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Performance Improvement of Electro-Discharge Machining of Titanium Alloy Using SiC Powder Mixed in EDM Oil

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Abstract:
Electric discharge machining is a popular unconventional machining that is widely used to machine any conductive material, regardless of hardness and strength. In this work, significant improvements in machining properties such as material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR) were observed when machining Ti-6Al- V material using SiC powder mixed with standard EDM oil . It was also observed that the crack density of the machined surface is reduced when silicon carbide powder is added to the EDM oil. Finally, using the MRSN technique, optimal sets of process parameters are presented both with and without powder mixture. Keywords: EDM activity; powder mixed EDM; Multiple response optimization; MRSN technology; Taguchi orthogonal matrix

Introduction
Electric Discharge Machining (EDM) uses electrical energy that is converted into thermal energy in the form of an electric spark. When the spark hits the workpiece, a very high temperature of the order of 10000-12000 ºC is reached at that point [1] When the spark goes out, a vacuum is created between the tool and the workpiece, resulting in vaporization and the melting. metal being forced out into the dielectric medium as the pressurized insulator surges into the vacuum region. This process typically uses hydrocarbon oil as the dielectric fluid. In order to improve the processing, many previous researchers tried to mix different powders with a common dielectric fluid. Shabgard and B.khosrozadih [2] investigated the effect of carbon nanotubes added to ELF2 dielectric material in petroleum fluid on surface properties and machinability of Ti-6Al- V alloy in EDM process. They claimed that the processing stability was improved due to the addition of carbon nanotubes to the aforementioned dielectric. They also found that tool wear rate, surface roughness, and the length and size of surface microcracks decreased. MRR decreased during short pulse duration and the same increased during long pulse duration. S. Tripathy and D.K. Tripathy [3] investigated the effect of silicon carbide powder mixed with EDM oil on machining results in machining H-11 steel material. They found that material removal rate, surface roughness, remelted layer thickness (RLT), and microhardness and surface quality improved greatly as the powder concentration increased. B. Ekmekli and others [ ] investigated the effect of deionized water in a silicon carbide powder mixture on discharge separation in EDM. According to them, the main outlet channel was completely separated into uniformly distributed side outlets under certain processing conditions. They found that under these conditions, the deformation of the machined surface was minimal in terms of microcrack roughness and thermal layer thickness. B. Kuriachen and J. Mathew [5] investigated the effect of silicon carbide powder mixed with EDM-3 oil on

