STUDY ON POWDER MIXED ELECTRICAL DISCHARGE MACHINING PROCESS: A REVIEW

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Abstract: Powder mixed electric discharge machining (PM-EDM) process is a hybrid machining process by which the required profile is attained using thermal energy of sparks between tool and workpiece with addition of powder in dielectric fluid at low pulse energy. PM-EDM process enhances the capabilities of EDM process on machining of difficult to cut materials. This chapter explores the findings of research work carried out so far in the domain of PM-EDM of different hard and conductive materials. The effect of aided conductive powder into the dielectric fluid, electrical and non-electrical EDM process parameters on performance characteristics for machining various advanced materials has been studied under this chapter. This chapter also reviewed the industrial and academic work performed by various researchers from the origin to development of PM-EDM over the past decades. The research findings with major challenges along with the future scope have also been paved out.

Key words: PM-EDM, process parameters, performance parameters, powder

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1. Introduction

At present era, applications of advanced materials such as ceramics, hardened steels, composites, and super alloys are in various fields namely in automobile, aerospace, missiles, nuclear reactors and marine industries. The applications are owing to its remarkable properties viz. high thermal conductivity, hardness, strength and better corrosion resistance (Singh and Yeh, 2012; Singh et al., 2010; Rouniyar and Shandilya, 2019b). Thus, for machining of the advanced materials, today's machining industries are facing challenges for achieving the higher machining rate, better surface morphology and an accuracy of machined components with the traditional machining as well as non-traditional machining process (Vishwakarma et al., 2012; Rouniyar and Shandilya, 2019c). Non-traditional machining process such as abrasive water jet machining, laser machining, electrical discharge machining (EDM), plasma machining were used for machining of advanced materials. However, EDM was found most suitable for machining of advanced conductive materials irrespective of material hardness. In this process, removal of materials occurs due to spark energy that melts and evaporates the material from the surface of electrodes when both electrodes immersed in dielectric. Lower machining rate, higher surface roughness, presence of residual stress and higher crack limits the use of EDM process at higher production scale. Hence, it is essential to improve and develop the new machining technology, which can machine the advanced materials with required features and eliminate the drawbacks of EDM process. Therefore, the researchers have developed hybrid-machining technology with the aid of powder particles mixed in dielectric fluid in EDM known as powder mixed EDM. The advantages of machining the advance materials with PM-EDM process include increment in MRR, lesser surface cracks, lower surface roughness and increase in corrosion resistance (Choudhary and Jadoun, 2014; Cogun et al., 2006). Applications of PM-EDM process are in the areas of automotive, military, surgical, defence and aviation industries for machining of parts and accessories (Talla et al. 2015; Rouniyar and Shandilya, 2019d).

In this paper, critical review of research on machining of difficult to cut conductive materials using PM-EDM process has been focussed. The author has explored the PM-EDM material removal mechanism, effect of different powders impregnated in dielectric and process parameters on various performance characteristics. The current scenarios on PM-EDM of difficult to cut materials such as metal matrix composites, titanium alloys, different grades of steels, and nickel based super alloys have been discussed in depth. The future scope of research work is also highlighted towards the last section of this chapter.

1.1 Principle of powder mixed electrical discharge machining

The mechanism of material removal in PM-EDM is different from the machining mechanism of traditional EDM. Figure 1(a) shows the principle of the PM-EDM mechanism (Kansal et al., 2005).

The mechanism of material removal in PM-EDM is divided into four parts i.e. bridge formation of powder particles mixed in dielectric fluid, spark commencement due to breakage of a chain of powder, a zigzag motion of the particle due to explosion and re-bridging of powder particles as shown in Fig. 1(b) (Vhatkar and Jadhav, 2013). On application of 70-315 V voltage across the electrodes, electrical field intensity in the range of 10^5 to 10^7 V/m has been produced. Under the influence of the electric field, the conductive powder particles present in the sparking area has energized. These conductive powders form the chains like structure by bridging the spark gap between the workpiece and the tool causing an early explosion. Thus the reduction of dielectric strength and gap voltage occurs, which increases the frequency of discharging causing faster erosion from the surface of the workpiece. The discharge particles behave in a zigzag motion and spread uniformly in all directions causing enlargement and widening of discharge passage resulting in a reduction of discharge density and enhancement of discharge heat area. Thus due to the reduction in the discharge density uniformly distributed shallow crater is formed improving the surface finish (Tripathy and Tripathy, 2016; Singh et al., 2010; Roy et al., 2016).

