Optimization of Surface Roughness and MRR in Powder Mix EDM Die-Sink for Inconel 718 using RSM

M. Ahsan Ul Haq*, Salman Hussain, Wasim Ahmad, Mirza Jahanzaib, Waseem Iqbal and Saira Shehzadi

Industrial Engineering Department University of Engineering and Technology Taxila, Pakistan

Abstract: Product quality depends on the surface quality of the machined part and machining performance relay on the production rate of the process. Whereas surface quality of a part is based on surface roughness (SR) and production rate depend on the material removal rate (MRR). Minimum surface roughness and maximum MRR are of great value in the field of manufacturing. In powder mix Electrical Discharge Machined (EDM) selection of input parameters and their ranges are of great value because its helps to achieve the optimize values of the SR and MRR. This study contains the effect of four input variables; pulse on time (Pon), discharge current (DC), pulse off time (Poff) and powder concentration of EDM on SR and MRR of Inconel 718. Response Surface Methodology (RSM) center composite design (CCD) and Analysis of Variance (ANOVA) are used with 5% significant coefficient. It was observed that DC significantly affects the SR and MRR followed by the Pon.

Keywords: Powder mix EDMs, Response Surface Methodology, Surface Roughness, MRR, Inconel 718.

1. INTRODUCTION

Electrical Discharge Machining (EDM) is one of the most extensively used nontraditional machining which is used to remove material efficiently. Electrically conductive parts can be machined using EDM irrespective of the hardness. There is no mechanical forces exist because there is a gap between the tool and work piece, only thermal energy is used to manufacture parts [1-3]. EDM can easily tackle exact tolerance because the exact shape of the electrically conductive tool is punched on the work piece material [4, 5]. EDM is used for brittle and conductive materials, in this process a spark is produced with the help of DC and a small gap between too and work piece [4, 6]. EDM also have some limitation such as high surface roughness and low material removal rate (Effect of Si). To overcome these limitations powder EDM is introduced. In powder EDM process a small amount of fine powder (Al_2O_3, SiC, Gp, SiO_2, Cu, Al, Si, Cr) is mixed in the dielectric fluid of the EDM which enhance the machining properties of EDM (Zhao, Meng, and Wang 2002; Wong, Lim, and Tee 1998 Si).

In early days before Second World War, stainless steel served as the high temperature material for the aerospace industry. After second world war the need of more specific material for elevated temperature services was raised because steel cannot bear high temperature produced in turbines and aero engines [7]. An alternative material with low thermal expansion can fulfill the requirements. The lower thermal expansion will help the material to bear more temperature. Bu-Yeol Yang reported that coefficient of thermal expansion for super alloys is ten times smaller than steel approximately [8]. Super alloys can replace stainless steel in high temperature activities. Nickel-based super alloys are used in the aero engine industry due to their high temperature strength [9]. Inconel 718 is a Nickel based super alloy used for the gas turbine engines due to its brilliant strength properties up to 650°C [7]. Some researcher stated that 50% of the aero-engine is made up of nickel-chromium alloys [10]. Due to high strength and low thermal coefficient machining of such material is difficult, therefore forces and tool wear increase during machining [11]. For the machining of hard materials like Inconel 718 non-conventional manufacturing processes such as EDM is used. EDM is extensively used in the field of manufacturing dies and molds, also used to manufacture hard components for aerospace industry and automotive industries [1-3].

Machining performance can be improved by increasing material removal rate and minimizing surface roughness (SR) of the final product. Machined surface quality is being expressed by surface roughness, which belongs to the smoother surface [4, 12]. SR is a critical requirement of the manufactured parts in various cases. To achieve the desired surface finish of a part has a great value for its functional behavior [13]. Material removal rate (MRR) directly influences the production rate of the system. To achieve greater production rate higher MRR is required.

*Address correspondence to this author at the Industrial Engineering Department University of Engineering and Technology Taxila, Pakistan; Tel: 051-9047828; Fax: 051-9047420; E-mail: ahsanulhaq233@gmail.com

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Table 1: Composition of Inconel 718

Element	Ni	Cr	Mo	Co	Mn	Cu	C	S
Composition Weight (%)	50	18.1	3.2	1	0.35	0.4	0.08	0.015

Some of the machining parameters for EDM are discussed [14] such as Pon, also known as machining time current flows and material removed during this time period so MRR and SR depend on Pon, DC, is among the main variables which effect SR and MRR significantly basically it is the current applied to produce spark, Poff, is the time between the two consecutive sparks removed material is washed away during this time.

