International Journal of Automotive and Mechanical Engineering
ISSN: 2229-8649 (Print); ISSN: 2180-1606 (Online)
Volume 15, Issue 2 pp. 5221-5237 June 2018

DOI: https://doi.org/10.15282/ijame.15.2.2018.6.0403

Effects of Machining Parameters on Performance Characteristics of Powder Mixed EDM of Inconel-800

S. Kumar[1*] and A. K. Dhingra[2]

[1]University Institute of Engineering & Technology, Maharshi Dayanand University, Rohtak-124001, Haryana, INDIA
[*]E-mail: itsarungarg@gmail.com
Phone: 09416741612
[2]Department of Mechanical Engineering, University Institute of Engineering & Technology, Maharshi Dayanand University, Rohtak-124001, Haryana, INDIA
Phone: 09541153059

ABSTRACT

This research work explores the connection of machining parameters, i.e. peak current (I_p), pulse on-time (T_{on}), pulse off-time (T_{off}), tool material (copper, copper-chromium, graphite) and powder particles (tungsten carbide, cobalt, boron carbide) on surface roughness (SR) for Inconel-800 superalloy in powder mixed electrical discharge machining process (PMEDM). The Box–Behnken design had been applied to design the experiments, and response surface methodology (RSM) was employed to cultivate the empirical models. Forty-six experiments were conducted as per Box-Behnken method of RSM. The results indicated that when current increases from 4 to 12 A, SR increases from 4.23 to 12.57 µm, while with the increase of T_{off} from 30 to 60 µs, SR decreased from 9.23 to 7.10 µm. Results also indicated that copper as a tool electrode and boron carbide as a powder additive has significantly effect on SR. The predicted results based on developed models are found to be in good agreement with the experimental results reasonably well with the coefficient of determination 0.96 for surface roughness. Furthermore, certain machined specimens were analyzed using energy-dispersive x-ray analysis (EDX) and scanning electron microscope (SEM) techniques.

Keywords: Powder mixed electrical discharge machining; Inconel-800; surface roughness; energy dispersive x-ray; surface cracks; crater.

INTRODUCTION

Inconel-800is an iron-nickel-chromium alloy having ample resistance to carburization and oxidation at elevated temperatures as well as moderate strength. It is especially advantageous for high-temperature equipment in the petrochemical industry, heat exchangers, furnace components and electric range heating-element sheathing. The unique properties of the Inconel-800 contain the power to keep high strength and outstanding surface stability. Machining of such material is very difficult using conventional methods of machining because of these characteristics and the machining can be easily done by using different non-conventional machining techniques.

In this frame, electrical discharge machining (EDM) is unitary of non-conventional machining method that can be well used for the machining of complex geometrical form [1]. In spite of the capability to the machine fundamentally any electrically conductive material, the applications of EDM is barred to a few industries,

due to poor productivity and surface quality of machined components. In the past few years, researchers have advanced new modifications to EDM for improving its performance [2, 3]. PMEDM has one of the progressivemethods in the flank of the augmentation of the capabilities of EDM. In this process,a fine powder of appropriate material is mixed into the EDM oil so that the spark gap is filledup with additive conductive particles. The electrically conductive additive particles detract the insulating vigor of the dielectric fluid so that the process becomes more static and thus reforming themachining rate and surface finish by Gudur et al. [4].Before actual experimentation, Pilot experimentation was carried out by using one factor at a time approach for the selection of input process parameters and their levels i.e. current, pulse on-time, pulse off-time. Design of experiments analysis has been carried out by using RSM approach. After that analyzed the results for different composition of powder based dielectric and effect of different composition were studied on the different response parameters considered. The surface integrity of machined surfaces will be analyzed through scanning electron microscope (SEM), and Energy dispersive spectrography (EDS).

Compared the EDM characteristics, i.e. SR and material removal rate obtained by using kerosene dielectric and mixtures of deionized water with abrasive powder and concluded that aluminum as a powder additive improved the surface roughness as compared to other powder additives[5]. Uno et al. [6], added nickel as a powder additive in the EDM oil while performing the experiments on aluminum bronze work specimen andobtained a good surface finish as compared to conventional EDM. Wu et al. [7], mixed aluminum powder in the EDM oil and reported that a more apparent discharge distribution effect which resulted in an SR value of less than 0.2 μm.Tzeng and Chen. [8],conducted experiments on SKD-11 steel with chromium, aluminum,siliconcarbide and copperpowders and found that aluminum powder provide the best surface finish followed bychromium, whereas copper powder produced the worst surface characteristics. Powder additive properties such as density, thermalconductivity and electrical resistivity impressed the performance.Klocke et al. [9], compared the performance of standard dielectric EDM with aluminum powder-mixed dielectric and found that a larger plasma channel in contrast to the standard dielectric. Zhao et al. [10] performed the experiments on powder-mixed EDM for the response, i.e. machining effectiveness and SR. Reported that powder-mixed EDM clearly improved the responses as compared with conventional EDM. Talla et al. [3], investigated the influence of various powders (aluminum, graphite, silicon) suspended dielectrics and machining parameters on EDM characteristics of Inconel-625. Found that powder properties play a vital role in changing the machining performance and the quality of the machined surface. Among the three powders, silicon powder has a significant effect on surface finish and a least radial overcoat. Kumar [11] and Kumar et al. [12], developed mirror-like surface finish on the surface of AISI-D2 die steel by EDM using carbon nanotubes (CNTs). To analyse the surface characteristics of AISI-D2 die steel, carbon nanotubes are mixed in the EDM oil in defining proportions. Results indicated that the suitable addition of CNTs into EDM oil hikes the machining rate and reduction in SR. Jabbaripour et al. [13] used four levels of current and three levels of on time in their study. The graph is plotted between four points and three points for the output characteristics.

