JJMIE

Volume 19, Number 3, Sep. 2025
ISSN 1995-6665
Pages 599– 608
https://doi.org/10.59038/jjmie/190312
Editor-in-Chief: Prof. Ali M. Jawarneh

Jordan Journal of Mechanical and Industrial Engineering

The Effect of Non-Conductive Al2O3nano Powder with Flushing Pressure on Electrical Discharge Machining Characteristics

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Received 3 Jun 2025 *Accepted 28 Jul 2025*

Abstract

In recent times, nano powder mixed electrical discharge machining (NPMEDM) is one of the leading machining processes when applications are based on nano powders. The process is a unique way of machining wherein electrical discharge machining (EDM) is clubbed with nano powders in dielectric fluid. This new combination produces better results and improves the process responses, like material removal and surface roughness, which are very well handled. The intention here is to focus on eliminating the frequent usage of finis

hing processes.

An experimental work was realized to determine the influence of the machining parameters, namely, flushing pressure (FP), peak current (I), and pulse on time (TON) on the dependent variables, especially on the material removal rate and surface roughness. during the finishing stage, to break through the constraints generated by the conditions of the EDM process.

It was found that the lower MRR was achieved at both the higher and lower flushing pressures with nano powder at 0.2 kg/cm² and 1 kg/cm², respectively. The optimal flushing pressure with nano powder has been found to be around 0.5 kg/cm² and does not significantly influence the material removal rate. At the same time, the use of nano powder in EDM with flushing at optimum value has shown promising results in enhancing surface roughness.

Hence, we can state that the flushing pressure (FP), when combined with the nano powder in the dielectric, is significant at its optimal value in the finishing operations in EDM.

Keywords: AL_2O_3 Nano powder, EDM, NPMEDM, flushing pressure, finishing stage in EDM.

Nomenclature

NPMEDM	Nano Powder Mixed Electrical Discharge Machining
EDM	Electrical Discharge Machining
I	Peak Current
FP	Flushing pressure
T_{on}	Pulse-On Time
T_{off}	Pulse-Off Time
MRR	Material Removal Rate
Ra	Arithmetic Average Roughness
Al_2O_3	Alumina Nano Powder
SVR	Support Vector Regression
WEDM	Wire Electrical Discharge Machining
ANOVA	Analysis of Variance

1. Introduction

NPMEDM, or nano powder mixed electrical discharge machining, is an interesting variant of conventional electrical discharge machining (EDM)employing nano powders added to dielectric fluid. By the addition of nanomaterials, multiple features can be enhanced, some of them being a higher material removal rate as compared to conventional EDM, a favorable surface finish, and a rate of tool wear that can be reduced. As a result, frequent usage of finishing processes can be skipped. These features provide significant benefits. In general, the nano powder will ensure higher performance when compared to conventional EDM with pure liquid dielectrics. With multiple benefits, these types of machining processes have gained a unique place in fulfilling the needs of commercial operations. The GAMA TEC technology owned by the CHARMILLES Company was intended to work on surface modification. The purpose was to add lamellar graphite to ensure a better surface finish with respect to EDM machining parameters. Then impulses of low energy with the help of lamellar graphite were achieved. The team of CHARMILLES successfully demonstrated a good mirror surface finish with a value of Ra up to 0.2 μm. The result was showcased on the surface above 50 cm² and the elimination of finishing operations. Therefore, a comprehensive and methodical study to fully understand the implications and identify the pertinent applications is needed.

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1.1. Literature Review

The breakthrough work on micro powder was made by Mohri et al. [1] using the micro powder-mixed EDM method to get better results. Their work projected that the involvement of conductive or non-conductive micro powders in dielectric fluid can get better outcomes. They noticed lower tool electrode wear, and surface quality was improved, thereby lowering the finishing time. Many global researchers are interested in studies related to the behavior of various micro powders over the process responses. Kozak et al. [2] used two different micro powders under various working fluids. The working fluid considered was kerosene and deionized water. The intention was to get data related to electro-discharge machining. The projected results confirm favorable improvements in surface performance. The values of Ra and Rz with respect to process parameters are reported to be in the range of 1.3 to 2.5 times smaller when compared to powder suspended in deionized water with EDM.

Later, special attention was given to the application of nano powders. Researchers mention that analogous results can be obtained by nano powder-mixed electrical discharge machining. Joshi et al. [3] presented a review-based paper focusing on NPMEDM parameters, which were classified into two groups as process parameters and performance parameters. Several researchers have observed that powder-mixed dielectric decreases the rate of tool wear and increases MRR as compared with conventional EDM operation. Furthermore, the researchers discovered that there are many other factors able to influence the quality of the work part and process mechanisms, such as powder size, powder concentration, and powder conductivity.

Adding nonconductive nano powder like Al_2O_3 attracts most attention from researchers due to high purity, lower cost, and high stability in dielectric fluid [4]. Chaudhari et al. [5] found that using Al_2O_3 nano powder improved machining performance compared to conventional EDM. However, in comparison with nano graphene, the enhancement was less significant, which exhibited higher conductivity and better results. Agarwal et al. [6] performed a study on the impact of Al_2O_3 nano powder mixed dielectric for micro-drilling operations. The study discloses that Al_2O_3 nano-powder significantly improved EDM performance by increasing overcut by 55.13%, reducing taper angle by 37.9%, and reducing tool wear rate by 12.2%. It also reduced altered layer thickness by up to 56.6%, improving surface quality. When an overall perspective is considered, EDM with nano powder additives has promising enhancement as compared to conventional techniques [7]. The key parameters, such as efficiency and performance of the EDM process, have shown better results [7,8]. With Al_2O_3 Nano powder used, the performance improvement is noticed in the stability of a process as well as the material removal rate being enhanced [9]. Additionally, a small quantity of Al_2O_3 nano powder along with dielectric fluid can be an intersecting combination to enhance the machining capabilities. These nano powders can give better results with wire electrical discharge machining (WEDM), which has application on shape memory alloy (SMA) [10].

Oskueyan et al. [11] considered two nano powders namely Al_2O_3 and SiO_2. The nano powders were tested using deionized water, for the Ti-6Al-4V alloy material. The input variation was made by changing suitable values for current and pulse on times. The gradual change in the concentration of nano particles was also made. The outcome was reported by comparing the tool wear rate and material removal rate. A clear conclusion was made on performance: nano particles in deionized water acted better with respect to MRR. The breakdown intensity and spark delay time were also checked across all the possible concentration values. Further key results indicate that the best enhancement was reported when the particle range was 2 g/l with a pulse value of 100 µs and a current of 12 A.

