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Parameter optimization in the enhancement of MRR of titanium alloy using newer mixing method in PMEDM process

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Abstract

The addition of powders in electrical discharge machining (EDM) reduces the breakdown strength of the liquid dielectric, thereby enhancing the occurrence of early spark, and aids in machinability. Challenges occur in the sustainability of the powder mixed electrical discharge machining (PMEDM) process in terms of homogeneity of the powder-dielectric mixture and adverse effects of these powders on the impellor of the pump, maintaining the concentration of the powder–dielectric mixture for a wide range of powders at varied size. In this investigation, an attempt is made to address these challenges and limitations in performing PMEDM process by developing a newer mixing method for PMEDM. The Taguchi L18 orthogonal array has been selected to study the material removal rate (MRR) of titanium grade 5 alloy. Gap current, duty factor, pressure of the powder mixed dielectric fluid, type of powder, and concentration of the powders have been considered as the process variables. The results found to be satisfying with increase in MRR. The confirmation experiments indicate considerable increase in MRR. This newer system is capable of performing sustainable manufacturing method irrespective of the nature of the powder and the particle size of the additive powders, that are permissible in the inter-electrode gap as it restricts the size of the powder, added in the PMEDM process.

Keywords: Eductor, PMEDM, MRR, Taguchi method, L18 orthogonal array

Introduction

Losing weight is a real struggle for the automotive industry, which inevitably affects CO_2 emissions and fuel efficiency. In the 1990s, the automobile industry was driven by this quest to put aluminium, magnesium, titanium, and other materials in car engines. Among the more recent materials used in car engines, titanium has long been a favorite because of its strength-to-weight ratio, resistance to corrosion, attractive surface look, and sumptuous feel. However, because of its hardness and chemical reactivity at high temperatures, it presents a difficult task during conventional machining [1]. Electrical discharge machining (EDM) is a well-known non-traditional machining process attempted to machine titanium. EDM is also called spark erosion machine, in which the stock from the work piece is removed by a series of controlled electrical sparks between the electrically conductive materials in the presence of a dielectric fluid [2]. In EDM, there is no direct physical contact between the tool and the work piece, thereby rendering it free from mechanical stresses and tool chatter problems [3]. Under the applied gap voltage, the tool electrode moves towards the work piece until the tool-work piece gap is very small of the order of 10–100 μm and the voltage ionizes the dielectric fluid in the gap causing a series of sparks [2]. Lack of mechanical erosion enables the EDM method to work with any materials, regardless of their toughness and hardness [4]. Though EDM is said to be a non-conventional machining process, rapid industrialization and continuous research in improving the efficiency of EDM make its presence everywhere and could called as established or a conventional machining process. Applications of the EDM process include making of dies and moulds to component of medical electronics to parts of aeronautical industries. Slow rate of production in EDM, which is one main limitation, made the researchers investigate novel ways in EDM to increase the productivity. Ultrasonic vibration-assisted EDM, dry EDM, and EDM with powder additives [5] are some of the new variants in the EDM process, which aims at enhancing the machining performance. These modified forms of EDM process help to improve the sparking characteristics and changing the property of the dielectric fluid used in the process. One such process is the PMEDM process, where suitable powders are added in fine form to the dielectric fluid at the tool work gap, which reduces the breakdown strength of the dielectric resulting in lower spark voltage for the same spark gap [6].

These powders in the EDM enhance the machinability but up to a critical concentration [3]. Natasi and Koshi [7] addressed the presence of gap debris beyond the critical limits. They suggested a slot on the tool surface to wipe out this excess gap debris for higher removal rate. In the PMEDM of Titanium, Bhavani et al. [8] added graphite and Boron carbide in the ratio of 1:1 and observed higher MRR and better surface finish. Sager Patel et al. [9] presented another dimension of increasing the MRR by using a rotary work piece, which controlled the gap debris and helped in higher MRR. Later researchers attempted the addition of artificially added gap debris in the name of PMEDM process. Surya and Gugulothu [10] added graphite powders in the dielectric to achieve higher MRR in Aluminum-based metal matrix composite. Hamid and Samin [11] used TiO_2 powder mixed dielectric along with magnetic field-assisted rotary tool in EDM process and observed an improvement in MRR and better surface finish due to controlled gap debris. Addition of powders into the dielectric liquid in EDM process causes the occurrence of bridging effect between the work piece and tool, which eventually resulted in earlier spark [12]. Recently, Jeavudeen et al. [13] conducted an isolated experiment to verify the lowering of breakdown strength of dielectric fluid, when various additive powders were added at different concentrations and reported that subsequent to the reduction of dielectric strength of liquid, a significant drop in breakdown voltage occurred for the same spark gap. Tahsin et al. [14] employed SiC powders in the machining of titanium alloy and observed that the machinability was affected at higher concentration of powders as it ceased the discharge beyond critical concentration. Shih-Fu and Cong-Yu [15] used hydroxyapatite (HA) powder in the machining of titanium-tantulam-based alloy and observed an substantial increase in MRR at higher concentration of powders.