Literature review indicated that a very limited work has been reported on the machining of Inconel-800 with powder particles,i.e. tungsten carbide, cobalt and boron carbide. Also, the effect of tool material, i.e. copper, copper-chromium, and graphite on Inconel-800 material has not been explored. The aim of the present study is to

investigate the effect of tool material along with powder particles mixed in EDM oil on surface characteristics for Inconel-800 material.

EXPERIMENTAL PROCEDURE

Materials

The material used for the experiments was Inconel-800. Samples were rectangular type with dimensions of 150×15×6 mm. The chemical composition of work specimen and tool electrode as shown in Table 1, while mechanical properties of Inconel-800 material as shown inTable 2.

Sanjeev et al. [12], found that copper, copper-chromium has a high melting point and high electrical conductivity. Khazraji et al. [14], reported that graphite is also most widely applied because of its wide industrial applications. Therefore, copper, copper-chromium and graphite were selected as tool electrodes with ø 12 mm and 40 mm length. The tool electrodes of copper-chromium, graphite and copper as shown in Figure 1 (a), (b) and (c) while the workpiece specimen after machining is shown in Figure 1 (d).

Table 1. Chemical composition of work specimen and tool electrode material.

Work material		Electrode material	
Elements	Inconel-800	Copper	Copper- chromium
Ni	Base material	0.0083	0.0104
Fe	39.5	0.109	0.0319
Cu	< 0.75	99.7	98.4
Si	< 1	< 0.0050	< 0.0050
Cr	20.5	0.0061	1.36
Al	_	< 0.0020	< 0.0020
S	< 0.015	< 0.0020	< 0.0020
Bi	_	< 0.0050	< 0.0050
Sb	_	< 0.0050	0.0072
Zn	_	0.0148	< 0.0050
Pb	_	0.0206	0.0118
Sn	_	0.0356	< 0.0050
Mn	_	0.005	0.006

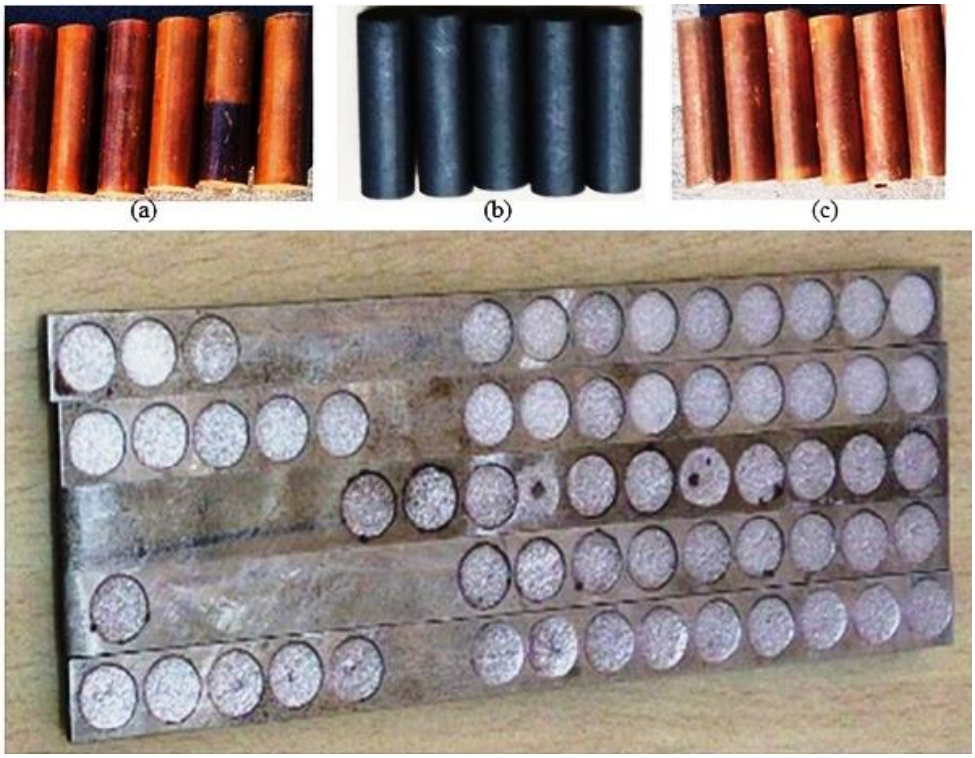
Table 2. Mechanical properties of Inconel-800.

Density	Melting Point	Yield strength	Tensile Strength	Elongation
7.94 g/cm^3	1385 °C	205- MPa	520- MPa	30%

Process Parameters

There are a large number of input process parameters to be considered within the EDM process for determining the optimal process parameters. Considering the related studies, it was concluded that process parameters such as discharge current, T_{on}, T_{off}, electrodematerial and powder concentration have a clear influence on the EDM performance [13]. Before performing the main EDM tests, pilot experiments have been

done. The pilot experiments were completed with the addition of tungsten carbide, cobalt and boron carbide powder ranging from 1 to 20 g/l into the dielectric fluid to study the effect of SR [15, 16].



(d)

Figure 1. Tool electrodes of (a) copper-chromium, (b) graphite and;(c) copper. (d) Inconel-800 workpiecesafter machining.

It was observed that at 6 g/l tungsten carbide, cobalt and boron carbide powder concentration resulted better in SR. Hence, for main experimentation, the powder concentration is selected at 6 g/l. The range selected for the discharge current, T_{on} and T_{off} is based on pilot experiments and literature. In this study, these three main EDM parameters were selected as input parameters along with tool material (copper, copper-chromium, graphite) and powder particles (tungsten carbide, cobalt and boron carbide). So total five input parameters were selected and the level of each parameter was three. The working range of the input parameters and their level is shown in Table 3.

