A review on machining of metal matrix composites using nanoparticle mixed dielectric in electro-discharge machining

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ABSTRACT

The growth in the new advanced materials that are harder till date have led to the improvement of technologies used to machine them. Nowadays, new materials have been developed to be used in different sectors where lighter and harder materials are in vast requirement. Moreover, materials machined with high precision machine tools have to provide the greatest surface finish such that it catches the pace with other competitive materials. Research has shown that the electro-discharge machining (EDM) is the only machine tool that has created history in machining hard materials. In the recent years, metal matrix composites (MMCs) have an increasing demand in the industries since they are hard materials to machine and a good finish is required in the aerospace, marine, aircraft, nuclear and other similar industries. Thus, EDM has gained fame in machining MMCs. With due course, the powder mixed electro-discharge machining (PMEDM) has created efficient EDM, with the use of powders in the dielectric. The dielectric mixed EDM has been used for efficient material removal rate (MRR). With the change in technologies, the sizes of powders that have to be added in the dielectric fluid go on decreasing. In this review, studies by numerous researchers on the MMCs that are machined with the use of PMEDM are mentioned. The powders used in the experimentation are of nano size. Furthermore, the optimization technique used by the researchers is discussed in the present study.

Keywords: Electrical discharge machining, metal matrix composite, powder mixed dielectric, nanoparticle

INTRODUCTION

In the age of advanced materials like nano-materials, super alloys, ceramics and metal matrix composites, the need of machining the same materials has challenged many researchers in the era of modern machining [1]. These materials find their place in the hard and difficult to cut machine category, requiring high precision and better surface quality pertaining to the higher machining cost. The properties include high strength, high flexural strength, good damping capacity, minimum thermal expansion and desirable fatigue characteristics. To meet the challenges of machining these advanced materials, precision engineering with better surface finish has to be implemented. The thermal, mechanical, chemical and electro-magnetic properties of these advanced materials have failed the conventional machines [2]. On the other hand, the non-conventional machining is gaining speed in the modern manufacturing industries to establish its name and fame

and obtain improved surface finish and minimal machining cost in case of advanced materials [3]. One such non-conventional machining process is the electro-discharge machining (EDM) which is gaining popularity in machining these difficult machine materials with complex shapes. In this process, the material is removed by erosion through a series of continuously electrical sparks between the tool and work piece. The heat or thermal energy developed between the interface cause the melting and vaporization of work piece material. Sometimes the obtained poor surface finish and machining efficiency restricts the application. To superimpose this problem, the EDM with powder mixed dielectric was used [4]. The spark gap had to be increased by adding up powders in the dielectric fluid so as to reduce the insulating strength, thereby making the process more stable than before and improving the material removal rate (MRR) and surface finish (SF) [5-8].

Continuous advancement has led to the use of more and more composite materials [9-11]. The most used are the metal matrix composites (MMCs). The importance of composite is revealed by the truth that it is widely used for all sorts of industrial applications [12-14]. The difficulty in machining by EDM over a MMC has been sorted out by the use of powder mixed dielectric EDM (PMEDM). The powders that are used till date are aluminium, graphite, copper, chromium, silicon carbide, etc.[15]. The use of powder enhances the EDM process which includes the increase in MRR and improves the surface quality. With the improvement of nanotechnology, nanoparticles were introduced in the EDM dielectric fluid to improve yet more surface quality and hence eliminating micro-cracks. Moreover, the suspension of nanoparticles produces a high sparking gap [15]. Factors such as particle size, density and concentrations, electrical resistivity and thermal conductivity of powder sustain effectively in improving the surface quality of the EDM processes [16]. With the use of nano-sized powders, the suspended SiC and Al_2O_3 in the dielectric medium will affect the surface properties. The average reduction in the surface roughness was observed to be ranging between 14% and 24% less as compared to the pure dielectric [17]. The optimisation of various process parameters will yield to the emergence of better surface finish with better MRR and other characteristic properties. In the present work, a study was carried out related to fabricating the different types of MMCs and effect of nano powder mixed dielectric in the EDM process. The utilization of optimization processes upon various process parameters was studied.

