Study on machining performances of Near-dry EDM

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Abstract: In this paper, the machining performances of near dry EDM such as material removal rate, tool wear rate and surface roughness are investigated on its process parameters. A Taguchi OA L_9 is used to design the experiment with three process parameters such as discharge current, duty factor and tool rotational speed. Effect of each process parameters on the machining performance is analysed and evaluate the significant process parameters. Analysis of variance (ANOVA) was performed and determine the percentage of contribution of each process parameters on the machining performance. It was observed that discharge current is the most significant and highest contribution parameter. A non-linear regression analysis is carried out and developed mathematical regression model for each machining performance. All the regression model has minimum percentage of residual error. A confirmation test is conducted and validated the experiment.

***Keywords:* -** Near dry; EDM; MRR; TWR; SR; Regression analysis

I. INTRODUCTION

In the year 1940s, electrical discharge machine (EDM) simply wet EDM was first introduced and becoming the oldest and reliable non-conventional machine process. EDM works on without mechanical contact force between the tool and workpiece, thus it has advantages to machine harder material by using soft tool. EDM is widely used in the field of engineering, medical and aerospace. In EDM process, the tool and workpiece are kept within the dielectric medium that works as insulator [1]. When a sufficient voltage is applied between the electrodes, breakdown of the dielectric medium occurs that produce ionization takes place at inter electrode gap and formed plasma channel and sparks. These sparks associate higher thermal energy with the temperature of 8000-12000^{0}C. The temperature is enough to melt and vaporize the metal from the workpiece, thus eroding the material from the workpiece in the form tiny crater. EDM process is dead without ionization of dielectric medium. Moreover, dielectric plays important role in refreshing the enter electrode gap and also dispersing the plasma channel.

In spite of many advantages of EDM, it has also many limitations such as low surface finish, higher tool wear and environmental hazards. Carcinogenic substances like benzene (C_6H_6) and benzopyrene ($C_{20}H_{12}$) are released from the burning of dielectric medium while machining that is dangerous for health, mainly operator [2]. Thus, research on different dielectric medium instead of single phase dielectric medium was started to investigated. Near dry EDM (ND-EDM) is one of the modern modified EDM process which used mist of liquid and gas (two-phase dielectric medium). The concept of near-dry EDM with liquid-gas mist was first suggested by Tanimura et al. [3] in the year 1989. Yang et al. [4] have suggested that ND-EDM has less pollution & explosions and also save from fire hazards as compared to the conventional EDM. Gholipoor et al. [5] have also suggested that ND-EDM can improve the MRR and the surface finish as compared to wet EDM at low energy levels. They also found that ND-EDM has good surface finish, lower micro-cracks and craters from the wet EDM. Khundrakpam et al. [6] have found that ND-EDM has negligible tool wear rate. They also suggested with rotational of tool improved the material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR) of machined surface from without rotational of tool. Many researcher have used different two-phase near dry dielectric medium such as deionized water-air [7], air-water [8,9] and kerosene-air [10,11].

This paper mainly focused on the machining performance of ND-EDM with near dry dielectric medium. From the literature, it is essential to study the effect of process parameters on the machining performance such as MRR, TWR and SR and to generate an acceptable regression model of each machining performance of ND-EDM.

NOMENCLATURE

Symbol	**Abbreviation**
MRR	Material removal rate (mm^3/min)
TWR	Tool wear rate (mm^3/min)
SR	Surface roughness (µm)
ΔW	Loss of workpiece before and after machining (g)
ΔT	Loss of workpiece before and after machining (g)
ρ_w	Density of workpiece (g/cm^3)
ρ_t	Density of tool (g/cm^3)
t	Machining time (min)

II. Experimental setup and methodology

An MQL device is used to produce the near dry dielectric medium. The liquid dielectric medium (deionized water) from the MQL reservoir and compressed air is mixed at the MQL device and produce two-phase near dry dielectric medium (deionized water and air). The supply of compressed air to the MQL device is controlled by a solenoid vale which works on pulsating current from the EDM controller. A ZNC EDM machine with a tool rotational attachment is used to conduct the experiment (Fig. 1). The schematic working diagram of the EDM is shown in Fig. 2. The material used in the experiment are Mild steel EN-8 as workpiece and copper as tool.