Fig. 1. (a) Principle of PM-EDM (Kansal et al., 2005), (b) Particles arrangement (Vhatkar and Jadhav, 2013)

2. Experimental Setup

The experimental machining setup for PM-EDM comprises of five elements as shown in Fig. 2 (Gugulothu et al., 2015; Marashi et al., 2015). Dielectric Circulation system an integral element of PM-EDM setup contains the circulating pump and dielectric fluid that clears debris under the inter-electrode gap by flushing. It also helps in maintaining the temperature of dielectric below its flash point, reusing of powder, cooling of tool and workpiece (Kumar et al., 2011). Power supply system called as mother of system controls the current, polarity, voltage, pulse duration and spark frequency to produce effective spark for removal of materials.

The servo-controlled feed system helps in adjustment of spark gap between the tool and workpiece resulting in proper sparking so that stable and efficient machining occurs. Stirring system comprises of pulley, belt, stirrer, and DC motor.

The stirring system ensures the proper mixing of powder particles in dielectric and avoids settlement of powder at bottom of tank (Ekmekci et al., 2016; Rajendra and Rao, 2014; Rouniyar and Shandilya, 2019a). Figure 3 illustrates the schematic diagram of the PM-EDM setup.

Fig. 2. Elements of PE-MDM setup (Gugulothu et al., 2015; Marashi et al., 2015; Rouniyar and Shandilya, 2019a).

Fig. 3. Schematic diagram of PM-EDM setup (Garg and Ojha, 2012)

3. Major EDM Parameters

Powder mixed EDM parameters generally consists of two categories i.e. 1) Process parameters and 2) Performance parameters.

3.1 Process Parameters

Process parameters in PM-EDM defines the machining conditions in which experiments are carried out. Figure 4 illustrates the classification of different types of process parameters (Choudhary and Jadoun, 2014; Gudur and Potdar, 2014; Singh and Singh, 2015, Jamadar and Kavade, 2014).

Fig. 4. Classification of process parameters

3.2 Performance Parameters

Performance parameters describes about the output response measure that has effect of process parameters. Figure 5 shows the classification of performance parameters (Choudhary and Jadoun, 2014; Gudur and Potdar, 2014; Singh and Singh, 2015).

Fig. 5. Classification of performance parameters

4. Literature Review

At the present prospects, the PM-EDM is well-organized hybrid EDM process widely used in industries with importance given to productivity, surface quality, and accuracy. In 1946, the application of EDM was firstly introduced in manufacturing industries for the manufacturing of dies and moulds. However, with the passage of time and technological advancement was introduced in 1954's in the EDM with variation in electrical, non-electrical and electrode based EDM process parameters. The EDM process introduced had the limitation of low material removal rate and poor surface finish.

Thus in the late 1980's, PM-EDM hybrid manufacturing process was first introduced in industries to enhance the machining rate and surface finish with the addition impurities in the form of powder in the dielectric fluid (Erden and Bilgin, 1980; Jeswani, 1981). PM-EDM process was used for machining of various conductivity materials such as die tool steels, aluminium alloy, stainless steels, Inconel, metal matrix composites, and Monel metals. Figure 6 depicts the comparative analysis in the form of the pie chart of published research work by the different researcher in the areas of PM-EDM on different materials. The effect of process parameters effect on performance characteristics have been investigated so that the required parameters can be effectively used for machining on the given materials for obtaining the desired quality level of machined components.

Fig. 6. Comparative analysis of research work on PM-EDM

An attempt to organise and consolidate the results of research work in the field of PM-EDM process by various researchers have been summarised in this chapter along with the future scope of research work

4.1 PM-EDM of Steels

Steel is an alloy of iron, which consists of carbon content ranging from 0.03% to 1.075% of its composition, depending on its grade.

Various researchers have carried out the machining of different grades of steel such as stainless steel, die steel, alloy steel, high carbon high chromium steel, etc. Jeswani (1981) first used PM-EDM process for machining the mild steel plate using graphite as powder added in the dielectric.