METAL MATRIX COMPOSITE

Metal matrix composite includes the matrix as a metal or an alloy, giving high strength to it. The use of various MMCs is due to the fact that it possesses low density, good fatigue response and high strength, specific modulus, thermal conductivity, abrasion resistance, vacuum environmental resistance and wears resistance [9, 14, 18-20]. Since they are difficult to machine using the conventional way, a non-traditional way has been adopted to machine them. EDM being a thermal material removal process is widely used in machining these advanced materials [2]. MMC being machined under EDM has created a benchmark in the field of research. Researchers nowadays are taking interests into advanced materials for the development of yet more advanced products, equipment or accessories for the current generation [1]. The matrix phase in MMCs serves as the load transferring and distributing elements upon the reinforcement or dispersed phase. The load transfer mainly depends on the type of matrix, bonding between the matrix and reinforcement, type of reinforcement and fabrication technique to manufacture the MMC

[21]. The MMCs are mainly classified as the continuously reinforced composites and discontinuously reinforced composites. The continuously reinforced composite comprises long fibres or filaments whereas the discontinuously reinforcement composite constitutes short fibres, whiskers or particles. The properties and behaviour of the matrix material should be as such that it should match the requirements of the reinforcement. Being the primary constituent, the matrix should be chosen with due care so that its chemical attributes should be compatible with that of the reinforcement, pertaining to its own behavioural characteristic properties [22, 23]. Taya and Arsenault [24] suggested many matrix material types such as Al, Cu, Pb, Mn, Ti, Ni, Mg, Fe, Ti, Si, Zn, Ag, etc. on account of corrosion resistance and oxidation properties. Most widely available and used metal alloys are aluminium and titanium. Aluminium fulfilling all the requirements of a good matrix is the best suitably used matrix material [25]. It means it has low density, good fatigue response, and high strength, specific modulus, thermal conductivity, abrasion resistance, vacuum environmental resistance and wears resistance [18] making it best fit for matrix material.

The reinforcement provides strength, stiffness, and temperature resistance capacity, hence lowering the density of MMC. Its characterization is done on the basis of its shape, dimensions, volume fraction, chemical composition and distribution of the matrix [24]. With the use of fibres as the reinforcing material, the anisotropic behaviour of fibre reinforced matrix has been observed. The most commonly used reinforcement elements include Al_2O_3, TiB_2, SiC, graphite, Thorium and Boron. Graphite reinforcement gives high thermal conductive composites with good mechanical properties and high damping coefficients at increasing temperatures [26]. Aluminium reinforcement gives dry properties, and cavity formation upon graphite oxidation leading to manufacturing difficulty, and hence high temperature suitability is denied for these elements [25]. The increased tensile strength, hardness and wear resistance of Aluminium MMC is obtained by the use of Alumina, TiO_2, oxides of others, etc., as reinforcements [27]. On the other hand, Silicon Carbide ceramics shows excellent oxidation, wear resistance, creep resistance and corrosion properties [26]. Thus, they find a huge application in the reinforcement material till date. The most commonly available and used MMCs are silicon carbide particulate (SiC_p) reinforced aluminium composite [28]. Aluminium, being light weight is used as structural material in the aerospace, aircraft and automobile industries. With significant improvement thrusted to the weight ratio, the alumina-based composite is best fit in such applications owing to its temperature resistance up to 750°F (400°C). The difficulty faced from the low strength and low melting point of aluminium was solved by using it as a composite with addition of some reinforcement to increase its strength. Silicon carbide (SiC) in the form of particles or whiskers (short fibres) is used with aluminium matrix to replace the existent super alloys. Continuous fibres of SiC are used in the aerospace applications to reach the desired objective of the high specific strength for design, as compared to that of monolithic materials. The major areas of use of SiC in aluminium are missiles, aircraft and engines of the automotive sectors. Being cost effective, aluminium has taken its place in such industries [29, 30]. The applications of Al-SiC composites are many, starting from moving parts of vehicle such as bearings, pistons, rotors, etc. to the structural parts of aircraft industries. For example, in order to reduce the heat, noise and vibration, brake rotors are made up of 20 vol.% mixed with aluminium matrix with small amount of magnesium in it, as compared to that of rotors made of cast iron.

Fabrication techniques of MMCs

The primary processing in the fabrication of MMCs is done by the following three techniques:

i)   Liquid phase fabrication
ii)   Solid phase fabrication
iii)   Vapour state processing

Liquid Phase Fabrication

Liquid state fabrication technique, being cost effective is used for acquiring complex shapes with liquid metals in casting industries. Some methods included by the researchers are dispersion [31], stir casting [32], infiltration [33, 34], squeeze casting [35], spraying [36], in-situ fabrication [37] and compo casting [38]. On the other hand, the process cannot control the process parameters and there is a certain chemical reaction between the interface of a liquid metal and reinforcement, which is not desirable.

Solid Phase Fabrication

The solid phase fabrication technique is used to obtain the best mechanical properties of the MMCs. The fine-grained micro structured composite is obtained with the discontinuous distribution of the reinforcement. The methods used are diffusion bonding [39] and powder metallurgy [40, 41].

Vapour State Processing

When the vapour phase of the matrix is deposited into the individual reinforcement elements of the component, by means of plasma spraying [42] or physical vapour deposition [43] or chemical deposition [43, 44], then it is said to be the vapour state processing of the composites.