After machining, the MRR and TWR is measured by volumetric weight loss method and shown in Eq. 1 & 2.

$$\text{MRR} = \frac{[\Delta W]}{\rho_w t} \times 1000\ mm^3 / min \tag{1}$$

$$\text{TWR} = \frac{[\Delta T]}{\rho_w t} \times 1000\ mm^3 / min \tag{2}$$

Density of EN-8 workpiece and copper tool are 7.8 g/cm^3 and is 8.9 g/cm^3 respectively. Experiment is run for 20 minutes for each trial.

The value of surface roughness (SR), Ra is measured by Taylor Hobson Sutronic S-128.

Fig. 1. ZNC EDM Machine

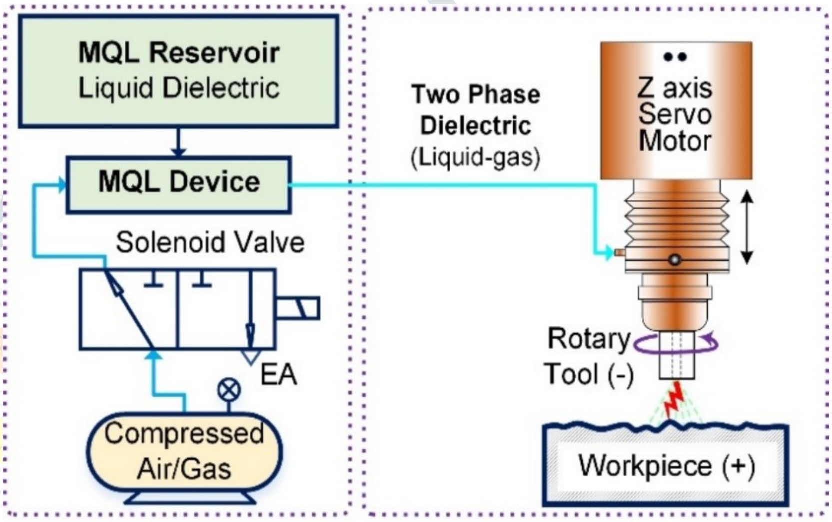


Fig. 2. Schematic working diagram of ND-EDM

Experiment is design for the low discharge energy of the machine. The process parameters of the near dry EDM is chosen from the pilot test, experimental data and literature review. The process parameters and their levels are tabulated in Table 1 and the basic process parameters are tabulated in Table 2. The three process parameters such as discharge current, duty factor and tool rotational speed is selected to design the experiment. Experiment is design with Taguchi L_9 OA with three machining performance such MRR, TWR and SR. Each raw data of machining performance is measured using taguchi design table. The raw data are computed into corresponding signal to noise (S/N) ratio. S/N ratio can be computed on 'larger-the-better, LB' characteristics and 'smaller-the-better, SB' characteristics (Eqs. 4 & 5). Effect of each process parameters on the machining performance is determined on both raw data and S/N ratios to find the significant process parameters. Analysis of variance for each machining performance is carried to determine the percentage of contribution of each process parameters on the machining performance. A non-linear regression analysis for each machining performance is analysed to develop a mathematical model of each machining performance.

$$LB: \quad S/N\ ratio = -10\ log_{10}\left[\frac{1}{n}\sum_{n=1}^{n}\frac{1}{y_i^2}\right] \tag{3}$$

$$SB: \quad S/N\ ratio = -10\ log_{10}\left[\frac{1}{n}\sum_{n=1}^{n}y_i^2\right] \tag{4}$$

Table 1. ND-EDM process parameters and levels

Process Parameters	Units	Symbol	Level 1	Level 2	Level 3
A: Discharge current	A	Ip	2	5	8
B: Duty factor	%	DF	70	80	90
C: Tool rotational speed	rpm	N	100	300	500

Table 2. Machining process parameters for the experiment

Process parameter	Unit	Values
Tool polarity	-	Negative
Machining time	min	20
Gap voltage	V	50
Working Pressure	bar	5 bar
Tool lifting time	sec	0.2

III. RESULTS AND ANALYSIS.

The experiment is conducted on Taguchi L_9 OA which reduces the number of experiment. The raw data of the machining performance such as MRR, TWR & SR are measured and the corresponding S/N ratio data are also computed considering 'Higher-the-better' characteristics for MRR and 'Smaller-the-better' characteristics for TWR & SR. The values are depicted in Table 3.