According to the abovementioned literature, the researchers employed one of the experimental methods listed below to introduce the powder-mixed dielectric liquid into the spark gap: (i) with or without a stirrer, powder additives are combined directly in the machining tank itself [11, 14, 16–21]; (ii) the additives are combined with the dielectric liquid in a separate secondary tank and then poured into the spark gap [22–26]; and (iii) maintaining the predetermined concentration of powder-mixed dielectric liquid in a tank-in-tank configuration using an ultrasound vibrator [15, 27, 28]. It was never widely researched how to maintain consistency in the powder-dielectric liquid regardless of the nature of the powders, their particle size, concentration, etc. The PMEDM technique, which can be utilized for all powders regardless of their nature, size, and needed concentration, is therefore utilized in this investigation in an effort to retain the homogeneity of the powder mixed dielectric.

Experimental

Custom-engineered PMEDM experimental set-up

From the literature surveyed, the following observations were made about the experimental procedures that were used to perform PMEDM process: (1) the use of stirrer to maintain the homogeneity of the powder mixed dielectric may maintain the homogeneity at lower concentration and not at higher level of concentration; (2) in premixing and pumping technique, prolonged usage of additives may hamper the impellor of the pump; (3) the claim of maintaining the homogenous mixture is not qualitatively evidenced, especially at higher concentration and for the powders at larger grain size; and (4) also, the claim of uniform mixing of powder with dielectric may be valid for a set of powders at particular grain size and at particular concentration. A special custom-engineered PMEDM set-up has been developed to conduct a sustainable PMEDM experiment that is capable of homogeneously mixing any powder additions into the liquid dielectric.

It was found that the devised setup could mix powder additives of any kind, regardless of the type of powder and its particle size, at a precisely calibrated concentration. Figure 1 depicts the experimental setup that was used in the experiment. It is formed of an EDM (Electranica Make, India) machine with a 320-l primary internal tank for

Fig. 1 Arrangement of the experimental setup for the newer mixing method in PMEDM system

circulating liquid dielectric. The PMEDM process also included the use of a 120-l secondary tank as a secondary recirculating cycle. Figure 2 depicts the Eductor that was used to combine the powder and the dielectric. The dielectric was delivered into the suction side of the eductor of the powder mixing system using a low discharge pump (10 lpm) and high pressure pump (1–10 bar). The delivery pressure of the centrifugal pump was adjusted using a three-phase auto transformer with variable voltage. This pressurised dielectric was then introduced into a specially designed powder mixing setup, which could mix liquid with additive powders, at the specified pressure.

System design for mixing powders

Maintaining the consistency in the powder-dielectric mixture, regardless of the added powders, its size, concentration, etc., are the challenges in the PMEDM process. Hence, in this experimental set-up for doing PMEDM process, care is taken to achieving the challenges. It lies in selecting a particular type of machining, which should mix the powder additives thoroughly into the dielectric liquid at all the levels of concentration for the powders selected. This was achieved by using powder mixing set-up which consisted of the following:

- Metering device—to deliver the required amount of powder to the screw conveyor to maintain the concentration of the powder mixed dielectric liquid in the PMEDM process.
- Screw conveyor—to continuously feed powders into the Eductor's suction side.
- Eductor—it draws high pressure motive fluid (liquid dielectric) and powders from the suction, causing a homogeneous mixing of the additive powders and dielectric, which is then delivered at the spark gap of the experimental setup.