It is evident that SR is directly proportional to the Pon. Reason behind the increasing surface roughness with the increase in discharge duration is the discharge energy released for this period of time[15]. The DC was one of the most significant factor for both the SR and MRR, tracked by Pon for MRR [2]. The RSM based SR model can be optimized using GA to obtain the optimum values of independent variables [16].

Mathematical and statistical techniques are used in RSM; these techniques are useful for modeling and analysis. Generate a relation between the input variables and the responses of the system and develop a correlation between them [17, 18]. In the recent years, Neelesh Singh *et al*. used RSM to study the machining performce of EDM process [19]. They concluded that current increases MRR also increases. Debnath *et al*. focused on On Die Sinking EdM machining process and develop a mathematical model for the Surface roughness, tool wear rate and metal removal rate.

Detailed literature review shows that there is a little or no work has been reported on the powder mix EDM of Inconel 718 using RSM to optimize input parameters and to analyze their effect on the performance measures. In this study Inconel 718 is machined under variable input parameters such as DC, Pon, Poff, Powder concentration using powder mix EDM to investigate their effects on SR and MRR.

2. MATERIALS AND METHODS

2.1. Material

Inconel 718 is used for investigation of input parameters on SR and MRR by using powder mix EDM. Inconel 718 belongs to the famous family of Ni-Cr super alloys with extra ordinary hardness. Composition of Inconel 718 has been provided in the Table **1**. Al_2O_3 powder particles with an average size of 10 nm were added in the kerosene oil (dielectric fluid), addition of Al_2O_3 nano particles to kerosene oil increases the material removal rate because it enhance the gap [20], while electrolytic copper (99.9% pure) was used as electrode material having the diameter of 15.6mm.

2.2. Experimental Method

The experiments were conducted on Neu-ar M-30 die-sinking EDM machine. Positive polarity was assigned to copper electrode and dielectric fluid pressure 0.5 kg/cm^2. Before and after experimentation work piece has been weighted using a weigh machine. Machining has been calculated using electronic timer, while the machining depth was kept constant at 0.2 mm throughout the machining. MRR was calculated using Eq. 1 and SR was measured with the help of SJ-410 surface roughness tester. The machining parameters such as DC, Pon, Poff and powder concentration and their levels are illustrated in Table **2**.

$$MRR = \frac{(Initial\ weight\ of\ work\ piece - Final\ weight\ of\ work\ piece)}{(Machining\ time)} \quad (1)$$

In this study Center Composite Design of response surface methodology was employed with 5 center points and half design to reduce number of experiments 21. Four input parameters with three levels were selected. Table **3** shows the experimental results with their respective input parameters.

Table 2: Input Parameters and their Levels

Name	Unit	Low	Medium	High
DC	A	4	8	12
Pon	μs	40	80	120
Poff	μs	15	20	25
Powder Conc.	g/l	0	3	6

3. RESULTS AND DISCUSSION

3.1. Surface Roughness

The summary suggests the quadratic relationship for surface roughness of powder mix EDM process.

Table 3: Input Parameters with Observed Variables

Runs	DC (A)	Pon µs	Poff µs	Powder Conc. g/l	Surface Roughness (Ra)	Material Removal Rate(MRR)
1	8	80	25	3	3.25	98
2	8	80	20	6	3.3	108
3	8	80	20	3	3.52	93
4	8	120	20	3	3.76	83
5	8	80	15	3	3.65	100
6	4	40	25	0	3.01	38
7	4	120	15	6	2.9	79
8	8	80	20	3	3.5	84
9	12	40	25	6	2.95	69
10	8	80	20	3	3.56	82
11	12	120	15	0	4.2	91
12	4	80	20	3	2.9	53
13	8	40	20	3	3.3	63
14	8	80	20	3	3.44	88
15	4	40	15	0	3.57	46
16	12	80	20	3	3.8	97
17	8	80	20	0	3.6	78
18	12	120	25	0	3.87	88
19	8	80	20	3	3.48	89
20	4	120	25	6	2.64	55
21	12	40	15	6	3.57	81

ANOVA result shows the significant effects of the DC (A), Pon (B), powder concentration (D), Poff (C) and quadratic effects of AB, AD, BC, BD, A^2 are captured. Values of R^2, adjusted R^2 and predicted R^2 are shown in Table **4**. Models is significant. Final mathematical model for the prediction of the surface roughness in powder mix EDM is shown in the Eq. 2.

