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ORIGINAL ARTICLE

An Investigation on Surfactant Added PMWEDM of Inconel 718

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ABSTRACT – This paper shows the impact of different process parameters and powder characteristics on the material removal rate and surface roughness obtained in surfactant added Powder Mixed Wire Electric Discharge Machining (PMWEDM). Inconel-718 is selected as the workpiece material, which has ample application in the industries handling environment of extreme stress, pressure and temperature. It has high work hardening properties along with high rupture strength, fatigue, and creep, making it extremely difficult to machine. So, additives having different thermo-physical properties are studied to improve the machining efficiency. The additives experimented includes aluminium, silicon carbide, graphite, and aluminium oxide. It is found that the electrostatic force present creates an agglomeration effect with dielectric additive powders, causing inhomogeneity in the mixture. So, a surfactant SPAN20 is used here to maintain the homogeneity of the mixture. The obtained MRR and SR are then modelled and optimised through Particle Swarm Optimization technique (PSO). It is observed that the addition of SPAN20 has improved the MRR by 13.56% and, SR by 45.05%. Also, it has been found that due to the combined abrasive action, abrasive powders increase MRR significantly than others. Furthermore, it is found that low grit size powders with lower density produces better machined surfaces.

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Wire EDM; Surfactant; Abrasive; Particle swarm optimisation; Surface topography.

INTRODUCTION

Wire electrical discharge machining is an electro-thermal machining process that uses the heat of electric sparks generated between the workpiece and the tool wire in a dielectric fluid for machining. The process can be used precisely to machine metals, which, through conventional methods, are very difficult to machine [1]. Kumar et al. [2] have used it to machine low conductive materials. Inconel 718 is a nickel-based superalloy having 50-55% nickel, 17-21% chromium and 4-5% niobium and tantalum. It has numerous applications in the industry, where extreme stress, pressure and temperature conditions are present. It has high work hardening properties along with high rupture strength, high fatigue, and creep, making it very difficult to machine [3]. It also has high toughness because of which post-machining the machined surface has a minimal amount of micro-cracks [4].

The wire EDM process is a flexible machining process that can generate highly accurate profiles on these superalloys using computerised numerical control (CNC) programming [5]. Powder mixed wire electric discharge machining (PMWEDM) is a similar process in which electrically conductive and non-conductive powders are mixed into the dielectric present to reduce their insulating strength and thus increasing the gap between the tool and the electrode. This reduces the dielectric strength of the dielectric and results in a more stable process with improved material removal rate (MRR) and surface roughness (SR) values [6], [7]. Mirror-like surface finish with improved corrosion resistance, wear-resistance and hardness have been recorded with silicon powder additives. In contrast, SKD-11 aluminium powder has been shown to have the best surface finish with the finest recast layer between chromium, silicon carbide and copper powders. [8, 9]. In [10], machining has been performed using tungsten carbide, cobalt and boron carbide powders on Inconel 800 and a better surface characteristic has been reported with lower current and higher pulse off time. Density, thermal conductivity, and electrical resistivity are found to be the significant factors in additive powder selection [11]. During the machining of Inconel 718 with an aluminium powder additive of 325 mesh size and concentration ranging from 0.5 to 1.5 gm/litre, MRR showed first increasing and then decreasing trend [12]. Whereas, surface hardness is found to be increasing when chromium powder is mixed with kerosene as a dielectric [13].

In the presence of additive powders, the electrostatic forces create agglomeration effect, that resulted in inhomogeneity of the mixture. So the need for a surfactant arises. Surfactants are chemical compounds by mixing of which the powder particles get well-distributed, resulting in uniform energy distribution. Here the hydrophilic end groups of surfactant absorb the surface of powder particles, and hydrophobic tail connects to the dielectric fluid. Surfactant molecules function as a steric barrier separating powders from agglomeration. Also, during discharge, it can produce oxidation which can further result in an explosion and thus better MRR. Mixing of 4 gm/litre of surfactant, in graphite powder and dielectric mixture, resulted in a decrement in SR [14]. SPAN20 is a non-ionic surfactant which is less irritating and pollution-free. With the use of SPAN20 as the surfactant in the mixture, agglomeration of aluminium powder particles decreased; thus, the MRR has increased. It also enhanced the surface finish of the workpiece obtained after machining [15].

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Geometric inaccuracy is also observed after machining, and the two main reasons for errors include inaccuracies in hardware and software and inappropriate process parameter settings [16]. Poor selection of machining parameters may lead to highly affect the productivity and efficiency of the process [17]. Wire electrode vibrations result in hardware inaccuracies [18]. A high pulse of time generated an additional error in [19] whereas pulse on time (T_{on}) and gap voltage (V_g) are the critical parameters in the case of errors due to process parameter settings [20]. There has been an increase in overcutting and cutting rate with an increase in I_p and T_{on} [21]. Whereas scanning electron microscopy (SEM) shows that voltage has a significant contribution in material removal of metals [22]. Some studies have also taken generated residual stress under consideration while machining. [23] have performed analysis on the EDM affected layers generated after machining and studied the generated micro to nano level residual stress.