NPMEDM has revealed opportunities for improving the effectiveness and performance of the EDM process for composite materials. Prakash et al. [12] examines how Al_2O_3 and B_4C nano particles affect the strength and workability of Al7075 composites. The results indicate that nano powder improved tensile strength, hardness, and wear resistance, as observed. Although the EDM method has many limitations, numerous research studies have focused on improving EDM technology to improve the shape of the machining profile.

In the instance of additional micro powder in dielectric, the shape of the machining profile could be improved [13,14]. Also, the same effect can be achieved using nano powder. Studies indicate that the addition of nano powders into dielectric fluid enhances thermal conductivity and spark frequency, subsequently increasing the material removal rate and improving the machining profile and surface quality of the material [15,16].

In NPMEDM, there are several electrical parameters (peak current, polarity, pulse duration, power supply voltage) and non-electrical parameters (flushing pressure, type of dielectric, temperature). Furthermore, powder plays a vital role (type of powder, powder concentration, shape, and size), as does the electrode (material, size). All these parameters significantly modify the machining responses in PMEDM, mainly material removal rate and roughness.

This research aims to explore the effectiveness of the operating parameters, namely, flushing pressure (FP), peak current (I), and pulse on time (T_{ON}), on responses, such as material removal rate (MRR), and surface finish, during the finishing stage of the process in association with finishing parameters. The aim is to break through the constraints generated by the conditions of the EDM process. In general, it is not during roughing operations that flushing problems are experienced, where the larger gap allows for sufficient flow of dielectric material, but in the final stages of operations when the gap becomes smaller and the flow of dielectric becomes impeded.

2. Theoretical Background

The effectiveness of EDM depends on both nano powders and the distance between the electrodes; a larger gap distance results in lower electrostatic capacity. Generally, the conductivity and concentration of nano powder in the dielectric medium impact the gap [17]. Researchers have reported that this mechanism can be useful, whether nano powder is electrically conductive or nonconductive, through better distribution of the sparks across the workpiece, associated with the gap enlargement, a better surface finish was achieved.

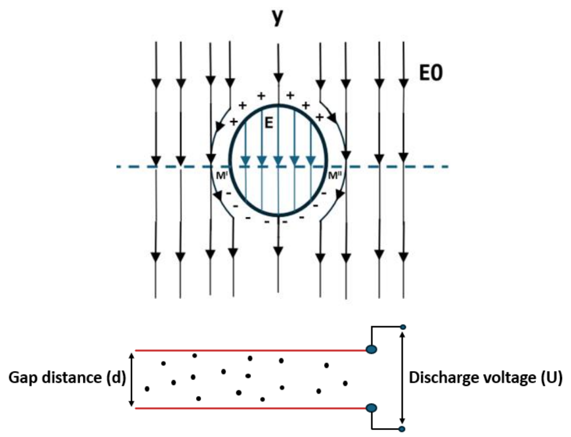

Figure 1. Flat parallel electrodes form the gap-electric field distribution in a dielectric around a non-conductive particle [2].

Furthermore, an increased gap distance results in reduced stray capacitance, thereby impacting surface quality [2]. The gap formed by flat electrodes (Fig. 1), without considering grains and with the neglect of the non-uniformity of the electric field due to surface roughness, the electric field intensity E0 can be related to the below expression [2]:

$$E0 = \frac{U}{d} \quad (1)$$

Where, Uis the voltage, and d is the gap distance.

In the accrual EDM condition, the influence of surface roughness and erosion products directly impacts the field intensity when the process is running. It is a very clear situation where the non-uniform electric field appears across the use of powder-suspended dielectric, as shown in figure 1. The peak values of electric field intensity are at M^I and M^{II} [3], and the relationship between E, U, and d can be better synchronized mathematically, as shown in Eq. 2 [3].

$$Emax = \frac{3}{2}E0 = \frac{3}{2}\frac{U}{d} \quad (2)$$

It can be noticed that the gap plays a vital role when a nonconductive particle is involved. It is reported that electrical breakdown in the gap containing a non-conductive particle should occur at 1.5 times higher compared with the case of the EDM in a pure dielectric. Furthermore, the powder concentration from low to high can greatly impact the behavior of the working fluid. Additionally, with the set of experimental trials, there was much evidence that the conductive particle promotes the gap to a much higher level when compared with nonconductive particles [18, 19].

3. Materials and methods

3.1. Work material

AISI D3 steel type was employed for the testing; a workpiece size of 75 mm X 150 mm X 12 mm was prepared, and the chemical composition is presented in Table 1. The workpiece was bathed in oil and quenched at 980°C to achieve a close value of 62 HRc. The next process in line was hardening, wherein tempering values were kept at 200°C. AISI D3 was enabled with cold dies as well as tooling. Blanking dies were implemented for paper and plastics. The reason for shortlisting these materials was for their properties of better accuracy in hardening as well as good performance during tempering.

Table 1. Chemical composition of AISI D3 Steel (wt. %).

C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Zn	Fe
2.06	0.55	0.449	0.036	0.056	11.09	0.277	0.207	0.0034	0.13	0.27	84.8716

3.2. The powder used in the NPMEDM process

In the present research work, alumina (Al_2O_3) nano powder was adopted. The density of alumina (Al_2O_3) was 3.9 g/cm³ with size varying from 60 to 100 nm [20]. The liquid solution used for mixing was hydrocarbon kerosene. A sample of alumina (Al_2O_3) nano powder is as indicated in Fig. 2.

3.3. Experimental setup

To carry out all the necessary experiments, an EDM Aristech LS 350 machine was utilized. The front view of the machine is as clarified in Fig. 3. There are multiple challenges for getting a nano particle in a homogenous condition. Ensuring particle homogeneity in the dielectric under NPMEDM was one of the major tasks in the present work. To understand the circulation system for NPMEDM, a line diagram was shown below Fig. 4. A clear relation is shown between the pump, flushing pipe, electrode, and workpiece.

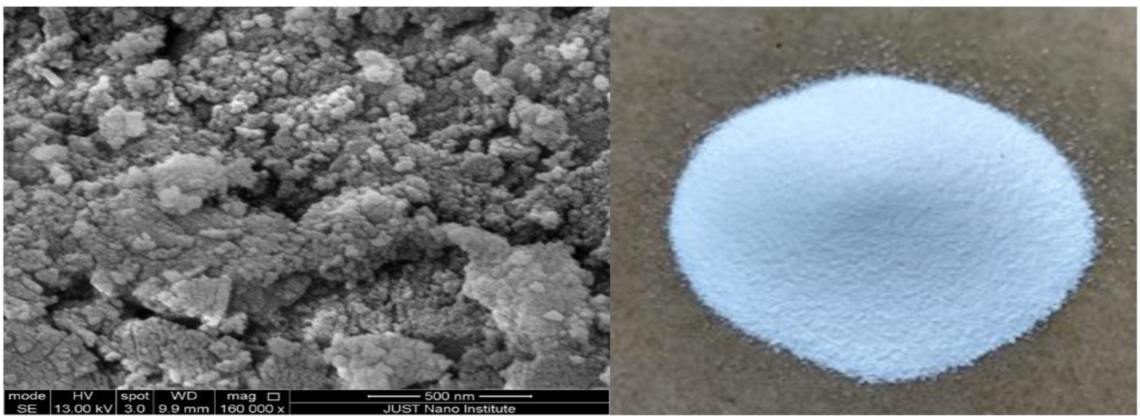

Figure 2. SEM of Al_2O_3Nano powder.