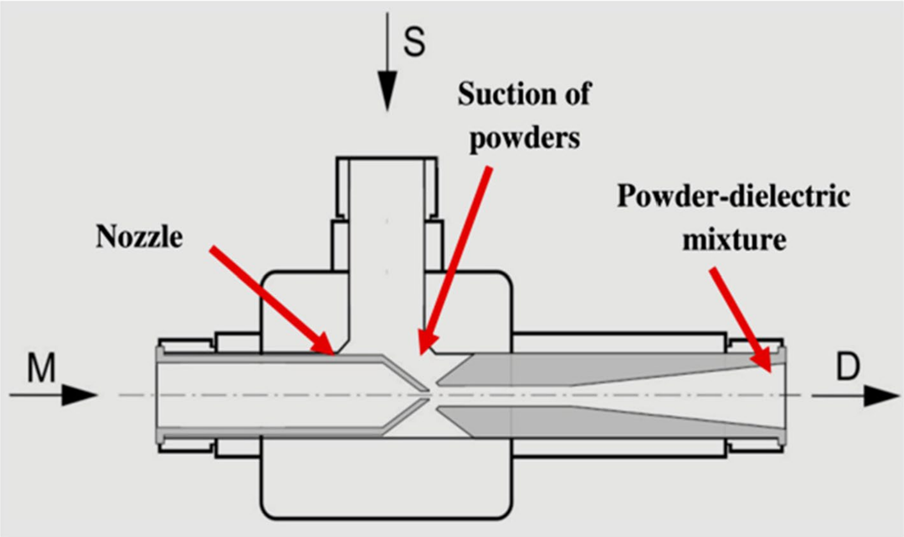


Fig. 2 Details of Eductor used to mix the powder in the newer PMEDM system

The metering apparatus was a hood with two electrically powered (0–30 V DC) vibratory motors. Power supply to the motor was precisely varied to convey the required amount of powders to the screw conveyor. This metering device ensured that the powders were admitted at a concentration of 0, 2, and 4 g/l. The powders were delivered into the suction side of the Eductor using the screw conveyor, which was also powered by another 0–30 V DC motor. In principle, Eductors are similar to that of the industrial mixing chamber that are used to mix liquid–liquid or liquid–solid, to extract huge volumes of debris say (say 500 kg solid mass per hour) without affecting the pump. A customised tubular Tee type eductor known as the liquid jet solid pump was used in the experimental setup which is capable of handling very tiny masses, say 50–100 g/minute was conceptualized to mix the powder with the dielectric. The specifications of the Eductor are presented in Table 1, which uses no moving parts. It works on the principle of venturi effect, wherein the liquid dielectric is admitted on the high pressure motive side with divergent nozzle causing acceleration of the dielectric to gain kinetic energy resulting in drop in pressure there at suction side. This enables the admission of additive powders at the suction side of the Eductor. Thus, the turbulence created by the motive fluid in the diffuser chamber is just sufficient to mix the powders thoroughly with the dielectric in the diffuser zone, and later, the mixer is admitted at the suction side. In the spark gap between the tool and the work piece at the delivery side of the eductor, the powder-mixed dielectric liquid is introduced. By trial and error method, the speed of the vibratory motor and conveyor are varied for the precise metering of the powders with the pressurized dielectric.

A known volume of the powder-dielectric mixture was gathered at the delivery side of the Eductor and checked for the presence of additional powders in a sintered crucible filtering test. The residue left in the filter paper was weighed in an electronic balance. This further validated accuracy of Eductor-based powder mixing system used in PMEDM setup.

Experimental procedure

Before conducting experiments with Eductor-based powder mixing system, initial experiments were conducted with identical machining conditions for the both the premixing and pumping type and Eductor based type viz., gap current—30 A, duty factor—80%, and Alumina powder at an avg. particle size of 44 µm. These experiments

Table 1 Details of Eductor used in the system

Fluid used	**EDM oil**
Temperature	Ambient
Flow	10 lpm at 2 bars
Pressure	2–10 bars
Suction solid	Abrasive powders
Suction pressure	Atmospheric
Suction flow	4 lpm
Discharge	1 kg/cm^2
Nozzle and diffuser	Teflon
Body of the Edcutor	SS304

were conducted on conventional PMEDM setup and also with the novel Eductor-based PMEDM setup, and the observations are given in the Table 2. When the concentration of the powder-dielectric mixture was increased from zero to 2 g/l, the percentage rise in MRR obtained from the Eductor-based PMEDM process was found to be higher than with the conventional PMEDM process.

Since the results of the initial tests utilising by the Eductor-based PMEDM setup were promising and subsequent tests were conducted using additive powders with an average particle size of 44 microns for Alumina, Copper, and Silicon Carbide. Necessary precaution was taken to ensure that the powders were free from any volatiles. The centrifugal pump admitted the pressurized dielectric into the high pressure motive side of the Eductor. Simultaneously, the powders were metered into the suction side of the Eductor through metering and conveyor systems. In the mixing chamber of the Eductor, both the liquid dielectric and additive powders were mixed thoroughly creating a turbulent flow which was then admitted to the spark zone. Thus, irrespective of the kind of powders employed in the experiment or the requisite concentration level, the uniformity of the powder-dielectric mixture was maintained. In this experiment, an ASTM C 348 Grade 5 titanium alloy plate of $150 \times 50 \times 7$ mm was employed as the work piece material, and a cylindrical copper rod with a diameter of 12 mm was used as the tool electrode. Using an electronic balance (Metler, India) with a least count of 0.00001 g, the material removal rate (MRR) was computed by comparing the mass of the material removed from the work piece per unit of time.