the material removal rate and tool wear rate during machining of Ti-6Al- V material in micro-EDM. They found that maximum MRR was achieved at low powder concentrations (5 g/L) and medium levels of capacitance and voltage. Minimum TWR was observed at low concentration levels, which increased with capacitance and voltage. They performed multi-response optimization to achieve maximum MRR and minimum TWR. The analysis concluded that minimum TWR and maximum MRR targets can be achieved with low capacitance and voltage. T.T. Opoz et al. [6] investigated the particle migration and surface modification of Ti-6Al- V in silicon carbide powder mixture, electrical discharge. They found that a low pulse current combined with a high concentration of suspended particles in deionized water mixed with a green 800-mesh SiC powder dielectric fluid improves the transfer mechanism of the material in the form of solid particles. The resolidified layer decreased when the concentration of silicon carbide powder in the aforementioned insulator increased. S. Mohanty et al [7] performed surface alloying using tungsten disulfide powder mixed with deionized water as dielectric medium on Ti-6Al- V material in micro-EDM. They used a tungsten tool electrode and maintained reverse polarity between the tool electrode and the workpiece. They conducted nine tests according to Taguchi's experimental design and observed higher material removal rates as they increased powder concentration and tension. The microhardness of the workpiece increased with increasing powder particle concentration and at high stresses. They confirmed the surface doping with an SEM micrograph. B. K Paul et al [8] investigated the EDM machining performance of Inconel 718 using copper powder in the EDM oil dielectric. They varied the peak current and pulse duration and studied MRR, SR, surface cleavage and white layer thickness. According to them, the MRR increased as the peak discharge current increased. However, with powder mixture EDM, the crack density decreased. N.J. Saharia and others [9] experimentally investigated the effect of hybrid aluminum graphite powder on MRR and TWR during machining of EN19 workpiece with brass electrode. They found that MRR increased with hybrid aluminum and graphite kerosene insulation than with aluminum or graphite mixed kerosene alone. A.Y. Joshi and A.Y. Joshi [10] reviewed various powder mixture EDM processes by previous researchers. They made two results. In the first, PMEDM improved MRR by reducing tool wear compared to conventional EDM. In the second, a dielectric material mixed with powder helped to achieve a mirror-like surface, while the doping of additional powder particles changed the surface properties. S. K. Sahu et al [11] compared the EDM performance of Inconel 718 superalloys using two different powder mixed insulators. In the first case, copper powder was mixed with kerosene insulation, and in the second step, copper powder was mixed with transformer oil. They concluded that when copper powder was mixed with transformer oil, it achieved better results in terms of MRR, surface finish and surface cracking. M. A. Iiani and M. Khoshnevisan [12] reported that PMEDM showed an increase in MRR, TWR and SR of 33%, 31% and 77%, respectively. B Gugulothu et al [13] experimentally investigated the effect of drinking water graphite powder on the electromagnetic phase of Ti-6Al- V. According to them, .5 g/L graphite powder was the optimal powder concentration to maximize MRR and reduce SR and restore layer thickness. A. Abududeen et al [1] reviewed previous literature based on powder mixing with EDM. According to them, different conductive powders at different concentrations would improve MRR, TWR, SR and surface integrity. It has been observed from previous literature that the machining performance is clearly improved when the EDM operation is performed using a different powder in the insulator compared to the standard dielectric. Ti-6Al- V material is most popularly used in aircraft structural applications. It is noted that some previous researchers have used expensive flours to study the effect of processing ability. But some other researchers

1. Experimentation

In order to use the costly EDM process in a techno-economical way, the different input parameters are to be optimized to obtain the best possible overall performances. In the present experimental work, two different sets of experimentations on EDM have been performed, i.e. first, without using any powder in the dielectric and second, using SiC powder in the dielectric.

2.1 Workpiece details

Since the previous researchers have not done extensive experimental work on titanium alloy (Ti-6Al-4V), present experimental work has been carried out on this workpiece. The workpiece is a shoot metal of Titanium alloy, Ti-6Al-4V. The size of the workpiece is 55 × 50 × 3 mm. It has a smooth surface. The physical properties of Ti-6Al-4V are presented in Table 1and the chemical compositions of the Ti-6Al-4V are given in Table 2.

Table 1: Physical properties of Ti-6Al-4V

Atomic Volume (Avg)	0.01m^3/kmol
Density	4.429 Mg/m^3
Compressive strength	848 Mpa
Ductility	0.05
Elastic Limit	786 Mpa
Endurance Limit	529 Mpa
Tensile strength	862 Mpa
Maximum service temperature	620 K
Melting point	1878 K
Thermal conductivity	7.1 W/mK
Hardness	3370 Mpa

Table 2: Chemical composition of Ti-6Al-4V (in weight %)

N	C	H	Fe	O	Al	V	Ti
0.05	0.1	0.0125	0.4	0.2	5.5-6.75	3.5-4.5	Balance

2.2Tool Material

The tool material taken for this experiment is copper. It is a cylindrical copper bar machined with a diameter of 13mm and length of 150 mm. The circular face is machined to get a uniform surface. The physical properties are presented in Tab.3:

Table 3: Physical properties of copper tool

Melting Point	1357.77K
Density	8.96gm/cm^3
Heat of fusion	13.26kJ/mol
Thermal conductivity	401 W/mK

2.3Powder and Dielectric material

The SiC powder with mess size-220 is mixed in EDM-30 dielectric fluid 25 (gm/L) for powder mixed EDM. The Physical properties of SiC are presented in Tab 4.

