece can be treated to full hardness before machining thus minimizes dimensional instability due to post-treatment. It is also effective for machining brittle materials, as there is practically no contact between the tool and work-piece. The intent of machining process is to achieve higher MRR at low TRR with tolerable surface roughness [5, 6].

Customarily, the considerable cost and time components in machining by EDM are in the electrode fabrication, which can charge for over 70% of the total machining cost [7]. An essential requirement is the selection of a suitable material for use in EDM electrodes. Commonly used materials for EDM electrodes are various forms of copper, graphite, tungsten, brass, silver and steel [8]. Copper (Cu) is the most frequently used commercial EDM electrode material due to its admirable electrical and thermal conductivity. However, Cu has high electrode wear rate due to its low melting point and makes it imperative for another material to be introduced. To reduce electrode wear, materials having high melting point with good electrical and thermal conductivity are used in copper based electrodes. Commonly used materials in the manufacturing of electrodes are Graphite powder, SiC, TiC, ZrB_2, WC, CNT powder etc.

The traditional machining processes are generally used for the manufacturing of the EDM electrodes. But with the introduction of new electrode materials, the method of fabrication of EDM electrode has also diversified. For the complicated shapes electrodes may be fabricated by machining, metal spraying, electroforming, casting, rapid prototyping, powder metallurgy etc. [9]. In the current study the focus will be on to study the materials used in the composites and the fabrication methods of the EDM electrode from composites.

2. PERFORMANCE RATING OF EDM PROCESS

The commonly used process parameters in EDM are discharge current, gap voltage, pulse on time, pulse off time, flushing pressure, duty cycle and polarity. The performance of the EDM is measured in terms of material removal rate (MRR), tool wear rate (TWR) and surface roughness of the surface machined (SR).

In EDM process, to obtain the desirable performance, the optimization of process parameters required. Besides MRR, TWR and SR, the dimensional accuracy and geometry of electrode and the material properties also has very big influence on the EDM of performance [10]. In figure 2, the evaluation of electrode performance is done in terms of process parameters, electrode shape, surface finish, dielectric fluid, workpiece material and dimensional accuracy**.**

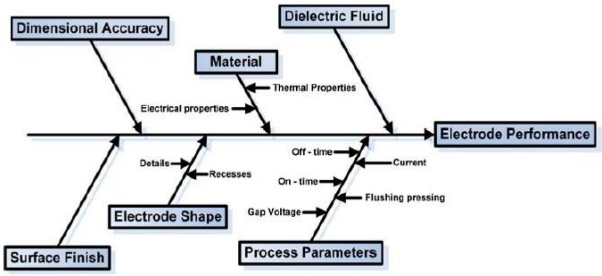

Figure 2: Factors affecting the electrode performance [10]

3. METAL/CERAMIC POWDERS USED FOR THE FABRICATION OF ELECTRODES

The use of copper has very restricted use due to its low hardness, low wear strength and creep resistance properties. The strength of copper can be increased by alloying materials like Cr and Zr but these elements loose these properties by dissolving in copper at high temperature [11]. To avoid this problem, the copper matrix composites are made by the addition of oxide, carbide and the addition of ceramic particles in the copper [12, 13]. When high electrical and thermal conductivity along with high wear resistance is required Cu matrix composites are good choice [14].

Compounds of ZrB2 and TiSi with Cu at various compositions were investigated for EDM electrodes by solid-state sintering and liquid phase sintering by Zaw et al. [9]. Norasetthekul et al. [15] implemented conventional method to synthesize ZrB2-Cu electrodes, starting from mechanical pressing of polymer-coated ZrB2 powders, followed by infiltration of copper into the green body in a high-temperature furnace. It was found that electrode could cut the steel work piece faster than graphite- and copper-shaping tools. For the rapid production of EDM electrodes, direct laser sintering was used by Tay and Haider [16]. Mixture of copper, tin, nickel and phosphorus was used. The results obtained with newly developed electrode were very similar to that of conventional copper electrodes. Meena and Nagahanumaiah [17] tried material "EOS DirectMetal 50" with estimated composition of Cu-65.95 %, Ni-25.35 %, Sn-7.23 % and P-1.40 % as EDM tool. Due to porosity (which was about 20%) excessive tool wear was reported, which limited the use of tool for EDM. Hascalık et al. [18] examined the EDM of titanium alloy (Ti–6Al–4V) with graphite, electrolytic copper and aluminium electrodes. The surface hardness was increased due to formation of Ti24C15 carbides on the surface and cracks were seen in re-solidified layer when machining with copper electrode. The graphite electrode resulted in good results for material removal rate, electrode wear and surface crack density but comparatively poor on surface finish.