Table 3. Taguchi L_9 OA machining performance table

Run	A	B	C	MRR (mm^3/min)	S/N Ratio	TWR (mm^3/min)	S/N Ratio	SR (μm)	S/N Ratio
1	1	1	1	1.384	2.823	0.07937	22.0067	2.94	-9.367
2	1	2	2	1.617	4.174	0.08493	21.4189	2.96	-9.426
3	1	3	3	1.544	3.773	0.07085	22.9927	2.98	-9.484
4	2	1	2	1.966	5.872	0.09118	20.8022	3.13	-9.911
5	2	2	3	2.228	6.958	0.09887	20.0983	3.11	-9.855
6	2	3	1	2.139	6.604	0.09732	20.2360	3.31	-10.397
7	3	1	3	2.214	6.904	0.09864	20.1191	3.22	-10.157
8	3	2	1	2.617	8.356	0.11121	19.0770	3.36	-10.527
9	3	3	2	2.531	8.066	0.09848	20.1332	3.37	-10.553

3.1 Analysis of MRR

Fig. 3 & 4 shows the effect of each process parameters on the mean and corresponding mean of S/N ratio of MRR. It is observed from the Fig. 3 & 4 that both the mean and mean of S/N ratio of MRR increases with the increase of discharge current from 2 to 8 A significantly. The increase in discharge current increases the discharge energy that helps in improving the ionization of dielectric medium at inter electrode gap. Moreover, it improves the thermal energy, thus increases rate of melting and evaporation of workpiece thus increases the MRR. Both the mean and mean of S/N ratio of MRR initially increases with the increase of duty factor from 70 to 80 % then decreases with the increase of duty factor from 80 to 90%. Increase in duty factor increase the spark duration time, thus provide more amount of discharge energy for of duty cycle with the increase of duty factor, thus improve the MRR. Further increase in the duty factor enormously reduces the pulse off time that causes insufficient in cooling on the machine surface, so spark is restricted on the machined surface due to presence of larger amount of eroded molten metal, thus slightly reduces the MRR. Increase in the tool rotational speed slightly decreases both the mean and mean of S/N ratio of MRR. Increase in the tool rotational speed disturbs the discharge duty cycle and reduces the localize heating on the machined surface, thus reduces the MRR. It is suggested level 3 of peak current (8 A), level 2 of duty factor (80%) and level 1 of tool rotational speed (100 rpm) for maximum value of MRR of near dry EDM.

Fig. 3. Mean of MRR vs process parameters

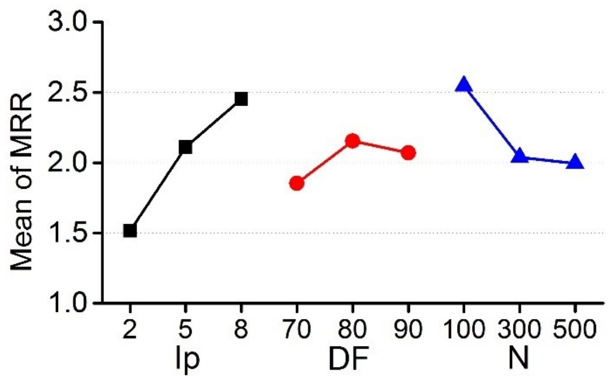
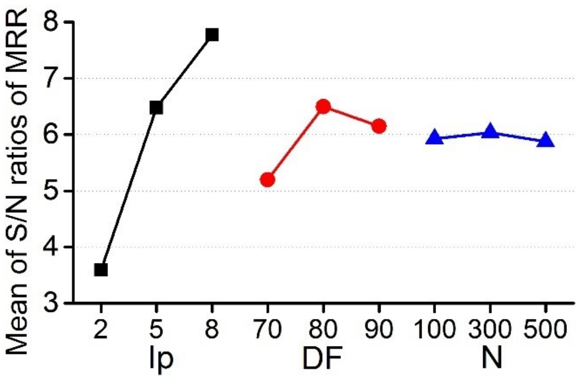