Design of experiments using L18 orthogonal array

Taguchi method has been widely accepted for optimizing the process parameters, due to its simplicity and ease of adaptability. It provides the designer with an efficient and systematic approach to find the optimum setting of design factors among the experimental trials and it gives necessary information from the minimum number of experiments trials with different levels. The Taguchi optimization technique is a statistical approach to engineering design that aims to improve the quality and reliability of a product or process by identifying the key factors that influence performance and optimizing their settings. One of the key advantages of Taguchi optimization is its ability to produce robust designs that are less sensitive to variations in the input factors. Also, Taguchi optimization is a simple and easy-to-use method that does not require complex statistical analysis or modeling and it relies on a small number of experiments to identify the most important input factors and their optimal levels, which can save time and resources. Since it requires fewer experiments, it can be a more cost-effective approach to optimization.

Table 2 Comparison of MRR (under similar machining conditions)

	MRR in (g/min) at		% rise in MRR
	No powder	**2 g/l of powder conc**	
Pre-mixing and pumping type PMEDM	0.033967	0.041586	22.43
Eductor-based PMEDM	0.042005	0.057856	37.74

Table 3 Input parameters and its levels

Parameters	Symbols	Levels			DoF
		Level 1	Level 2	Level 3	
Current (A)	A	25	30	35	2
Duty factor (%)	B	70	80	90	2
Pressure (bar)	C	4	6	8	2
Powder type	D	Al_2O_3	SiC	Cu	2
Powder Conc. (g/min)	E	0	2	4	2

Table 4 Experimental design based on Taguchi L18 orthogonal array

Trial	Input factors				
	P -1	P -2	P -3	P -4	P -5
	Current (A)	Duty Factor (%)	Pressure (Bar)	Powder Type	Powder Conc (g/litre)
1	25	70	4	Al_2O_3	0
2	25	80	6	SiC	2
3	25	90	8	Cu	4
4	30	70	4	SiC	2
5	30	80	6	Cu	4
6	30	90	8	Al_2O_3	0
7	35	70	6	Al_2O_3	4
8	35	80	8	SiC	0
9	35	90	4	Cu	2
10	25	70	8	Cu	2
11	25	80	4	Al_2O_3	4
12	25	90	6	SiC	0
13	30	70	6	Cu	0
14	30	80	8	Al_2O_3	2
15	30	90	4	SiC	4
16	35	70	8	SiC	4
17	35	80	4	Cu	0
18	35	90	6	Al_2O_3	2

The objective of this research is to device a mixing method to perform PMEDM process without affecting the performance of the pump. Subsequently, Eductor is developed. To assess the performance of this Eductor, the following parameters were used: (1) current & duty factor (these are predominant electrical parameters); (2) powders' type and its concentration are the factors that influence the performance in PMEDM process; and (3) delivery pressure of the powder of the powder mixed dielectric (since the mixing of the powder with the dielectric in the Eductor requires pressurized flow). L18 orthogonal array (OA) was chosen as per the Taguchi design of experiments. Tables 3 and 4 show the input factors and their levels and the experimental design based on L18 orthogonal array, respectively. Table 5 gives the MRR obtained from the PMEDM experimental observations. For each trial, three experiments were conducted to find the MRR.

Table 5 Results of MRR

Exp. No	MRR (g/min)				
	Trial 1	Trial 2	Trial 3	$\overline{\text{MRR}}$	S/N ratio
1	0.0187	0.0190	0.0199	0.0192	− 34.324
2	0.0186	0.0183	0.0191	0.0187	− 34.566
3	0.0547	0.0560	0.0567	0.0558	− 25.064
4	0.0267	0.0260	0.0264	0.0264	− 31.557
5	0.0628	0.0629	0.0627	0.0628	− 24.036
6	0.0247	0.0243	0.0251	0.0247	− 32.126
7	0.1185	0.1176	0.1174	0.1178	− 18.574
8	0.0415	0.0405	0.0410	0.0410	− 27.738
9	0.0600	0.0579	0.0596	0.0592	− 24.551
10	0.0336	0.0340	0.0336	0.0337	− 29.430
11	0.0250	0.0256	0.0247	0.0251	− 31.995
12	0.0125	0.0128	0.0130	0.0128	− 37.845
13	0.0219	0.0210	0.0212	0.0214	− 33.382
14	0.0516	0.0513	0.0518	0.0516	− 25.744
15	0.0339	0.0339	0.0334	0.0337	− 29.423
16	0.0157	0.0155	0.0159	0.0157	− 36.073
17	0.0327	0.0318	0.0318	0.0321	− 29.860
18	0.0510	0.0489	0.0498	0.0499	− 26.038

In order to find the deviation between the desired value and the experimental value of performance characteristics, Taguchi suggested quality loss function. These values of loss function have been further modified into a signal to noise ratio (S/N Ratio), which would in-turn serve as an objective of the optimization problem. There are three types of S/N ratios used in Taguchi method depending upon the objective of the problem viz., larger-the-better, smaller-the-better, and nominal-the-better. In this experiment, the output response considered was MRR; hence, the larger-the-better characteristics was used to convert the output response into S/N ratios using Eq. 1 [29].

$$S/NRatio = -10 * \log\left(\frac{1}{x}\right)\sum\left(\frac{1}{{Y_{nj}}^2}\right) \tag{1}$$

where “x” is the number of experiment replications and “Ynj” is the output response of nth trial of jth dependent level.