Sintering of the ZrB2 powder with the addition of carbon (C) in the range of 0 to10 % and titanium carbide (TiC) in the range of 0 to 30 % was examined by Mishra and Pathak [19]. The addition of Carbon aided densification in the range of 0 to 4 % and blocked densification for 4 to 10 %, whereas, the addition of TiC above 5 wt.% was found to have adverse effect the sintering of ZrB2. The addition of Carbon was also found to hinder the grain size and fine grained ZrB2–C composite could be attained with high densification. The performance of this formed material was compared with that of conventional electrode materials such as Cu, Graphite, and CuW. TiSi/Cu compound was not found suitable as an EDM electrode due to its high electrode wear rate resulting in damage at the workpiece surface. Cu-Cr tool electrode made by powder metallurgy was used to machine hastealloy by Kumar et al. [20]. The highest MRR was obtained at 60V voltage and 18A current. With the increase in current increased TWR was observed due to the presence of high energy at higher current.

According to Geric [1] ceramic cutting tools are the 5% of all the cutting tools used. The shift of use of single phase ceramic material of high purity to multiphase ceramic composite was noticed. The strength and toughness of alumina matrix composite was also analysed. Rise in the properties of Al_2O_3 with the addition of hard particles was also observed. Figure 3, is showing the percentage application of various cutting materials used in industry.

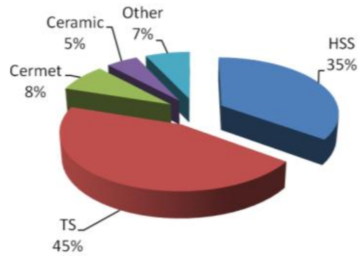

Figure 3: Application of cutting tool materials [1]

Copper-tungsten (solid), copper-graphite and graphite were used as electrode material by Janmanee and Mutumara [21] for the EDM of Tungsten carbide- cobalt work material with on time, off time, open-circuit voltage, electrode polarity and discharge current as process parameters. The electrodes prepared with powder material showed better results for MRR and TWR. The best result for MRR was obtained with negative polarity graphite electrode at 11% duty cycle. Srivastava and Pandey [7] studied the behavior of sintered copper–titanium carbide electrode tip and conventional copper tool tip in ultrasonic assisted cryogenically cooled electrical discharge machining. Electrodes were fabricated by the cermet by mixing, pressing, and sintering. EWR increased with the increase in discharge current however EWR was lower when cermet tooltip is used as compared to Cu tooltip. With the increase of duty cycle there was more spark energy eventually resulted into higher EWR. Cermet electrode tip decreased out of roundness as compared to conventional tooltip. Increased MRR and SR was also recorded when cermet tooltip was used. The surface crack density and crack width on workpiece was less on the surface machined by cermet tooltip. Beri et al. [22] fabricated the electrode with Cu25-W75 and Cu20-W80 by powder metallurgy (PM) and the EDM of Inconel 718 alloy steel was done with these electrodes. The microhardness and the recast layer of the machined surface with PM electrode were compared with the machined surface obtained with solid copper electrode. The microhardness of the surface machined with PM electrode increased from 380.9 HV of the base metal to 496.7 HV of the machined surface. XRD showed the enhanced surface microhardness was as a result of formation of $Fe_2W_3C_6$ phase. Li et al. [23] compared the results obtained from the EDM of Inconel 718 with solid copper electrode and Cu-SiC electrode manufactured by elcetro-deposition. The Cu-SiC electrode enhanced the material removal efficiency by 15.12% as related with the conventional Cu electrode at 7.5 µs pulse-on time and by 16.3% at 24.5 µs pulse on time. At peak current 14.2A there was reduction in Ra by 17.1% and at25.6A the reduction in Ra was 16.5%. High toughness value of Inconel 718 resulted in absence of microcracks on the surface. The electrode wear in Cu-SiC composite was also low due to fine microstructure and higher melting temperature.