AN OVERVIEW OF ELECTRICAL DISCHARGE MACHINING

EDM being a sophisticated non-conventional machining process has created its own image for machining those materials that are very difficult to cut in a conventional manner. Out of all non-conventional machining processes, one of the most extensively used processes is the electrical discharge machine (EDM). It finds application in modern industries such as aerospace, aircraft, nuclear, bio-medical sectors etc. Materials of any hardness can be cut by this process [45-48]. The most popular advanced materials that are being machined these days are the MMCs. These materials have gained popularity in the aerospace, underwater and transportation industries [3, 49]. Thus, the machining of MMCs in the non-traditional methods is gaining popularity for their use in extremities. EDM is better known as the thermal erosion process, where the tool and the work-piece are applied with a potential difference in a dielectric medium which establishes an electric field. On the establishment of electric field, free electrons are subjected to the electrostatic forces and move towards the work-piece while gaining velocity. As they gain velocity and energy, there would be collisions between the electrons and dielectric molecules. Spark is generated by this process and subsequently, these high speed electrons impinge upon the work-piece and the heat generation takes place. Subsequently the work material melts and vaporizes.

Figure 1 shows the schematic of EDM where the work-piece is submerged in the dielectric medium with the help of a fixture and the tool is held by the tool holder, being operated by a servo controlled mechanism [4]. The voltmeter, ammeter, and pressure

gauge show the readings of potential difference, current flow, and pressure, respectively. The filter is used for removing external unwanted particles, if any, from the dielectric so that machining is carried out smoothly.
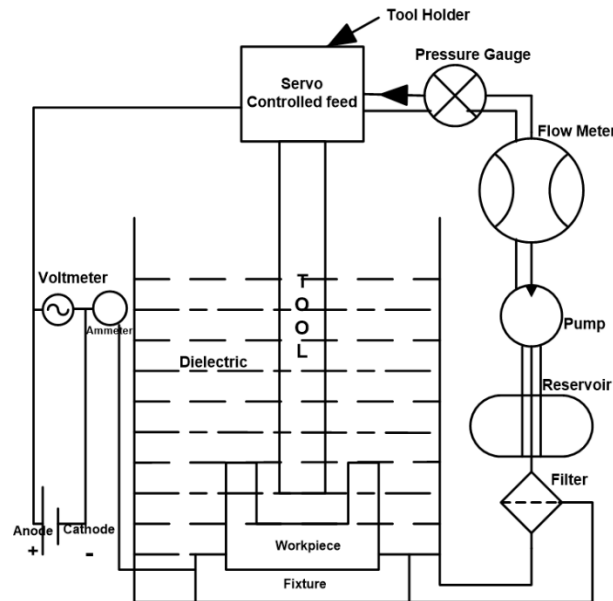

Figure 1. Schematic diagram of EDM [4].

A huge number of MMC components are being manufactured by using EDM which in current trend is used in various applications making EDM gaining pace in the race. A few of them are mentioned in Table 1. EDM has been extensively used in the automotive, aerospace, defence and many such micro industries [2]. Due to this fact of using this unconventional machining process in many advanced industries and being an outstanding developer of low cost products with better quality, EDM has many varieties of its own. The classification goes on with the die-sinking EDM, wire cut EDM (WEDM), dry EDM and rotary disk electrode EDM. The review is based on the die-sinking EDM upon MMCs. Some of the EDM applications upon MMCs are mentioned here in this review.

Wire-Cut EDM

The Wire-Cut electrical discharge machining (WEDM) was first introduced in the late 1960s to be used in manufacturing industries. It is a production process in which the electro-thermal material erosion takes place from the work-piece by a continuous succession of discrete sparks. The sparks occur between the work-piece and wire which are separated by a continuous stream of the dielectric fed to the machining zone [50]. Heat is generated from the electrical sparks, and a thin strand of metallic wire is used for cutting through the work piece material in the dielectric medium. In Figure 2, the WEDM setup is shown, where the wire is seen driven by pulleys onto the work piece. The process is typically used with the de-ionised water as dielectric and brass, zirconium, copper, etc. as wire electrode.

The Wire-cut EDM is meant to cut thick and harder plates to suit well for punches, dies, tools, etc. There is a low cutting force involved in the WEDM since the low residual stress is involved. It has been employed on various hard to cut materials despite precision accuracies. Moreover, composites have created a place in the field of hard to cut materials, in which, WEDM plays an important role. Various researchers have studied the effect of

process parameters upon composites with the help of WEDM [51-62]. A semi-empirical model for MRR was proposed to study the thermo-physical properties of the work-piece [63]. The response surface methodology (RSM) approach was used to study the pulse-on-time and average gap voltage. Furthermore, Patil and Brahmankar [51] studied the effective results of the combination of reinforcement, feed, current, speed, pulse-on-time, pulse-off-time, servo voltage, surface finish and kerf width on Alumina particulate reinforced aluminium metal matrix composites by WEDM using the Taguchi analysis.