SR =+4.00564+0.13385× DC-0.018490× Pon-0.012994× Poff-0.23431× Powder Conc.+1.08594E-003× DC × Pon-8.12500E-004× DC × Poff+0.013854× DC × Powder Conc.+3.68750E-004× Pon × Poff+1.17708E-003× Pon × Powder Conc.+8.33333E-005× Poff × Powder Conc.-8.34594E-003× DC^2+2.90406E-005× Pon^2-1.34140E-003× $Poff^2$-3.72611E-003 × Powder $Conc.^2$ (2)

3.1.1. Response Surface Plots

Figure **1a** explains the impact of DC and Pon on the SR produced by powder mix EDM. The graph shows that SR increases with the growing value of Pon and DC. DC more significantly affects the SR as compared to the Pon. The effects of DC and Poff is shown in Figure **1b**. Surface roughness decreases with the increment in Poff.

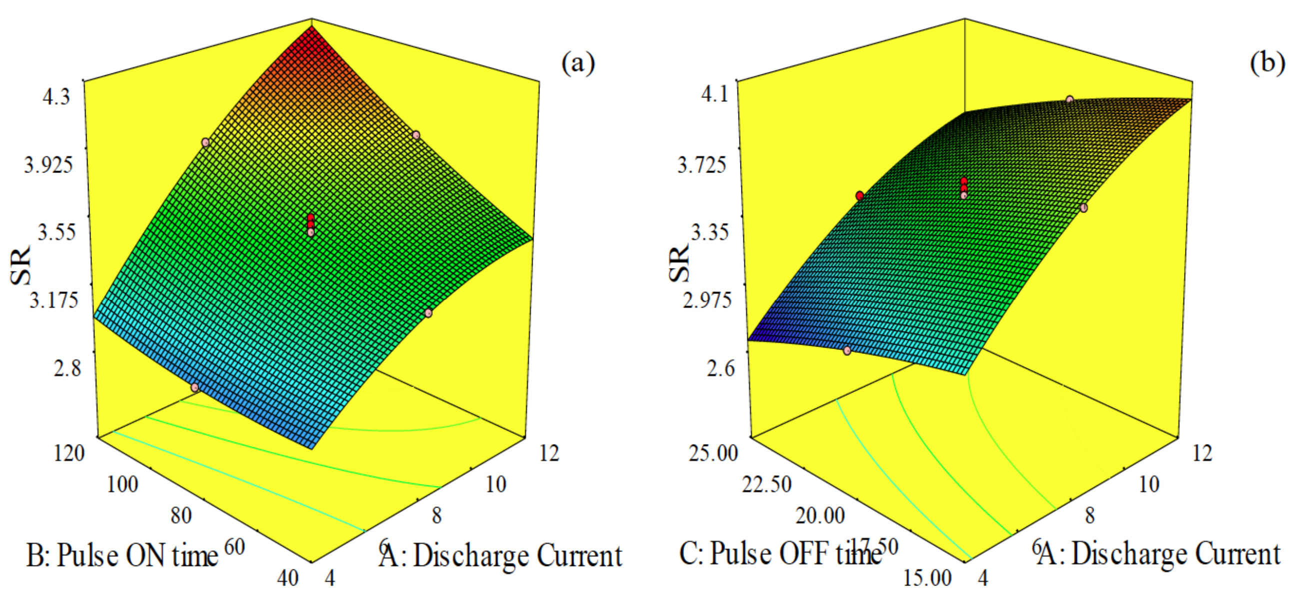
The effects of powder concentration, on surface roughness, with DC and Pon are shown in Figure **1c** and **d**. Both these graph shows that with the addition of Al_2O_3 powder in the dielectric fluid decreases the surface roughness.