At powder concentration (P_C) of 4 g/l, 60% improvement in material removal rate (MRR) was observed. Ming et al. (1995) used powder suspended in dielectric to carry out experiments on machining of high carbon steel through PM-EDM process. The process noticed improvement in MRR, surface roughness (SR) and tool wear ratio with addition of powder. Furutani et al. (2001) studied the accretion mechanism with titanium (Ti) powder added to dielectric on ED machining of carbon steel.

At higher P_C , TiC layer was accreted using thin electrode. Tzeng and Lee (2001) investigated the effect of different types of powders to enhance the machining efficiency on machining of mould steel SKD-11. Highest MRR and lower TWR was associated with machining using chromium (Cr) powder. Pecas and Henriques (2003, 2008) used kerosene-Castrol SE fluid 180, silicon (Si) as powder, and hardened mould steel AISI-H13 as workpiece on machining with an electrolytic copper electrode to study the influence of using different electrode and flushing flow on surface topography and roughness.

On addition of Si powder in dielectric, the surface witness improvement in the surface quality, crater depth and diameter, white layer thickness and surface heterogeneity. Figure 7 depicts the surface topography of machined samples with and without powder mixed in dielectric. Kansal et al. (2005) and Padhee et al. (2012) proposed multi-response optimization based on response surface methodology (RSM), non-dominated sorting genetic algorithm (NSGA), and grey relational analysis (GRA) to determine the optimal input parameters on ED machining EN-31 tool steel with Si powder.

Combination of high I_p and P_C promotes lower SR and higher MRR. Kansal et al. (2006) carried out machining by mixing Si powder in the dielectric on H11 steel workpiece on machining rate (MR), SR and TWR. I_p and P_C were most significant parameters having effect on response characteristics.

Cogun et al. (2006) machined the SAE 1040 steel with PM-EDM process and studied the influence of input parameters on SR, MRR, TWR, micro-hardness (MH), relative wear, and microstructure of machined surface. Improvement in MH was observed with the use of boron-based powder mixed with kerosene. Figure 8(a) & (b) display the surface morphology and recast layer on the machining of SA1040 steel with and without powder.

Fig. 7. Surface topography of samples machined (a) with and (b) without PMEDM conditions at 3200 mm² electrode area (Pecas and Henriques, 2008)

Fig. 8. (a) Surface morphology, (b) Recast layer on machined surface (Cogun et al., 2006)

Kansal et al. (2007, 2008) and Khazraji et al. (2016) performed modeling using FEM method on ANSYS software on machining of AISI D2 Die Steel using silicon powder. Influence of EDM parameters on temperature distribution, white layer thickness (WLT), MRR, heat flux and fatigue life has been studied. Powder mixed machined surface witness small and shallow craters. Sharma et al. (2010) and Singh et al. (2010) analyzed TWR, SR, percentage wear rate and MRR on machining of Hastelloy steel by mixing the aluminium (Al) powder in the dielectric fluid. On decreasing particle size of Al powder in dielectric improved SR, MRR, and TWR. Bhattacharya et al. (2011) and Bhattacharya et al. (2012) discussed the influence of EDM parameters on hot die steel, EN-31 steel and high carbon high chromium die steel on machining with different powder on MRR, MH, TWR and SR. Optimization was performed using Taguchi method and analytic hierarchy process. I_p was most influential parameters for MH, while kerosene produced better results than EDM oil as the dielectric fluid. Ojha et al. (2011) and Garg and Ojha (2012) machined EN-8 steel with Cr powder added to dielectric using EDM process.

Optimum parameters for MRR, SR and TWR were performed using response surface methodology. Batish et al. (2012) studied the mechanism of material transfer and investigated the influence of EDM parameters on MH in machining of three different grades of die steels using graphite and Al powder mixed with a different dielectric medium through EDM.

