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On Electro Discharge Machining of Inconel 718 with Hollow Tool

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Inconel 718 is a nickel-based alloy designed for high yield, tensile, and creep-rupture properties. This alloy has been widely used in jet engines and high-speed airframe parts in aeronautic application. In this study, electric discharge machining (EDM) process was used for machining commercially available Inconel 718. A copper electrode with 99.9% purity having tubular cross section was employed to machine holes of 20 mm height and 12 mm diameter on Inconel 718 workpieces. Experiments were planned using response surface methodology (RSM). Effects of five major process parameters—pulse current, duty factor, sensitivity control, gap control, and flushing pressure on the process responses—material removal rate (MRR) and surface roughness (SR) have been discussed. Mathematical models for MRR and SR have been developed using analysis of variance. Influences of process parameters on tool wear and tool geometry have been presented with the help of scanning electron microscope (SEM) micrographs. Analysis shows significant interaction effect of pulse current and duty factor on MRR yielding a wide range from 14.4 to 22.6 mm^3/min, while pulse current remains the most contributing factor with approximate changes in the MRR and SR of 48 and 37%, respectively, corresponding to the extreme values considered. Interactions of duty factor and flushing pressure yield a minimum surface roughness of 6.2 µm. The thickness of the sputtered layer and the crack length were found to be functions of pulse current. The hollow tool gets worn out on both the outer and the inner edges owing to spark erosion as well as abrasion due to flow of debris.

Keywords EDM, hollow tool, Inconel 718, material removal rate, process parameters, surface roughness, tool wear

1. Introduction

Processing of super alloys has been an active area of research owing to the increasing demand of this class of material and typical problems associated with their processing. Inconel 718 is a nickel-based high strength and high thermal resistance super alloy. Due to its high creep-rupture strength and high fatigue endurance limit, Inconel 718 is widely used in gas turbines, rocket engines (including the space shuttle application), spacecraft structural components, and also in nuclear power plant components, such as reactor and pump. This alloy is characteristically difficult to machine due to its poor thermal properties, high toughness, high hardness, and high work hardening rate. The presence of highly abrasive carbide particles in the microstructure and its strong tendency get to welded to the tool to form built up edge pose considerable processing difficulties (Ref 1). Further, its low thermal conductivity results in heat concentration in the cutting zone making it ineffective to be processed through conventional machining (Ref 2). In order to overcome such limitations, usually, a nonconventional machining method like electric discharge machining (EDM) is chosen for machining Inconel 718.

Electro discharge machining is a nonconventional machining process extensively used in industry for processing of difficult-to-machine materials and parts having unusual profiles with reasonable precision. At present, EDM is a widely accepted machining technique used for all types of conductive materials including metals, metallic alloys, graphite, composites, and selected ceramic materials. The EDM processing is widely employed in die and mold-making industry to generate complex cavities. Examples include precision machining of hardened steels, carbides, and ceramic materials. However, research attention was mainly focussed on the work material issues rather than the tools used. The EDM tools, on the other hand, experience various phenomena including sputter coating and erosion. Marafona and Wykes (Ref 3) reported that while machining D2 tool steel with copper-tungsten electrodes at low current intensity and long pulse duration, a layer of carbon was deposited on the tool leading to reversal in tool wear. Further, it was suggested that to improve material removal rate with nominal increase in tool wear rate (TWR), a high current intensity can be used. Analysis also showed that the deposits contained carbon and steel elements such as iron and chromium. It was likely that the carbon came from the dielectric medium. Shankar et al. (Ref 4) have reported that copper and aluminum electrodes yield the best MRR with an increase in discharge current, followed by copper-tungsten electrodes. Brass does not indicate significant increase in MRR with the increase in discharge current while EDMing of EN-31 materials. Payal et al. (Ref 5) have also demonstrated that copper electrode shows good response to MRR toward the high value discharge current while brass shows good surface finish. The authors showed that the graphite electrode results better MRR