Table 3. Input parameters and their levels.

Input factors		Current, *Ip* (A)	Pulse on-time, T_{on} (µs)	Pulse off-time, T_{off} (µs)	Tool material	Powder (g) (Suspended particles)
Symbol		A	B	C	D	E
Level	I	4	60	30	Copper	Tungsten-carbide
	II	8	90	45	Copper-chromium	Cobalt
	III	12	120	60	Graphite	Boron-Carbide

Experimental Setup

A series of experiments were conducted on a die sinking EDM machine (Model OSCARMAX S 645) at the Central Institute of Hand Tools, Jalandhar-Punjab-INDIA. The EDM machine set-up and powder mixing system for EDM is as shown in Figure 2 (a) and (b). The work specimen was firmly clamped in the vice and absorbed in EDM oil. In this experimental study, spark erosion 450EDM oil was used as a dielectric fluid because of its high dielectric strength, high flash point and less surface tension. Forty-six experiments is as shown in Table 4.

The experiments were conducted as per RSM methodology. In each experiment a hole is machined to a depth of 0.5 mm. Before machining, the work specimen and electrodes were cleaned with acetone and bright with emery papers. Positive polarity was used during the experiments as recommended in [2, 21].

(a) (b)

Figure 2. Experimental setup for(a) EDM machining and; (b) Powder mixing system.

Table 4. Design of experiments.

Run	Current (A)	T_{on} (µs)	T_{off} (µs)	Tool Material	Powder
1	4	90	60	Cu-Cr	Co
2	8	90	45	Cu-Cr	Co
3	8	90	60	Gr	BC
4	8	90	45	Cu	WC
5	8	90	30	Cu-Cr	BC
6	8	120	30	Cu-Cr	Co
7	8	90	60	Cu-Cr	BC
8	8	90	60	Cu	Co
9	4	90	45	Cu	Co
10	8	90	45	Cu-Cr	Co
11	8	90	45	Cu-Cr	Co
12	8	90	45	Gr	WC
13	8	90	30	Gr	Co
14	12	90	30	Cu-Cr	Co
15	8	90	30	Cu	Co
16	12	90	45	Cu-Cr	BC

17	12	90	60	Cu-Cr	Co
18	8	120	45	Cu-Cr	WC
19	4	90	45	Gr	Co
20	12	90	45	Gr	Co
21	8	120	60	Cu-Cr	Co
22	4	90	45	Cu-Cr	BC
23	8	90	45	Gr	BC
24	8	120	45	Cu	Co
25	12	60	45	Cu-Cr	Co
26	8	90	45	Cu-Cr	Co
27	8	90	60	Cu-Cr	WC
28	4	90	30	Cu-Cr	Co
29	12	90	45	Cu	Co
30	4	120	45	Cu-Cr	Co
31	8	120	60	Cu-Cr	Co
32	12	90	45	Cu-Cr	WC
33	8	90	45	Cu	BC
34	8	90	45	Cu-Cr	Co
35	8	60	45	Cu-Cr	WC
36	12	120	45	Cu-Cr	Co
37	8	120	45	Gr	Co
38	8	120	45	Cu-Cr	BC
39	8	90	45	Cu-Cr	Co
40	8	90	30	Cu-Cr	WC
41	8	60	60	Cu-Cr	Co
42	4	60	45	Cu-Cr	Co
43	8	60	45	Cu-Cr	BC
44	8	60	45	Gr	Co
45	8	60	45	Cu	Co
46	4	90	45	Cu-Cr	WC

RESULTS AND DISCUSSION

Determination of Main Effects on Surface Roughness

Table 5 shows the result of the experiments to be conducted as per the RSM methodology. Equation (3) and (4) shows the connection between machining parameters and response in coded as well as in actual form respectively. According to analysis of variance (ANOVA) as shown in Table 6 (before elimination) factors A, C, D, E and two interactions factor AC and CE, i.e. discharge current, T_{off}, tool material, powder particles and interaction ($I_p \times T_{off,}$ T_{off} × powder particles) are significant for surface roughness. The p value for lack offit is 0.2909 indicating that this model sufficiently fits the data.

The "Pred R-Squared" of 0.93 is in proper contract with the "Adj R-Squared" of 0.96. "AdeqPrecision" measures the signal to noise ratio. To fit the quadratic model for SR suitable, non vital terms was removed by backward elimination.The backward elimination procedure is applied to get rid of the non-vital terms so that the quadratic model to be fit.Reduced model for SR is as shown in Table 7. After backward

elimination, the results indicate that the model is validated having R-Squared and Adjusted R-Squared as 97 % and 96 %, respectively.

From the maineffect plots based on Figure 3 (a), it has been found thatwhenever current was increased from 4 to 12 A,the SRhikes significantly.The increment of SR was approximately from 4.23 to 12.57 µm. When T_{off} reduced from 60 to 30 µs, itshowed themost significant effect on SR i.e., from 7.10 to9.23 µm as shown in Figure 3 (c).The same trend was observedby [22,23]. As for pulse on-time, a slight increment of surface roughness occurred when pulse on-time was hiked from 60 to 120 µs with 9.19 to 10.19 µm as shown in Figure 3 (b).

Table 5. Surface roughness of samples after experimentation.

