Improvement of Electro-Discharge machining performance of Ti-6Al-4V using Silicon Carbide powder mixed in EDM oil and optimization of process parameters

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Abstract- Electrical discharge machining process is a popular non-traditional machining process widely used to machine any conducting material irrespective of hardness and strength. In the present work, remarkable improvement of machining performances like material removal rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (SR) have been observed using SiC powder mixed in the usual EDM oil while machining Ti-6Al-4V material. It is also observed that there is decrease of crack density of the machined surface due to addition of SiC powder in EDM oil. At last, optimum sets of process parameters have been reported using MRSN technique in both powder mixed case and without powder mixed case.

Keywords – EDM performance, Powder mixed EDM, Multi-Response optimization, MRSN Technique, Taguchi's orthogonal array

I. Introduction

In electrical discharge machining (EDM) process, electrical energy is used which is converted into thermal energy in the form of electrical spark. When the spark hits the work piece, a very high temperature is achieved at that location, which is of the order of 10000 to 12000 ºC [1] When spark is extinguished, a vacuum is created in between tool and work piece as a result of which the vaporized and some of the molten metal is ejected out into the dielectric medium when the pressurised dielectric splashes into vacuum zone. In this process, usually hydrocarbon oil is used as dielectric liquid.

S. K. Sahu et al [2] compared the EDM performance on Inconel 718 super alloys using two different powder mixed dielectric. In the first case, copper powder was mixed in kerosene dielectric and in the second phase, copper powder was added in transformer oil. They concluded that when copper powder was mixed with transformer oil, it was giving better performance with respect to MRR, surface finish and surface crack density. M. A. Iiani and M.

Khoshnevisan [3] proposed that PMEDM was showing increment of MRR by 33% , TWR by 31% and SR by 77% . B Gugulothu et al [4] experimentally found the effect of graphite powder in drinking water while machining Ti-6Al-4V. According to them, 4.5 gm/ltr graphite powder was optimum powder concentration to maximize MRR and to reduce SR and recast layer thickness. A. Abududeen et al [5] reviewed past literatures based on powder mixed dielectric on EDM. According to them different conductive powders with different concentrations would improve the MRR, TWR, SR and surface integrity.

It is observed from the previous literatures that there is definite improvement of machining performance when EDM operation is carried out using different powder in the dielectric medium as compared to plain dielectric. Ti-6Al-4V material is most popularly used for aircraft structural applications. It is observed that some of the past researchers had used costly powders to study the effect of machining performance. However, some other researchers though use cheaper powder, could not compare most of the machining performance like MRR, TWR, SR and crack density etc. In the present investigation, first it is tried to compare the improvement of machining performance like MRR, TWR, SR and crack density with and without using SiC powder in EDM oil. In the second phase, optimization of different input variables such as current, duty factor, pulse on time, and tool electrode gap voltage have been found for optimum MRR, TWR and SR applying MRSN techniques.

II. 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 work piece. The work piece is Ti-6Al-4V. The size of the work piece is 55 × 50 × 3 mm. It has a smooth surface. The different properties of Ti-6Al-4V are presented in Tab. 1

Table 1: 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**

The compositions of the Ti-6Al-4V are given in Tab. 2:

Table 2: 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**

2.2 Tool Material –

The tool material taken for this experiment is copper. It is a cylindrical copper bar machined to 150 mm length with 13 mm diameter. 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**

2.3 Powder 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 parameters i.e. current (peak), pulse on time, duty factor and work piece tool gap voltage have been considered. Taguchi's L_9 orthogonal array is 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 MRR, TWR, 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

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. The tool holder and workable can move in three directions (i.e. in x, y and z direction). The machine also consists of a generator and an oil tank. A photo of the machine is shown in Fig. 1

Figure 1. EDM machine

The specification details of this machine are presented in Tab.6

Table 6: Specification of EDM machine

Machine Dimensions	**2525×1710×2092 mm**
Machine weight	**1150 kg**
X and Y travel	**300×200 mm**
Z travel	**200 mm**
Worktable	**600×300 mm**
Work piece size(max)	**800×400×290 mm**
Weight of work piece(max)	**550 kg**
Weight of electrode (max)	**120 kg**
Tank capacity	**350 L**

2.6 Experimental Procedure

The experiments are conducted in two phases i.e., with and without using powders. Before machining was started (without powder), the work piece and the tool were weighed. Then the work piece 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 work piece, 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 work piece 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 work pieces after machining are presented in Fig.2 and Fig.3.