Results and discussion

In this investigation, the material removal rate (MRR) was determined by calculating the ratio of difference in mass of the work piece before and after each of the experiment trial to the time taken for the machining of the titanium alloy in the PMEDM set-up. The experimental results for MRR, its mean, and S/N Ratio are presented in Table 5.

Figure 3a, b shows the XRD pattern of Ti–6Al–4 V alloy before and after machining with the PMEDM setup. Most of the peaks observed in Fig. 3a matches with Titanium peaks, in which the maximum peak occurs at 2θ value of 40.4°, which corresponds to Ti (1 0 1). The XRD pattern for the machined surface of the titanium workpiece at 30 A

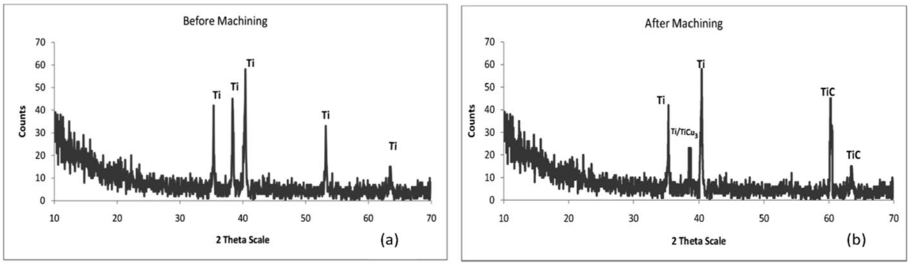
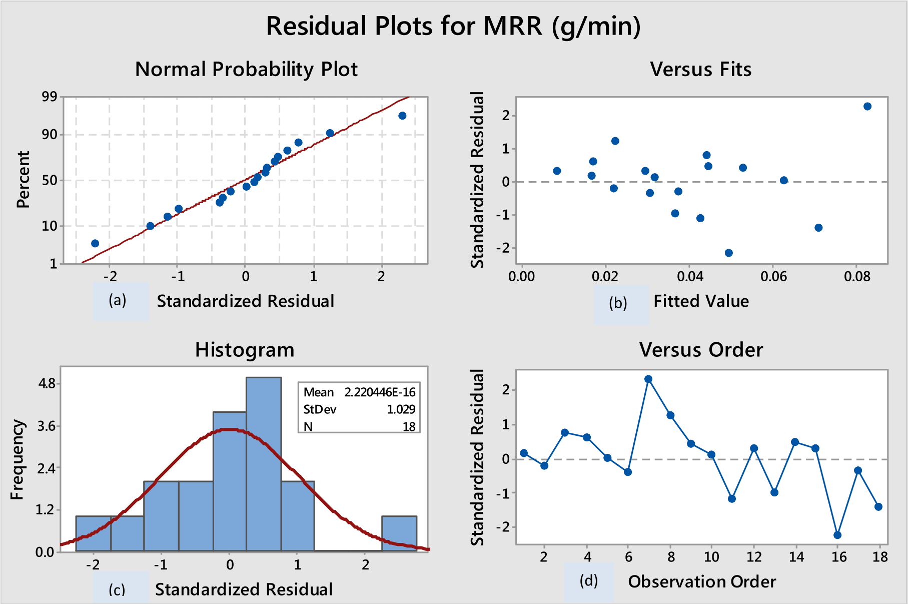


Fig. 3 XRD image of titanium alloy **a** as received. **b** Titanium alloy machined in PMEDM at 30 A gap current, 70% duty cycle, and at 4 bar pressure of dielectric fluid



Residual plots for MRR a) Normal Probability Plot b) Versus Fits c) Histogram d) Versus Order

Fig. 4 Residual plots for MRR (**a**) Normal Probability Plot (**b**) Versus Fits (**c**) Histogram (**d**) Versus Order

gap current, 70% duty cycle, and at 4 bar pressure of dielectric fluid is shown in Fig. 3b, where the peak occurs at 2θ value of 38.64°, 60.28°, and 63.4°, which indicates TiCu3 and TiC. TiCu3 possibly be formed from the tool electrode. Since the dielectric material used is a hydrocarbon oil, decomposition of C and H due to electric spark results in the formation of titanium carbide [30].