3.2. Material Removal Rate

For material removal rate the summary suggest the quadratic model as a best model. ANOVA identify the significant main variables with the interactions and quadratic relations. In this case DC (A), pulse off time (C), powder concentration (D) and Pon (B) are the main significant varibles. AB is the significant interaction and A^2, B^2, C^2 are significant quadratic relations. Values of R^2, adjusted R^2 and predicted R^2 for both the environments are shown in Table **5**. Final

Table 4: ANOVA Table for SR

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2.827379073	14	0.201955648	126.1975798	< 0.0001	significant
A-DC	0.405	1	0.405	253.0754663	< 0.0001	
B-Pon	0.1058	1	0.1058	66.11206007	0.0002	
C-Poff	0.47089	1	0.47089	294.2486575	< 0.0001	
D-Powder Conc.	0.045	1	0.045	28.11949625	0.0018	
AB	0.0483025	1	0.0483025	30.18315484	0.0015	
AC	0.0021125	1	0.0021125	1.32005413	0.2943	
AD	0.0442225	1	0.0442225	27.63365384	0.0019	
BC	0.0435125	1	0.0435125	27.18999068	0.0020	
BD	0.0319225	1	0.0319225	19.9476582	0.0043	
CD	1.25E-05	1	1.25E-05	0.007810971	0.9325	
A^2	0.045521332	1	0.045521332	28.44526524	0.0018	
B^2	0.005511576	1	0.005511576	3.444061093	0.1129	
C^2	0.002870926	1	0.002870926	1.793977556	0.2289	
D^2	0.002870926	1	0.002870926	1.793977556	0.2289	
Residual	0.009601879	6	0.001600313			
Lack of Fit	0.001601879	2	0.000800939	0.400469745	0.6942	not significant
Pure Error	0.008	4	0.002			
Cor Total	2.836980952	20				
Std. Dev.	0.040003914			R-Squared		0.996615459
Mean	3.417619048			Adj R-Squared		0.988718196
C.V. %	1.170519996			Pred R-Squared		0.893547039
PRESS	0.302005024			Adeq Precision		45.88949823



(Figure 1). Continued.

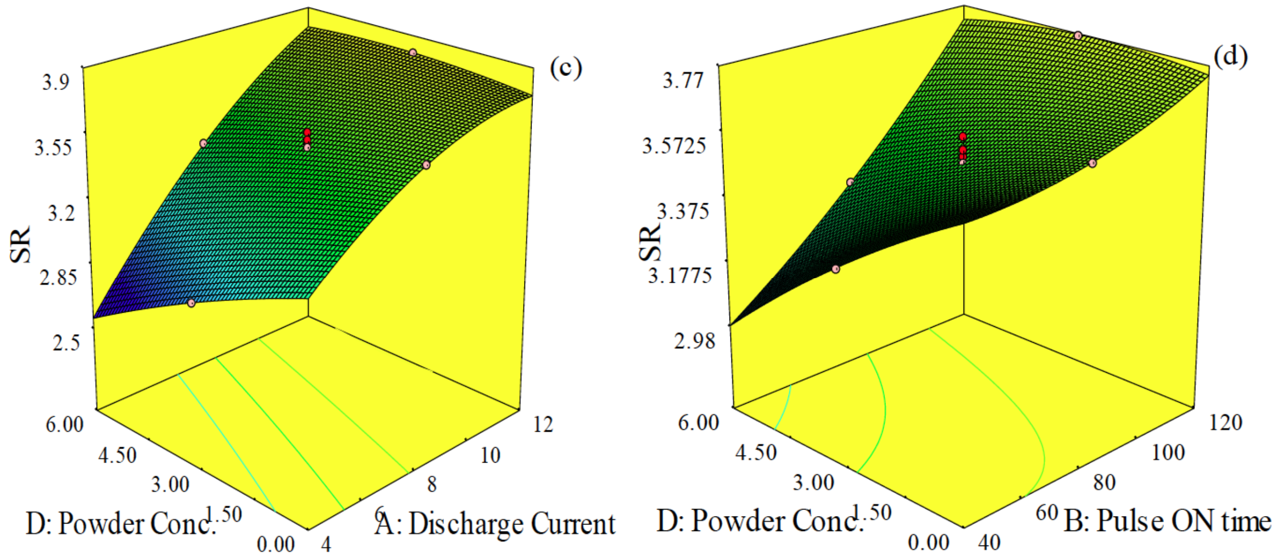


Figure 1: (**a**, **b**, **c**, **d**) 3D surface plots of surface roughness.