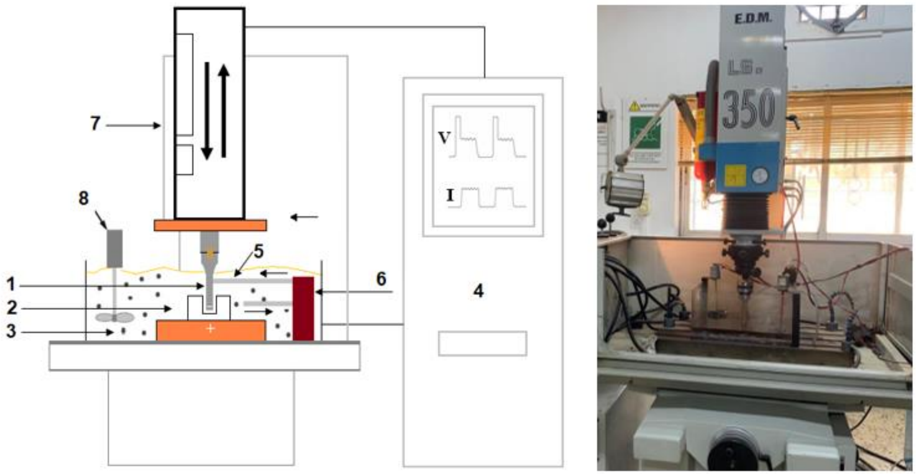

Figure 3. Setup along with schematic diagram form NPMEDM

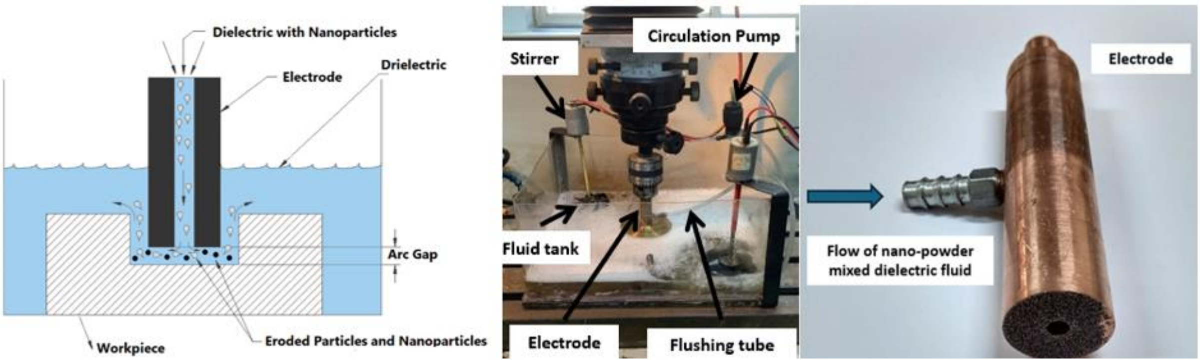

Figure 4. Schematic of flushing Pressure through the electrode - actual processes component.

In the above Fig. 3, the numbers from 1 to 8 indicate the electrode, workpiece, nano powder, generator and control panel, flushing pipe, flushing pump, servo controller, and stirrer, respectively. Movement of fluid is a key function when ensuring homogeneity. To cater to this gradual and continuous stirrer mechanism was integrated. Then, the addition and removal of electrodes was performed as and when needed. A dedicated servo mechanism was used. With all these settings and mechanisms, the position of the workpiece and tool was maintained in a professional way, leading to minimal errors.

A custom circulation system without a filter was made; a pump with a maximum flushing pressure of

5 kg/cm² was installed with an operating voltage of 12 V, having a maximum discharge rate of 7 liters per minute (LPM); and a controller unit was implemented to regulate the flushing pressure in the range from 0.2 to 1 kg/cm². Fig. 2 schematically presents the experimental arrangements used. To achieve internal flushing, a quick connector was used to connect the electrode to the flushing tube.

A workpiece holder was situated at the base of the upper part of the working fluid tank. A cylinder made of copper with a 25 mm diameter and 90 mm length and a 5 mm diameter hole through its center was attached as atool. Kerosene FLUXELF 2 was used, as a dielectric fluid; its resistivity was 7:4 X 1010 Ω cm.

4. Machining factors of experiment

The generation of data and collection from the NPMEDM process is a very challenging task. The reasons are due to the complexity of the process and the physics associated with it in a very small gap. To address this issue, various alternative methods were considered, and finally a model that suits the experimental model was shortlisted. In the present work, the response surface method (RSM) was utilized since it matches our research needs and is a well-known method to compare results with other researchers.

Table 2. Variations in level across considered process parameters.

Factor Symbol	Parameter	Levels		
		Low (-1)	Medium (0)	High (+1)
I	Peak current [A]	2	4	6
T_{ON}	Pulse on time [µs]	9	18	36
FP	Flushing pressure [kg/cm^2]	0.2	0.5	1

In connection with the design of experiments, the presented work utilizes the Box–Behnken technique to collect and process the experimental data. It includes of 2^k factorial points, where "k" is the quantity of factors. These plans with three independent variables are offered with 15 runs, which contain corner, central, and star run points[21].

Table 3. Results and characteristics - EDM and NPMEDM.