Run no.	1	2	3	4	5	6	7	8	9	10
R-1	3.50	9.92	6.45	8.89	9.16	9.16	5.90	6.88	3.01	8.72
R-2	4.59	9.92	6.48	7.89	11.21	9.45	6.11	6.78	3.91	8.72
R-3	3.51	7.17	5.08	7.29	9.36	9.67	5.11	6.14	4.78	8.94
Mean Value	3.87	9.00	6.00	8.02	9.91	9.43	5.71	6.60	3.90	8.79
Run no.	11	12	13	14	15	16	17	18	19	20
R-1	8.70	10.33	10.68	13.71	6.71	10.39	9.48	11.66	4.15	13.42
R-2	8.76	10.38	10.70	13.70	7.10	10.19	9.48	10.56	3.10	13.60
R-3	9.21	11.51	11.59	13.26	7.20	9.22	8.05	10.57	3.28	13.63
Mean Value	8.89	10.74	10.99	13.56	7.00	9.93	9.00	10.91	3.51	13.55
Run no.	21	22	23	24	25	26	27	28	29	30
R-1	9.16	3.54	7.89	9.07	12.06	10.32	8.71	3.25	10.52	4.33
R-2	9.10	3.70	7.88	8.42	13.50	10.32	8.84	3.07	9.70	4.56
R-3	8.15	3.71	7.89	8.63	13.66	9.34	8.87	2.68	10.80	4.57
Mean Value	8.80	3.65	7.89	8.71	13.07	9.99	8.81	3.00	10.34	4.49
Run no.	31	32	33	34	35	36	37	38	39	40
R-1	8.99	14.05	8.19	10.09	10.40	15.03	10.71	10.56	8.71	8.38
R-2	8.61	13.98	8.01	9.31	10.03	14.09	10.03	9.35	9.46	8.28
R-3	9.65	14.99	8.51	9.38	10.04	14.10	9.03	9.60	8.81	7.23
Mean Value	9.08	14.34	8.23	9.59	10.16	14.41	9.92	9.84	8.99	7.96
Run no.	41	42	43	44	45	46				
R-1	5.90	4.05	8.57	10.64	7.97	5.88				
R-2	6.01	3.80	7.49	9.60	7.09	5.01				
R-3	6.10	4.44	7.69	9.09	7.35	4.03				
Mean Value	6.00	4.09	7.92	9.78	7.47	4.97				

$$Ra=+9.18+4.17\times A+0.50\times B-1.06\times C+0.76\times D-0.80\times A^2+0.49\times B^2-1.04\times C^2 -0.55\times D^2-1.36\times A\times E+0.90\times B\times C-1.15\times C\times D-1.26\times C\times E-0.77\times D\times E \quad (3)$$

$$Ra=-5.69+2.86\times current -0.17\times T_{on}+0.34\times T_{off}+2.39\times tool+4.52\times powder -0.50\times current^2+5.44E\text{-}4\times T_{on}^2-4.61E\text{-}3\times T_{off}^2-0.55\times tool^2-0.022\times current\times T_{off} \quad (4)$$

+0.22×current×tool-0.19×current×powder+1.99E-3×T_{on}×T_{off}-0.77×T_{off}×tool
-0.08×T_{off}×powder-0.76×T_{off}×tool-0.08×T_{off}×powder-0.76×tool×powder

Table 6. Analysis of variance for surface roughness (before elimination).

Source	Sum of Squares	DF	Mean Square	F-Value	Prob > F	
Model	370.04	20	18.5	65.45	< 0.0001	significant
A	278.13	1	278.13	983.9	< 0.0001	
B	3.59	1	3.59	12.72	0.0015	
C	16.28	1	16.28	57.59	< 0.0001	
D	9.14	1	9.14	32.34	< 0.0001	
E	10.31	1	10.31	36.47	< 0.0001	
A2	5.75	1	5.75	20.36	0.0001	
B2	1.97	1	1.97	6.97	0.0141	
C2	9.4	1	9.4	33.28	< 0.0001	
D2	2.78	1	2.78	9.84	0.0043	
E2	0.01	1	0.01	0.04	0.834	
AB	0.22	1	0.22	0.78	0.3851	
AC	7.35	1	7.35	26.01	< 0.0001	
AD	3.24	1	3.24	11.48	0.0023	
AE	2.38	1	2.38	8.42	0.0076	
BC	2.78	1	2.78	9.85	0.0043	
BD	0.29	1	0.29	1.05	0.3143	
BE	0.33	1	0.33	1.19	0.2857	
CD	5.25	1	5.25	18.59	0.0002	
CE	6.36	1	6.36	22.5	< 0.0001	
DE	2.34	1	2.34	8.3	0.008	
Residual	7.06	25	0.28			
Lack of Fit	5.9	19	0.31	1.6	0.2909	Not significant
Pure Error	1.16	6	0.1938806			
Cor Total	377.11	45				
R^2	0.98		Pred. R^2	0.93		
Adj. R^2	0.96		Adeq. Precision	31.21		

Table 7. Analysis of variance for surface roughness (after elimination).

Source	Sum of Squares	DF	Mean Square	F-Value	Prob > F	
Model	369.17	16	23.07	84.32	< 0.0001	significant
A	278.13	1	278.13	1016.47	< 0.0001	
B	3.61	1	3.61	13.21	0.0011	
C	16.26	1	16.26	59.45	< 0.0001	
D	9.14	1	9.14	33.41	< 0.0001	
E	10.31	1	10.31	37.68	< 0.0001	
A2	6.06	1	6.06	22.16	< 0.0001	
B2	2.2	1	2.2	8.06	0.0082	
C2	9.91	1	9.91	36.22	< 0.0001	

D2	2.89	1	2.89	10.59	0.0029	
AC	7.35	1	7.35	26.87	< 0.0001	
AD	3.24	1	3.24	11.86	0.0018	
AE	2.38	1	2.38	8.7	0.0062	
BC	2.78	1	2.78	10.16	0.0034	
CD	5.25	1	5.25	19.2	0.0001	
CE	6.36	1	6.36	23.24	< 0.0001	
DE	2.34	1	2.34	8.57	0.0066	
Residual	7.93	29	0.27			
Lack of Fit	6.77	23	0.29	1.51	0.3166	Not significant
Pure Error	1.16	6	0.19			
Cor Total	377.11	45				
R^2	0.97		Pred. R^2	0.94		
Adj. R^2	0.96		Adeq. Precision	35.35		

From Figure 3 (d), it is clear that among the three tool electrode material, copper has significantly effected on SR, while among the three powder particles, boron carbide has a significant effect on the SR as illustrated in Figure 3 (e). With the use of tungsten carbide as a powder particle, surface roughness was 9.98 µm, while with boron carbide surface roughness was 8.37 µm. With the increase of current, longer the spark is sustained and more material is removed from the work specimen. Therefore craters formed on the surface will be deeper, resulting an increase in SR.In order to obtain better SR during PMEDM of Inconel-800, the optimum parametercombination obtained is current at 4 A, T_{on}= 90 µs, T_{off}= 60 µs, copper as a tool electrode material and boron carbide as a suspended powder.