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at lower pulse current, however, MRR decreases with high pulse current. Khan (Ref 6) has investigated the MRR while machining the aluminum and steel with the copper and brass tools. It was reported that at lower pulse current, the MRR is low and increases with high pulse current; also the brass electrode yields better MRR while machining aluminum than machining steel with copper electrode. In an attempt to enhance MRR, planetary (helix) mode tool motion was also introduced. Motion at high frequency even at low pulse current was found to enhance the MRR (Ref 7). In a quest for enhancing MRR in EDM, it was found that the duty factor is of the important parameters in EDM process that has considerable influence on MRR. Duty factor is a ratio of pulse on-time and total cycle time. It was reported by many authors that higher duty factor results in higher MRR (Ref 8-10).

The quality of the EDMed surface is also influenced by the thin resolidified layer of the ablated particles of the work and the tool material. The work materials in EDM inevitably experience re-solidification due to cooling by dielectric fluid. The re-solidified layer is a mix of elements of dielectric fluid, melting workpiece, and melting electrode. Post-machining, this layer forms a recast structure on the machined surface that results in deteriorated surface quality. Barash and Kahlon (Ref 11) reported that when mild steel was eroded in liquid medium paraffin using copper electrode, the workpiece got coated with a very hard layer which was difficult to remove. Lee et al. (Ref 12, 13) investigated the depth of recast layer and quantified it with respect to the process parameters and surface roughness. It was also shown that higher current implies high discharge energy that consequently causes a larger crater on the work surface (Ref 14).

The interaction effect of pulse current and pulse on-time on surface roughness is significant while machining the soft steel with copper electrode. Better surface finish can be achieved at high pulse current and low pulse on-time (Ref 15). Puertas et al. (Ref 10), while machining tungsten carbide, concluded that the effect of duty factor on surface roughness is not significant**.** The surface roughness follows a nonlinear curve with the combined effect pulse current and pulse on-time (Ref 16), however, Jeswani (Ref 17) observed that surface roughness increases with pulse current. Dielectric fluid flushing was also found to be a significant process parameter while controlling surface roughness. The molten material gets solidified and forms a white layer during the cooling process. The texture of the white layer is influenced by the dynamics of discharge zone. The flushing pressure appreciably influences the cooling pattern in the zones and hence the surface roughness gets affected (Ref 18). This study also discusses few issues correlating flushing pressure with MRR and surface quality.

Hole drilling by EDM is a common practice, however, studies concerning machining of advanced materials including Inconel 718 are limited. Kuppan et al. (Ref 19) have carried out process optimization while deep hole drilling on Inconel 718 (25 mm depth) through EDM using the copper 3 mm electrode and reported that the electrode speed and pulse current are the most influencing process parameters. The available literatures indicate that no study has been carried out so far on parametric influence while machining Inconel 718 with a hollow tool. However, if the through hole size is considerably big, potentially, a hollow tool can be attempted. In this work, studies on behavior of process parameters on optimization of EDM process while machining Inconel 718 material with a hollow tool was carried out. Pulse current, duty factor, sensitivity, gap control, and flush pressure were considered as process parameters, while material removal rate and surface roughness were monitored as process responses. Optimization was carried out using central composite design and response surface methodology. Mathematical models were developed to investigate the influence of the process parameters on the process performance. The influences of the process parameters on tool wear and sputtered layer deposition have been discussed with the help of SEM micrographs.

2. Experimentation Procedure

In order to assess the process performance, a series of experiential trials were conducted as per design of experiment methodology. Details about material selection of process, parameters, and designing of the trials have been explained in the following sections.