From the literature review, it is quite evident that the life of the tool can be enhanced by adding some hardness to the electrode. The inclusion of ceramic reinforcements such as carbides upgrades the properties such as elastic modulus, strength, wear resistance, and high-temperature durability. Self lubricant reinforcement like graphite enhances antifriction properties due to its lamellar structure [19]. The inclusion of graphite to copper matrix surely reduces the strength of the composites. The reduction in strength can be controlled by the ceramic reinforcement. Reinforcements such as SiC have improved the strength of composites, sacrificing the electrical conductivity property [20, 21]. The newer addition of TiC, increases the strength with a marginal effect in electrical conductivity [22].With the availability of lot of tool materials with different properties and with the possibility of different combinations according to specific properties of work material may lead to better results in terms of MRR, SR and TWR.

4. FABRICATION TECHNIQUES FOR EDM ELECTRODE

The machining success of EDM process is dependent on the proper selection of tool. There are many processes available for the fabrication of tools. Due to the availability of different tool materials the techniques used for the manufacturing of tools has been diversified. Machining, metal spraying, electroforming, casting, rapid prototyping and powder metallurgy etc. are the few of the fabrication processes available. In this section, various tool fabrication techniques and the result obtained in the EDM process will be discussed.

Green compact composite electrode and sintered composite electrodes were used by Mohari et al. [28] for surface alterations on work pieces of carbon steel and aluminum in the presence of hydrocarbon oil. Copper, Titanium, aluminium and tungsten carbide were used as material of the electrode. More wear rate was observed due to the low conductivity of green compact or sintered product. Samuel and Philip [29] found Increase in conductivity with the increase in compacting pressure and sintering temperature for copper powder. Low mechanical strength was noticed for the electrodes compacted at low pressure. At high sintering temperature more bond strength was observed resulting in reduced erosion during machining. The increased compacting pressure and sintering temperature earned better performance. Rapid prototype patterns were made by Yarlagadda et al. [30] by stereo lithography technique for the manufacture of EDM electrodes. Their research work dealt with the use of electroformed shell of copper, backed with a suitable material, as an electrode and it was found that electroformed copper electrodes possess very good potential for use as EDM electrode. Durr et al. [31] used direct metal laser sintering to produce metal sintered electrodes from the metal powder consisted of Ni, bronze and a few percent of copper phoshite. The MRR obtained with these electrodes was up to12.5 mm^3/min and showed better TWR than conventional electrodes. Yang et al. [32] built a part by steriolithography which was metalized by electroless plating and then placed in an electroplating solution for metal deposition by electrolysis. After attaining the desired thickness, the part was removed from the metal shell by heating. The shell was then backed with other materials to form an EDM electrode. Rennie et al. [33] revealed an initial study into the use of electroforming for the manufacturing of EDM electrodes. Their study investigated the use of electroforming for the production of thin walled electrodes. It was found possible to use filled thin walled electroforms as EDM electrodes.

Li et al. [6, 34] did the fabrication of electrodes were done by mixing, ball milling, pressing, and liquid phase sintering with copper (Cu) and copper-tungsten (Cu-W), respectively with titanium carbide content varying from 5% to 45%. Electrodes with 15% TiC showed lowest tool wear ratio at low current. Tsai et al. [35] blended the copper powder containing resin with chromium powders to produce tool electrodes. The manufacturing of electrodes was done in a hot mounting machine at low pressure (20 MPa) and temperature (200°C). Such electrodes formed a modified surface layer on the workpiece after EDM, with excellent corrosion resistant properties. Zhao et al. [36] revealed the use of Selective laser sintering (SLS) as a useful method to fabricate an EDM metal prototype directly. The parametric experiment proved that the wear rate of the electrode approached to that of a general electrode, and the surface roughness of the cavity was found acceptable. Electroforming and spray-metal deposition methods were used by Blom et al. [37] for the production of EDM electrodes. The performance in terms of MRR, TWR and R_a obtained with solid electroformed copper and spray metal copper was compared with the performance achieved with the conventional copper electrodes. Due to porosity and uneven thickness in the thermal spray electrode the backing material penetrated and made the electrode unsuitable.