Coded factors				Response variables			
Run	I [A]	T_{ON} [µs]	FP [kg/cm^2]	Ra [µm]		MRR [mm^3/min]	
				EDM	NPMEDM	EDM	NPMEDM
1	2	9	0.5	3.05	2.79	0.420	0.424
2	6	9	0.5	4.90	4.27	1.752	1.967
3	2	36	0.5	3.41	3.01	0.572	0.584
4	6	36	0.5	5.41	4.60	1.941	2.011
5	2	18	0.2	3.14	2.82	0.488	0.510
6	6	18	0.2	5.11	4.50	1.81	1.917
7	2	18	1	3.56	3.23	0.412	0.494
8	6	18	1	5.38	4.58	1.678	1.894
9	4	9	0.2	4.05	3.49	0.998	1.067
10	4	36	0.2	4.33	3.73	1.012	1.109
11	4	9	1	4.10	3.57	0.981	1.122
12	4	36	1	3.99	3.71	0.912	1.210
13	4	18	0.5	4.13	3.82	1.409	1.382
14	4	18	0.5	3.909	3.78	1.317	1.390
15	4	18	0.5	3.660	3.41	1.422	1.466

The process factors and levels were established based on literature, prior experiences, and preliminary experiments, and their levels were determined. Each parameter is tested at three levels. Selection of the current (I) and pulse-on-time (T_{ON}) values was chosen to maintain the machine parameters in the finishing stage. The flushing pressure (FP) was varied in steps from 0.2 to 1 kg/cm². More information and variation of data with all the parameters/levels can be found in Table 2. Selection of pulse-on-time (T_{ON}) is a challenging task in the present experiment; the value was moved from 22.5 to 18 µs. This variation in value was very much needed to set the machine in line. Additional information about the design matrix is listed above in Table 3. In the present experiment, alumina (Al_2O_3) nano powder was used to perform the test in line with EDM. The experimental trials were carried out after the realization of the experiment with flushing pressure (FP) and without the alumina (Al_2O_3) nano powder. The powder concentration was kept at 3 g/l as a constant value, and the pulse-off-time (T_{OFF}) was fixed at 9 µs. Apart from these, the less dependent parameter was unaltered and kept constant. Fluctuations of polarity are another issue that needs to be addressed, in the present experiment, it was maintained positive. Further, the experiment was required to run in low-voltage mode, so the voltage value was kept at 50 V with a constant tool surface area.

Initially, response parameters were focused on by considering the material removal rate (MRR) and surface roughness (Ra), where MRR is determined by measuring the weight difference of the workpiece before and after machining, along with the machining time, using a precision electronic digital balance device (model RADWAG WPS 50/C/2) with a precision of 0.001 grams. The samples went through cleansing with compressed air after the EDM process. Afterward, MRR is calculated using Eq (3).

$$\text{MRR} = \left(\frac{\text{M initial} - \text{M final}}{\rho t}\right) \quad (3)$$

The variables $W_{initial}$ and W_{final} represent the initial and final weight of the workpiece, respectively, ρ represents the density of the workpiece, and (t) refers to the manufacturing time. The Ra was measuredusing RT10, which is appropriate for current work. It has an accuracy of ±150 µm and a resolution of 5 nm. In the preliminary stage of data collection, focus was given to the generation of data for average surface roughness. This value was noted for the three different directions. The total sampling length and average speed were 0.8 mm and 0.5 mm/s, respectively. The SEM model FEI Quanta FEG 450 (Thermo Fisher Scientific, Czech Republic, Brno) was used.

4.1. Development of research results

The connection between variables and responses needs to be built up. This connection helps to understand the quantitative relationship among the parameters considered. For the present work to fulfill this need, RSM optimization was adopted. Among the various commercially available tools, MiniTab 19 was used in the present work due to this vast versatility. The necessary data related to both EDM and NPMEDM is as shown in Table 3. For better understanding I, T_{ON}, and FP are used as peak current, pulse on time, and flushing pressure respectively. The polynomial regression equations for the proposed model areindicated in Equation (4). This equation also demonstrates performance parameters [22].

$$y = B_1 + B_2X_1 + B_3X_2 + B_4X_1X_2 + B_5X_1^2 + B_6X_2^2 \quad (4)$$

where y is the dependent variable (response), X_i is the value of the control parameter, and B_i are the coefficients of regressions. The models for surface roughness Ra and MRR for EDM and NPMEDM were created using the experimental values obtained, and a mathematical relationship was established for both responses.

Regression Equation for EDM and NPMEDM, respectively.

MRR = -1.256+0.4249(I)+0.581(T_{ON})+ 0.530(FP)-0.135 (I)^2-0.01168(T_{ON})^2- 0.00655(FP)^2-0.0002 (I)*(T_{ON})-0.0035(I)*(FP)- 0.00060(T_{ON}) (5)

Ra = 2.769+0.015(I)+0.01078(T_{ON})-0.02964 (FP)+0.02031 (I)^2-0.000003(T_{ON})^2+0.000391 (FP)^2- 0.002398 (I)*(T_{ON})- 0.000938 (I)*(FP)+ 0.000538 (T_{ON})*(FP) (6)

MRR = -1.132 + 0.4703 (I) + 0.622 (T_{ON})+ 0.449 (FP)+ 0.089 (I)^2- 0.00794 (T_{ON})^2- 0.00482 (FP)^2- 0.0313 (I)*(T_{ON})+ 0.0102 (I) *(FP)- 0.00073 (T_{ON})*(FP) (7)

Ra = 1.654+ 0.267(I)- 0.00136 (T_{ON})- 0.03170 (FP)+ 0.03094 (I)^2+ 0.000239 (T_{ON})^2+ 0.000483(FP)^2-0.002471(I)*(T_{ON})- 0.002063 (I)*(FP)+ 0.000463(T_{ON})*(FP) (8)

The model needs to predict the outcome based on the inputs, which include the values of Ra and MRR. Here the p-value is greater than 0.05. During the data collection for, the strong relations between dependent and independent variables are as shown in Tables 5 and 6. Now, statistical analysis needs to be performed to relate the data in a more efficient way; hence, Analysis of Variance (ANOVA) was enabled. The Analysis of Variance (ANOVA) procedure enabled the statistical examination of Ra and MRR.

The F and P-values of the ANOVA table highlight the significance/non-significance of input variables for selected response variables. At a 95% confidence interval, the P-value must be lower than 0.05 to mark asignificant independent variable. The variance inflation factor (VIF) was computed to estimate multicollinearity. VIF explains how much the variance of the estimated regression factor is inflated, caused by multicollinearity in the model. Multicollinearity is not observed because the VIF is ≤ 1.01. Significant variation can be interpreted based on the data generated by ANOVA with respect to MRR, as shown in Table 5. The values indicate inconsistency across various parameters considered; not all the parameters show a positive trend. With detailed observations, pulse on time (T_{ON}) and flushing pressure (FP) have marginal importance as compared to peak current (I).

In the case of MRR, data generated from ANOVA, the value of R-squared and adjusted R-squared were found to be 98.39% and 95.48%, respectively. From the absolute values of R-squared and adjusted R-squared, the difference is marginal, which can be conveyed as less than 20%. With this information, the model considered can be taken as the optimum choice. Whereas other parameters such as standard deviation values were noted to be 0.052. With the help of Table 6, relevant information about Ra is generated; the considered parameters include FP, I, and TON. Now the impact of parameters can be well understood, and conclusions can be drawn. From the information, it is evident that peak current (I) is the most effective factor, next the pulse on time and flushing pressure.