Fig. 4. Mean of S/N ratio of MRR vs process parameters



Analysis of variance (ANOVA) of the raw data of the MRR is analysed and outcomes are depicted in Table 4. It is observed that discharge current is the most significant process parameters with a percentage of contribution (% CB) of 89.79% followed by duty factor with (9.50 % CB). However, tool rotational speed is not a significant factor.

Non-linear regression analysis is conducted and evaluated coefficient values are depicted in the Table 5. Later, a mathematical regression equation is generated (Eq. 5).

$$MRR = -11.9746 + 0.2971\, I_p + 0.3164\, DF + 0.0001\, N - 0.0140\, Ip * Ip - 0.0019\, DF * DF \quad (5)$$

Table 4. ANOVA of MRR (raw data)

Source	DF	Seq SS	Adj MS	F	P	% CB
A	2	1.35459	0.677293	222.33	0.004	89.79
B	2	0.14338	0.071689	23.53	0.041	9.50
C	2	0.00453	0.002265	0.74	0.574	0.30
Error	2	0.00609	0.003046			0.40
Total	8	1.50859				100

S = 0.05519 R^2= 99.6% R^2 (adj) = 98.4%

From Table 5, the value of R^2 and R^2 (adj) are 99.60% and 98.38% respectively which shows the regression equation is signified at 98% confidence level. The predicted values with percentage of residual of the regression equation of MRR is depicted in the Table 6. It is observed that percentage of residual for the model of MRR is small and within the acceptable range.

Table 5. Evaluated regression coefficients of MRR

Term	Coef	SE Coef	T	P
Constant	-11.9746	2.48104	-4.82645	0.04
A	0.2971	0.04401	6.74975	0.021
B	0.3164	0.06249	5.06414	0.037
C	0.0001	0.0006	0.21247	0.851
A*A	-0.0141	0.00434	-3.24128	0.083
B*B	-0.0019	0.00039	-4.89395	0.039
C*C	0	0	-0.43559	0.706

S = 0.0551936 R^2= 99.60% R^2 (adj) = 98.38%
PRESS = 0.123377 R^2 (pred) = 91.82%

Table 6. Predicted and % of residual of MRR

Run	A	B	C	MRR	Predicted	% of Residual
1	2	70	100	1.384	1.363	1.52
2	2	80	300	1.617	1.654	-2.27
3	2	90	500	1.544	1.528	1.01
4	5	70	300	1.966	1.950	0.80
5	5	80	500	2.228	2.207	0.94
6	5	90	100	2.139	2.176	-1.71
7	8	70	500	2.214	2.251	-1.66
8	8	80	100	2.617	2.601	0.60
9	8	90	300	2.531	2.510	0.83

3.2 Analysis of TWR

Fig. 5 & 6 shows the effect of each process parameters on the mean and corresponding mean of S/N ratio of TWR. TWR has 'smaller-the-better' characteristics, whereas the S/N ratio has 'higher-the-better' characteristics'. Thus, the trend of mean and mean of S/N ratio of SR is opposite. From the Fig. 4 & 5, increase of discharge current (from 2 to 8 A) increases the mean of TWR and decreases the mean of S/N ratio of SR significantly. Thus, TWR increases with the increase of discharge current. Higher discharge current associates larger discharge energy that helps in higher thermal energy at inter electrode gap. Increase in the discharge energy increases explosive force that helps in eroding of material from the tool, thus increased the TWR.

From the Fig. 5 & 6, increase in the duty factor from 70 to 80 % initially increase the mean of SR and decreases mean of S/N ratio of SR then decrease the mean of SR and increase mean of S/N ratio of SR with further increase in the duty factor (80 to 90%). Thus, TWR increased with the increase duty factor then decreases. TWR is mainly depend on the thermal energy and adhesion of eroded material to the tool. Pulse duration of discharge energy increases with the increase duty factor, thus more material is eroded from the tool that increases TWR. As increase in the duty factor increased the eroded material from both tool & workpiece and more adhesion of material on the tool that compensate the eroded of material from tool, thus decreases TWR.