Table 4: Physical properties of Silicon Carbide

Density	3.21 gm/cm3
Thermal Conductivity	41 W/mK
Dielectric constant	10.2 MHz
Electrical resistivity	108 Ωm

2.4 Plan of Experiment

In the present experimental work, four input variables, such as peak current, pulse on time, duty factor and gap voltage have been considered. Taguchi's L9 orthogonal array has been used for different combination of input variables. The experiments have been planned to be conducted in two phases. In the first phase, without using any powder in the dielectric, the experiments are conducted. In the second phase, the experiments have been conducted by mixing 220 mess SiC powder (25 gm/l) in EDM oil. It is decided to study material removal rate (MRR), tool wear rate (TWR), surface roughness (SR) and surface crack density of the machined surface in both the cases. The input parameters taken in this experiment are shown in Tab.5

Table 5: Different combinations of input variables as per Taguchi's L_9 orthogonal array

Sl No.	Input current, Amp	Pulse on time, µs	Duty factor	Gap Voltage, V
1	5	200	2	10
2	5	400	4	20
3	5	800	8	30
4	10	200	4	30
5	10	400	8	10
6	10	800	2	20
7	20	200	8	20
8	20	400	2	30
9	20	800	4	10

2.5 EDM setup

The experiments have been conducted using an EXCETEK ED30 (die sinking type) EDM machine. It has user friendly control panel with a screen where, the input data can be entered. The tool holder is having a servo system with movement in x, y, z direction and workable movement in x and y direction. The machine also consists of a generator and an oil tank. A photo of the machine is presented in Figure 1.The specification details of this machine are presented in Table 6.

Figure 1: EDM machine

Table 6: Specification of EDM machine

Machine Dimensions	2525×1710×2092mm
Machine weight	1150kg
X/Y travel	300×200mm
Z travel	200mm
Worktable	600×300mm
Max. work piece size	800×400×290mm
Max. work piece weight	550kg
Max. electrode weight	120kg
Tank capacity	350L

2.6Experimental Procedure

The experiments are conducted in two phases i.e., with and without using powders. Before machining was started (without powder), the weights of the workpiece and the tool were noted down. Then the workpiece was fixed on a fixture by a mechanical holder and the tool was fixed on the tool post. The input parameters are set in the control panel. Then the dielectric was filled by the fluid pump to sink the workpiece, and the machining was continued for five minutes. After five minutes of machining, the machine was stopped, and the dielectric was drained out. Then weights of workpiece and the tool were noted down. Then the next experiment was started repeating the same procedure. In this manner nine experiments have been conducted using the different combinations of input parameters as stated in Tab. 5. In the second phase, SiC powder was mixed (25 gm/L) in EDM oil dielectric and another nine experiments have been conducted considering input variables as presented in Tab. 5. The workpieces after machining are presented in Figure 2 and Figure 3.

Figure 2: Ti-6Al-4V (Without Powder)

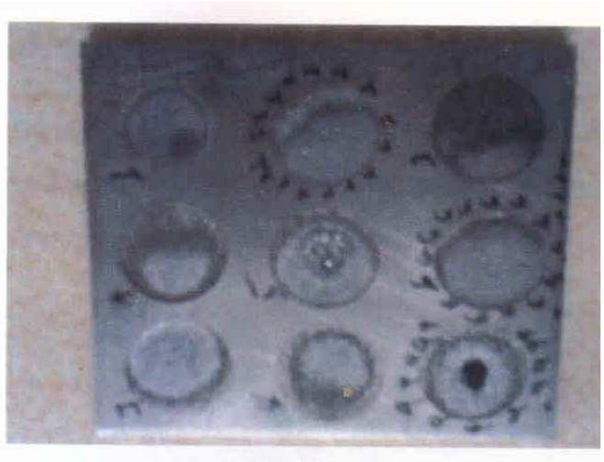

Figure 3: Ti-6Al-4V (With Powder)

In order to obtain the output parameters, the following equations are followed:

2.7Measurement of MRR

The MRR can be obtained using Eq.1. as presented in the following.

$$MRR = \frac{w_i - w_f}{\rho\, t}\ \mathrm{mm}^3/\mathrm{min} \qquad (1)$$

Where, W_i = Initial weight of the workpiece,
W_f = final weight of the workpiece,
ρ=Density of workpiece and
t =machining time

2.8Measurement of TWR

The TWR can be obtained using Eq.2. as presented in the following.

$$TWR = \frac{w_{ti} - w_{tf}}{\rho \times t}\ \mathrm{mm}^3/\mathrm{min} \qquad (2)$$

Where, W_{ti} = Initial weight of the workpiece,
W_{tf}= final weight of the workpiece,
ρ= Density of workpiece and
t = machining time

The surface roughness of the machined workpiece is measured with the help of a surface roughness tester (MITUTOYO's surface roughness instrument SJ.210) as shown in Figure 4.