With the help of Table 6, the percentage values of R-squared and adjusted R-squared can be compared. The values reported for R-squared and adjusted R-squared are 97.53% and 93.10%, respectively. These values are with respect to Ra. From the percentage values, the difference can be given the validity of the model. Here, the difference is less than 20%, which means the model can be the best choice. Whereas the standard deviation values were calculated to be 0.157. Hence, necessary statistical data ensures that the considered parameters have good arguments, and the model is very proper.

Table 5. List of ANOVA results for MRR -NPMEDM.

Source	DF	Adj. SS	Adj. MS	F	P-Value	VIF
Model	9	427.275	47.475	33.89	0.001	
Linar	3	363.335	121.112	86.45	0.000	
Peak current (I)	1	357.173	357.173	254.96	0.000	**1.05**
Pulse on time (T_{ON})	1	6.160	6.160	4.40	0.090	**1.05**
Flushing pressure (FP)	1	0.002	0.002	0.00	0.971	**1.05**
Square	3	27.910	9.303	6.64	0.034	
Peak current*Peak current	1	0.509	0.509	0.36	0.573	**1.01**
Pulse on time*Pulse on time	1	7.372	7.372	5.26	0.070	**1.06**
Flushing pressure*Flushing pressure	1	20.717	20.717	14.79	0.012	**1.01**
2-Way Interaction	3	3.842	1.281	0.91	0.497	
Peak current*Pulse on time	1	3.016	3.016	2.15	0.522	**1.05**
Peak current*Flushing pressure	1	0.664	0.664	0.47	0.522	**1.00**
Pulse on time*Flushing pressure	1	0.163	0.163	0.12	0.747	**1.05**
Error	5	7.004	1.401			
Total	14	434.280				
S = 0.0524575	R^2 = 98.39%		R^2 (adj) = 95.48%			

Table 6. List of ANOVA results for Ra - NPMEDM.

Source	DF	Adj. SS	Adj. MS	F	P-Value	VIF
Model	9	5.33310	59257	431.04	0.000	-
Linar	3	4.05150	1.56956	1141.71	0.000	-
Peak current (I)	1	4.39561	4.05150	2947.11	0.000	1.05
Pulse on time (T_{ON})	1	0.45125	0.45125	328.24	0.001	1.05
Flushing pressure (FP)	1	0.20592	0.20592	149.79	0.010	1.05
Square	3	0.17663	0.05888	42.83	0.001	-
Peak current*Peak current	1	0.05654	0.05654	41.13	0.001	1.01
Pulse on time*Pulse on time	1	0.00483	0.00483	3.51	0.120	1.06
Flushing pressure*Flushing pressure	1	0.13154	0.13154	95.69	0.000	1.01
2-Way Interaction	3	0.11213	0.03738	27.19	0.002	-
Peak current*Pulse on time	1	0.01879	0.01879	13.67	0.014	1.05
Peak current*Flushing pressure	1	0.02723	0.02723	19.80	0.007	1.00
Pulse on time*Flushing pressure	1	0.06611	0.06611	48.09	0.001	1.05
Error	5	0.00687	0.00137			-
Total	14	5.33997				-
0.157216	R^2 = 97.53%		R^2 (adj) = 93.10%			

4.2. Impact of flushing pressure on MRR

For the three main parameters, peak current, pulse on time, and flushing pressure, the graphs are plotted with respect to MRR as shown in Fig. 5. Flushing pressure did not have much impact at the two values, minimum and maximum, which were 0.2 kg/cm² and 1 kg/cm², respectively. While the best values for MRR were found to be around 0.5 kg/cm² [23].

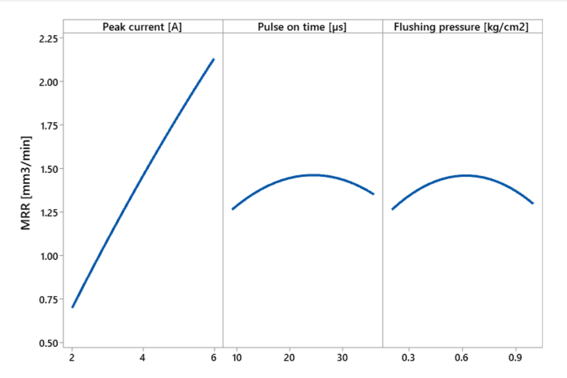

Figure 5. Variation of input process parameters on MRR.

The range of MRR values from 0.424 mm³/min to 2.011 mm³/min was obtained in NPMEDM. Consequently, in the EDM, in the equal setting through flushing pressure and without nano powder, the variety of MRR values gained was 1.941 mm³/min to 4.20 mm³/min. The material removal rate in this process has been affected by low flushing pressure, resulting in the inability to remove the EDM products. Moreover, high flushing pressure leads to a low material removal rate by reducing the number of sparks and interrupting an acceptable flow of the dielectric fluid [24]. It can be concluded that the Al_2O_3 nano powders have been found to enhance MRR in finishing operations at relatively lower values of peak current (I) and pulse on time (T_{ON}). In the meanwhile, the MRR is not influenced significantly by optimum flushing pressure with nano powder [25], even considering the trend shown in Figure 5. Simultaneously, controlling the flushing pressure is a crucial aspect of finishing operations [26].

Figure 6 illustrates the influence of the two parameters, peak current and pulsed on time, on the MRR, while the additional parameters are kept at their selected levels in the model. Peak current and pulse on-time generate larger pulse energy, resulting in deeper discharge craters, thereby increasing the MRR [27]. We can see where the different answers agree by using the contour plot. Based on the findings, the maximum MRR was obtained at maximum values of peak current and medium values of pulse on time and flushing pressure, which are

6 A, 22.5 µs, and 0.5 kg/cm², respectively, and the maximum MRR was obtained at medium values of peak current, pulse on time, and flushing pressure, which are 4 A, 22.5 µs, and 0.5 kg/cm², respectively, as shown in figure 6. This effect of TON at a medium level and the interaction with flushing pressure can be a subject for further study with a larger range of parameters.

4.3. Impact of flushing pressure on Ra

Figure 7 shows the variations of Ra with independent variables. The efficient flushing pressure with nano powder was higher than 0.2 kg/cm² to ensure proper dielectric flow [27,28]. An optimal flushing pressure was found to be at about 0.5 kg/cm²[29].