So an optimal combination of process parameters is required. In order to obtain optimised process parameters for different non-conventional machining, various optimisation techniques have been applied in the past. In [24], the desirability function approach has been used for multi-objective optimisation. In [25], the optimised value of MRR, EWR and SR has been obtained using particle swarm optimisation (PSO) technique. Also, PSO generated the Pareto front in less time than the Genetic algorithm due to the less complicated structure and limited parameters in [26].

A decent number of studies in the PMWEDM area have already been done, but to the best knowledge of authors, very few investigations have been carried out in the field of surfactant added PMWEDM. Also, a minimal attempt has been made to consider the effect of surfactant addition on the dimensions of the workpiece. Moreover, there is little research into the addition of different powder as additives along with the surfactant. By taking these factors into account, this article details the optimisation of wire electric discharge machining and its numerous performance characteristics after adding powder and surfactant into the dielectric.

MATERIALS AND METHODS

Design of experiment has been performed by several researchers to reduce the time and cost of experimentation. In [27], a full factorial design was used with four parameters at two levels, while Taguchi L27 array with four control parameters having three levels has been used for the design of experiment in [28]. Kumar and Dhingra [10] used the Box Benhken method with RSM. In the present work, RSM has been used to design experiments and for modelling of process parameter responses. Box-Behnken blocked design has been used for DOE modelling with factors; gap voltage (V_g), pulse off time (T_{off}), pulse on time (T_{on}), and peak current (I_p), all continuous in nature. Analysis of variance (ANOVA) has been used to check which parameters are significant and how they are affecting the responses. A regression equation has also been obtained for each output.

Several researchers have used different powders to improve the MRR and SR after machining. A couple of abrasives have also been examined. According to the literature survey, a gap in the selection of the powder has been found based on its particle size. So far, the effect of mixing powders of various physical properties with the surfactant has not been explored. Thus, considering the gaps, the selected mixing powders are Al_2O_3 powder, SiC powder, aluminium powder and graphite powder in grit sizes of 10 microns and 40 microns each. Whereas, the mixture used the sorbitan monolaurate (SPAN20) as the surfactant. The surfactant concentration is set at a value of 3 gm/l based on the trials. Also, based on the machine limit, literature review and trials the range of input electrical parameters are selected as 2-4 A for peak current (I_p), 30-70 V for gap voltage (V_g), 30-90 sec for pulse on time (T_{on}) and 4-12 sec for pulse off time (T_{off}).

EXPERIMENTATION

The experimental work has been carried out on electric discharge machining of "Ezeecut plus" a CNC WEDM. A separate chamber equipped with a stirring system has been used for powder mixing. Many powders have been used by different researchers to improve the MRR and SR of the workpiece after machining. A few abrasives have also been investigated. Based on the literature survey, it has been found that there is a gap in the selection of powders based on their particle size. Also, the effect of powders mixing of different physical properties along with the surfactant has not been studied so far. So considering the gaps the mixing powders and a surfactant selected are presented in Table 1.

Table 1. Mixed powders in experimentation

S. No.	Abrasive powder	Size (µm)	
1	Al_2O_3 powder	10	40
2	SiC powder	10	40
3	Aluminium powder	10	40
4	Graphite powder	10	40

Sorbitan monolaurate, which is also known as SPAN20 has been used as the surfactant in the mixture. The concentration of surfactant is fixed to a value of 3 gm/litre based on the trial experiments. Considering the literature survey and the machine limits, trial experiments were performed. Based on the results, a range of input parameters is tabulated in Table 2.

Table 2. Selected input parameters range

Input parameter	Range
Peak current, I_p	2 – 4 A
Gap voltage, V_g	30 – 70 V
Pulse on time, T_{on}	30 – 90 s
Pulse off time, T_{off}	4– 12 s

A workpiece profile was created in RRAPT software for machining. The profile design has been done considering the necessity to machine different geometrical shapes in an intricate part produced in industries. The actual geometry of workpiece is illustrated in Figure 1. The profile generated covers the linear cutting, angular cutting, and external cutting along a curve and internal cutting along a curve. The surface roughness value is measured using MarSurf PS1 surface roughness tester, and the rate of material removal is obtained using the formula as in Eq. (1).

$$MRR = \left[\left(w_i - w_f\right) \times 60 \times 1000\right]/(T \times \rho) \tag{1}$$

where W_i is the workpiece weight before machining (g), W_f is workpiece weight after machining (g), T is the consumed time (s) and ρ is workpiece density (g/mm^3)

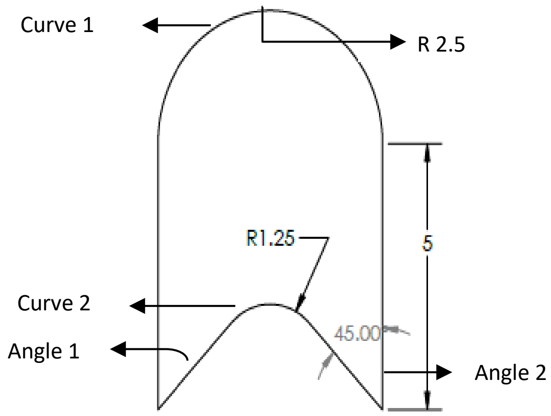


Figure 1. CAD geometry of the workpiece profile.