Table 1. Research progress with the use of MMCs using various EDM.

| Type of MMC used	Type of EDM used	Remarks	Author (year)
ZrO2-TiB2, ZrO2-TiN, ZrO2, TiC, ZrO2TiCN	Die Sink EDM		Put, Vleugels [64]
AlSiC	PMEDM	MRR improvement	Syed, Anuraag [65]
Al/Al2O3	PMEDM (Al)	Increase in MRR and decrease in SR	Talla, Sahoo [66]
Al6061/Al2O3p20%	PMEDM (SiC)	L18 orthogonal array was used	Singh, Maheshwari [67]
Al/10%SiCp	PMEDM	MRR increased with peak current rise	Kansal, Singh [68]
Al/SiCp	WEDM	Wire breakage showed limitations	Patil and Brahmankar [57]
Al-4Cu-6Si 10% SiC	Die Sink EDM		Singh, Raghukandan [69]
Al/ZrO2	WEDM	RSM approach was used for optimization	Garg, Manna [60]
Al 6063/SiC$_p$	WEDM		Satishkumar, Kanthababu [54]
Al 7075/SiC/Al$_2$O$_3$	WEDM	Current has more effect on kerf	Lal, Kumar [53]
AlSi7CuMg/SiC	Die Sink EDM	MRR improvement	Iosub, Nagit [70]
Al-CuTiB2	Die Sink EDM	TOPSIS method of optimization	Prabhu and Vinayagam [71]
Al-TiB$_2$	Die Sink EDM	low frequency vibrating tool	Madhavan and Balasivanandha Prabu [72]
AlSi7Mg/SiC and AlSi7Mg/Al$_2$O$_3$	WEDM		Rozenek, Kozak [55]
Al6063/ZrSiO4	WEDM	Impact of process parameters	Sharma, Garg [62]
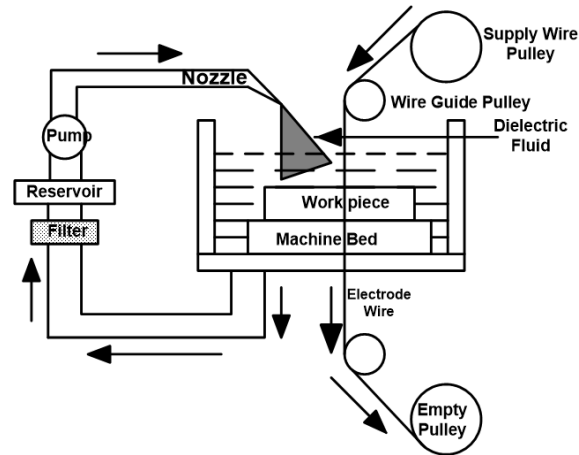
Figure 2. Schematic diagram of WEDM.

Aluminium matrix composite (Al_2O_3/6061 Al) was machined with the analysis of pulse-on-time, surface roughness, cutting speed and width of slit [52]. They found that the wire broke since the cutting speed, width of slit and surface roughness depend on the volume fraction of the Al_2O_3 particles. The low concentrated particles indicate better surface roughness and width of slit. Lal, Kumar [53] investigated the effect of parameters upon Al 7075/SiC/Al_2O_3 hybrid composite and found out that current has more effects upon kerf than the discharge time. Satishkumar, Kanthababu [54] studied the machining characteristics of Al 6063/SiC_p and developed regression equations to predict the output parameters. Rozenek, Kozak [55] carried out experiments to analyse the machining process parameters upon surface roughness of $AlSi_7Mg$/SiC and $AlSi_7Mg$/Al_2O_3 using WEDM. They found that the cutting speed of the specified composites was obtained to be 3 and 6.5 times lower than that of the aluminium alloy. Again, Ebeid, Fahmy [56] initiated a mathematical formulation on $AlSiC_p$ composites and optimized the process parameters (machining voltage, volume fraction, pulse frequency, kerf size and work-piece height of SiC particles) with the WEDM characteristics (MRR, cutting speed and SR).

Patil and Brahmankar [57] conducted experiments on the performance of AlSiCp composites using WEDM by the Taguchi method and found that the cutting speed of an unreinforced alloy was higher than that of the composites, whereas the surface finish in composites was found to be superior to that of the unreinforced alloy. The wire breakage showed limitations post machining process. Shandilya, Jain [58] optimized the process parameters in machining of SiCp/6061 Aluminium MMC by WEDM using RSM. The input parameters pulse-off time, pulse-on time, servo voltage and feed were studied in terms of cutting width. ANNOVA results showed that the voltage and feed rate were more significant than that of the pulse-off time.