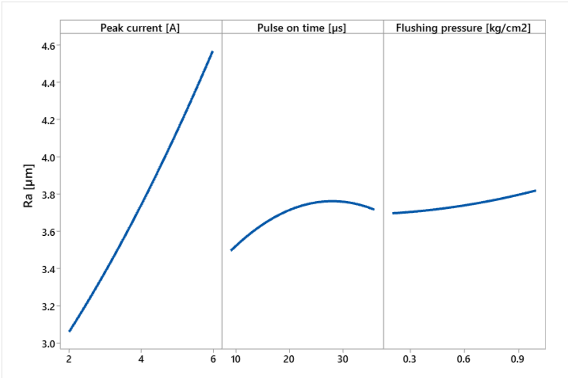

Figure 7. Variation of Ra across input process parameters.

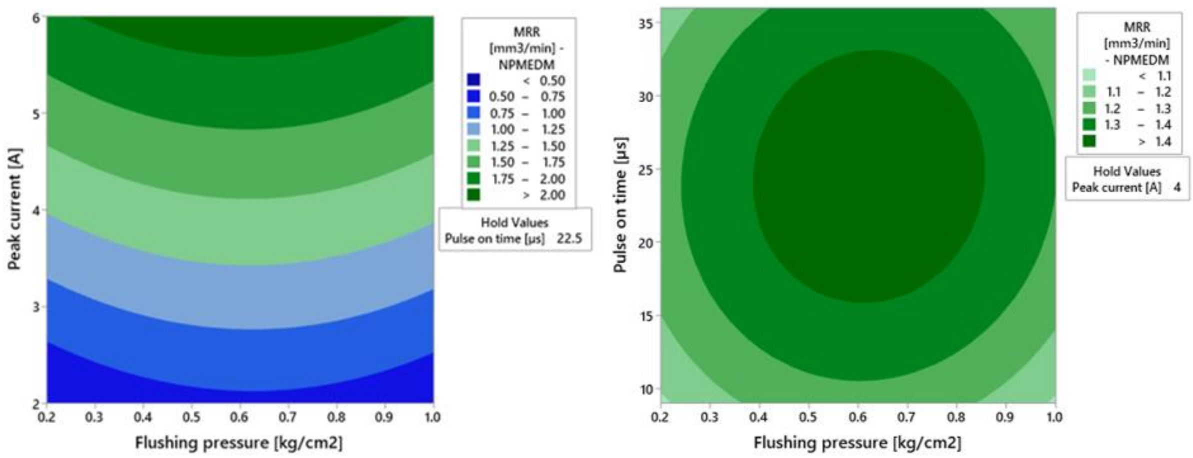

Figure 6. Contour plot for peak current (I), pulsed on time (T_{ON}) and flushing pressure (FP) for MRR.

The variety of Ra values from 2.79 µm to 4.60 µm was recorded in NPMEDM, and for EDM (with flushing pressure and without nano powder), the data ranges from 3.05 µm to 5.41 µm. These values convey the EDM flushing technique in the best way possible. The techniques highlight a positive result. Overall, the use of nano powder in EDM with flushing at optimum value has shown promising results in enhancing surface roughness, especially the Ra parameter.

During machining, Carter's size is a critical aspect of the EDM that influences the surface finish. The quality of the surface finishes is exponentially reduced with thermal levels reaching new higher values. Deeper craters on the machined surface led to poor surface roughness in the case of EDM [30]. Therefore, the usage of nano powder in working fluid creates pulses with lower energy [6]. On the other hand, larger discharge gaps caused by nano powder have helpful effects on the improvement of spark distribution. Subsequently, spread them throughout a larger portion of a workpiece [31]. And we noted that the flushing pressure prevents the arcing in the gap, and the process works efficiently, resulting in better surface [32]. Furthermore, the results indicate that optimal flushing pressure can reduce surface roughness by minimizing the accumulation of molten material [33], and excessive flushing pressure negatively affects surface finish over time.

With the help of Fig. 8, a good visual relation can be noticed across the two key parameters. The two design parameters involved here are peak current (I) and pulsed on time (T_{ON}), keeping other variables at their selected levels. The localized variation in contour can be well justified based on the color coding. The behavior of flushing pressure can be captured effectively. A negative impact on surface properties was reported when dealing with peak current and pulse on-time. Thereby higher values of discharge energy were related when peak current and pulse on-time increased its values.

4.4. Response optimizer

In the commercial world of optimization, multiple tools are available to predict responses. In the present case, the design of experiments software MiniTab was shortlisted to obtain the result. The intention of using MiniTab was to get the optimum combination of variables for input parameters so the best possible results can be achieved. Further RSM technique was implemented to streamline the data.

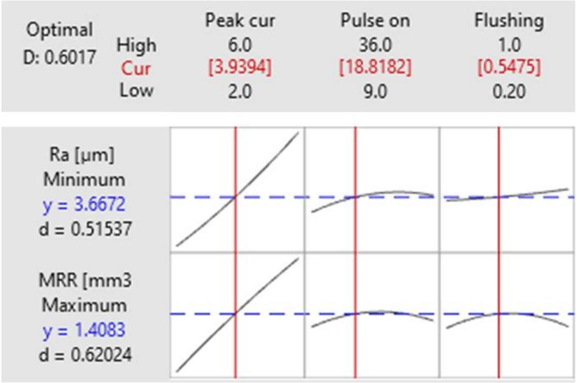

Figure 9. Variation in MRR with respect to surface roughness.

With the help of Fig. 9, RSM outputs of the maximum MRR and minimum Ra; the independent variables are peak current at 4 A, pulse on time at 18 µs, and flushing pressure at 0.5 kg/cm².

Table 7. Information about Ra and MRR according to the model.

	Peak current (I)	Pulse on time (T_{ON})	Flushing pressure (FP)	Predicted	Experimental
Ra	4	18	0.51	3.667	3.78
MRR	4	18	0.62	1.4083	1.573

The outcome from the model was interesting and in line with the literature [10-21]. From the presented work, optimization results for MRR were closely in line with all the critical experimental points. Even the confirmation test was performed to ensure the collected data had no possibility of errors. The data can be found in Table 7. In terms of absolute value of error, it was approximately 8%. Thus, a clear acceptable range of data was reported by taking up both experimental and software-based data.