2.1 Material Details

Demand for high strength and a high thermal resistance material has been on the rise owing to their superior performance under severe condition. Such materials, on the other hand, exhibit typical processing difficulties and consequently are preferred to be processes through high energy rate process like EDM. Being a high strength temperature resistance (HSTR) material, the Inconel 718 is a popular super alloy in a wide range of applications. Thus, a commercially available Inconel 718 super alloy, with an average hardness of 414 Hv, and dimensions $\varnothing 21$ mm $\times$ 20 mm was used as the work material for the experimentation trials. Electron Probe Micro-Analyses (EPMA) of a typical workpiece material is shown in Table 1.

Drilling of large hole with low (*l/d*) ratio requires significant machining time. Further, the removed material in EDM, in general, gets wasted. Taking account of these factors, a cylindrical electrode with tubular section having 12 mm external and 9 mm internal diameter cooper was used as the electrode (tool). The purity of the tool material was found to be 99.9% electrolytic copper. Figure 1 shows few typical copper electrodes used in the experimentation trials. The hollow copper electrodes were prepared by conventional machining methods. Use of hollow tool is particularly useful for drilling holes with low tool wear rate. It was found that, while machining the same length of the Inconel 718 with a solid tool, it takes approximately 40% more machining time, than taken by a hollow tool. Hollow tool also helps in minimizing the dielectric fluid degradation. Consequently, the approach might

Table 1 Typical composition of Inconel 718 workpiece

Element	Ni	Fe	Cr	Nb	Mn	C	Co	Al	Si	Ti	Mo	Other
Weight %	51.05	19.95	18.83	5.52	0.03	0.04	0.04	0.26	0.04	1.08	3.1	0.06

be cost effective with higher yield, and reduced material and energy loss.

Commercially available kerosene with electrical conductivity: 1.6×10^{-14} S/m, and dynamic viscosity: 0.92 mPa·s was used as the dielectric fluid.

2.2 Selection of Process Parameters and Experimental Design

Effectiveness of any investigation depends highly on suitability of selected parameters and their range. Most of the published literatures have not reported on the effect of sensitivity control, gap control, and flushing pressure on machining. However, these factors are considered significant while processing with EDM. Accordingly, pulse current, duty factor, sensitivity control, gap control, and flushing pressure were selected as a process variables to investigate their influences on the process responses MR and SR. Experiments were designed on the basis of the experimental design technique been proposed by Box and Hunter (Ref 20). Thirty-two set of experiments were conducted according to the central composite design (CCD) of response surface methods. Half replication for five variables with $\alpha = 2$ $(2^{(k-1)/4}$, where $k = 5)$ were considered. The experiments were performed according to the plans arrived at using standard design of experiment tool. The process parameters and there levels in the experimentation are shown in the Table 2. The ranges of the parameters were decided based on the widely practiced limits and machine tool constraints.

2.3 Machining and Measurements

The workpieces in required length were initially cut by wire EDM (Make: Electronica, Model EL10-VGA, India) prior to the trials. The experiments were conducted using a ZNC-EDM machine (make: Sparkonix Ltd., Pune, India). The experimental set-up used for the trials is shown in the Fig. 2. A special fixture was designed to hold the cylindrical workpieces to eliminate any possibility of misalignment. Figure 3 shows workpieces prior to and during the progress of the EDM with a hollow tool. The center pieces approximately measuring ∅9 mm × 20 mm were obtained as a result of the present