Rajaneesh and Sadashivappa [59] studied the behaviour of ZA43/SiCp composite with variations in process parameters; it was revealed that the MRR was reduced and surface roughness increased with the increase in the reinforcement percentage. Garg, Manna [60] conducted experiments to study the effect of WEDM parameters on Al/ZrO_2 particulate reinforced MMC. RSM approach with the central composite design with full factorial was used to optimize and validate the pulse width and duration, voltage and wire tension and feed rate. Srivastava, Dixit [61] showed that the surface roughness increased with the increasing pulse-on time, peak current and volume percentage of reinforcement while machining Al_2024/SiC using WEDM. On the other hand, the MRR increased with

pulse-on time. With the increase in the reinforcement percentage, MRR decreased. Sharma, Garg [62] investigated the impact of process parameters such as voltage, pulse-on time, pulse-off time and current upon cutting rate using WEDM of Al6063/ZrSiO4 composite with the help of a series of experiments. Box-Behnken on RSM was implemented as an experimental approach. The ANNOVA and F-test were performed to reach optimality and it was found that the increase in the current and pulse time shows an increase in the cutting rate. The surface topography of the machined surface showed crater and cracks formation with high pulse-on time and low pulse-off time.

Die Sinking EDM

The die sinking electrical discharge machining is the most widely used techniques for replication of products such as die-casting, injection moulding, etc [73-75]. It is also better known as the cavity type EDM or volume EDM. The set up consists of an electrode and a work-piece submerged in a dielectric fluid, where the power is supplied to both of these as shown in Figure 3. There is a potential difference developed between the workpiece and electrode. The dielectric breakdown takes place, as the electrode substantially move towards the workpiece during the course of power supply. Spark generation takes place with the formation of plasma from the dielectric break down. The sparks strike upon the electrode, and hence the material is removed from the base metal. With the increasingly removal of the base metal, the spark gap increases, hence lowering the electrode for uninterrupted machining. Kathiresan and Sornakumar [76] carried out series of experiments using EDM upon LM24 Al-SiC MMCs and studied the resultant effect of volume fraction of composites and effect of current on MRR and surface roughness. It was found that the MRR and surface roughness increased with the increasing current. Garg, Singh [77] reviewed a comparative study of the die-sinking EDM and WEDM on the metal matrix composites. It was concluded that the SiC reinforced composites are popular among researchers till then, and work includes the performance characteristic analysis and optimization. The study of EDM characteristics of AlSi7CuMg/SiC metal matrix composites [70] showed that an increase in electrode diameter increases the MRR and decreases the tool wear rate. It was also concluded that the increase in the pulse-on time increases the tool wear rate and MRR. Nanimina, Abdul-Rani [78] investigated the effect of process parameters upon Aluminium MMCs. They considered the pulse-on-time, pulse-off-time and peak current and found that an increase in the pulse-on-time and current increases the MRR. The vice-versa showed more tool wear. Ahamed, Asokan [27] conducted a study on the inclusions of B_4C and glass reinforced AlSiC composites. They found that an increase in the reinforcement ratio decreases the surface defects or cracks and the MRR. The in-situ composite fabrication method has limited work and Prabu, Ramadoss [79] experimented upon Al-TiB$_2$ with the help of a low frequency vibrating tool. The results showed that with the increasing current, the MRR and surface defects increase. Prabhu and Vinayagam [71] carried out the parametric optimization using TOPSIS, upon in-situ composite Al-CuTiB$_2$, considering MRR, tool wear rate, and surface roughness. The results were found in good agreement with the run while optimization.

Powder mixed EDM

Powder mixed electrical discharge machining (PMEDM) is the recent generation development to match the innovative technologies. Technologies, no doubt, are reaching beyond limits but beside all innovations, super-finished products have their own image in industries. Thus, the super-finished products can only be obtained by enhancing the

quality, capability, and smartness of the machines these days. Catalysts play an important role in improving the surface quality of products in machining. In EDM, powders play an important role, which when mixed with the dielectric medium, giving the super quality product. Hence, powders are useful in EDM to improve the performance characteristic properties as well as all capabilities of the machine tool. The process involves introduction of fine powders into the dielectric medium to be thoroughly mixed into the fluid. The importance of using the powders is to enhance the breakdown attributes of the dielectric. As the insulating strength of the dielectric fluid decrease, the spark gap between the tool and work-piece increases hence making flushing of debris uniform. Uniformity in flushing results in the improvement of MRR and surface quality.