RESULTS AND DISCUSSION

Twenty-seven experiments were performed in the first set of experiments, based on the design of the experiment. The variation with that of the input process parameters in the two output parameters MRR and SR has been analysed. The results of the experiments are summarised in Table 3.

Table 3. Experimental results

S.No	I_p (A)	V_g (V)	T_{on} (s)	T_{off} (s)	MRR (mm^3 / min)	SR (μm)
1	3	50	60	8	3.410	2.287
2	3	70	60	12	1.254	2.665
3	3	50	60	8	3.140	2.303
4	3	30	60	12	2.826	2.555
5	3	50	90	12	1.723	2.842
6	3	30	90	8	4.011	2.500
7	2	50	30	8	3.437	2.306
8	3	50	60	8	2.532	2.354
9	4	50	90	8	4.496	2.748
10	3	50	30	4	8.168	2.467
11	4	50	60	12	2.449	2.447
12	3	30	60	4	5.123	1.800
13	3	70	90	8	2.566	3.056
14	3	30	30	8	4.829	2.186
15	2	70	60	8	2.293	2.682
16	2	30	60	8	3.958	2.438
17	2	50	90	8	2.579	2.955
18	3	70	30	8	4.141	2.902
19	2	50	60	12	1.620	2.895

S.No	I_p (A)	V_g (V)	T_{on} (s)	T_{off} (s)	MRR (mm^3 / min)	SR (μm)
20	4	50	30	8	6.021	2.789
21	3	50	90	4	7.297	2.534
22	4	50	60	4	8.590	2.789
23	3	50	30	12	3.233	2.468
24	3	70	60	4	5.525	2.970
25	4	30	60	8	5.820	2.232
26	2	50	60	4	5.176	2.170
27	4	70	60	8	4.191	3.304

Regression equations for each MRR and SR have been obtained as in Eq. (2) and Eq. (3).

$$MRR = 10.77 - 0.91 \times I_p + 0.0191 \times V_g - 0.087 \times T_{on} - 0.572 \times T_{off} + 0.593 \times I_p^2 + 0.055 \times T_{off}^2 \\ - 0.0056 \times I_p \times T_{on} - 0.1615 \times I_p \times T_{off} - 0.00617 \times V_g \times T_{off} - 0.00133 \times T_{on} \times T_{off} \tag{2}$$

$$SR = 2.25 - 0.764 \times I_p - 0.0198 \times V_g - 0.069 \times T_{on} + 0.296 \times T_{off} + 0.1995 \times I_p^2 + 0.00346 \times T_{off}^2 \\ + 0.01035 \times I_p \times V_g - 0.00575 \times I_p \times T_{on} - 0.0667 \times I_p \times T_{off} - 0.00331 \times V_g \times T_{off} \tag{3}$$

The R-square correlation coefficient has a value of 94.7% for MRR and 90.2% for SR, which indicates that the model equations are nearly correct. Through Figure 2, it can be noticed that with a percentage contribution of 62.38% and 13.61%, T_{on} and I_p contribute the most to the MRR. At a percentage share of 39.58% and 9.03% respectively, in the case of SR, Vg, and T_{on}-I_p interaction contribute the most to the MRR. The sequence of experiments is given in Table 4.

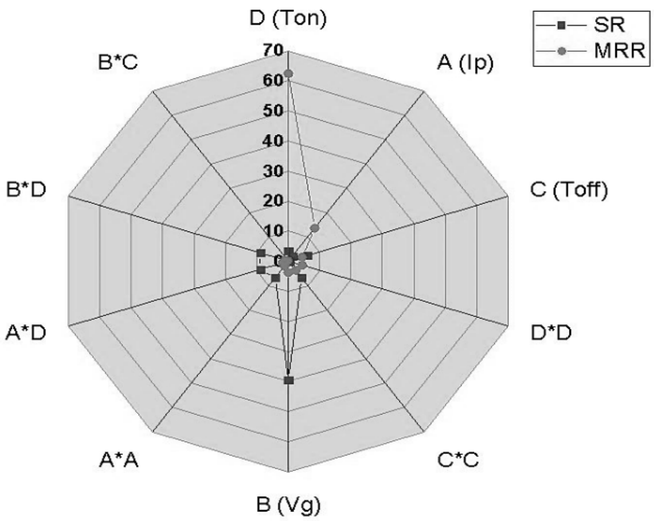


Figure 2. Graph representing the percentage contribution of different electrical parameters on MRR and SR.

Table 4. Experiment sequence.