Singh et al. (2012) and Assarzadeh and Ghoreishi (2013) developed the model to predict the SR and MRR on machining of CK45 heat-treated die steel with alumina oxide powder mixed with kerosene through EDM process. Higher value of I_p , lower value of pulse on time (T_{ON}) and source voltage witness higher MRR, while at lower I_p and T_{ON} better surface finish was observed. The experiments using as silicon carbide (SiC) powder on premium stainless mold steel was carried out by Razak et al. (2015) to investigate the effect on SR, MRR and tool wear ratio. Powder mixed in dielectric improves the machining efficiency as the result of which machining time and machining cost was reduced. Multi-objective optimization was performed using TOPSIS and GRA on machining of H-11 steel for determining the optimum process parameters by Tripathy and Tripathy (2016). The optimum set of process parameters found from TOPSIS was at $T_{ON} = 100 \mu s$, $P_C = 6 \text{ g/l}$, duty factor (τ) = 90%, gap voltage (V_g) = 50 V and $I_p = 6 \text{ A}$ while from GRA optimum was at $T_{ON} = 150 \mu s$, $P_C = 6 \text{ g/l}$, $\tau = 70\%$, $V_g = 30 \text{ V}$ and $I_p = 3 \text{ A}$. Özerkan (2018) achieved higher MH on electrical discharge machined surface of AISI 1040 steel with boron oxide powder added to kerosene. Le et al. (2018) suggested improvement in SR and MH on ED machining of SKD61 with tungsten carbide (WC) suspended in EDM oil. Luzia et al. (2019) machined AISI H13 tool steel with silicon powder added in dielectric through EDM process. The effect of I_p and P_{ON} was measured on the output measures such as MH, SR, RLT, friction coefficient, and wear resistance. Increase in MH was observed with the formation of martensitic phase in the recast layer.

4.2 PM-EDM of Metal Matrix Composites

Metal matrix composites (MMCs) are particularly light weight metal alloys consisting of titanium, magnesium or aluminium reinforced with fibers/ particulate of boron oxide, graphite or silicon carbide (Bisaria and Shandilya, 2015). MMCs offers specific properties such as high operating temperature, specific stiffness, strength, better wear resistance and low thermal expansion. MMCs have been widely used in different industrial applications namely automotive engine, brake parts, missiles, aircraft, satellites, jet engine, connecting rod etc (Gibbons, 1988; Shandilya et al., 2016).

Thus various researchers have carried out powder mixed ED machining of MMCs. For example, Kumar and Davim (2011) machined the Al-10%SiCp MMCs and analyse the influence of EDM parameters on SR and MR with Si powder suspended on kerosene. The optimum settings of parameters for high MR using Taguchi method was at $I_p = 9 \text{ A}$, $P_C = 4 \text{ g/l}$, $V_g = 50 \text{ V}$ and $T_{ON} = 100 \mu s$, while for low SR was at $I_p = 3 \text{ A}$, $P_C = 4 \text{ g/l}$, $V_g = 50 \text{ V}$ and $T_{ON} = 100 \mu s$. Taguchi coupled with GRA was applied to optimize the process parameters on machining of aluminium matrix composites by Singh and Yeh (2012) for multiple responses by mixing abrasive as a powder in the dielectric fluid.

Arya et al. (2012) experimentally analyzed the effect of EDM parameters on SR and MRR on PM-EDM of Al-SiC MMCs using graphite powder. Empirical model for predicting the SR and MRR was developed in terms of process parameters. Agrawal et al. (2013) reported that TWR on copper-iron-graphite can be reduced by 94.57% by using graphite powder added to dielectric. Artificial neural network was used to develop the predictive model for TWR and genetic algorithm used to obtain an optimum value of control factors for minimum TWR. Hu et al. (2013) machined SiC_p/Al composites using Al powder in kerosene and reported 31.5% decrease in SR and 100% increment in wear resistance.

The microstructure shown in Fig. 9 depicts cracks and pores with EDM process while smoother surface was observed with PM-EDM process. Sidhu et al. (2014) machined three different grades of MMCs by EDM on suspending different types of powder in EDM oil. XRD was performed to observe the surface integrity and microstructural analysis was performed to analyze the recast layer of the machined workpiece as shown in Fig. 10. Behera et al. (2015) focused on optimization of process parameters using Taguchi and GRA on machining of SiC reinforced ZA-27 MMCs. SR, MRR and TWR were responses considered for experimental work.

Talla et al. (2015) modeled the MRR and SR of PM-EDM process using dimensional and regression analysis on machining of aluminium/alumina MMCs. Optimum EDM parameters for higher MRR and lower SR were at $P_C = 4$ g/l, $T_{ON} = 150$ μ s, $\tau = 85\%$ and $I_P = 3$ A. Prabu et al. (2015) machined Al-TiB₂ composites to determine the influence of flushing pressure, T_{ON} and I_P on MRR and TWR by mixing graphite powder on kerosene using EDM process. On increasing the I_P and T_{ON} , MRR tends to increase, while decrease in TWR was reported with the use of powder in kerosene. Anuraag and Reddy (2016) observed improvement in MRR on machining Al-SiC composite by suspending the silicon in kerosene.