Figure 3 (f) shows the perturbation plot to compare the effect of all the facts at a specific point in the design area. Basically, it provides silhouette views of the response surface. Factor A, C, D and E show the slope means the response is sensitive to that factor.In addition to this normal plot of residuals and residual versus predicted plots have also been drawn. The data are normally distributed as shown in Figure 4 (a). It has also been observed from Figure 4 (b) that all the experimental results are nearly very close to expected values.

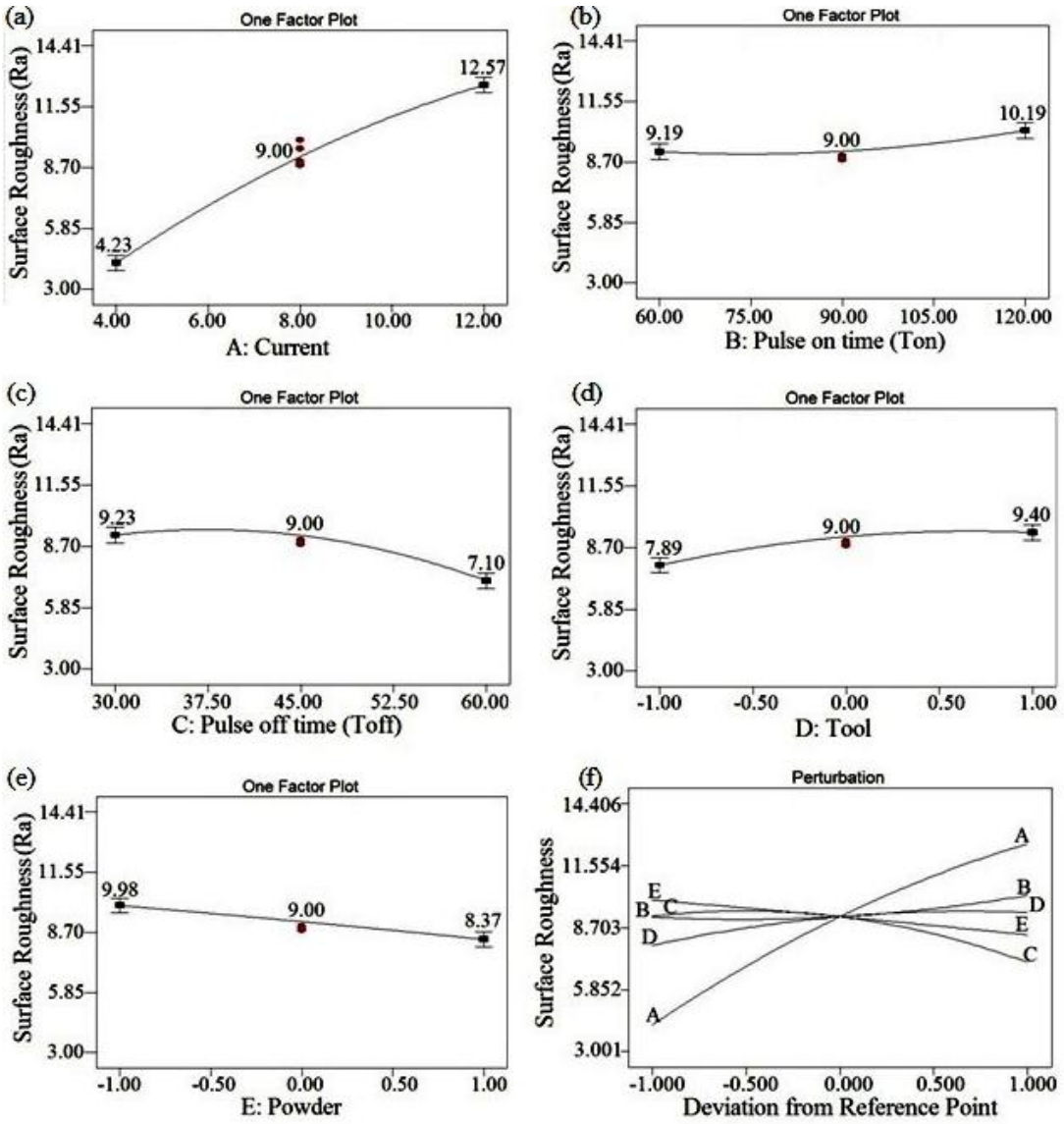


Figure 3. One factor plots for surface roughness.

Determination of Interaction Effects on Surface Roughness

Based on Table 5, there are two interactions have been involved (I_p× T_{off}, T_{off} × powder particles) as shown in Figure 4 (c) and (d). The "Prob>F" value of both interactions, i.e. I_p× T_{off} and T_{off} × powder particles are <0.0001. It is clear from the Figure 4 (c) that when current increased from 4 to 12 A and T_{off} vary from 30 to 60 µs then SR hiked from 2.88 to11.17µm.