Powder	Al		Al_2O_3		SiC		Graphite	
Size (μm)	40	10	40	10	40	10	40	10
Exp. no.	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24

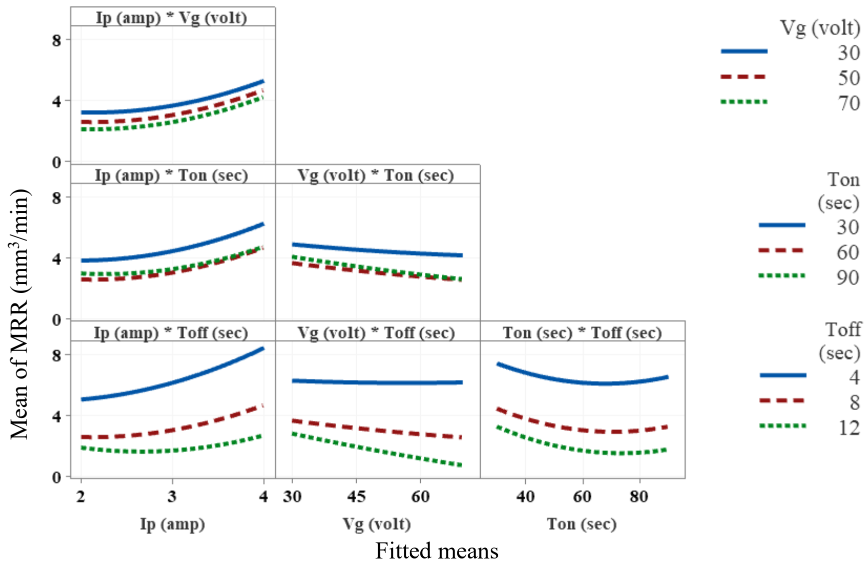
Optimisation of Process Parameter

Here concurrent optimisation has been done using particle swarm optimisation technique of two objectives MRR and SR which are of conflicting nature. The solutions obtained are Pareto optimal solutions as none of them are superior to anyone in the group. Several trials have been conducted for optimisation of parameters involved in multi-objective optimisation. Finally, a Pareto front has been obtained using an initial population of 300, an inertia weight of 0.4, a social and a cognitive parameter of 2 each and the maximum iterations count equal to 200. The ranking of the solution has been done using the Eq. (4).

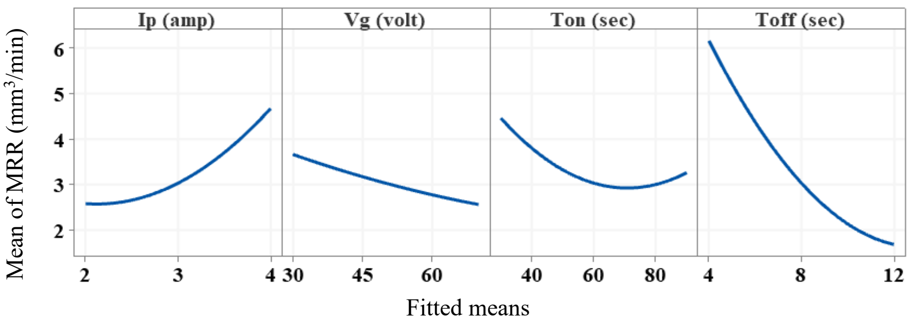
$$\begin{cases} R_{inb} = (\max(a_i) - a_i)/(max(a_i) - \min(a_i)) \\ R_{ib} = (a_i - \min(a_i))/(max(a_i) - \min(a_i)) \end{cases} \tag{4}$$

where R_{inb} is ranking for non-beneficial attributes, R_{ib} is ranking for beneficial attributes, a_i is value of ith attributes

A total of twenty-four experiments with different levels of powder concentration have been performed with the optimal electrical parameters obtained. The acquired outcomes are then plotted in Figure 3(a) and 3(b). With an increase in I_p and decrease in T_{off}, higher MRR is achieved as in Figure 3(b). This is due to high spark intensity which supports to easy material removal process. Also, due to enlarging the gap between tool and workpiece by the powder mixed dielectric, the eroded material removes rapidly and create the appropriate environment in the machining zone. Thus MRR is continuously enhanced by the proposed hybrid technique. Figure 4(a) shows the interaction plot of process parameters on SR. Figure 4(b) shows the main effect plot which reveals that higher SR is obtained at higher pulse on time and gap voltage. Higher pulse on time and gap voltage increases the spark timing, thus, surface roughness also increases.

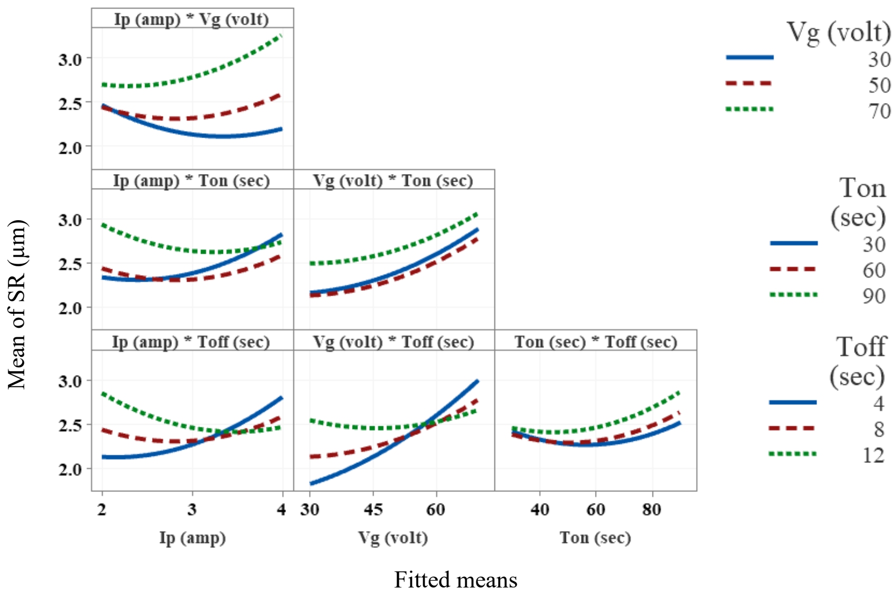


(a)