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Figure 4: Surface roughness Tester

For each experiment the weights of work piece and tool are measured using a digital electronic balance as shown in Figure 5.

Figure 5: Weighing machine

2. Experimental Results

The experimental results obtained in both the phases arepresented in Tab.7and Tab.8

Table 7: Experimental Results without using powder

Sl No.	Input current in Amp	Pulse on time in µs	Duty factor	Gap Voltage in V	MRR in mm^3/min	TWRin mm^3/min	SR in µm
1	5	200	2	10	4	0.167	5.18
2	5	400	4	20	4	0.200	3.82
3	5	800	8	30	6	0.267	3.50
4	10	200	4	30	4	0.256	4.26
5	10	400	8	10	8	0.435	10.51
6	10	800	2	20	10	0.535	5.32
7	20	200	8	20	12	0.502	7.18
8	20	400	2	30	6	0.368	5.63
9	20	800	4	10	10	0.569	8.14

Table 8: Experimental Results with SiC powder mixed in dielectric

Sl No.	Input current in Amp	Pulse on time in µs	Duty factor	Gap Voltage in V	MRR in mm^3/min	TWR in mm^3/min	SR in µm
1	5	200	2	10	4	0.0558	0.04
2	5	400	4	20	4	0.0669	3.28
3	5	800	8	30	8	0.0892	2.69
4	10	200	4	30	6	0.1004	3.56
5	10	400	8	10	10	0.1450	4.22
6	10	800	2	20	12	0.1785	4.42
7	20	200	8	20	12	0.1674	4.49
8	20	400	2	30	8	0.1227	5.79
9	20	800	4	10	16	0.9486	6.30

Four sample photographs showing the crack density are presented in Figure 6 to Figure 9 as follows:

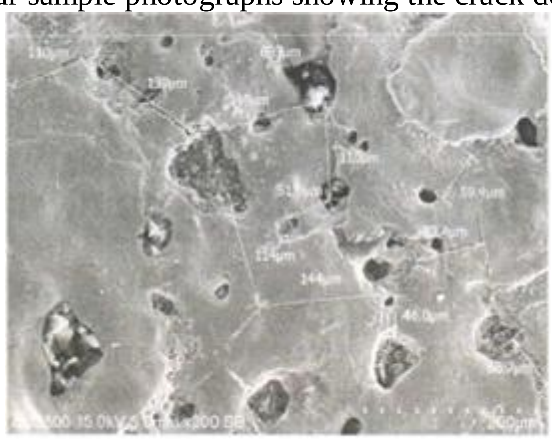

Figure 6: SEM photo of machined workpiece at current 10A; pulse on time 800µs; duty factor 2, gap voltage, 20 V (without powder).
Total Average crack length=1126.5 µm
Area = 633 × 633 = 400689 $µm^2$
Crack density = 1126.5/ 400689 =0.0028 $µm/µm^2$

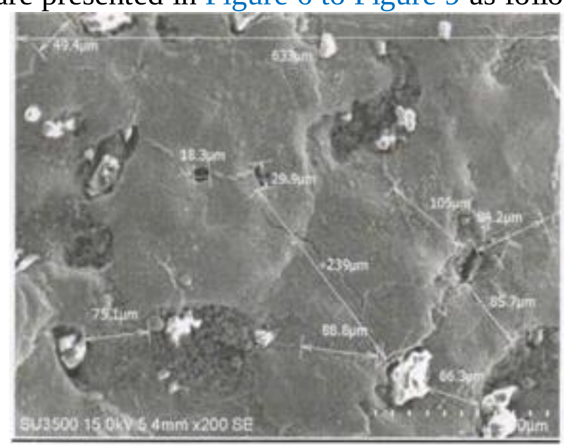

Figure 7: SEM photo of machined workpiece at current, 10 A; pulse on time, 800 µs; duty factor, 2 and gap voltage, 20 V (with powder).