From the Fig. 5 & 6, increase in the tool rotational speed (100 to 500 rpm) decreases the mean of TWR and increases the mean of S/N ratio of TWR. Dispersion of electrical spark increases with the increase of tool rotational speed that reduces the localize melting and evaporation of tool uniformly eroded material from the workpiece, thus TWR decreases with further increase in the duty factor. The level 1 of peak current (2 A), level 3 of duty factor (90%) and level 3 of tool rotational speed (500 rpm) for minimizing the TWR of near dry EDM.

Analysis of variance (ANOVA) of the raw data of the TWR is analysed at 95 % confidence level and outcomes are depicted in Table 7. It is observed that discharge current is the significant process parameters with a percentage of contribution of 79.78%. The duty factor (13.82 % CB) and tool rotational speed (5.56 % CB) are less significant factor.

Non-linear regression analysis evaluated the coefficient values for TWR and tabulated in the Table 8. The mathematical regression equation is given as Eq. 6.

$$TWR = -0.50087 + 0.009854\,Ip + 0.014408\,DF - 0.000034\,N - 0.000579\,Ip*Ip - 0.00009\,DF*DF \quad (6)$$

From Table 8, the value of R^2 and R^2 (adj) for SR are 99.18% and 96.71% respectively which shows the regression equation is signified at 96% confidence level. The predicted values of TWR is depicted in the Table 9 with percentage of residual. It is observed that percentage of residual for the model of SR is small and acceptance range.

Fig. 5. Mean of TWR vs process parameters

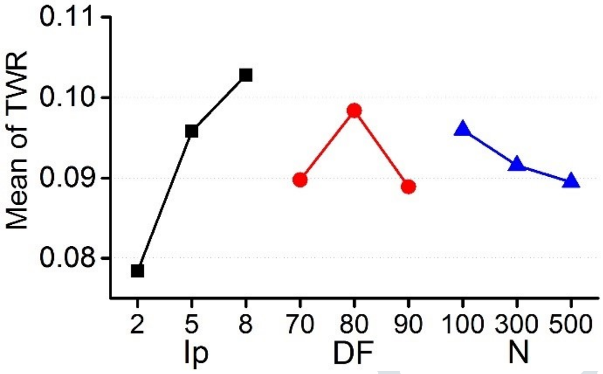


Fig. 6. Mean of S/N ratio of TWR vs process parameters

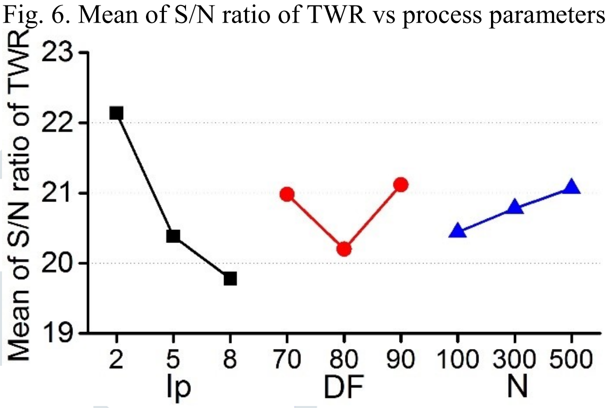


Table 7. ANOVA of TWR (raw data)

Source	DF	Seq SS	Adj MS	F	P	% CB
Ip (A)	2	0.00095	0.00047	96.99	0.01	79.78
DF (%)	2	0.00016	0.00008	16.82	0.056	13.82
N (rpm)	2	0.000006	0.00003	6.8	0.128	5.56
Error	2	0.00001	0.000006			0.84
Total	8	0.00119				100