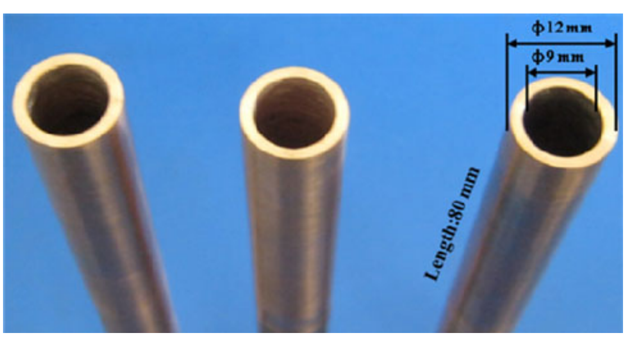

Fig. 1 Typical copper electrodes

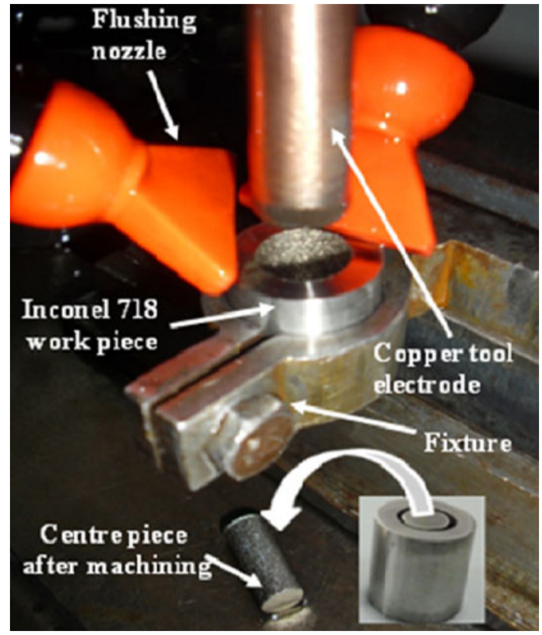

Fig. 2 Pictorial view of the experimental set-up, inset: a semi-finished workpiece

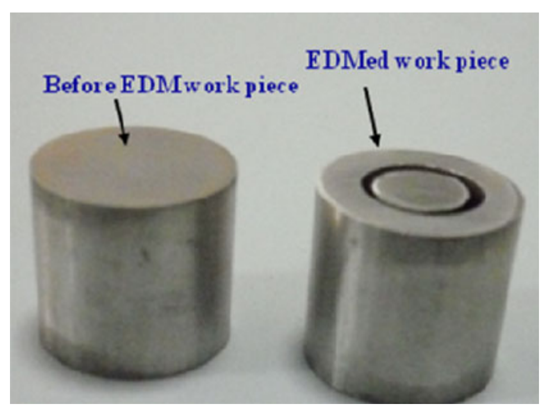

Fig. 3 Workpieces used in the experiments

Table 2 Levels of process parameters used in the experimentation

Serial no.	Process parameter	Unit	Parameter code	Level −2	Level −1	Level 0	Level +1	Level 2
1.	Pulse current	A	A	6	9	12	15	18
2.	Duty factor	…	B	0.67	0.72	0.77	0.82	0.87
3.	Sensitivity control	…	C	3	4	5	6	7
4.	Gap control	…	D	0	1	2	3	4
5.	Flushing pressure	kg/cm^2	E	0	0.25	0.5	0.75	1

Note: 1 kg/cm^2 = 0.98 bar

scheme of the machining. These spare pieces could be reused as per suitability. In order to assess the MRR, the initial weights of the workpieces were measured using a digital weighing machine (Shimadzu, Model: AUW220D) having 0.01 mg resolution.

The workpiece was connected to the positive polarity while the tool electrode was maintained at negative polarity. Side flushing method was employed for the dielectric fluid. A hole depth of 20 mm and diameter of 12 mm was machined throughout, for each run. The process parameters and depth of cut was programmed in the NC controlled unit. The servo moves up by 5 mm above the initial position after completion of machining each hole. Once the experimentation was completed, the workpieces were cleaned thoroughly using acetone and the final individual weight was measured. Machined surfaces were evaluated by measuring the surface finish using a Mahr Perthometer (Model: M2) profile measuring facility. Averages of the measurements at three different locations were considered.