Table 5: ANOVA Table for Material Removal Rate

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	6862.80784	14	490.20056	21.24682473	0.0006	significant
A-DC	968	1	968	41.95614614	0.0006	
B-Pon	200	1	200	8.668625236	0.0258	
C-Poff	240.1	1	240.1	10.4066846	0.0180	
D-Powder Conc.	450	1	450	19.50440678	0.0045	
AB	245.025	1	245.025	10.62014949	0.0173	
AC	36.125	1	36.125	1.565770433	0.2574	
AD	0.025	1	0.025	0.001083578	0.9748	
BC	6.125	1	6.125	0.265476648	0.6248	
BD	105.625	1	105.625	4.578117703	0.0762	
CD	78.125	1	78.125	3.386181733	0.1154	
A^2	575.1221842	1	575.1221842	24.9275934	0.0025	
B^2	738.601859	1	738.601859	32.01331357	0.0013	
C^2	206.3416964	1	206.3416964	8.943494185	0.0243	
D^2	22.82950132	1	22.82950132	0.989501956	0.3583	
Residual	138.4302548	6	23.07170913			
Lack of Fit	63.63025478	2	31.81512739	1.701343711	0.2920	not significant
Pure Error	74.8	4	18.7			
Cor Total	7001.238095	20				
Std. Dev.	4.803301899			R-Squared		0.980227746
Mean	79.19047619			Adj R-Squared		0.934092488
C.V. %	6.065504502			Pred R-Squared		0.814413316
PRESS	12703.13963			Adeq Precision		16.60996352