Total Average crack length=841µm
Area = 633 × 633 = 400689 $µm^2$
Crack density = 841/400689 =0.0023 $µm/µm^2$

Figure 8:SEM photo of machined workpiece at current, 20A; pulse on time 800µs; duty factor 4, gap voltage, 10 V (without powder).
Total Average crack length=1507 µm
Area = 630 × 630 = 396900 μm^2
Crack density = 1507/396900 = 0.0038 $\mu m/\mu m^2$

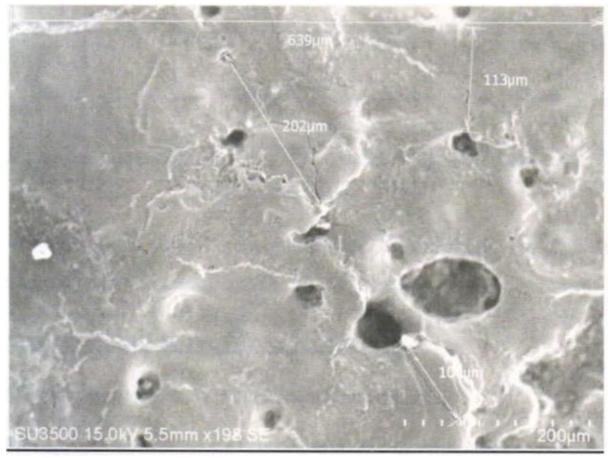

Figure 9:SEM photo of machined workpiece at current, 20 A; pulse on time, 800 µs; duty factor, 4 and gap voltage, 10 V (with powder).
Total Average crack length = 402 µm
Area = 639 × 639 = 408321 μm^2
Crack density = 402/408321= 0.00098 $\mu m/\mu m^2$

3. Result Analysis

In the present research work first, a comparison is made between different values of output parameters in two cases (with and without using powder). In the second, a multi-response optimizations technique i.e., MRSN technique has been used to optimize the input parameters in both the cases for obtaining optimum overall machining performance.

4.1 Comparison of machining performances

In order to determine the changes in the output parameters due to mixing of powder in the dielectric the average values of different output parameters are determined and the changes with respect to usual dielectric are presented in Table 9.

Table 9: Comparison of machining performance

Sl No.	Output parameters	Unit	Average value without powder	Average value with powder	% Change w.r.t. without powder
1	MRR	mm^3/min	7.111	8.88	25 (increase)
2	TWR	mm^3/min	0.3665	0.2082	43 (decrease)
3	SR	µm	5.9488	3.865	35 (decrease)

It is observed from Table 9 that the MRR has been increased by 25% due to mixing of SiC powder in EDM oil. Similarly, TWR has been decreased by 43% and SR has been decreased by 35%.

4.2. Optimization of machining performance

In the present work, it is tried to optimize all output parameters simultaneously and the optimum combinations of input parameters in both the cases (with and without powder) are determined. Among different multi-response optimization techniques, Multi-Reponse Signal to Noise (MRSN) ratio is most popular. The different steps of this optimization techniques [15], [16] are presented in the following:

Step 1: Determination of loss function

Taguchi [15], [16]categorized the response variable into three different types, e.g., the smaller the better, the larger the better, and nominal the best. Assuming that there are m experimental trials and in each trial, quality losses of a set of p response are measured, the formulas for computation of quality loss (L_{ij}) for j_{th} response corresponding to i_{th} trial (i=1,2,…,m; j=1,2,…,p) for different types of response variables are given as follows:

For smaller the better, $L_{ij}= (\frac{1}{n}\sum_{k=1}^{n} y^2{}_{ijk})$ (3)

For larger the better, $L_{ij}= (\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y^2{}_{ijk}})$ (4)

For nominal the best, $L_{ij} = (\frac{S_{ij}{}^2}{\bar{y}_{ij}{}^2})$ (5)

where, $\bar{y}_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}$ and $S_{ij}{}^2 = \frac{1}{n-1}\sum_{k=1}^{n}(y_{ijk} - \bar{y}_{ij})^2$

n represents the number of repeated experiments, y_{ijk} is the experimental value of j_{th} response variable in i_{th} trial at k_{th} replication and L_{ij} is the computed quality loss for j_{th} response in i_{th} trial.