S = 0.002209 R^2= 99.2% R^2 (adj) = 96.7%

Table 8. Evaluated regression coefficients of TWR

Term	Coef	SE Coef	T	P
Constant	-0.50087	0.0993033	-5.04384	0.037
A	0.009854	0.0017615	5.59435	0.03
B	0.014408	0.002501	5.76111	0.029
C	-0.000034	0.0000239	-1.4262	0.29
A*A	-0.000579	0.0001736	-3.33551	0.079
B*B	-0.00009	0.0000156	-5.78177	0.029
C*C	0	0	0.75759	0.528

S = 0.00220911 R^2= 99.18% R^2 (adj) = 96.71%
PRESS = 0.000197647 R^2 (pred) = 83.35%

Table 9. Predicted and % of residual of TWR

Run	A	B	C	SR	Predicted	Residual %
1	2	70	100	0.07937	0.079447	-0.10
2	2	80	300	0.08493	0.083617	1.54
3	2	90	500	0.07085	0.072090	-1.74
4	5	70	300	0.09118	0.092414	-1.36
5	5	80	500	0.09887	0.098950	-0.08
6	5	90	100	0.09732	0.096008	1.35
7	8	70	500	0.09864	0.097326	1.33
8	8	80	100	0.11121	0.112447	-1.11
9	8	90	300	0.09848	0.098554	-0.08

3.3 Analysis of SR

Fig. 7 & 8 shows the effect of each process parameters on the mean and corresponding mean of S/N ratio of SR. SR has 'smaller-the-better' characteristics, whereas the S/N ratio has 'higher-the-better' characteristics'. Thus, the trend of mean and mean of S/N ratio of SR is opposite. From the Fig. 4 & 5, the mean of SR trend increases and the mean of S/N ratio of SR trend decreases with the increase of discharge current from 2 to 8 A significantly. Thus, SR increases with the increase of discharge current. The increase in discharge current increases the discharge energy that improve the spark energy with larger explosive force for removing material, thus larger and deeper crater on the machined surface is formed which increases the SR. From the Fig. 7 & 8, the mean of SR trend increases and mean of S/N ratio of SR trend decreases with the increase of duty factor. This shows increase in the duty factor increases SR. Increase in duty factor increase discharge energy with more spark duration time, thus larger and deeper crater on the machined surface is produced, thus SR increases.

From the Fig. 7 & 8, the mean of SR trend decreases and mean of S/N ratio of SR trend increases with the increase of tool rotational speed from 100 to 500 rpm. Increase in the tool rotational speed improves the dispersion of spark energy throughout the machined surface, thus decreases localize sparking and uniformly eroded material from the workpiece, thus swallow and small crater are formed which decreases the SR. Moreover, increase in the tool rotational speed adequately remove eroded material form the inter electrode gap. Thus, chances of inclusion of material on the machined surface is reduced that enhances the surface finish. The level 1 of peak current (2 A), level 1 of duty factor (70%) and level 3 of tool rotational speed (500 rpm) for minimizing the SR of near dry EDM.

Analysis of variance (ANOVA) of the raw data of the SR is analysed and outcomes are depicted in Table 10. It is observed that discharge current is the most significant process parameters with a percentage of contribution (% CB) of 83.28% followed by duty factor with (9.94 % CB). However, tool rotational speed is less significant factor.