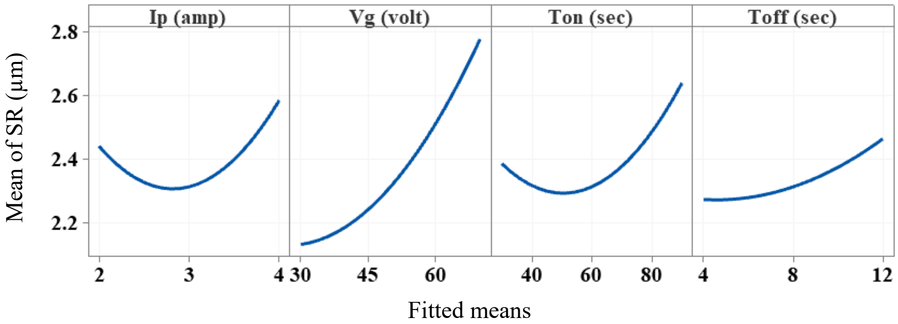


(b)

Figure 3. (a) Interaction plot and, (b) main effect plot for MRR.



(a)



(b)

Figure 4. (a) Interaction plot and, (b) main effect plot for SR.

The optimised process parameter values obtained from PSO are 2.475 A, 30 V, 46.516 s and 4 s for I_p, V_g, T_{on}, and T_{off} respectively. A pareto front has been obtained between MRR and SR as shown in Figure 5. Moreover, the corresponding optimal MRR and SR values obtained are 5.806 mm^3/min and 2.323 µm, respectively. A confirmation test has also been performed to find the error produced as presented in Table 5 and it has been found that MRR has a 2.996 % error whereas SR has a 3.553 % error which is very marginal and permissible.

Table 5. Values of SR and MRR from PSO and that obtained after confirmation test

Optimised values obtained from PSO			Confirmation test	Error (%)
Process parameters	I_p	2.475	-	
	V_g	30.000	-	
	T_{on}	46.516	-	
	T_{off}	4.000	-	
Output parameters	MRR	5.806	5.632	2.996
	SR	2.323	2.240	3.553

Keeping other parameters constant and just changing the powder, different MRR values are compared for no additive WEDM, PMWEDM, and surfactant added PMWEDM. Here from Figure 6(a), it can be observed that the addition of surfactant is increasing the MRR significantly with few powders. It can also be observed that experiment number 11 of SPMWEDM generates the best MRR. SR values are also compared for all three sets of twenty-four experiments, keeping other parameters constant, as shown in Figure 6(b). All measured SR values were taken with a 0.25 mm cut-off and a 1.75 mm travel length.

The main effective plot for surface roughness shows that middle value of pulse on time and peak current provides the best surface finish. At the same time, larger value of the pulse off time and gap voltage provides the poor surface finish. This is due to the high energy density, which is directly involved in modifying the plasma channel with the help of surfactant and powder mixed dielectric. Quick heating and cooling process affect the machined surface mostly, and resulted in micro-cracks, craters and globules.