The working principle of the powder mixed EDM is similar to that of EDM but with few changes in the system. Figure 3 depicts the working principle of PMEDM. With the application of voltage, the powders show energetic behaviour and follow zigzag movement within the dielectric fluid. The powder particles get charged up and are accelerated due to the effect of electric field. The gap between the work-piece and the tool is filled with powder and dielectric mixture, which promotes the breakdown of the dielectric. The spark generation area allows the particles to arrange themselves in chain structure and direction of the current flow permitting the interlocking of the powder particles. A bridging effect is produced out of this chaining of particles, due to the insulating strength of the dielectric decreases. The short circuit occurs during the process that helps in faster sparking and hence faster erosion from the surface of the work-piece material. This leads to the increase in MRR.
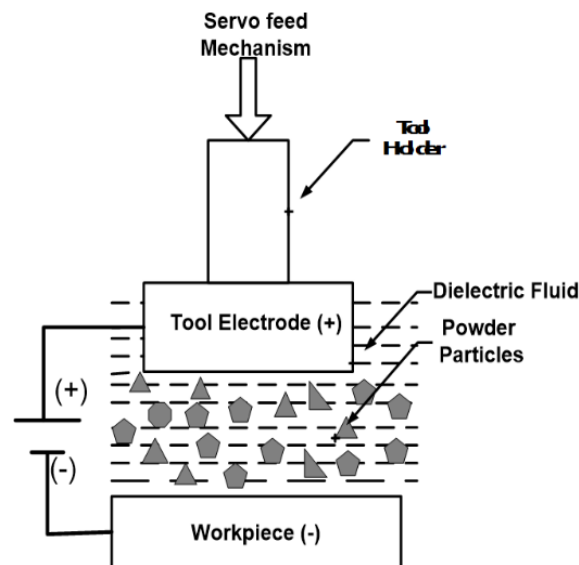

Figure 3. Working principle of PMEDM.

The powders for the powder mixed electrical discharge machining has been used since the 1980s when Erden and Bilgin [80] first reported that the addition of powder particles (Al, Cu, Fe) in the dielectric improved its breakdown characteristics. Many researchers since then started to experiment the use of powder particles in the dielectric. The list goes on with the use of graphite powders by Jeswani [81] . Silicon, aluminium and graphite powders were used by Narumiya, Mohri [82] and they showed that the increase in gap correlates with the concentration of the powders. YAN and CHEN [83] proved that powder particles reduced the surface cracks with the use of alumina particle.

The addition of silicon carbide and aluminium powders into the kerosene dielectric in micro-slit machining of Ti-alloy resulted to the high MRR and material removal depth and increasing gap distance [7]. Tzeng and Lee [84] studied the effect of powder on machine efficiency and concluded that 70-80nm sized powder showed the highest MRR and lowest increment of spark gap.

Table 2. Powders used by researchers.

Experimentation done with the help of urea in distilled water resulted in the formation of TiN layer, better wear resistance on machined surface and increased MRR and electrode wear rate (EWR) with the increasing peak current [91]. Some powders used

Powder used	Author (Year)	Dielectric fluid	Comments (If any)
Aluminium, SiC	Tzeng and Lee [84]	Kerosene	With the increase in particle size, MRR and discharge gap increased. Al produced larger gap than that of SiC
SiC	Chow, Yang [85]	Pure water	Process applied to produce micro-slit
Titanium	Furutani, Sato [86]	Kerosene	Accretion process application
Al	Syed and Palaniyandi [87]	Distilled water	Improvement of MRR, TWR and SR
Copper, diatomite, Al	Muniu, Nyaanga [88]	Distilled water	MRR increases to maximum and then decreases with further powder concentration
Chromium	Garg and Ojha [89]		
Tungsten	Khedkar N K [90]	EDM oil	Higher coefficient of friction in PMEDM
Urea	Yan, Tsai [91]	Distilled water	Improved friction and wear characteristics
CNT	Mai, Hocheng [92]		Machining efficiency increased by 66%
Si,tungsten, graphite	Bhattacharya, Batish [93]	Kerosene, EDM oil	
MoS$_2$	Prihandana, Mahardika [94]		Ultrasonic vibration was used
Nickel	Garg and Ojha [89]	Kerosene	Optimization was done using software
Nano-graphite	Choudhary and Jadoun [49]		Machining time reduced five times faster
Graphite and boric acid	Cogun, Özerkan [95]	Kerosene	Electrode wear rate, MRR, relative wear, SR, surface hardness was studied
SiC	Rival [96]	Kerosene	Higher MRR and SR values

by researchers are mentioned in Table 2. With the development of super alloys, composites and advanced materials the machining became a challenge for researchers. Out of many researchers, few started working on the metal matrix composites with powder mixed EDM. Kansal, Singh [68] developed an optimum machining conditions for PMEDM with Al powders upon Al-10% SiC MMC using the response surface