3. Results and Discussion

In this section, the effect of process parameters such as pulse current, duty factor, sensitivity control, gap control, and flushing pressure on material removal rate and surface roughness are presented through trend plots and changes in the form of the tool face and tool wear are discussed with the help of SEM micrograph. The MRR was calculated using Eq 1 and the surface roughness of the EDMed surface of workpiece was measured at three different locations for each specimen. The measured process responses corresponding to each experimental run (combination of parametric values) are shown in Table 3. The MRR is expressed in mm^3/min for the convenience of presentation of data as well as for ease of comparison with published data.

$$\text{Material removal rate (MRR)} = \frac{[\text{work piece weight loss(g)}]}{\left[\text{density}\left(\frac{g}{mm^3}\right)\right] * [\text{machining time (min)}]} \quad (mm^3/min) \tag{Eq 1}$$

Response surface methodology approach is one of the widely adopted procedures for determining the relationship between various process parameters with various machining criteria. The methodology can be effectively used to explore the effect of these process parameters on the coupled responses (Ref 20, 21). In order to study the effect of EDM process parameters while machining Inconel 718 material on the material removal rate and surface finish, a second-order polynomial response was fitted (Ref 21).

3.1 Mathematical Models for Response Characteristics

A mathematical model helps understanding the influence of the process parameters on process responses. Accordingly, the MRR and SR data were analyzed using a widely accepted commercially available software tool (DX6). The backward elimination process was used to eliminate the insignificant terms to adjust the fitted quadratic models. The regression coefficients of the responses were obtained using the second-order equation with experimental data. The hierarchy of the respective models was maintained to develop the mathematical models. The quadratic models of the respective response characteristics (MRR and SR) as a function of five input process parameters in terms of coded values are represented in Eq 2 and 3, respectively. The values of the considered factors have been specified according to their original units and ε represents the experimental error.

Table 3 Design of experiments matrix and corresponding responses

	Process parameters (coded levels)					Process responses	
Experiment run	A	B	C	D	E	Average MRR, mm^3/min	Average SR, μm
1	−1	−1	−1	−1	1	10.700	8.071
2	1	−1	−1	−1	−1	11.532	10.230
3	−1	1	−1	−1	−1	8.034	5.791
4	1	1	−1	−1	1	18.476	4.923
5	−1	−1	1	−1	−1	11.798	5.790
6	1	−1	1	−1	1	21.595	8.760
7	−1	1	1	−1	1	8.147	8.209
8	1	1	1	−1	−1	14.036	9.531
9	−1	−1	−1	1	−1	8.388	6.282
10	1	−1	−1	1	1	9.993	8.893
11	−1	1	−1	1	1	10.625	7.261
12	1	1	−1	1	−1	20.236	10.410
13	−1	−1	1	1	1	13.008	6.654
14	1	−1	1	1	−1	18.761	8.799
15	−1	1	1	1	−1	12.137	8.481
16	1	1	1	1	1	18.537	8.461
17	−2	0	0	0	0	14.395	6.079
18	2	0	0	0	0	27.066	9.660
19	0	−2	0	0	0	15.476	7.791
20	0	2	0	0	0	16.663	7.400
21	0	0	−2	0	0	5.548	6.992
22	0	0	2	0	0	10.630	7.922
23	0	0	0	−2	0	12.778	7.191
24	0	0	0	2	0	14.635	8.510
25	0	0	0	0	−2	14.395	8.951
26	0	0	0	0	2	15.872	7.667
27	0	0	0	0	0	17.504	7.422
28	0	0	0	0	0	16.450	7.563
29	0	0	0	0	0	17.474	7.591
30	0	0	0	0	0	17.417	7.692
31	0	0	0	0	0	17.446	7.482
32	0	0	0	0	0	16.597	7.586

$$\begin{aligned} MRR = {} & 17.265284 + 3.152958\ A + 0.284458\ B \\ & + 1.258292\ C + 0.461708\ D + 0.379708\ E \\ & + 0.897188\ AB + 0.334313\ AC - 1.816438\ BC \\ & + 1.144813\ BD + 0.397938\ CD - 1.304813\ DE \\ & + 0.778341\ A^2 - 0.386909\ B^2 - 2.382034\ C^2 \\ & - 0.977659\ D^2 - 0.620909\ E^2 \pm \varepsilon \end{aligned} \tag{Eq 2}$$