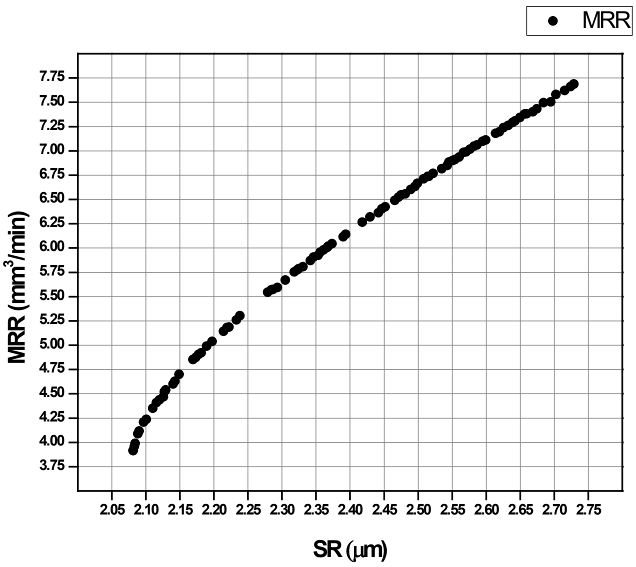
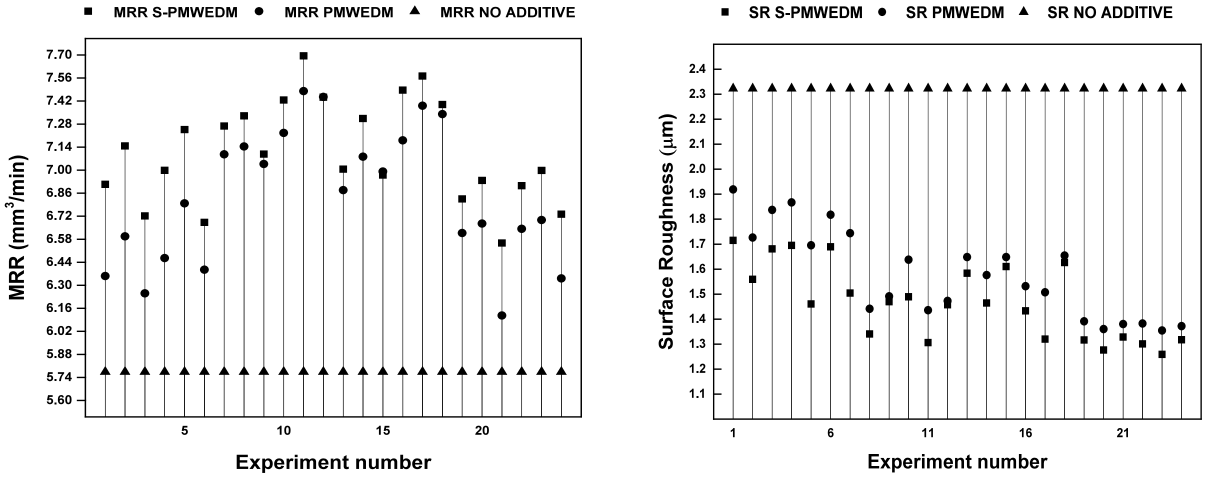


Figure 5. Generated Pareto front for SR and MRR values.

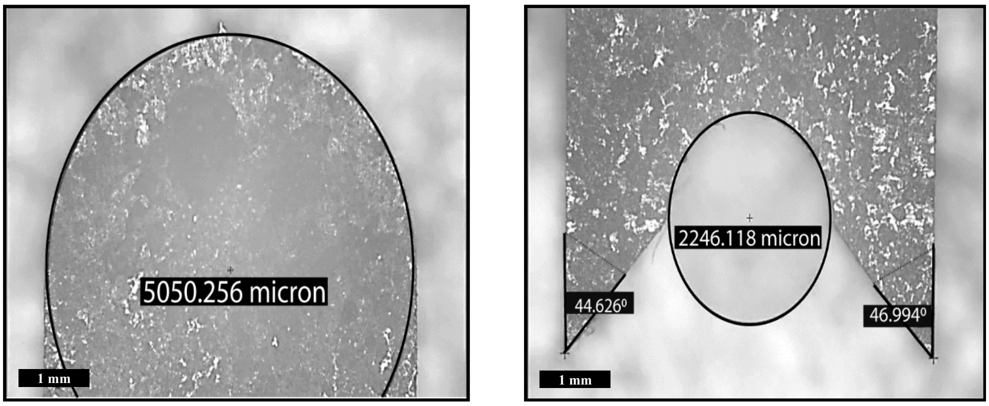
An optical microscope is used to measure the dimensions of the machined workpiece. The percentage deviation was then calculated, as shown in Figure 7 from the actual profile generated. Now, for each of the three cases of no additive

WEDM, PMWEDM, and surfactant mixed PMWEDM, the average percentage deviation is calculated and plotted in Figure 8(a). From Figure 8(b), it can be observed that in the case of internal curvature, the percentage deviation from the actual workpiece profile is the highest but decreases with the addition of surfactant in the mixture.



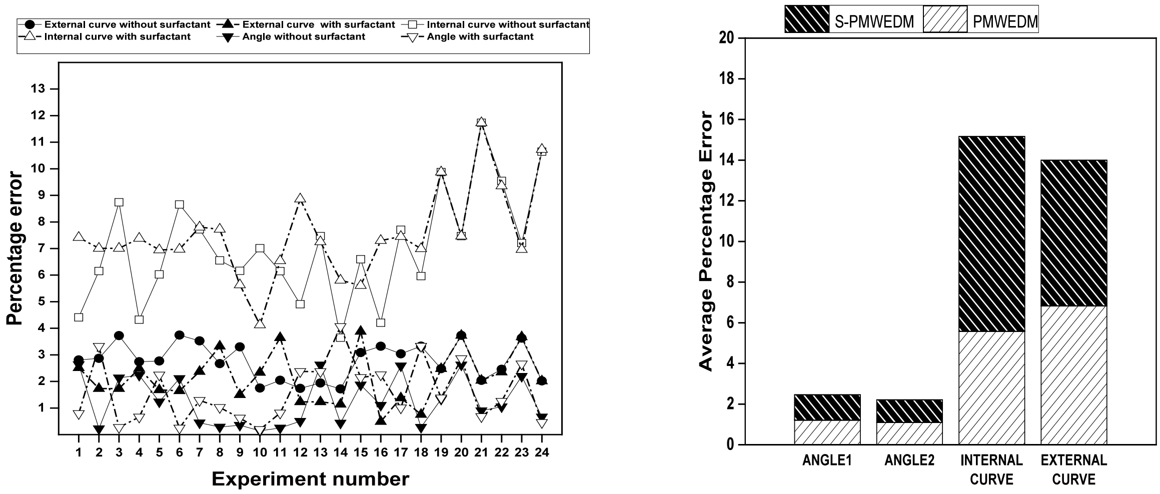
(a) (b)

Figure 6. Variation in (a) MRR and (b) SR with the addition of powder and surfactant.