Step 2: Determination of normalized loss function

The normalized loss function, $S_{ij} = \frac{L_{ij}}{L_i}$ (6)

Where, S_{ij} is the normalized loss function for the i_{th} performance characteristic in the j_{th}experiment is the loss function for the i_{th} performance characteristic in the j_{th} experiment and is the average loss function for the i_{th} performance characteristic.

Step 3: Determination of total loss function

Applying proper weightages to different normalized loss function, the total loss function,

$TL_j = \sum_{i=1}^{m} W_i S_{ij}$ (7) where, W_i is the weighting factor for the i_{th} performance characteristic and m is the number of performance characteristics.

Step 4: Transformation of the total loss function into MRSN as follows:

$MRSN = -10\log_{10}(TL_j)$ (8)

Following steps 1-4, the different values are calculated and presented in Table10 and Table11.

Table 10: Experimental results of normalized loss function and MRSN (without powder)

Sl No.	MRR, mm³/ min	TWR, mm³/m in	SR, µm	Loss Function			Normalized Loss Function			Total Loss Function	MRSN in db
				MRR in	TWR in mm³/min	SR, µm	MRR	TWR	SR		

	min			mm³/min							
1	4	0.167	5.18	0.0625	0.0278	26.8324	1.9704	0.1798	0.6706	1.0433	-0.18404
2	4	0.200	3.82	0.0625	0.04	14.5924	1.9704	0.259	0.3647	0.97519	0.1091
3	6	0.267	3.5	0.0277	0.7128	12.25	0.87332	0.4611	0.3061	0.5794	2.3702
4	4	0.256	4.26	0.0625	0.06554	18.1476	1.9704	0.424	0.4535	1.0514	-0.2176
5	8	0.435	10.51	0.0156	0.18922	110.460	0.4926	1.2241	2.7607	1.3925	-1.4378
6	10	0.535	5.32	0.01	0.28622	28.3024	0.31527	1.8515	0.70737	0.8937	0.488
7	12	0.502	7.18	0.0069	0.2520	51.5524	0.21893	1.6302	1.28847	0.9631	0.1632
8	6	0.368	5.63	0.0277	0.13542	31.6969	0.87332	0.8760	0.79221	0.8498	0.7068
9	10	0.569	8.14	0.01	0.32376	66.2596	0.31527	2.0944	1.65605	1.2512	-0.973

Table 11: Experimental results of normalized loss function and MRSN (with powder).

Sl No.	MRR, mm³/min	TWR, mm³/min	SR, µm	Loss Function			Normalized Loss Function			Total Loss Function	MRSN in db
				MRR in mm³/min	TWR in mm³/min	SR, µm	MRR	TWR	SR		
1	4	0.0558	0.04	0.0625	0.0031134	0.0016	2.65652	0.16991	0.000105	1.11361	-0.4673
2	4	0.0669	3.28	0.0625	0.004476	10.7584	2.65652	0.24423	0.7086	1.3484	-1.2981
3	8	0.0892	2.69	0.015625	0.007957	7.2361	0.6441	0.43419	0.4766	0.538877	2.6851
4	6	0.1004	3.56	0.0277	0.010080	12.6736	1.17737	0.55007	0.8347	0.88637	0.5238
5	10	0.1450	4.22	0.01	0.021025	17.8084	0.42504	1.14723	1.173	0.866115	0.6242
6	12	0.1785	4.42	0.006944	0.03186	19.5364	0.29515	1.7386	1.2868	1.02568	-0.1101
7	12	0.1674	4.49	0.006944	0.02802	20.1601	0.29515	1.529	1.3279	0.97513	0.1093
8	8	0.1227	5.79	0.015625	0.015055	33.5241	0.66413	0.82155	2.2381	1.1745	-0.6985
9	16	0.2082	3.865	0.0039063	0.04334	14.9382	0.16603	2.36507	0.9839	1.071103	-0.2983

Step 5: Determination of optimum level combinations of input parameters

A set of graphs is plotted taking average value at low, medium and high level of each input parameter in x axis and corresponding MRSN value in the y axis. The level showing highest value of MRSN will give us the optimum level.Using the values from Table 10 and Table 11 two different sets of graphs are plotted, one set for without powder and the other set is for with powder.