approach. The results show that MRR increased with the increase in peak current for no specific value of pulse duration. Moreover, the surface roughness increased with the peak current and pulse duration rise. Peças and Henriques [97] studied the effect of Silicon powder in dielectric with a conclusion that a small amount of additive in dielectric significantly reduces the crater wear and white layer thickness. They also concluded that powder concentration affects the surface characteristics. Singh, Maheshwari [67] in their work on EDM with SiC abrasives in dielectric fluid upon Al6061/Al_2O_3/20p used quantitative analytical method to optimize the process parameters. The Length's method was used to analyse the results and it was found that as compared to the conventional EDM, PMEDM gave better MRR and reduced surface roughness. Talla, Sahoo [66] fabricated and machined Al/Al_2O_3 MMC with PMEDM using aluminium powder. They developed semi-empirical models as well as carried out multi-response optimization using the grey relational analysis. The proposed parameters include powder concentration= 4g/L, pulse-on-time=150ms, peak current =3A and 85% duty cycle. Singh and Yeh [98] did multi-objective optimization using the grey relational analysis for 6061Al/Al_2O_3 MMC with SiC abrasives using PMEDM and found the results for low surface roughness and high MRR.

Micro particles came into existence with the trending technologies.Prihandana, Mahardika [94] suspended MoS_2 in a micro form into the dielectric fluid and an extra ultrasonic vibration. The results show that ultrasonic vibration and the addition of micro particles significantly increase the MRR with improvement in the surface quality. In another set of experiments, [94]introduced graphite powders in the dielectric fluid and reduced the machining time by five times faster than that required in the pure dielectric. Moreover, the vibration of the electrode upon the work-piece shows significant variations in machining time up to three times faster. Garg and Ojha [89] introduced the nickel micro powder in the dielectric fluid to analyse the performance upon EN 19 steel. In a further study, Ojha, Garg [99] varied the electrode shapes upon the same material using the nickel micro powders and developed an optimization model to assist the process parameters. During the course of super-finished products from the powder mixed electrical discharge machining with the help of introduction of powders to micro-powders, the race still abides the technological advancements. The greediness of achieving yet more of something available i.e. super-finishing to ultra-finishing has made researchers to work harder. The growing pace of nano-technology has astonished many researchers to think of introducing nanoparticles for many machining applications. The list of using nanoparticles in EDM are although few, overall analysis showed that in the era of manufacturing nanoparticles as powder mixed in EDM gives the best surface finish to date. To this aspect, Jahan, Rahman [100] studied the effect of nano-particles and micro-particles in EDM of WC-Co and reported that the smoother and defect-free surface was obtained as compared to that of the die-sinking micro-EDM. The lowest and highest surface roughness value was found to be 37nm and 17µm respectively. Choudhary and Jadoun [49] proposed a novel method of using discharge pulse to improve the accuracy of nano-graphite powder mixed dielectric for the micro-EDM process. The Nano-graphite with ultrasonic vibration of the dielectric fluid improved surface quality and reduced machining time. Prihandana, Sriani [101] worked on improving the machining time in micro EDM in addition to workpiece vibration and nano-graphite powder mixed in dielectric fluid. They found that machining time was three times faster than the conventional one. Tseng, Lee [102] in their work focused in the preparation of the silver nanofluid by the EDM system. They derived the relationship between the process parameters and product characteristics. The system used intense energy to splatter the electrode surface in dielectric fluid, and this method has a

wide application in the nanofabrication technology, for example, Ni-C powders in pure ethanol, silver nano fluid in ethylene glycol, gold nanoparticles in water or ethanol and carbon nanotubes (CNTs). Tseng, Lee [102] explained that for the nanofluid application issue, nanofluid must be strongly stable which does not sediment before any application or analysis but many other factors affect the stability of suspension such as concentration of particles, particle size in diameter, solution properties, electrical conductivity and pH. A. Singh [103] studied the surface characteristics with the use of mixed carbon nano tubes (CNTs) in EDM to obtain high surface finish value because of the high thermal conductivity of CNTs.

INFLUENCE OF PROCESS PARAMETERS

The electrical discharge machining has various process parameters that affect the performance parameters surface roughness and recasts layer thickness and material removal rate [73, 104-106]. The quality of component is solely affected by the process parameters. Considering the powder mixed EDM, the process parameters can be classified as electrical, non-electrical, dielectric, electrode and powder parameters. The electrical process parameters include the peak current, input voltage, pulse-on-time, and pulse-off-time. On the other hand, the non-electrical process parameters include nozzle flushing time, electrode lifting time and working time. The dielectric parameters include the types of the dielectric used and dielectric strength whereas the electrode parameters are the types of the electrode, material, and size. The powder parameters are its type, concentration, size, shape, conductivity, etc.