(a) (b)

Figure 7. Dimension measurement of (a) external curve (b) internal curve and angles using optical microscope.

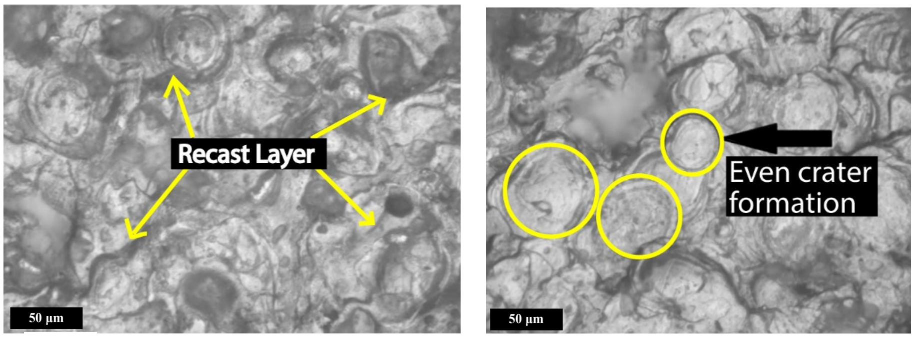


(a) (b)

Figure 8. (a) Percentage error and (b) average percentage error in dimension.

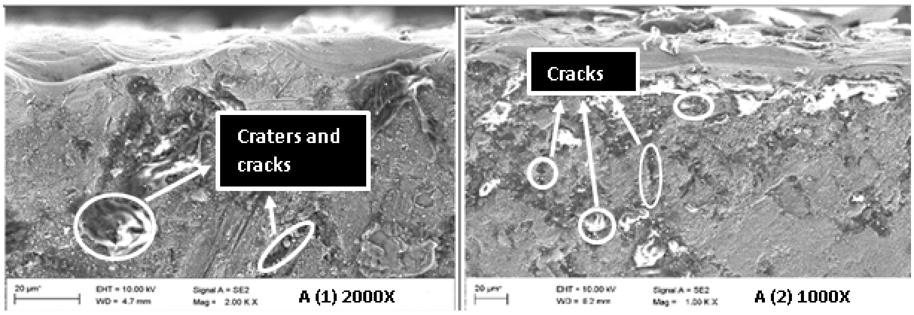
Figure 9(a) shows the character traits of the surface obtained with optimum parameters when there is no powder at a scale of 50 μm. Figure 9(b) shows the surface character traits obtained with optimum parameters in the presence of Al_2O_3, 10 μm powder with a concentration of 6 g/l at a scale of 50 μm. The craters formed in PMWEDM are found to be uniform, and thus the surface produced is very smooth. Dielectric mixing of powders has reduced SR values by 43.90 %. Additionally, the added surfactant reduced the SR value by 45.05 %.

Figure 10 and Figure 11 show the surface character traits of the machined workpiece with similar electrical parameters when inspected using the 2000×, 1000× and 500× scanning electron microscope. Since the addition of powder increased the discharge energy and filled the cracks up to a certain level, reduction in cracks, as well as craters, occurred. Presence of powder particles in the spark gap; thus, there occurs an increment in the number of sparks per unit time. Moreover, the powder particles enlarge the plasma channel leading to more uniformity in spark generation. This results in a better spark energy utilisation and reduction in strength, which also reduces cracks.

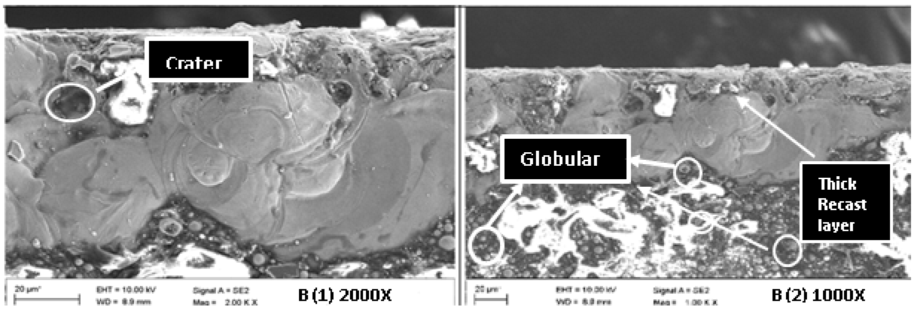


(a) (b)