Validation of experimental data

The experimental observations listed in Table 5 need to be verified for their normality and the nature of distribution, before analyzing. From Fig. 4a, it is observed that the data observed from the experimental results follows a straight line with a normal distribution without any deviation. Figure 4b shows a random distribution data on either side of the zero line, thus indicating a random error. Also, the distribution of data follows normal distribution or bell-shaped curve with no skewness in it, with outliers indicated as the distance between the two bars (Fig. 4c). The distribution of data about the zero line in Fig. 4d represents the observed mean MRR across the 18 experimental trials with the peak at trial 7 and the lowest value of the mean MRR at trial 16. In Fig. 4d, the residuals are falling randomly around the center line with permissible outliers and there are no trends or shift or cycle or patterns. This indicates the assumption that the residuals are independent from one another.

Effect of process parameters on MRR

The addition of additive powders into the dielectric fluid of the PMEDM process influenced the machining performance of the titanium alloy. These powders reduced the dielectric breakdown strength of the EDM fluid irrespective of the nature and grain size of the added powders [13]. From the main effects plot (Fig. 5), it can be observed that the increase in the concentration of powder enhances the MRR. This is in accordance with the fact that these powders increase the thermal conductivity of the powder mixed dielectric at the spark gap together with the rise in dynamic viscosity [31] resulting in lowered breakdown strength. Increase in duty factor results in better removal rate of the titanium workpiece. At a value of 90% of duty factor, there occurs a drop in MRR. The temperature of the material's surface increases when the duty factor value is above 80%, which increases the material's electrical resistivity and may make it less machinable [1]. Also, the MRR with powder is greater than without powder due to the increase in the occurrence of series of sparks between the tool-work gap in the Eductor-based PMEDM process [32]. This phenomenon increases the chance of metal melting and better flushing, which yields in higher MRR [33].

Among the selected process parameters, gap current and concentration of the powder mixed dielectric liquid have had profound effect in enhancing the MRR of titanium alloy using the present PMEDM set-up. Among the powders used, SiC powders have been

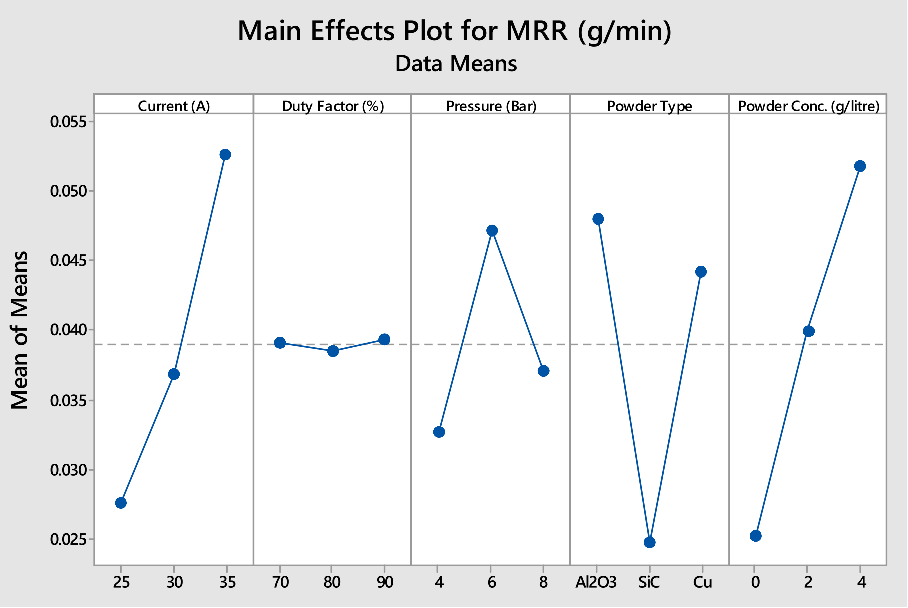


Fig. 5 Main effect plots for $\overline{MRR}$

Table 6 Thermo-electric properties of the additive powders

Property	SiC	Al_2O_3	Copper
Electrical resistivity (Ω-m)	10	1.43×10^{-5}	1.69×10^{-8}
Thermal conductivity (W/mK)	120	30	401
Density (g/cc)	3.16	3.986	8.96
Melting point (°C)	2,830	2072	1083

Table 7 ANOVA for MRR

Factors	Units	DoF	SS	Variance	*F* value	*P* value
Current	A	2	0.00192	0.000964	1.63	0.262
Duty factor	%	2	0.000002	0.000001	0.00	0.998
Pressure	Bar	2	0.000671	0.000336	0.57	0.591
Powder type	–-	2	0.001876	0.000938	1.59	0.270
Powder Conc	g/l	2	0.002134	0.001067	1.80	0.233
Error		7	0.004140	0.000591		
Total		17	0.010752			

found to have least effect on the machinability in terms of MRR. Higher value of melting point and electrical resistivity of SiC powder when compared to the other powders used in the experiment could possibly hinder the MRR in titanium alloy. Lower values of electrical resistivity of Alumina powder than SiC causes better removal rate than that of SiC. Conversely, copper powder with higher thermo-electrical property among the powders used in the experiment (Table 6) resulted in better machinability in terms of MRR.