OPTIMIZATION TECHNIQUES USED IN EDM

The recent developments in the changes to EDM with its sophisticated use in manufacturing industries have led to the rise of effective and economic technique requirements [5]. The needs of finished products have attracted many industries towards the art of EDM. The arising of super-finished and ultra-finished products requires a high cost in the technique and hence, optimality in terms of price and efficiency has to be cross-checked during the course of machining [4]. Many researchers have led their hands in reaching out an optimality to get better access to[107, 108] the machine tool. To this aspect, optimization techniques such as the Taguchi analysis [109], Grey relational model [110], Response Surface Methodology [111-115], Particle Swarm optimization [116], etc. were used by researchers. Some of which have been highlighted in this review work. Kolli and Kumar [109] employed the Taguchi method to optimize the surfactant and graphite powder concentration in dielectric fluid for the machining of Ti-6Al-4V using EDM. The results showed that the addition of graphite powder and surfactant in the dielectric fluid improves the MRR, reduces the SR and TWR and recasts layer thickness (RLT). Ho and Newman [2] adopted the non-dominated sorted genetic algorithm (NSGA-II) to optimize the responses of powder mixed EDM and found that the use of powder mixed dielectric promotes the reduction of surface roughness and enhances MRR. Padhee, Nayak [4] carried out a comparative study of the electrode performances by the desirability approach and ANNOVA using Fuzzy model in EDM and found that current was the most influencing factor followed by the pulse-on-time and pulse-off-time. Sengottuvel, Satishkumar [111] presented a model and analysed the rapidly resolidified layer of spheroidal graphite (SG) cast iron in the EDM process using the RSM approach. The results of ANNOVA indicated that the quantity and area fraction of the graphite particle

are the most influential factors on the rapidly resolidified layer thickness and ridge density in EDM process. The layer thickness decreases with the increase in the diameter of graphite particle. Chiang, Chang [117] investigated the influence of various EDM process parameters like pulse current, pulse-on time, tool work time and tool lift time on various aspects of surface integrity like the white layer thickness (WLT), surface crack density (SCD) and surface roughness (SR). Using the response surface methodology (RSM), it was found that the surface crack density was the most sensitive response and hence to be chosen and analysed carefully. In another study, Dewangan, Gangopadhyay [110] optimized the parameters of EDM using the grey-fuzzy logic based hybrid optimization technique. The results indicate that the pulse-on time was the most significant parameter followed by discharge current.

Dewangan, Gangopadhyay [116] studied the performance of tool materials (graphite, niobium, titanium, tantalum, tungsten) upon ZrB2-SiC MMC and optimized the performance parameters using the Particle swarm optimization (PSO) algorithm technique. Sivasankar S [118] investigated the influence of process parameters (current, voltage, pulse-on-time, pulse-off-time) while machining Al6061/10%SiC MMC and found the results to be in good agreement with other researchers. Singh, Kumar [119] used the artificial neural network (ANN) technique to develop a reliable model in predicting the tool wear rate with the least predictive error. They used graphite powder in the dielectric to reduce the tool wear rate during machining MMCs. The peak current was found to be the most significant factor and then the powder concentration. Agrawal, Dubey [120] an optimization outline for the EDM process parameters of the WC/Co composites with the help of NSGA-II. With the technological advancements, soft computing techniques and multi-response optimization techniques are being adopted to obtain the best compatible parameters of EDM. To this aspect, Kanagarajan, Karthikeyan [121] used the grey relational approach (GRA) and Taguchi, a combination of multi-optimization to study the tool wear exit and entry clearance, machining duration and number of short-circuits generated. Jung and Kwon [122] also used the same GRA technique on EDM of Al 10% SiC_p composite for multi-optimization for multiple responses. The experimental data proves that there is visible improvement in the EDM characteristics. A mathematical model was developed with the help of the regression analysis by Singh, Raghukandan [69] for MRR and TWR, while the electro-discharge machining of Al-4Cu-6Si alloy was reinforced with 10% SiC composites.

CONCLUSIONS

The study presents the wide use of EDM on metal matrix composites. The powder mixed EDM gives better surface finish as compared to that of WEDM and Die sinking EDM as depicted from the previous work. The powders introduced in the EDM help in increasing the spark gap between the electrode and the workpiece and reducing the insulating strength of the dielectric medium. This improves the MRR, makes the process stable and reduces the surface roughness. The electrical density was reduced on the machining spot with the addition of powders. The use of the metal matrix composites in EDM implies its vast application in the modern industries as stated in the work. In order to obtain the super-finished surfaces on such materials, EDM has been used. The super finished composites are thus used in the precision industries. The review depicts various powders used in EDM and the results show better surface finish and improvement of MRR. Many powders in the micro to nano form have been used yet it is evident that the use of nano powders was not much prevalent among the researchers. More and more work can be

carried out with the use of nano powders. The optimization techniques used by various researchers with different techniques were mentioned in the review. It is seen that the use of soft computing techniques such as the artificial neural network, genetic algorithm, particle swarm optimization, etc. have not been used by many researchers in the case of powder mixed EDM. Moreover, the process parameters in the nano powder mixed dielectric in EDM are optimized using traditional methods of optimization. The use of soft computing techniques has been less prevalent. Thus, further work can be done using various other powders in EDM on different MMCs.

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