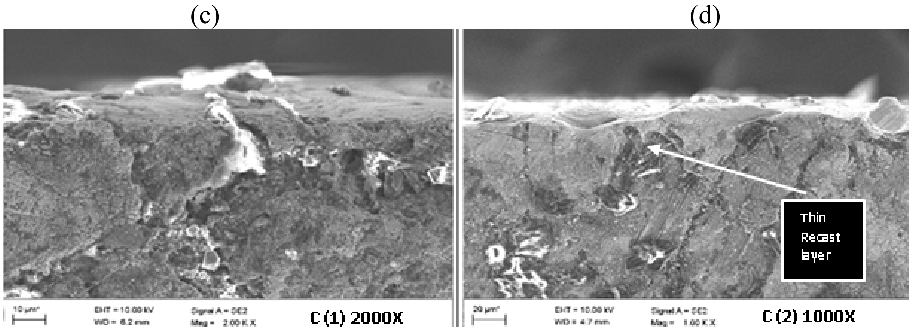
Figure 9. Comparison of surface character traits of the machined workpiece using optical microscope (a) without powder, (b) with Al_2O_3 powder size 10 µm and concentration 6 gm/litre



(a) (b)

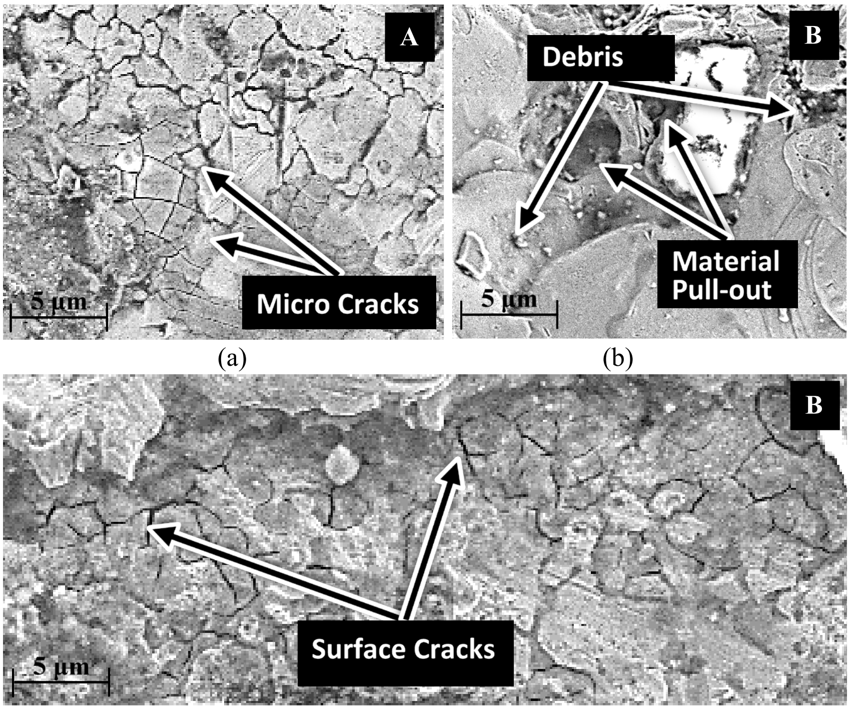


(c) (d)



(e) (f)

Figure 10. SEM images of workpiece after machining (a), (b) without additives (c), (d) with Al_2O_3 (10 micron- 6 g/l) (e), (f) with surfactant and Al_2O_3 (10 micron- 6g/l).



(a) (b)

(c)

Figure 11. SEM images of work piece after machining showing the surface cracks and debris produced after machining (a) without additives and (b), (c) with Al_2O_3 (10 micron - 6 g/l).

CONCLUSION

Adding different powders and surfactant to the dielectric has a positive effect on the output parameters of the process. Powders exhibited different impacts on the values of MRR and SR. In several instances, the addition of surfactant has increased the MRR and SR values. The following conclusion can be drawn according to the results obtained.

i. The addition of surfactant in the dielectric has a positive impact on the process. It has increased the MRR values by 13.56% (with surfactant) in comparison to 5.93% (without surfactant) and reduced the SR values by 45.05% (with surfactant) to 43.90% (without surfactant). The images obtained from the work-pieces surface by scanning electron microscopy also support the findings.
ii. MRR and surface finish increase up to 6g/l powder concentration after which they eventually decrease. There is also an increase in the concentration of debris particles with an increase in powder concentration, thus disturbing the plasma channel generated for machining.
iii. Surfactant addition has reduced the agglomeration of powder particles. Thus the output variables have increased initially up to a concentration level of 6 g/l. However, after this, further addition of surfactant into the mixture does not produce any significant change in the output parameters.
iv. Due to their combined abrasive action, abrasive powders increase MRR more significantly than others used in experiments. Also, due to the higher homogeneity of the mixture, the abrasive powders with small grit size produced better results.
v. Due to its lowest density, graphite powder generates the best surface finish.
vi. The distribution of discharge is better in the presence of surfactant. So, the percentage deviation from the actual workpiece profile is the highest in the case of internal curvature, but it decreases with the addition of surfactant in the mixture.

Scope of the present work is limited to improve the MRR and SR obtained with an optimal setting of process parameters pulse on time, pulse off time, peak current and gap voltage, in the presence of a surfactant and powder mixed wire EDM. There can be different future scopes of this work. One can study the process with an effect on the electrode and its wear rate. Also, the work can be extended to understand the residual stress due to machining. Residual stress can play a significant role if the machined is performed on micro-levels.

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