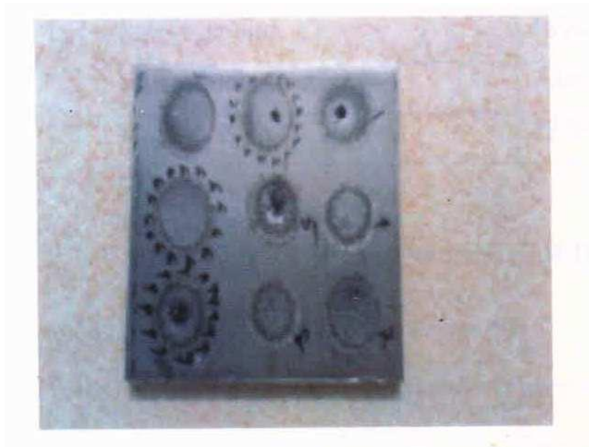

Figure.2 Ti-6Al-4V (Without Powder)

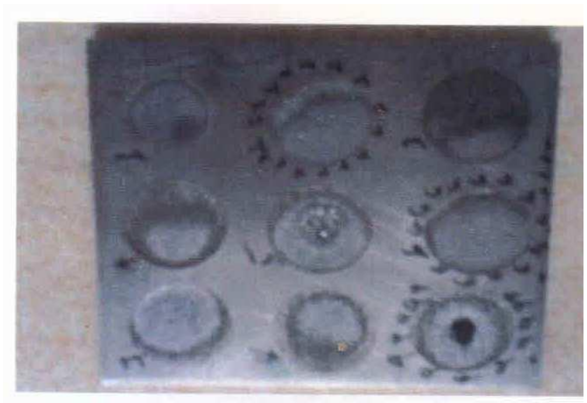

Figure.3 Ti-6Al-4V (With Powder)

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

1. *Measurement of MRR*

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

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

Where, w_i = weight work piece (initial),

w_f = weight of the work piece (final),

ρ = Density of the work piece and

t = time of machining

2. *Measurement of TWR*

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

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

3. The surface roughness of the work piece after machining is measured by surface roughness tester (MITUTOYO's surface roughness instrument SJ.210) as shown in Fig.4

Figure. 4 Surface roughness Tester

The weights of work piece and tool for each experiment are measured using a digital electronic balance as shown in Fig.5

Figure.5 weighing machine

2.7 Experimental Results

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

Table 7: Experimental Results without using powder

Sl No	Input current in	Pulse on time in µs	Duty factor	Gap Voltage in	MRR in mm^3/min	TWR in mm^3/mi	SR in µm
1	5	200	2	10	4	0.167	5.18
2	5	400	4	20	4	0.2	3.82
3	5	800	8	30	6	0.267	3.5
4	10	200	4	30	4	0.256	4.26
5	10	400	8	10	8	0.435	10.5
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 Fig.6 to Fig. 9 as follows:

Fig. 6 SEM photo of machined work piece at current, 10 A; pulse on time, 800 µs; duty factor, 2 and 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 $\mu m/\mu m^2$

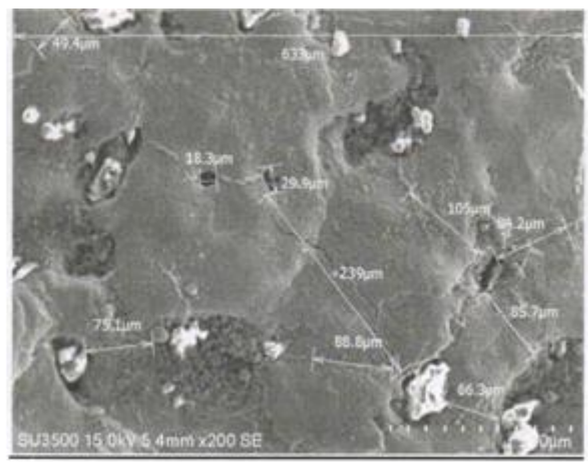

Fig.7 SEM photo of machined work piece at same parameters as stated in Fig.6(with powder).

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

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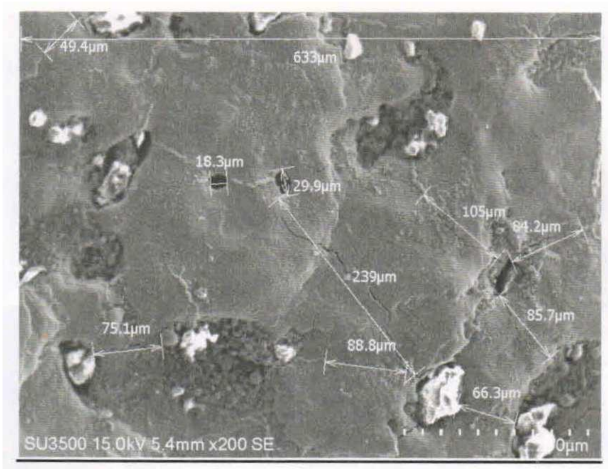

Fig. 8 SEM photo of machined work piece at current of 20 A; pulse on time, 800 µs; duty factor, 4 and gap voltage, 10 V (without powder).