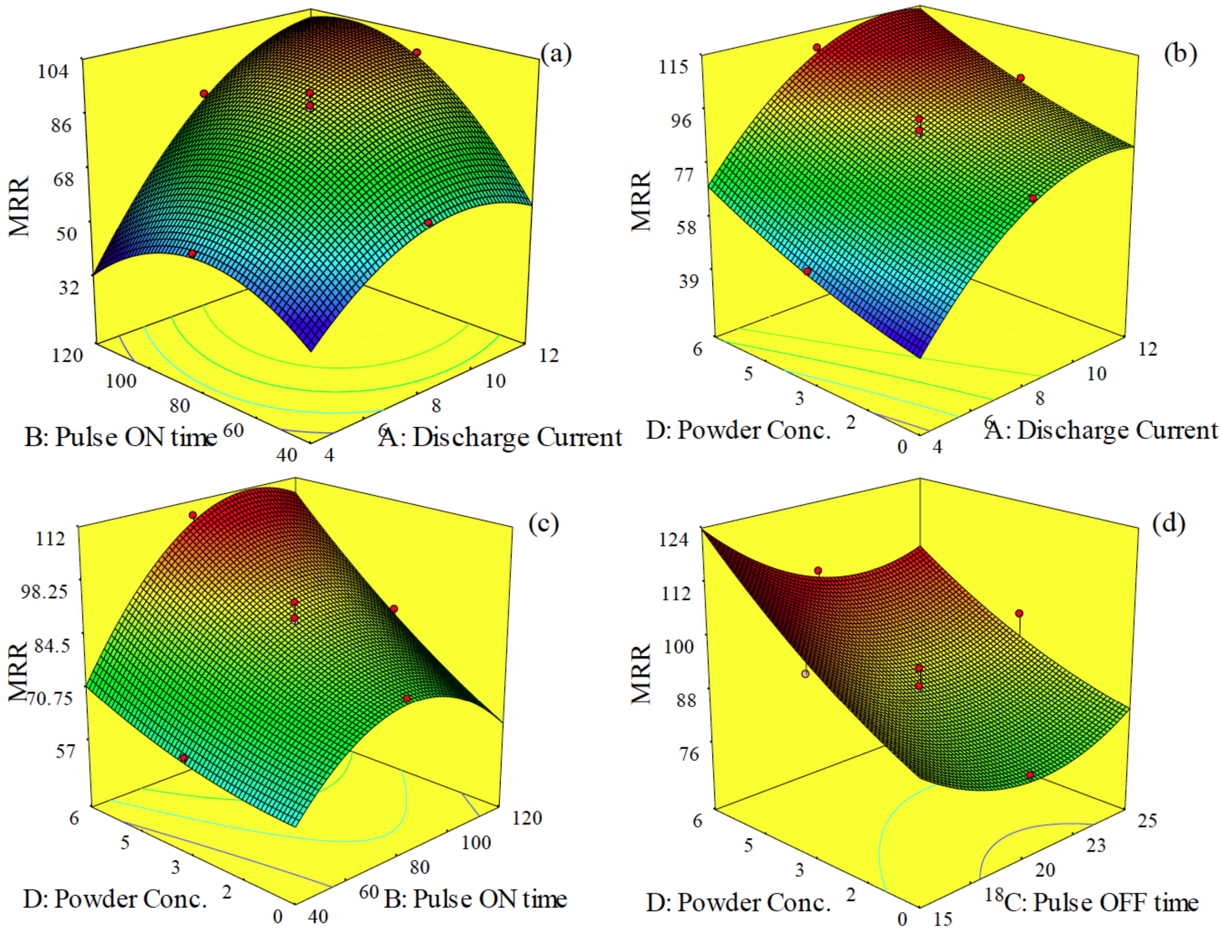


Figure 2: (a, b, c, d) 3D surface plots for Material Removal Rate.

mathematical model for the prediction of the material removal rate is shown in the Eq. 3.

$$MRR = +111.59363 + 12.16580 \times DC + 1.21658 \times Pon - 15.23971 \times Poff + 1.67304 \times Powder\ Conc. + 0.077344 \times DC \times Pon + 0.10625 \times DC \times Poff + 0.010417 \times DC \times Powder\ Conc. - 4.37500E{-}003 \times Pon \times Poff + 0.067708 \times Pon \times Powder\ Conc. - 0.20833 \times Poff \times Powder\ Conc. - 0.93810 \times DC^2 - 0.010631 \times Pon^2 + 0.35962 \times Poff^2 + 0.33227 \times Powder\ Conc.^2 \quad (3)$$

3.2.1. Response Surface Plots

The effects of DC and Pon on MRR is shown in Figure **2a**. The graph shows that with the increase in DC and Pon MRR increases.

Figure **2b**, **c**, **d** contains the graph of powder concentration, on material removal rate, with DC, Pon and Poff respectively. According to the results MRR increases with the increase in powder concentration in the dielectric fluid of the EDM. While when the Poff increases MRR decreases.

4. OPTIMIZATION ASSOCIATED WITH SUSTAINABILITY

The purpose of this study is to achieve high production rate (material removal rate) and less surface roughness simultaneously. The sustainability function for the current study is shown in Eq. 4.

$$Sustainability = \begin{cases} Maximaizing\ Material\ Removal\ Rate \\ Minimizing\ Surface\ Roughness \end{cases} \quad (4)$$

The constraints for multi objective optimization using desirability function have been presented in Table **6**. The achieved desirability along with process parameters values has been provided Table **7**. It can be observed that desirability as high as 86.5% can be achieved when all performance measures possess equal weights.

It is clearly evident from Table **7** and Figure **3a** that minimum surface roughness 2.8 μm and maximum material removal rate 99.5 g/min can be achieved with

Table 6:

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
DC	is in range	4	12	1	1	3
Pon	is in range	40	120	1	1	3
Poff	is in range	15	25	1	1	3
Powder Conc.	is in range	0	6	1	1	3
SR	minimize	2.64	4.2	1	1	3
MRR	maximize	38	108	1	1	3

Table 7: Results for Desirability

Number	DC	Pon	Poff	Powder Conc.	SR	MRR	Desirability	
1	7.1	75.51	25	6	2.870695	99.59848	0.865936	Selected
2	7.04	77.01	25	6	2.875937	99.809	0.865703	
3	7.24	75.75	25	6	2.896107	100.763	0.865688	
4	6.98	76.63	25	6	2.863111	99.20592	0.865632	
5	7.06	76.25	24.95	6	2.875698	99.57939	0.864171	
6	7.66	75.68	25	6	2.960137	103.5628	0.862789	
7	7.08	75.72	24.84	6	2.879064	99.24295	0.860712	
8	6.92	75.55	24.74	6	2.856881	97.78156	0.857491	
9	8.03	66.82	25	6	2.921263	100.3297	0.854332	
10	6.42	85.48	25	6	2.851944	97.09682	0.854131	