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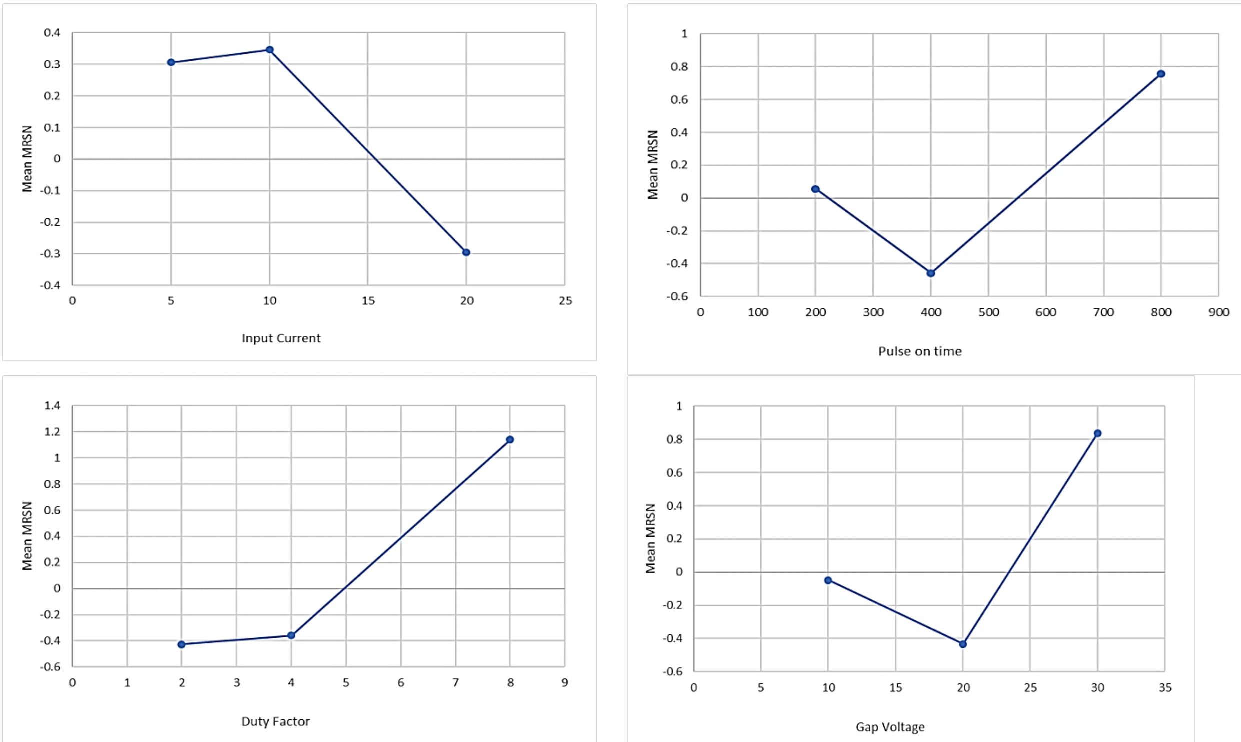

Figure 10: Average MRSN values with low, medium and high levels of input parameters (with powder).