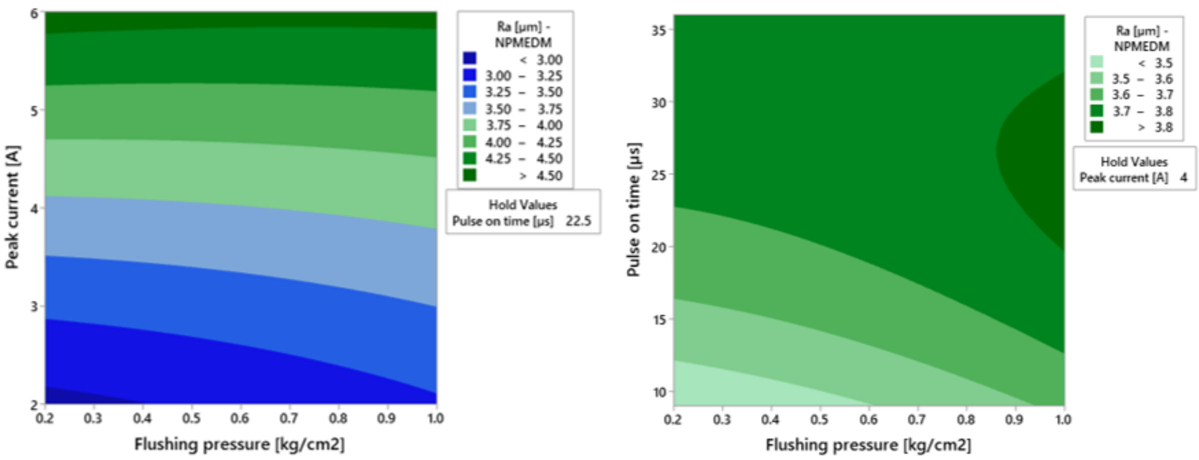

Figure 8. Contour plots for I, T_{ON} and FP across Ra.

5. Conclusion

The present study was realized to identify the relationship between parameters such as flushing pressure (FP), peak current (I), and pulse on time (T_{ON}) and the responses, specifically the material removal rate and surface roughness, during the finishing operation setting of the process with low peak current (I) ranging from 2 to 6 amperes and pulse on time (T_{ON}) from 9 to 36 microseconds and flushing pressure (FP) from 0.2 kg/cm² to 1 kg/cm². The comparison between EDM and NPMEDM was illustrated in a systematic way. The RSM has been integrated to ensure that the experimental study can be very well justified. Graphs for all the key functions were made efficiently. A clear and accurate description was made of a necessary location by producing additional sections. Some of the key conclusions are below:

- Lower MRR was reported at higher and lower values of flushing pressure, with actual values noted to be 0.2 kg/cm² and 1 kg/cm², respectively. The optimal FP was around 0.5 kg/cm².
- MRR is not influenced significantly by optimum flushing pressure with nano powder for finishing operations.
- The maximum MRR was obtained at maximum values of peak current and medium values of pulse on time and flushing pressure, which are 6 A, 22.5 µs, and 0.5 kg/cm², respectively.
- The use of nano powder in EDM with flushing techniques at optimum value has shown promising results in enhancing surface roughness, especially the Ra parameter. An optimal flushing pressure was found to be at about 0.5 kg/cm².
- The RSM model was symmetrically performed by giving all the necessary inputs and focused on both the relationship between the process parameters and the responses.
- Focusing only on the impact of flushing pressure with nano powder and a limited number of other factors was one of the constraints of this study. Further research on various other key parameters is necessary. Additional research, such as addressing the effects of process parameters on surface texture and morphology using SEM images and profilometers, is needed. Possible investigations in the future might find out the effect of nano powder on large areas. By adding nanoparticles to the dielectric, this generates new obligations to design a more effective circulation mechanism attached to the machine to confirm the presence of nanoparticles in the gap between the electrodes during material processing. Finally, measuring the discharge gap for both EDM and NPMEDM during machining was done to ensure correlation with the theoretical analysis of this process.

References

[1]. Mohri, Naotake, Nagao Saito, Hisayoshi Narumiya, Hidetoshi Kawatsu, Yoshio Ozaki, Kazuhiko Kobayashi and Yoshiki Tsunekawa. “Finish Machining by EDM Using Powder Suspended Working Fluid.” Journal of the Japan Society of Electrical-machining Engineers 25 (1991): 47-60 (In Japanese).

[2]. Kozak, Jerzy, Marek Rozenek and L. Dabrowski. “Study of electrical discharge machining using powder-suspended working media.” Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 217 (2003): 1597 - 1602. https://doi.org/10.1243/095440503771909971

[3]. Joshi, Ayanesh Y., and Anand Y. Joshi. "A systematic review on powder mixed electrical discharge machining." Heliyon 5, no. 12 (2019).

[4]. Joshi, Ayanesh Y. and Anand A. Joshi. “Feasibility Analysis of Powder-Mixed Deionized Water as Dielectric for Machining Ti6Al4V.” Journal of The Institution of Engineers (India): Series C 102 (2021): 337 - 347. https://doi.org/10.1007/s40032-020-00639-7

[5]. Chaudhari, Rakesh, Sakshum Khanna, Vivek K. Patel, Jay Vora, Soraya Plaza and Luis Norberto López de Lacalle. “Experimental Investigations of Using Aluminum Oxide (Al2O3) and Nano-Graphene Powder in the Electrical Discharge Machining of Titanium Alloy.” Micromachines 14 (2023). https://doi.org/10.3390/mi14122247

[6]. Agarwal, Deepak, Sharad Yadav, Rabesh Kumar Singh and Anuj Kumar Sharma. “An investigation on the effect of alumina nano powder mixed dielectric oil on EDM-assisted precision micro-drilling operation.” Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering (2024). https://doi.org/10.1177/09544089241277715

[7]. Ashok, M., T. Niranjan, Sangeetha Chokalingam and B. Singaravel. “Investigation of powder mixed electrical discharge machining and process parameters optimization using Taguchi based overall evaluation criteria.” IOP Conference Series: Materials Science and Engineering 1057 (2021). https://doi.org/10.1088/1757-899x/1057/1/012075

[8]. Shingare, Prashant P. and Soham Mujumdar. “Experimental Investigation of Powder-mixed Dielectrics for Electrical Discharge Machining.” Manufacturing Letters (2022). https://doi.org/10.1016/j.mfglet.2022.07.056

[9]. Kumar, Amit, Amitava Mandal, Amit Rai Dixit, Alok Kumar Das, Saroj Kumar and Rachit Ranjan. “Comparison in the performance of EDM and NPMEDM using Al2O3 nanopowder as an impurity in DI water dielectric.” The International Journal of Advanced Manufacturing Technology 100 (2018): 1327-1339. https://doi.org/10.1007/s00170-018-3126-z

[10]. Chaudhari, Rakesh, Parth Prajapati, Sakshum Khanna, Jay Vora, Vivek K. Patel, Danil Yurievich Pimenov and Khaled Giasin. “Multi-Response Optimization of Al2O3 Nanopowder-Mixed Wire Electrical Discharge Machining Process Parameters of Nitinol Shape Memory Alloy.” Materials 15 (2022). https://doi.org/10.3390/ma15062018

[11]. Oskueyan, Saeed, Vahid Abedini and Alireza Haji Ali mohammadi. “Effects of hybrid Al2O3- SiO2 nanoparticles in deionized water on the removal rate and surface roughness during electrical discharge machining of Ti-6Al-4V.” Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 236 (2021): 1122 - 1133.