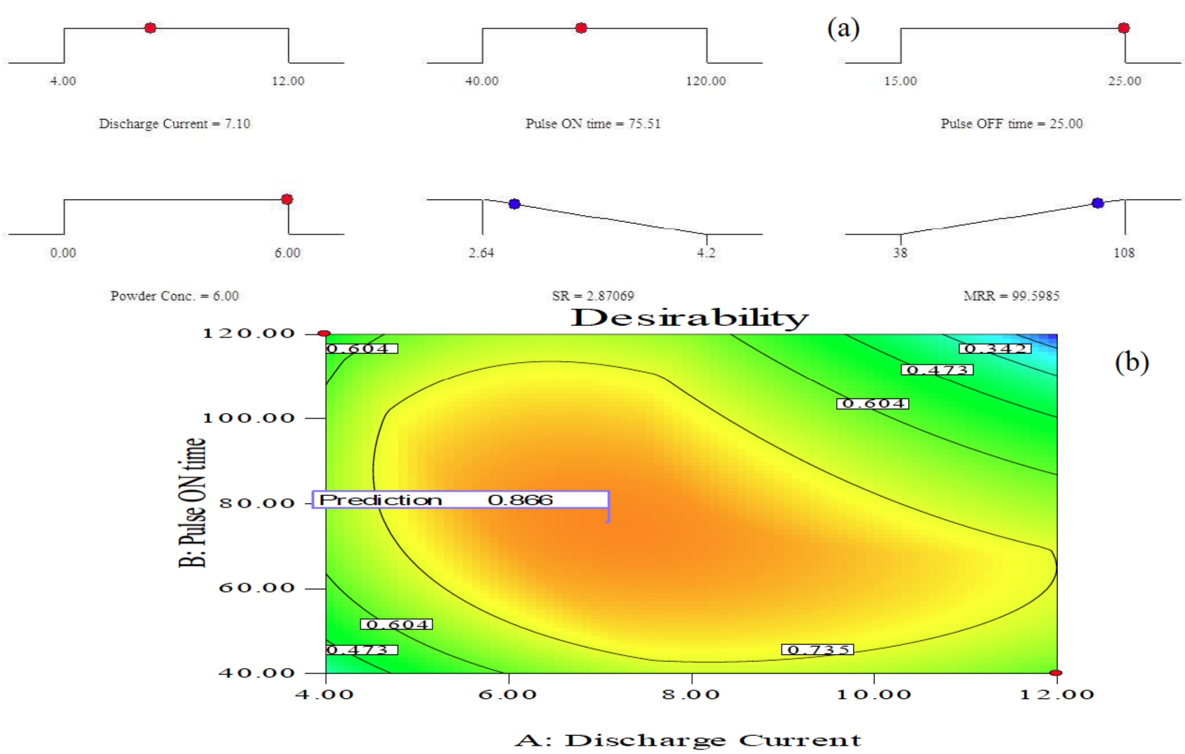


Figure 3: (**a**, **b**) Desirability Plots.

86.5% desirability using DC 7.1A, Pon 75.51 μs, Poff 25 μs and powder concentration 6 g/l. Figure **3b** shows the contour plot for desirability. This graph is used to select the values of input parameters to ensure the required desirability.

5. CONCLUSION

Current study deals with the effects of significant input parameters on SR and MRR with the help of RSM. Second order models of input parameters are developed and investigated that DC significantly affect the SR and MRR followed by the Pon.

Surface roughness has a direct relation to the Pon and DC and inversely proportional to the powder concentration and Poff. The lower value of surface roughness is achieved with DC = 4 A, Pon = 120 μs, Poff = 25 μs and powder concentration 6g/l within the experimental domain while maximum material removal rate can be achieved with DC = 8 A, Pon = 80 μs, Poff = 20 μs and powder concentration 6g/l.

For sustainable production both surface roughness and material removal rate assigned equal weights. In this case minimum surface roughness 2.8 μm and maximum material removal rate 99.5 g/min can be achieved with DC 7.1A, Pon 75.51 μs, Poff 25 μs and powder concentration 6 g/l. This research can also help researches for early prediction of surface roughness and material removal rate without experimenting with powder mix EDM process for Inconel 718.

NOMENCLATURE

DC = Discharge Current

Pon = Pulse on time

Poff = Pulse off time

SR = Surface roughness

MRR = Materail removal rtae

RSM = Response surface Methodology

EDM = Electric discharge machine

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