$$\begin{aligned} SR = {} & 7.544327 + 0.859583\ A - 0.049583\ B + 0.195417\ C \\ & + 0.273750\ D - 0.277083\ E - 0.394375\ AB \\ & + 0.144375\ AD - 0.736875\ AE + 0.610625\ BC \\ & + 0.524375\ BD - 0.414375\ BE - 0.233125\ CD \\ & + 0.190625\ CE - 0.083125\ DE + 0.084327\ A^2 \\ & + 0.079327\ D^2 + 0.194327\ E^2 \pm \varepsilon \end{aligned} \tag{Eq 3}$$

The analysis of variance (ANOVA) for the fitted quadratic models and regression models for both MRR and SR is given in the Table 4 and 5, respectively. The fit summaries given in Table 4 and 5 reveal that the fitted quadratic models are statistically significant to analyze the values of the desired responses. The values of "Prob $> F$" for the models are less than 0.05 (95% confidence). This is desirable since it demonstrates that the terms in the model have significant effect on the responses. The adequate precision measures the signal-to-noise ratio (it compares the range of the predicted value at the design point to the average prediction error). The ratio obtained for the models indicated an adequate signal. Thus, the models can be used to predict the values of the respective responses within the limits of the factors studied.

These models present higher values of the determination coefficient (R^2) and adequate precision at the same time. The determination coefficient (R^2) in the resulting ANOVA table is defined as the ratio of the explained variation to the total variation and is a measure of the degree of fit. When it approaches unity, the response model fits the actual data with fidelity. The various R^2 statistics are given for both MRR and SR in Table 4 and 5, respectively. The tabulated R^2 values indicate high fidelity of the models as presented in Eq 2 and 3. Further, pulse current, duty factor, sensitivity control, gap control, and flushing pressure are the significant process parameters for both MRR and SR at 95% confidence level.

3.2 Analysis of Process Parameter Interactions

Influence of the selected individual and combinations on the process responses have been analyzed and presented in the terms of response surfaces. Effect on the each response has been illustrated separately.

3.2.1 Effect on Material Removal Rate. The interactions between pulse current and duty factor, pulse current and sensitivity, duty factor and sensitivity, duty factor and gap control, sensitivity and gap control, gap control and flushing pressure, provide secondary contributions to the model. The combined effects of different process parameters are shown in the Fig. 4 to 9.

The response curve as shown in Fig. 4 illustrates that the MRR increases with an increase in pulse current. Higher the current, the spark intensity becomes higher resulting in increased heat flux within inter electrode gap; consequently, the sparking area temperature rises sharply that leads to rapid melting of workpiece material yielding higher MRR. Pulse current remains the most contributing factor with approximate changes in the MRR and SR of 48 and 37%, respectively, corresponding to the extreme values considered (Table 3). The