[12]. Prakash, T. B., M. Gangadharappa, Santhosh Somashekar and M. Ravikumar. “The Impact of nanoparticles (B4C-Al2O3) on mechanical, wear, fracture behavior and machining properties of formwork grade Al7075 composites.” Frattura ed Integrità Strutturale (2024). https://doi.org/10.3221/igf-esis.69.15

[13]. Bai, Xue, Qin-He Zhang, Ting-Yi Yang, and Jian-Hua Zhang. "Research on material removal rate of powder mixed near dry electrical discharge machining." The international

journal of Advanced manufacturing Technology 68 (2013): 1757-1766. https://doi.org/10.1007/s00170-013-4973-2

[14]. Molinetti, Anderson, Fred Lacerda Amorim, Paulo Soares and Tiago Czelusniak. “Surface modification of AISI H13 tool steel with silicon or manganese powders mixed to the dielectric in electrical discharge machining process.” The International Journal of Advanced Manufacturing Technology 83 (2015): 1057 - 1068. https://doi.org/10.1007/s00170-015-7613-1

[15]. Talla, Gangadharudu, S. Gangopadhayay, and C. K. Biswas. "State of the art in powder-mixed electric discharge machining: a review." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 231, no. 14 (2017): 2511-2526. https://doi:10.1177/0954405416634265

[16]. Abdudeen, Asarudheen, Jaber E. Abu Qudeiri, Ansar Kareem, Thanveer Ahammed and Aiman Ziout. “Recent Advances and Perceptive Insights into Powder-Mixed Dielectric Fluid of EDM.” Micromachines 11 (2020). https://doi.org/10.3390/mi11080754

[17]. Zhang, Yanzhen, Yonghong Liu, Yang Shen, Renjie Ji, Bao-ping Cai, Hang Li and Fei Wang. “A review of the current understanding and technology of powder mixed electrical discharge machining (PMEDM).” 2012 IEEE International Conference on Mechatronics and Automation (2012): 2240-2247.

[18]. Kozak, J., M. Rozenek, and L. Dabrowski. "Investigation of electrical discharge machining using abrasive powder suspended dielectric." Transaction of WUT-New Technologies 3 (2000): 25-34.

[19]. Zhao, Wei Lin, Qingyu Meng and Zhan Yong Wang. “The application of research on powder mixed EDM in rough machining.” Journal of Materials Processing Technology 129 (2002): 30-33. https://doi.org/10.1016/s0924-0136(02)00570-8

[20]. Nano shell LLC, www.nanoshell.com. Recovered on December 14, 2023.

[21]. Buttlar, L., & Powell, R. R. (1992). Basic Research methods for Librarians. Journal of Education for Library and Information Science, 33(2), 164. https://doi.org/10.2307/40323264

[22]. Perec, Andrzej, Frank Pude, Michael Kaufeld and Konrad Wegener. “Obtaining the Selected Surface Roughness by Means of Mathematical Model Based Parameter Optimization in Abrasive Waterjet Cutting.” Strojniski Vestnik-journal of Mechanical Engineering 63 (2017): 606-613. https://doi.org/10.5545/sv-jme.2017.4463

[23]. Ablyaz, Timur, Evgeny Sergeevich Shlykov and Karim Muratov. “Modeling of EDM Process Flushing Mechanism.” Materials 16 (2023). https://doi.org/10.3390/ma16114158

[24]. Gadeschi, Gonzalo Brito, Wolfgang Schroeder, Lennart Schneiders and Matthias Meinke. “Direct particle-fluid simulation of flushing in die-sink electrical-discharge machining.” (2017). https://doi.org/10.1080/19942060.2021.1877198

[25]. Lee, S. H. and X. P. Li. “Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide.” Journal of Materials Processing Technology 115 (2001): 344-358. https://doi.org/10.1016/s0924-0136(01)00992-x

[26].Gao, Minghao, Ming Liu, Jianqing Han and Qinhe Zhang. “Investigation of Machining Characteristics in Electrical Discharge Machining Using a Slotted Electrode with Internal Flushing.” Micromachines 14 (2023). https://doi.org/10.3390/mi14111989

[27]. Kumar, Amit, Amitava Mandal, Amit Rai Dixit and Alok Kumar Das. “Performance evaluation of Al2O3 nano powder mixed dielectric for electric discharge machining of Inconel 825.” Materials and Manufacturing Processes 33 (2018): 986 - 995. https://doi.org/10.1080/10426914.2017.1376081

[28]. Zhang, M., X. Jiang, Yong Feng, Binghui Jia and Jian Wang. “Effects of workpiece polarity and flushing pressure on the arc plasma and the crater of single-pulsed arc discharges.” The International Journal of Advanced Manufacturing Technology 112 (2021): 1593 - 1600. https://doi.org/10.1007/S00170-020-06549-3

[29]. Elias, Rasha R. “Investigation of the Effect of Nano Powder Mixed Dielectric on EDM Process.” Engineering and Technology Journal (2020). https://doi.org/10.30684/ETJ.V38I3A.337

[30]. Boominathan, Elumalai, Giridharan Krishnan, Chakravarthi Gurijala and Jothiprakash Vm. “Studies on the effect of SiC nanopowder concentration and discharge energy on surface roughness and recast layer in micro ED milling of Inconel 718 alloy.” Physica Scripta (2024). https://doi.org/10.1088/1402-4896/ad94b6

[31]. Thakur, Surend Singh, Brijesh Patel, Rajeev Kumar Upadhyay, DILIP KUMAR BAGAL and Abhishek Barua. “Machining characteristics of metal matrix composite in powder-mixed electrical discharge machining – A review.” Australian Journal of Mechanical Engineering 21 (2022): 1755 - 1777. https://doi.org/10.1080/14484846.2022.2030089.

[32]. Muthuramalingam, T., S. Vasanth, L. Ganesh Babu, Duraisamy Saravanakumar and P. Karthikeyan. “Flushing Pressure Automation for Efficient Machining in EDM Process.” 2019 7th International Conference on Control, Mechatronics and Automation (ICCMA) (2019): 232-236. https://doi.org/10.1109/ICCMA46720.2019.8988592

[33]. Das, Shirsendu, Rajdeep Paul, Abhijit Bhowmik, Jayant P. Giri, Ibrahim Albaijan and Chander Prakash. “Assessment of the influence of flushing on the wear and morphological properties of the tool during electrical discharge machining.” AIP Advances (2024). https://doi.org/10.1063/5.0196307