Total Average crack length=1507 µm
Area = 630 × 630 = 396900 µm^2
Crack density = 1507/396900 = 0.0038 µm/µm^2

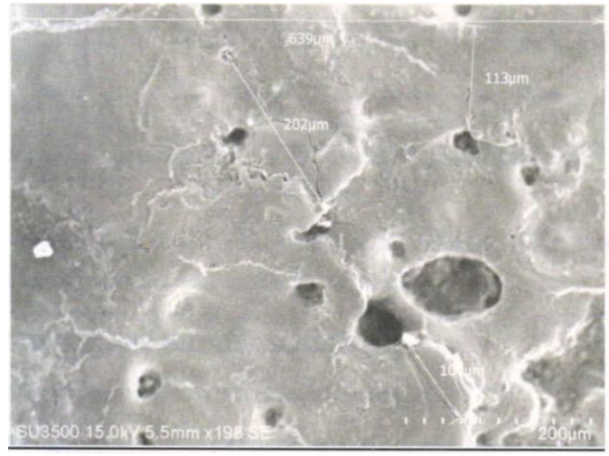

Fig. 9 SEM photo of machined work piece at same parameters as stated in Fig.8(with powder).

Total Average crack length = 402 µm
Area = 639 × 639 = 408321 µm^2
Crack density = 402/408321= 0.00098 µm/µm^2

III. Result Analysis

In this 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 obtain a set of input parameters in both the cases for obtaining optimum overall machining performance.

3.1 Comparison of machining performances

A comparison of output parameters is presented in Tab.9 to study the effect of mixing powder in the dielectric.

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 Tab.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%.

3.2. 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, MRSN ratio is most popular. The different steps of this optimization techniques [6], [7] are presented in the following:

Step 1: Determination of loss function

Taguchi [6], [7] categorized the response variable into three different types as stated in Eq.3, Eq.4 and Eq.5 in the following :

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

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

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

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 different performance characteristic.

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 Tab.10 and Tab.11.

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

Sl No.	MRR, mm^3/min	TWR, mm^3/min	SR, µm	Loss Function			Normalized Loss Function			Total Loss Function	MRSN in db
				MRR in mm^3/min	TWR in mm^3/min	SR, µm	MRR	TWR	SR		
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	110.4601	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, mm^3/min	TWR, mm^3/min	SR, µm	Loss Function			Normalized Loss Function			Total Loss Function	MRSN in db
				MRR in mm^3/min	TWR in mm^3/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 Tab. 10 and Tab. 11 two different sets of graphs are plotted, one set for without powder and the other set is for with powder.