Fig. 7. Mean of SR vs process parameters

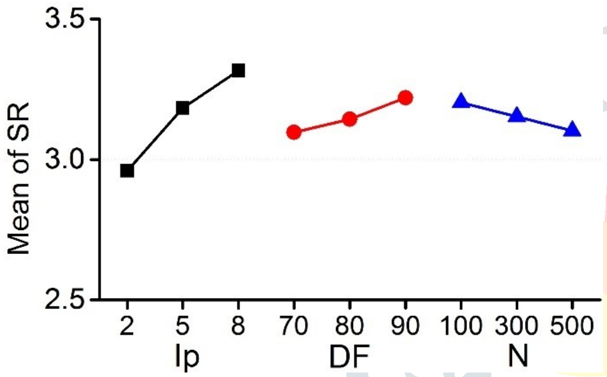


Fig. 8. Mean of S/N ratio of SR vs process parameters

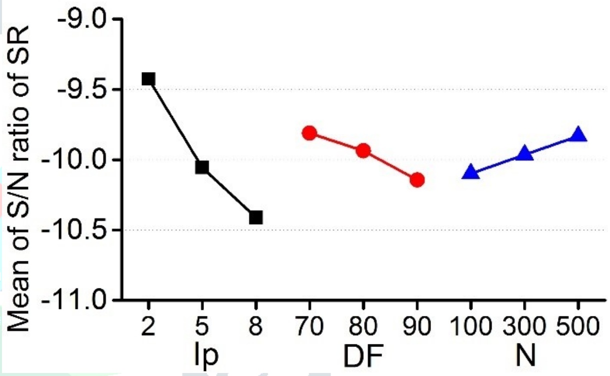


Table 10. ANOVA of SR (raw data)

Source	DF	Seq SS	Adj MS	F	P	% CB
A	2	0.19487	0.09743	224.85	0.004	83.28
B	2	0.02327	0.01163	26.85	0.036	9.94
C	2	0.015	0.0075	17.31	0.055	6.41
Error	2	0.00087	0.00043			0.37
Total	8	0.234				100

S = 0.02082 R^2= 99.6% R^2 (adj) = 98.5%

Evaluated coefficient values for SR by non-linear regression analysis are depicted in the Table 11. Later, a mathematical regression equation is generated (Eq. 7).

$$SR = 3.29278 + 0.10944\, Ip - 0.01783\, DF - 0.00025\, N - 0.005\, Ip * Ip + 0.00015\, DF * DF \quad (7)$$

Table 11. Evaluated coefficient values for SR

Term	Coef	SE Coef	T	P
Constant	3.29278	0.935744	3.51889	0.072
A	0.10944	0.016599	6.59358	0.022
B	-0.01783	0.023567	-0.75672	0.528
C	-0.00025	0.000225	-1.11187	0.382
A*A	-0.005	0.001636	-3.05715	0.092
B*B	0.00015	0.000147	1.01905	0.415
C*C	0	0	0	1

S = 0.0208167 R^2 = 99.63% R^2 (adj) = 98.52%
PRESS = 0.01755 R^2 (pred) = 92.50%

From Table 11, the values of R^2 and R^2 (adj) for SR are 99.63% and 98.52% which shows the regression equation is signified at 98% confidence level. The predicted values with percentage of residual of the regression equation of SR is depicted in the Table 12. It is observed that percentage of residual for the model of SR is less than 1%.

Table 12. Predicted and % of residual of SR

Run	A	B	C	MRR	Predicted	% of Residual
1	2	70	100	2.940	2.953	-0.45
2	2	80	300	2.960	2.950	0.34
3	2	90	500	2.980	2.977	0.11
4	5	70	300	3.130	3.127	0.11
5	5	80	500	3.110	3.123	-0.43
6	5	90	100	3.310	3.300	0.30
7	8	70	500	3.220	3.210	0.31
8	8	80	100	3.360	3.357	0.10
9	8	90	300	3.370	3.383	-0.40

IV. Confirmation Test

A confirmation test is conducted to verify the predicted machining performance such as MRR, TWR and SR at their optimal process parameters (Table 13). It is observed that percentage of error is very small and less than 1 %, thus it validated the experiment.

Table 13. Confirmation results

S No.	Machining performance	Optimum parameters			Experimental value	Predicted value	% Error
		Ip	DF	N			
1	MRR	8	8	80	2.617	2.601	0.6
2	TWR	2	90	500	0.07085	0.07209	-1.74
3	Ra	2	70	500	2.95	2.94	0.34

V. Conclusion

Study on machining performance of ND-EDM has been performed using Taguchi L_9 OA. Effect of three process parameters on the machining performance such as MRR, TWR and SR is studied. Discharge current is the most significant process parameter with highest percentage of contribution for MRR (89.79%), TWR (79.78%.) and SR (83.28%). the process parameters such as duty factor and tool rotational speed has less percentage of contribution. of contribution. The mathematical regression model equation of each machining performance has very small percentage of residual error and model is within the acceptable range.

VI. Acknowledgment

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VII. Area of conflict

The authors declare there is no area of conflict on this paper.

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