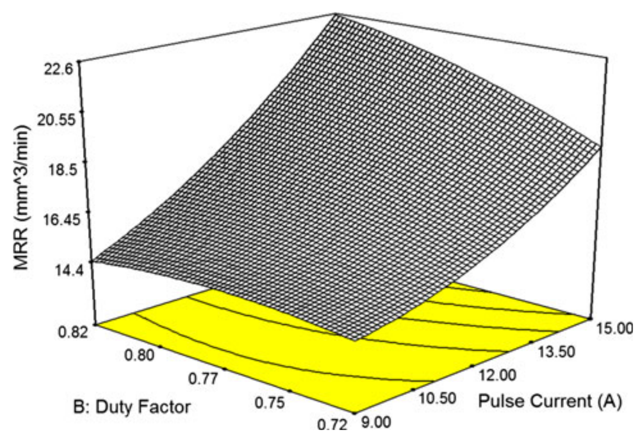

Fig. 4 Typical influence of pulse current and duty factor on MRR

Table 4 The ANOVA for the fitted RSM model for MRR

Source	Sum of squares	Degrees of freedom	Mean square	F value	Prob $> F$	Remark
Model	628.213	16	39.263	110.249	<0.0001	Significant
Residual	5.342	15	0.356			
Lack of fit	4.157	10	0.416	1.754	0.2780	Not significant
Pure error	1.185	5	0.237			
Cor. total	633.555	31				
Standard deviation = 0.597				$R^2 = 0.9915$		
Mean = 14.57				Adjusted $R^2 = 0.9825$		
Coefficient of variation (%) = 4				Predicted $R^2 = 0.9528$		
Predicted residual error of sum of squares = 30.05				Adequate precision = 49.3462		

Table 5 The ANOVA for the fitted RSM model for SR

Source	Sum of squares	Degrees of freedom	Mean square	F value	P value Prob $> F$	Remark
Model	49.914	17	2.936	194.954	<0.0001	Significant
Residual	0.211	14	0.015			
Lack of fit	0.167	9	0.018	2.110	0.2125	Not significant
Pure error	0.044	5	0.009			
Cor. total	50.125	31				
Standard deviation = 0.122				$R^2 = 0.9957$		
Mean = 7.81				Adjusted $R^2 = 0.9906$		
Coefficient of variation (%) = 1.5				Predicted $R^2 = 0.9558$		
Predicted residual error of sum of squares = 2.22				Adequate precision = 60.7242		

influence of duty factor on MRR, on the other hand, is not very significant. The MRR is seen low at lower levels of duty factor which is primarily due to increase in pulse off-time. An increase in pulse off-time leads to decreased electrical discharge frequency. The maximum MRR is observed corresponding to the second level of both the parameters. An increase in pulse on time in terms of higher duty factor along with higher pulse current resulted in increased energy inputs, developing enlarged pits with higher material removal (22.6 mm^3/min) corresponding to the extreme combination of both the parameters. Consequently, a poor surface finish is expected at this high rate of material removal.

The response curve in Fig. 5 shows that MRR increases with an increase in pulse current. However, as sensitivity increases, the MRR increases up to an optimum level and then gradually decreases. The servo power on the cutting axis is controlled by the sensitivity (gain) of the servo system. Higher servo power resists the increase in pressure within the spark gap during machining. Higher sensitivity means faster advancement of tool toward the workpiece; this means less time will be available for re-ionization of the dielectric fluid resulting in reduced arching intensity and instability of the EDM process. Such condition leads to the observed low MRR as shown in Fig. 5 compared to that of higher sensitivity control. A marginal reduction in the overall MRR is obvious as can be seen clearly corresponding to the higher levels of these parameters.

The response surface in Fig. 6 illustrates the interaction of duty factor and sensitivity control on MRR. Maximum MRR is obtained corresponding to the highest (0.82) duty factor, while a moderate control of the sensitivity (value = 5) results in the best MRR. An unstable sparking condition as discussed earlier might not result in enhanced MRR although higher duty factor favors it.

Interaction surface of the gap control and duty factor with respect to MRR is shown in Fig. 7. In general, higher the duty factor, lower is the MRR. However, while it comes to the combined effect with the gap control, it is observed that at higher levels of both the parameters, the MRR is maximum. This is due to the fact that at higher duty factor, the pulse on time is high. Thus, an increase in MRR with pulse on time is generally expected. However, very high pulse on time implies delayed flushing cycle, resulting in an accumulation of debris in the inter electrode gap. Such condition may impede MRR, but when the gap control is maintained at higher level, sufficient space becomes available to flush out the debris which leads to the observed improvement in MRR as illustrated in Fig. 7.

Figure 8 shows the interaction between sensitivity control and gap control. When the parameters are set at the middle level, the MRR is seen maximum. At a desired inter electrode gap, the pressure applied by the servo maintains the perfect spark gap leading to the higher MRR.