Fig. 9. Machined microstructure (a) EDM, (b) PM-EDM Process (Hu et al., 2013)

Fig. 10. SEM image of recast layer (a) Without and (b) With graphite powder mixed in dielectric (Siddhu et al., 2014)

4.3 PM-EDM of others

The development and technological advancement in society over period of time have produced various emerging materials like Inconel, nimonic, tungsten carbide, silicon carbide and super alloys which are applicable for industrial related applications. The machining of these emerging materials have been performed by researchers using PM-EDM process.

For example, Klocke et al. (2004) attempted machining of Inconel 718 and observed thinner recast layer and maximum MRR with Al powder, while grey recast layer was noticed with Si powder mixed in dielectric. Figure 11 shows the cross sectional view of machined area at different I_p for Al and Si powder mixed in dielectric. Kung et al. (2009) machined cobalt bonded tungsten carbide with PM-EDM process using Al powder in dielectric. Quadratic model was developed for predicting the MRR and electrode wear ratio. Improvement in machining efficiency of the process was observed with Al powder mixed in dielectric.

Jabbaripour et al. (2013) carried out ED machining of TiAl intermetallic using different powder. Improvement in MRR, SR, corrosion resistance and surface topography were observed with Al powder. Govindharajan et al. (2014) performed experiments on Monel 400^{TM} to analyze the influence of different concentration of nickel powder combined with 6 g/l of graphite in different dielectric on MRR and TWR. Increase in MRR by 14% and reduction in TWR by 3.16% was observed when machined in Kerosene servotherm combination as compared to EDM oil and kerosene.

Kaldhone et al. (2014) observed addition of Al, SiC and graphite powder to dielectric, increases the MRR on machining of tungsten carbide. SiC powder enhanced the MRR by 90% as compared to Al powder. Maximum MRR was observed with SiC at $P_c = 8$ g/l and flushing pressure of 1.5 kg/cm^2 .

Aliyu et al. (2014) used Al powder on machining of siliconized silicon carbide (SiSiC) and reported that SR and tool wear ratio had a decreasing trend at low T_{ON} and I_p . At high I_p and low servo voltage, enhancement of MRR was observed.

Gugulothu et al. (2015) used graphite as powder in dielectric to improve the SR and MRR on machining Ti-6Al-4V alloy. An empirical relationship of SR and MRR with process parameters was developed using non-linear regression analysis. Kolli and Kumar (2015) implemented taguchi method to find the optimal set of parameters on ED machining of Ti-6Al-4V alloy with surfactant and graphite powder. Regression model for recast layer thickness, electrode wear rate, MRR and SR were developed.

To study the surface morphology of the machined specimen EDS and SEM was performed. Rouniyar and Shandilya (2018) machined Inconel-718 with use of graphite powder mixed in EDM oil with EDM process. Multi-objective optimization was carried out using GRA to determine maximum MRR and minimum SR. Ramesh and Jenarthanan (2018) tried addition of Al powder in EDM oil to machine the Nimonic 75 through EDM process and found improvement in SR and TWR.

Sahu et al. (2019) reported increase in MRR and improvement in SR by 19% and 11%, respectively on machining of Inconel 825 with alumina powder suspended in EDM oil through EDM process. Surface morphology shown in Fig. 12 witness smaller crack, voids, and craters on the machined surface of PM-EDM as compared to conventional EDM process.

Fig. 11. Cross sectional view of machined area without powder, with Al powder and Si powder (Klocke et al., 2004)

Fig. 12. Surface morphology of machining using (a) Convectional EDM (b) PM-EDM process (Sahu et al., 2019)

5. Comments for Literature Review

The research work performed by worldwide researchers in the area of machining though PM-EDM is summarized in Table 1.