When current increased from 4 to 12 A along with boron carbide as a powder additive surface roughness vary from 4.15 to 8.40 µm, while along with tungsten carbide as a powder additive; it is changed from 4.15 to 11.61 µm as shown in Figure 4 (d). The SR increased when peak current increased along with pulse on-time due to the longer time for machining the work specimen.

The interaction graph between current and powder particles are as shown in Figure 4 (e). It is clear from the Figure 4 that with the same value of current, powder

particles has more effect on SR. The same effect is observed for the contour plot of current and powder as shown in Figure 4 (f).

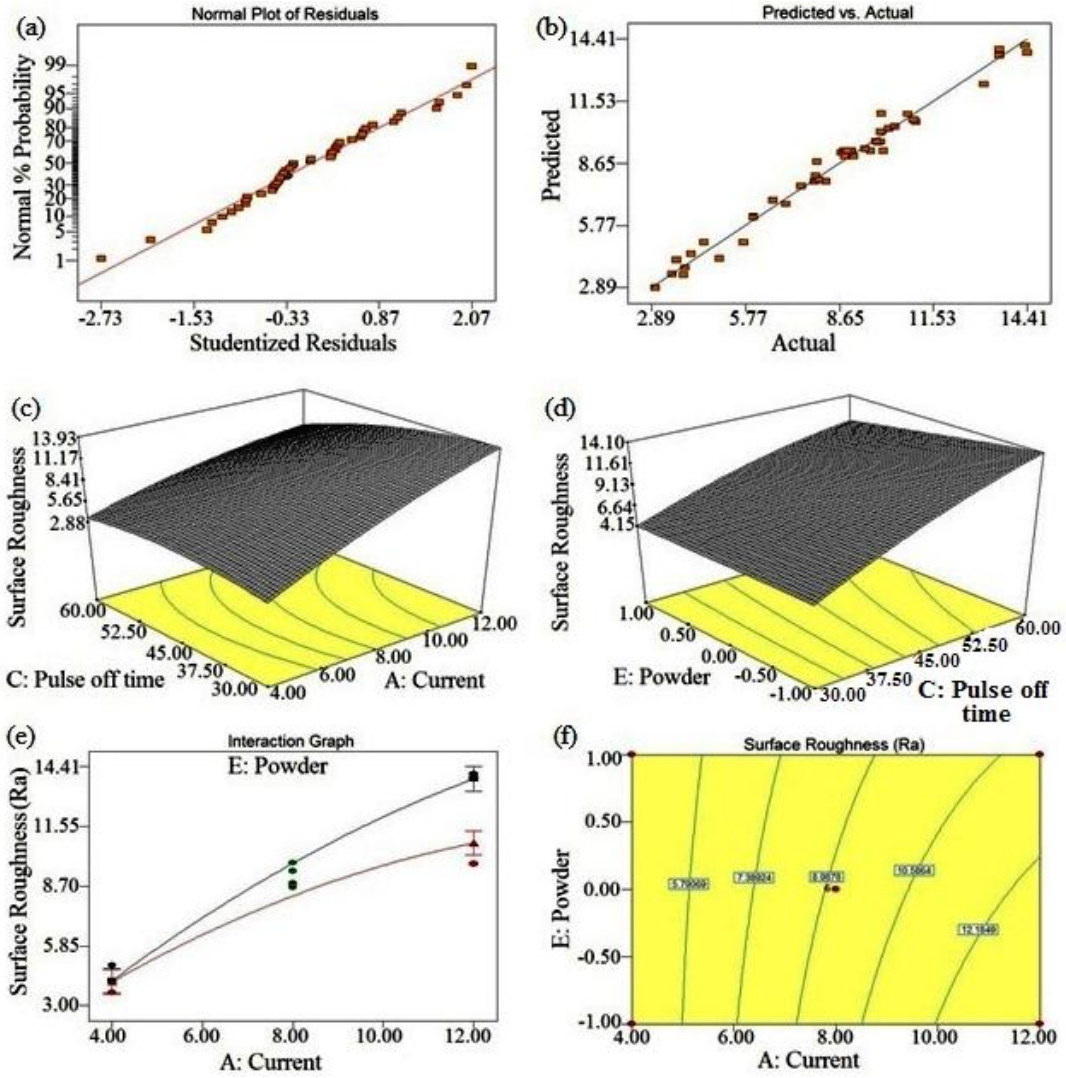


Figure 4. Response surface plots: (a) normal probability residual plot; (b) predicted v/s actual plot; (c), (d), 3D surface plot for SR; (e) interaction plot for SR and (f) contour plot for SR.

Microstructure Analysis

After PMEDM operations, surfaces of Inconel-800 has major microstructural changes after PMEDM. The characteristics of machined surface are represented by the formation of surface cracks, metallurgical changes on the machined surface. Current, T_{on}, electrode polarity, electrode, workpiece material and powder mixed dielectric medium are the main factors which are accountable for affecting the surface quality of the machined specimen during the machining with EDM [1],[24]. For the intent of scrutiny, three trials for current setting, namely (i) 4A, (ii) 8A and (iii) 12A along with three different tool materials and three powder particles, were analyzed in detail.