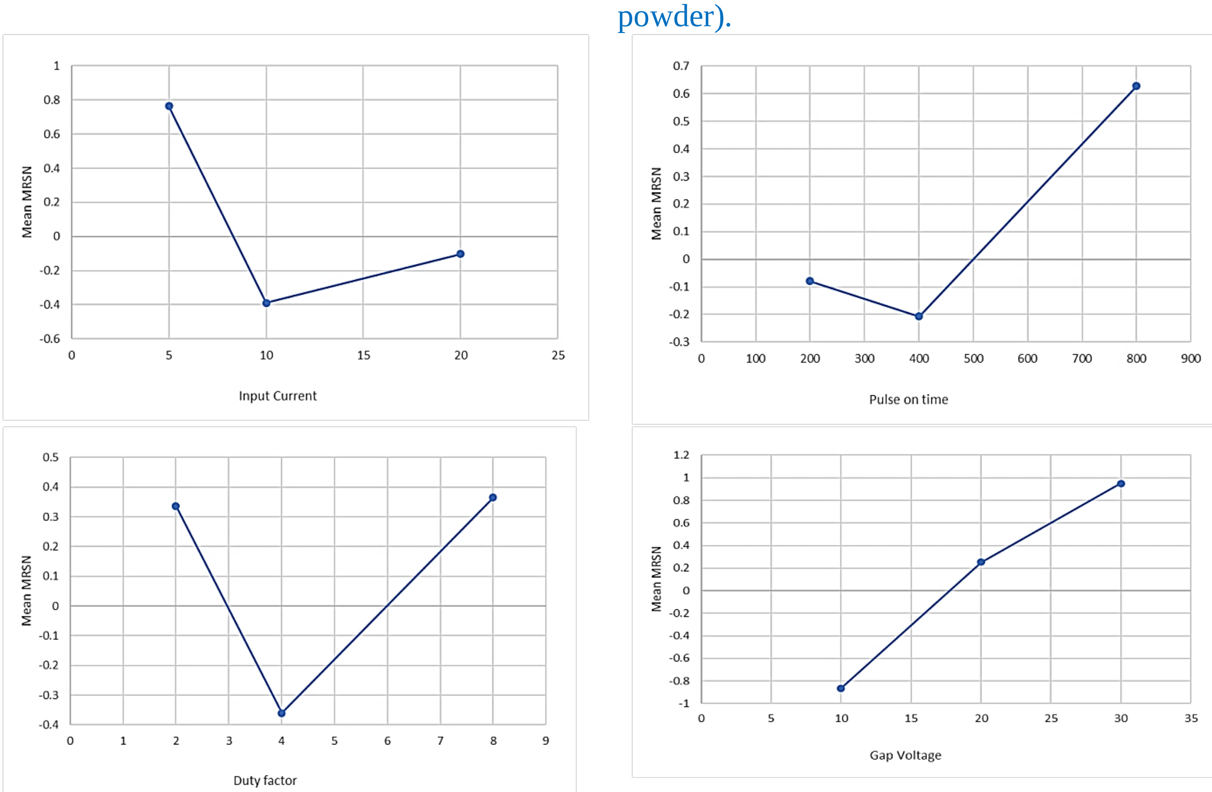

Figure 11: Average MRSN values with low, medium and high levels of input parameters (without powder)

In order to study the surface quality a comparison table as shown in the Table 12 is prepared to know the % decrease of crack density.

Table 12: Comparison of crack density with and without powder

Sl No.	Input current in Amp	Pulse on time in μsec	Duty factor	Gap Voltage in V	Crack density		% decrease in crack density
					without powder	with powder	
1	10	800	2	20	0.0028	0.0023	18%
2	20	800	4	10	0.0038	0.00098	74%

It is observed from Table 12 that there is definite improvement of surface quality with respect to crack density. The improvement will vary based on the combination of input parameters. In the present case, it is found that the maximum improvement of crack density is 74%.

4. Conclusion

The following conclusions are obtained from the present investigation:

1. Because of the mixing powder in the dielectric, the average MRR has been increased by 25%, the average TWR has been decreased by 43% and the average SR has been decreased by 35%.
2. The optimum input parameters with powder are current, 10 A; pulse on time, 800 μs; duty factor, 8; gap voltage, 30 V.
3. The optimum input parameters without powder are current, 5 A; pulse on time, 800 μs; duty factor, 8; gap voltage, 30 V.
4. The optimum sets of input parameters are different in both cases.
5. Further, it is observed that due to addition of powder in the dielectric, the crack density has been decreased. The percentage decrease of crack density is dependent on the set of process parameter. In the present investigation for current,10 A; pulse on time, 800 μs; duty factor, 2; gap voltage, 20 V, the crack density has been decreased by 18%. Similarly, for current, 20 A; pulse on time, 800 μs; duty factor, 4; gap voltage, 10 V, the crack has been density decreased by 74%.

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