Higher pressure in the delivery of powder mixed dielectric liquid enhances the MRR as it could assist in the machinability by increased erosive action at elevated pressure. However, when the powder-dielectric mixture's pressure was increased to 8 bar pressure, it was discovered that the MRR value was falling. This could possibly be ascribed to the hindrance caused by it due to spread of the spark away from the tool work piece gap and possibly could affect the gas explosion in the tool-work gap resulting in reduced MRR. Also this rise in delivery pressure will decrease the material removal per pulse in consecutive discharges [34].

The *F* value and *P* value for the various factors that are considered in this experiment are given in Table 7 and that the powder concentration is the predominant factor in enhancing the MRR, followed by gap current and powder type.

Optimization of process parameters for MRR

In order to find the optimal conditions for the machining of titanium alloy in the PMEDM set-up used in this research, main effect plots (Figs. 5 and 6), and ANOVA of the MRR (Table 7) have also been analyzed.

From the main effects plot for S/N ratios of MRR (Fig. 6): powder type, powder concentration, and gap current have had profound effect, with the rise in these factors resulting in increasing the MRR of the novel Eductor-based PMEDM set-up. Additive powders viz., Cu and Al_2O_3, were also found to be influencing the MRR. The same has been found in

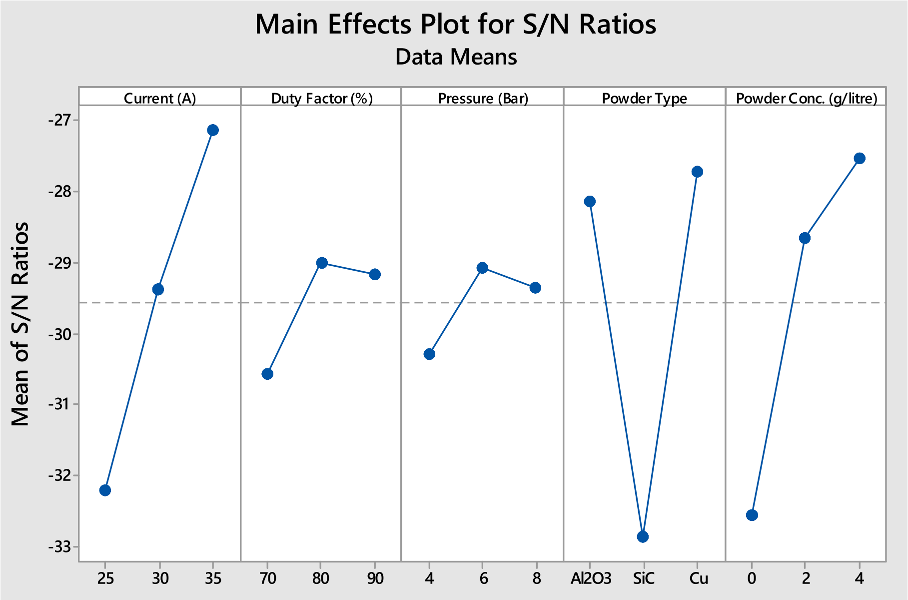


Fig. 6 Main effect plots for S/N ratios

ANOVA for S/N ratios of MRR as in Table 7, where powder type, powder concentration, and gap current are the major contributors in affecting the MRR. Also the poor electrical and thermal conductivity of SiC makes it poorly influence the MRR among the powders selected for the experiments. Optimal process parameters that contribute larger S/N ratio coefficient for MRR are listed as below: gap current of 35 A (A3), duty factor of 80% (B2), pressure of 6 bar (C2), Cu as optimal powder (D3), and 4 g/l of powder mixed dielectric liquid (E3). Based on the ANOVA for S/N ratios of MRR, the least contributing factor viz., duty cycle and pressure of powder mixed dielectric, is neglected and the predicted mean MRR is obtained by Eq. 2.

$$MRR_{OPT} = \overline{A_3} + \overline{D_3} + \overline{E_3} - 2\overline{T} \tag{2}$$

where $\overline{A_3}$ is the average value of MRR at third level of gap current = 0.0526484 g/min. $\overline{D_3}$ is the average value of MRR at third level of powder type = 0.0442070 g/min. $\overline{E_3}$ is the average value of MRR at third level of powder concentration = 0.0518605 g/min. $\overline{T}$ is the grand mean of MRR = 0.039015 g/min.