SEM micrograph of Inconel-800 machined with 8A current, 90µs T_{on}, 60µs T_{off}, graphite as a tool material and boron carbide as a powder additive in the EDM oil as

illustrated in Figure 5(a), (d) and (g) along with the magnification of 500×, 2000× and 5000× respectively. The Figure 5 (a) shows the formation of debris, crater and fragments, but with higher magnification, subsurface cracks with debris and deep cracks can be noticed on the surface as illustrated in Figure 5 (d) and (g). Figure 5 (b, e and h) shows the micrographs with the machining condition at 12A current, 60 μs T_{on}, 45 μs $T_{off,}$ graphite as a tool material and cobalt as a powder additive in the dielectric fluid. Micro cracks along with debris and crater are shown in Figure 5 (b). With the critical examination of highly magnified images, surface cracks and deep cracks were noticed on the surface as shown in Figure 5 (e) and (h). Figure 5 (c), (f) and (i) shows the micrographs with the machining condition at 4 A current, 90 μs T_{on}, 45 μs $T_{off,}$ copper-chromium as a tool material and tungsten carbide as a powder additive in the dielectric fluid. Micro-cracks, material pull out and debris were noticed on the surface as shown in Figure 5 (c) but with higher magnification surface and deep cracks can be noticed on the surface as shown in Figure 5 (f) and (i). The micro graphs presented in these figures exposed that surface maybe caused by an unequal fusing structure, micro cracks, pock marks, craters, globules of debris, sub surface cracks and fragments. It was noticed from Figure 5 (a), (b), (d), (e), (g) and (h) that PMEDM surface produceslarge uneven topography and defects included debris, fragments, deepcraters, pockmarks, surface cracks, sub-surface crack and micro-crackswhen compared with Figure 5 (c), (f) and (i).

The peak current is the most vital parameter thatis responsible for deterioration of the surface texture. This is due to the reason that with the hike of current high discharge energy is transferred to the machining area, so that melting and evaporation take place, resulting in the formation of a small crater [15]. Also, deep craters were formed by the successive electrical discharge and vaporized the work specimen [25]. The results of this study agree with [24].

EDX Analysis

With the continuous flow of dielectric fluid, the metal particles coming from electrode to workpiece are flushed out. Some material particles are left on the machined specimen surface because of the particles that cannot be transported completely of the discharge gap. The output of EDX analysis is a plot of how frequently an X-ray is received in each energy level [26]. EDX results show the improved quality and quantity values of elemental composition of the Inconel-800 work piece. Figure 6 (a) and (b) compares the EDX pattern of before and after machining samples, in order to investigate the chemical composition.

Before PMEDM machining, the weight percentage of elements are C= 12.33, O= 2.1, Cr= 17.16, Fe= 41.48 and Ni= 26.93 as shown in Figure 6 (a). With PMEDM at different machining conditions, weight, the percentage of element changes to C= 12.33 to 19.12, O= 2.1 to 3.93, Cr= 17.16 to 16.64, Fe= 41.48 to 37.95 and Ni= 26.93 to 22.36 as illustrated in Figure 6(b). The hike in the percentage of oxygen in Inconel-800 probably was due to oxidation as a result of high temperature involved in the process. Also, when graphite as a tool electrode along with boron carbide powder (concentration) is added into the EDM oil, there was an increase in the carbon content and during the machining process this carbon dissolves in the EDM oil and on the metal surface.

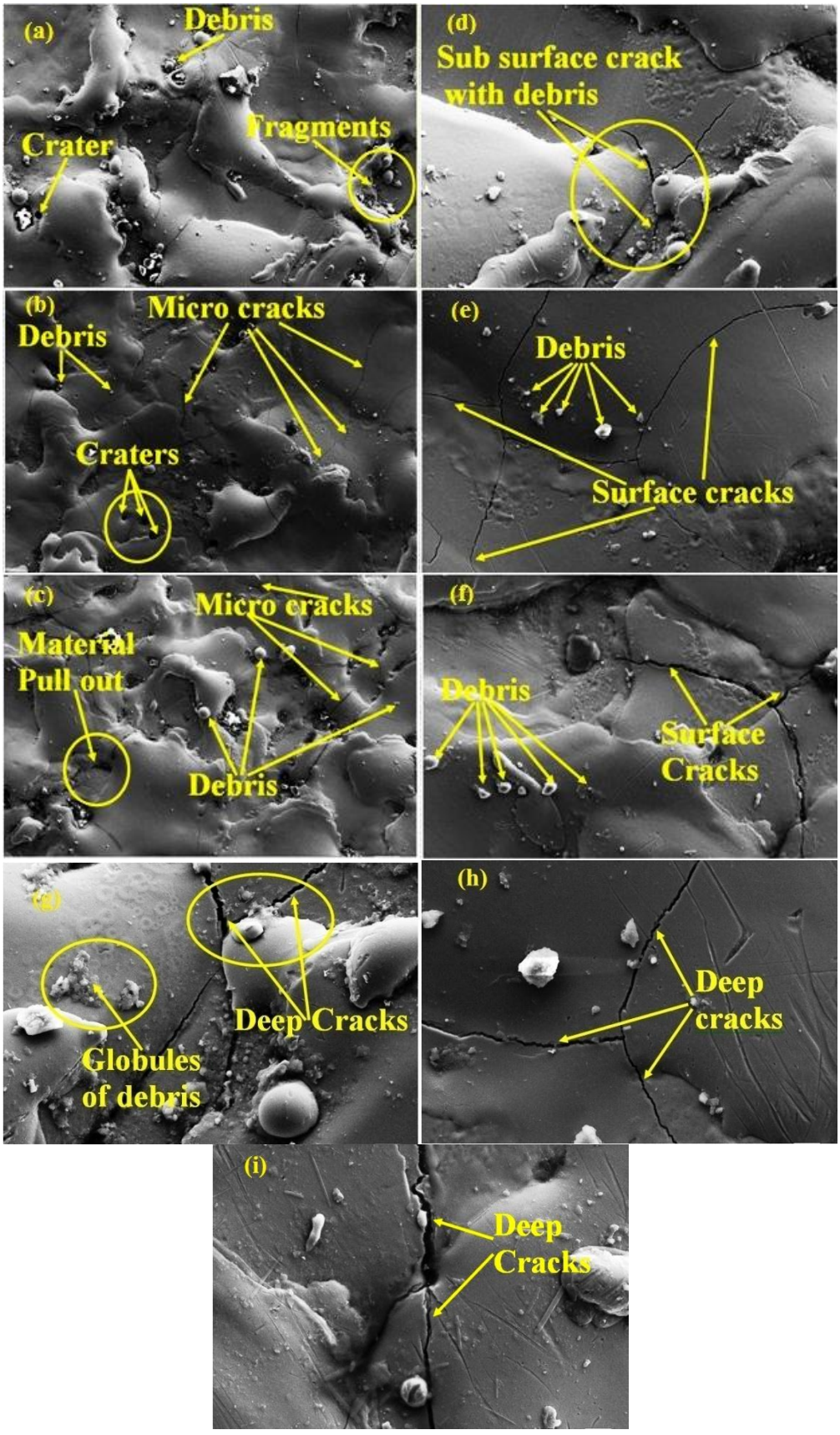
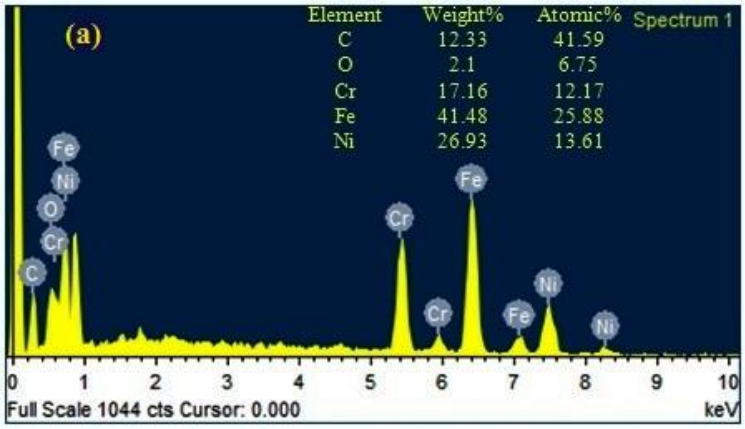
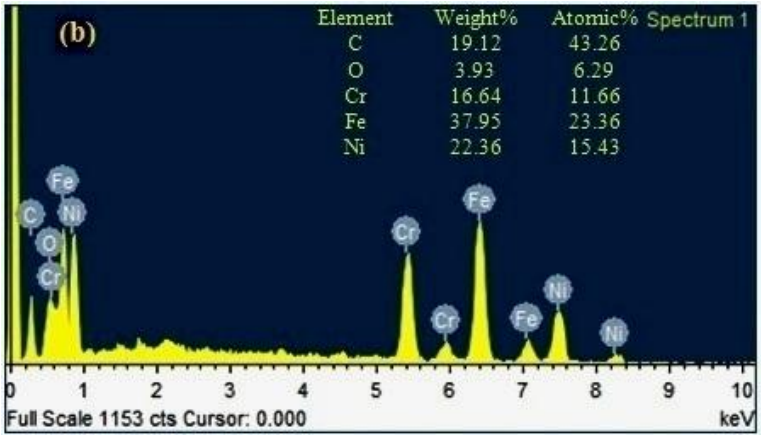