Author(s)	Investigation on	Process Parameter	Workpiece Material	Powder	Dielectric
Jeswani (1981)	MRR	P_C	Mild steel	Graphite	EDM oil
Ming et al. (1995)	MRR and SR	I_p , T_{ON}	High carbon steel	lipophilic surface agent	Kerosene
Klocke et al. (2004)	Recast layer and MRR	I_p , P_C	Inconel 718	Al, Si	Oil Held IME 63 oil
Kansal et al. (2006)	MR, SR and TWR	I_p , τ , P_C , T_{ON}	H11 steel	Si	EDM oil
Cogun et al. (2006)	SR, MRR, TWR and MH	P_C , T_{ON}	SAE 1040 steel	Graphite, boric acid	Kerosene
Pecas and Henriques (2008)	SR and Surface Topography	I_p , τ , P_C , Polarity	Hardened mould steel AISI-H13	Si	Kerosene-Castrol SE fluid 180
Kung et al. (2009)	MRR and Electrode wear ratio	I_p , P_C , T_{ON} and grain size	Cobalt bonded tungsten carbide	Al	Commercial-grade mineral oil
Kumar and Davim (2011)	SR and MR	I_p , P_C , T_{ON} , and V_g	Al-10%SiCp MMCs	Si	Kerosene

Hu et al. (2013)	Wear resistance and SR	I_p , P_c	SiCp/Al composites	Al	kerosene
Govindharajan et al. (2014)	MRR and TWR	P_c	Monel 400TM	Nickel, Graphite	Kerosene, EDM oil
Kolli and Kumar (2015)	MRR, SR, RLT, and electrode wear rate	I_p , P_c , Surfactant conc.	Titanium alloy	surfactant and graphite	EDM oil
Khazraji et al. (2016)	WLT, heat flux, MRR, fatigue life and temperature distribution,	I_p , T_{ON} , P_c , T_{OFF}	AISI D2 Die Steel	Si	Kerosene
Ozerkan (2018)	MH and microstructure	T_{ON} , P_c , types of powder	AISI 1040 steel	Boron oxide	Kerosene
Ramesh and Jenarathanan (2018)	MRR, TWR and SR	I_p , T_{ON} , P_c	Nimonic-75 and AISI P20 steel	Al	Kerosene
Le et al. (2018)	SR and MH	I_p , T_{ON} , P_c	SKD61 Steel	WC	Shell Oil EDM
Luzia et al. (2019)	Wear resistance, SR, RLT and Friction coefficient	I_p , T_{ON} , Machining time	AISI H13 tool steel	Si	Deionized water
Sahu et al. (2019)	MRR, SR	T_{ON} , I_p , V_g	Inconel 825	Al_2O_3	EDM oil

Tab. 1. Summary on literature review on machining using PM-EDM process

6. Summary

This book chapter focussed on PM-EDM of hard and conductive materials such as ceramics, metal matrix composites, hardened steel and super alloys that are difficult to machine by conventional and other advanced machining process. The applications of PM-EDM can be seen different industries involving in the manufacturing of various components namely automobile parts, dies, surgical instruments, military parts, and aerospace components. PM-EDM process has addressed the problem of lower machining rate and poor surface quality that arises in the conventional EDM process.

It was observed that most of the researchers have chosen the process parameters such as pulse on time, peak current, powder concentration, pulse off time for finding their effects on performance characteristics namely material removal rate, surface roughness, microhardness, recast layer and tool wear rate in PM-EDM. Improvement in surface integrity aspects namely SR, RLT, MH, and surface topography were observed by addition of required amount of fine powder in EDM oil as dielectric fluid. Peak current, pulse on time, and powder concentration were observed as most significant process parameters on machining of conductive materials. Machined surface witness presence of smaller globular debris particles, voids, and micro-cracks as compared to machining with conventional EDM process. Most of the researchers used Taguchi and RSM for designing the experiments, analysing, and optimizing the experimental results. The soft computing techniques namely grey relational analysis, genetic algorithm, etc. were also considered by few researchers for optimizing the experimental results for multi-response optimization to obtain desired quality of components.

7. Future Scope

Though the various researchers have contributed to improve cutting performance of PM-EDM of advanced materials, yet the following work can be done in future -

1. The hard and conductive materials such as molybdenum, high speed tool steels, OHNS die steel, Inconel, intermetallic alloy might be machined with different shape of electrode to create intricate profiles.
2. The effects of different powders such as manganese, chromium, molybdenum, vanadium, titanium and zirconium powder on machining of advanced materials are still unrevealed.
3. The advanced soft computing techniques can be utilized to enhance the process capability of PM-EDM parameters and reduce the error in the experimental results.

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