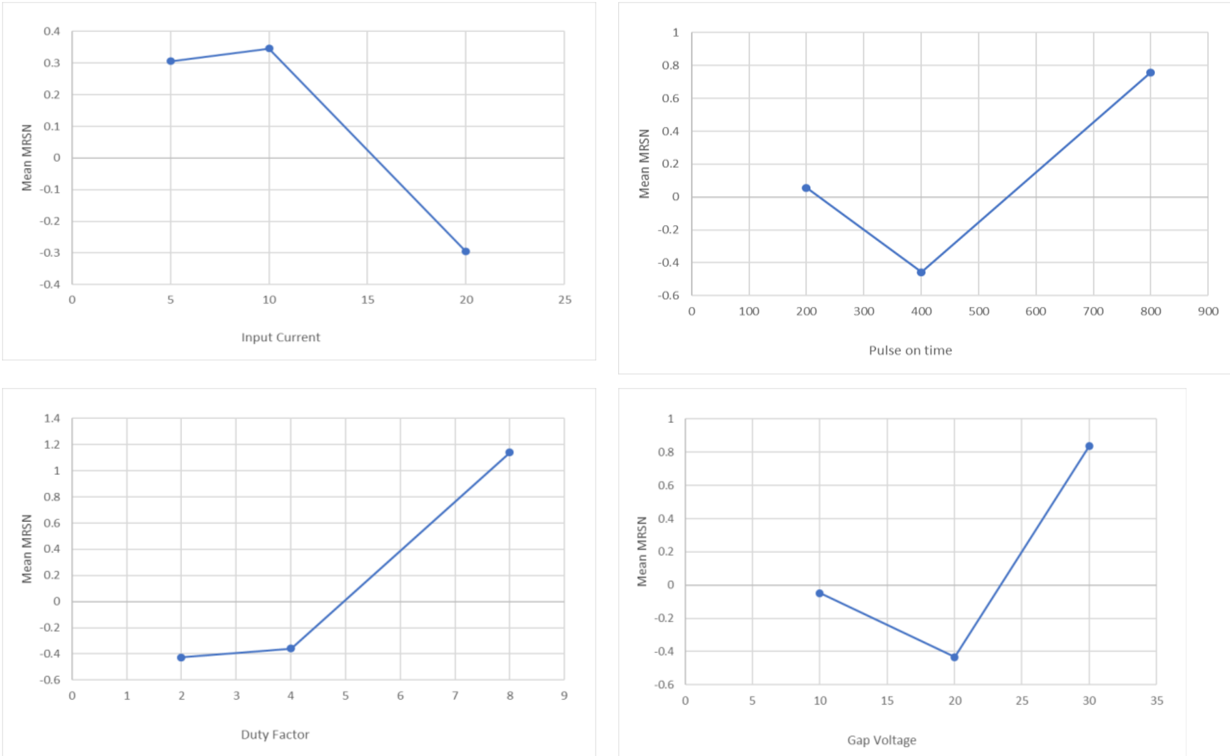

Fig. 10: Average MRSN values with different levels of input parameters (with powder).

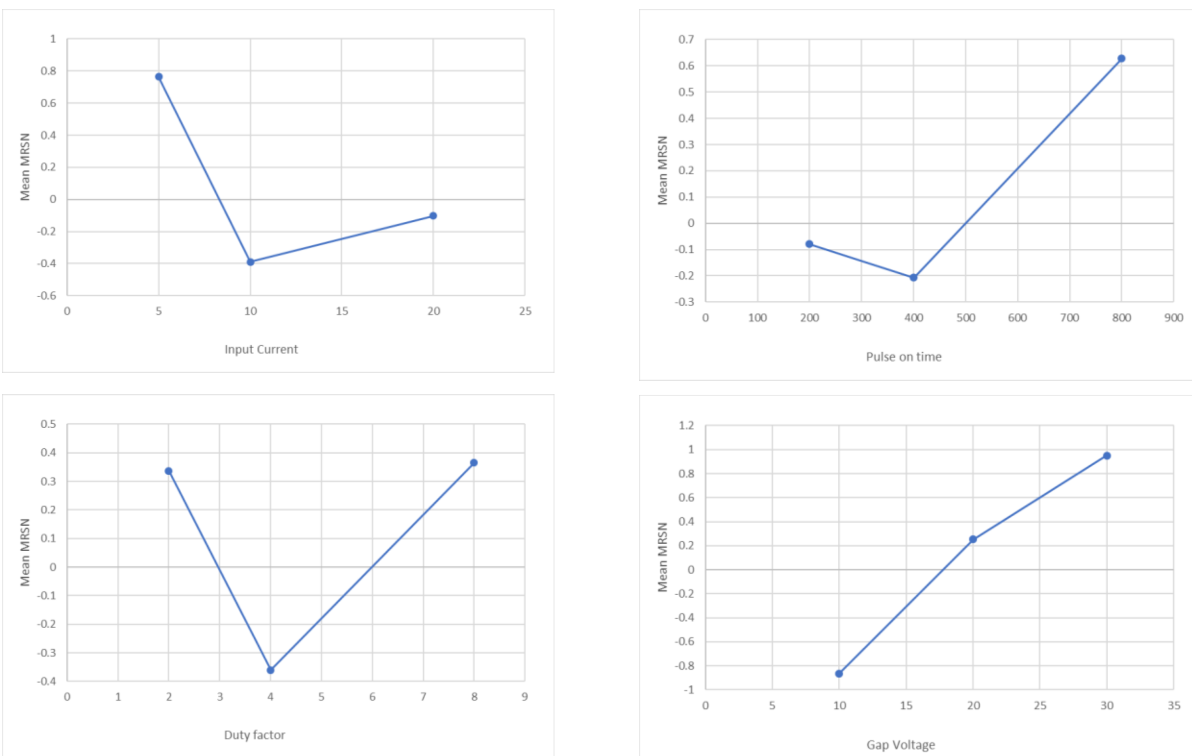

Fig. 11: Average MRSN values with low, medium and high levels of input parameters (without powder)

There is improvement of surface quality with respect to crack density as expressed in Tab.12 in the following.

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%.

IV CONCLUSION

The different conclusions as observed from the present study are:

(1) The optimum sets of input parameters such as current, pulse on time, duty factor and gap voltage (without powder) are: 5A, 800 µs, 8 and 30 V respectively.

(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 sets of input parameters are different in both cases.

(4) 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%.

(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.

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