Figure 5. SEM micrographs of samples from run no. (a),(d) 3, (b),(e) 44, (c),(f) 46, (g) 3, (h) 44 and; (i) 46.



(a) before machining.



(b) after machining

Figure 6. EDX analysis of Inconel-800.

CONFIRMATION EXPERIMENT

Three confirmation experiment has been performed for surface roughness. For the confirmation test, values of selected process variables lie in the ranges for which the formula was derived [16]. The data for the confirmation run and predicted designed for SR is shown in Table 8 and found that the calculated error is small. The error between experimental and expected values for SR is lying within -8.55% to 5.1%, respectively. Obviously, this confirms the superior reproducibility of the experimental outcomes.

Table 8. Conformation test.

	Machining Conditions					Surface Roughness (µm)		
Sample	Current (A)	T_{on}, B (µs)	T_{off}, C (µs)	Tool material, D	Powder, E	Exp. value	Pred. value	Error (%)
1	4	60	45	Cu-Cr	Co	4.09	4.44	-8.55
2	8	90	45	Cu	BC	8.23	7.81	5.1
3	12	90	45	Cu-Cr	WC	14.34	14.1	1.67

CONCLUSION

The quadratic model for SR has been developed to correlate the machining process variables: current, T_{on}, T_{off}, tool electrode and powder particles, in the PMEDM process of Inconel-800.To perform experimental work, a Box-Behnken method of RSM has been applied. Based on experimental study, results indicated that SR obtained was ranged from 4.23 µm to 12.57 µm.The SR was most significantly affected by current, T_{off}, tool material and powder particles. The minimum SR was obtained, when the parameters are set as Ip = 4 amp, T_{on} = 60 µs, T_{off} = 60 µs, tool material as a copper and boron-carbide as a powder particles. Surface roughness improves when T_{off}, copper as a tool electrode and boron carbide is used as a powder particle while SR increased with the increase of current. T_{on} has little bit effect on SR. The co-efficient of regression R^2, adj. R^2 and predicted R^2 obtained for the developed surface roughness is 0.98, 0.96 and 0.93. "PredR^2" of 0.93 is in an acceptable contract with the "Adj R^2" of 0.96. The confirmation test showed that the error between the expected and experimental value of SR is -8.55% to 5.1%, respectively. This confirms validation of results for predicted values and experimental values. It was noticed from the SEM micrographs of machined surfaces that peak current affects the surface structure of machined samples resulting in formation of micro cracks, craters, pockmarks and debris. At lower current and higher T_{off} better surface characteristics may be obtained.

ACKNOWLEDGEMENT

The authors would like to be obliged to Assistant Director, Central Institute of Hand Tools, Jalandhar, Punjab, India, for providing the EDM set-up.

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