Thus, the predicted MRR, $\mu_{MRR} = 0.0706859$ g/min.

Accuracy of confirmation experiments with 95% confidence intervals of MRR is calculated as in Eq. 3.

$$CI_{CE} = \sqrt{F_{\propto}(1,f_e)V_e\left(\frac{1}{n_{eff}} + \frac{1}{R}\right)} \tag{3}$$

where

$$F_{\propto}(1,f_e) = F\ value\ at\ 95\%\ confidence\ level = 5.5914$$

$$V_e = error\ variance\ from\ anova\ table = 0.0001012$$

$$n_{eff} = \frac{N}{1 + DoFforerror}$$

N = total number of experiments = 18.

DoF for error = 7

$$n_{eff} = 2.25$$

R = number of confirmation experiments = 3.

$CI_{CE} = \pm 0.020854\ 0$.

Hence, the predicted confidence interval for the confirmation experiments is:

$$\mu_{MRR} - CI_{CE} < MRR_{exp} < \mu_{MRR} + CI_{CE}$$

i.e., $0.0651172 < MRR_{exp} < 0.1068252$

Population at 95% confidence interval is given by Eq. 4.

$$CI_{Pop} = \sqrt{\left(\frac{F_{\propto}(1, f_e) V_e}{n_{eff}}\right)} = \pm 0.0157674 \tag{4}$$

Therefore, population lies between

$$\mu_{MRR} - CI_{Pop} < MRR_{exp} < \mu_{MRR} + CI_{Pop}$$

i.e., $0.0702038 < MRR_{exp} < 0.1017386$.

The empirical formula using regression analysis for the optimal MRR is given by the relation.

`MRR = 0.03901–0.01143 A1–0.00220 A2 + 0.01363 A3–0.0012 B1–0.0141 B2 + 0.0153 B3–0.0083 C1 + 0.0155 C2–0.0072 C3 + 0.0155 D1 + 0.0084 D2–0.0239 D3–0.01378 E1 + 0.00093 E2 + 0.01285.`

Confirmation

To verify the theoretical value of MRR obtained from the Taguchi analysis, confirmation test has been carried out with the optimal process parameters viz., as mentioned in Eq. 2. MRR thus obtained from the confirmation test has been found to be 0.0895460 g/min, which lies very much between the confidence interval mentioned in Eqs. 3 and 4.

Conclusions

The work attempted a novel method of conducting PMEDM experiments using Eductor-based powder mixing system. This was done without affecting the impellor of the pump and also the homogeneity in the mixing of powder with the dielectric was ensured. The following conclusions were drawn from the experimental results:

- Powder addition into the dielectric had a strong influence on increasing the MRR. It was observed that the powder type, powder concentration, and gap current were the predominant factors that affected the MRR.
- Increase in the powder concentration from zero to 4 g/l caused a rise in the MRR of about 105.5% and for the gap current from 25 to 35 A, rise in the MRR was observed to be 90.8% for the given experimental set-up. Rise in powder mixed dielectric pressure from 4 to 6 bar resulted in 44.7% rise in the MRR.
- From the Taguchi analysis optimal levels of parameter obtained as, gap current of (A3) 35 A, powder type as (D3) copper, and powder concentration of (E3) 4 g/l. And the predicted value of MRR from Taguchi analysis was found to be 0.0706859 g/min, and the same was verified by confirmation experiments whose value was 0.0895460 g/min.

Scope for the future work

The machinability of the PMEDM process was studied using different powder mixing systems. The suggestions for further research are as follows:

- Effect of nanoparticles in the Eductor-based PMEDM process may be investigated in comparison with the use of micro powders.
- The machinability of the Eductor-based PMEDM system may be further studied by the using ultrasonic-assisted dielectric also.
- The effect of tool materials and its geometry in Eductor-based PMEDM process may be examined.
- The system can be further analysed by using bio-inspired algorithm like barnacles mating optimizer (BMO), multi-verse optimization (MVO), and Yin–Yang-pair optimization (YYPO) to study the optimzations of various parameters.

Abbreviations

EDM	Electric discharge machining
PMEDM	Powder mixed electric discharge machining
MRR	Material removal rate
ANOVA	Analysis of variance
S/N Ratio	Signal to noise ratio
OA	Orthogonal array

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Authors' contributions

The first draft of the manuscript was written by SJ. experimentation part was done by SJ. JS and MPA performed the conceptualization of the research idea, participated in the interpretation of the results, and reviewed the edited manuscript. All authors have made a substantial contribution to the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interests

The authors declare that they have no competing interests.

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