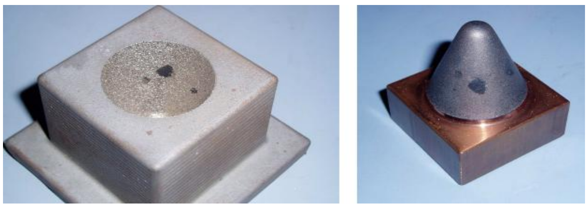

Figure 4: Casting inclusion and electrode wear [37]

Dimla et al. [38] employed copper coating of stereolithography models and copper coating of direct metal laser sintered (bronze) models. Problem was experienced in depositing the copper on both electrode models as in electroplating process enough copper was not deposited in the inner cavities of the electrodes, with very gradual decrease in copper layer thickness from the outer surface to virtually no deposition in the inner walls and bottom face. Resulting in the electrodes was not found usable for the EDM process. Gillot et al. [39] examined the dimensional accuracy of electroplated copper electrodes on positive shape. Due to lack of dimensional performances, electrodes obtained with this process were not satisfactory for industrial use. Ferreira et al.

[40] have investigated the application of indirect rapid tooling (RT) technology to manufacture EDM copper electrodes from investment casting, with wax prototypes made by Thermo Jet 3D printing, a rapid prototyping (RP) technique. 3D digitizing and reverse engineering validated the integration of these technologies as a tool fabrication processes. Hsu et al. [41] studied the use of rapid prototyping system based on electroless plating (nickel plating) and electroforming (copper) for the manufacturing of EDM electrode. This method decreased the manufacturing duration as well as the cost of electrodes.

Monzon et al. [42] used rapid prototyping and electroforming process for the manufacturing of EDM electrodes. In their research they were successful to achieve few things with these newer types of electrodes. The weight of the electroformed electrodes was quite low because of thin copper shell manufacturing. Geometries that were difficult to machine by conventional methods were handled more easily with the use of electroforming. Cast copper electrode and sintered powder metallurgy electrode were employed for electrical discharge machining of EN8 and D3 steels by Balasubramanian and Senthilvelan [43]. The cast copper electrode showed better MRR and low TWR compared to sintered copper electrode for both steels. Less surface roughness was obtained with sintered copper electrode. Pal and Choudhry [44] fabricated copper and brass electrode for EDM process by abrasive water jet machining. A set of holes were made on stainless steel and Ti-6Al-4V. Deviations in the dimensions of the workpiece and the dimensions of the tool produced by abrasive water jet machining recorded. Taper produced on the tool because in abrasive water jet machining jet produced kerf on the fin length. Gill and Kumar [45] did the EDM of hot die steel (H11) with Cu-Mn powder metallurgy electrode. Due to formation of manganese carbide (Mn_7C_3), ferrite (Fe-C) and cementite (Fe_3C) revealed by XRD the microhardness of the work material increased from 615HV to 1191.7HV.

From the review, it can be concluded that the electrodes fabricated by powder metallurgy showed better results in comparison to electrodes fabricated by rapid prototyping and electroplating. Ease of manufacture and flexibility of composition are found to be the main advantages of powder metallurgy technique, giving it an edge over the other fabrication techniques.

5. CONCLUSIONS

From the above study, the following conclusions can be drawn:

- Cermets can be used successfully for the fabrication of EDM electrode.
- Use of reinforcements like SiC, TiC, ZrB_2 and graphite helped in improving mechanical properties like hardness of the EDM tool electrode and reduced wear of electrode.
- The weight of the electrodes obtained with some of the new fabrication techniques like electroforming was less as compared with the conventional methods.
- Complex geometries can be made easily with the techniques like rapid prototyping and powder metallurgy.
- More close control of the properties of the electrode can be achieved with the process like powder metallurgy.
- For large number of electrodes quicker fabrication is possible with process such as electroforming.
- In some of the cases like stereolithography models, the uneven thickness of the material on the inner cavities was observed.

In the future, the study of application of composite electrodes for the EDM applications will be done.

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