The inadequate flushing results in erratic discharges; however, an increase in flushing pressure implies that effective discharges are possible that increases MRR (Ref 22). Very high flushing pressure, on the other hand, cools the electrode that leads to higher ignition delay (Ref 23). This decreases the discharge energy and consequently reduces MRR (Ref 14). This is observed in this study as illustrated in Fig. 9. Interaction surface in the Fig. 9 shows the typical relation of flushing pressure and gap control. At lower gap control with higher flushing pressure, greater MRR is observed. On the other hand, at higher gap control with low flushing pressure, the MRR

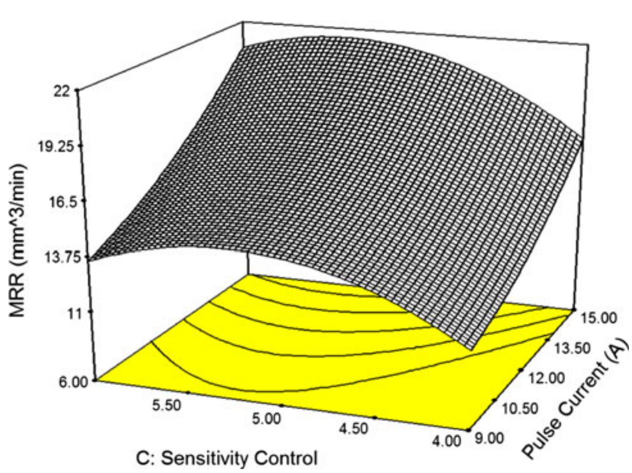

Fig. 5 Effect of pulse current and sensitivity control on MRR

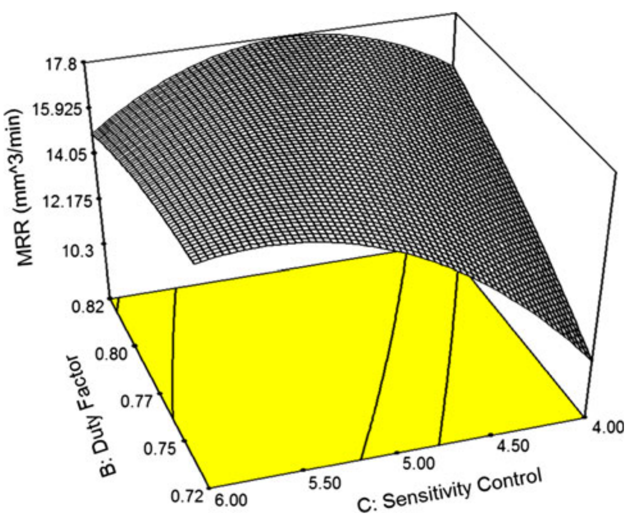

Fig. 6 Combined influence of duty factor and sensitivity control on MRR

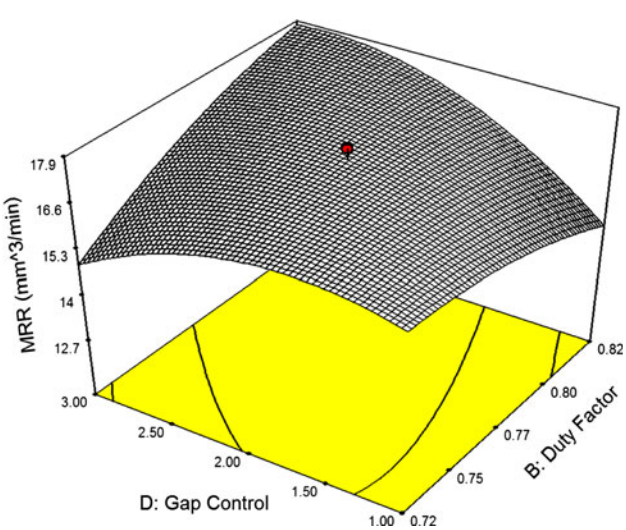

Fig. 7 Influence of duty factor and gap control on MRR

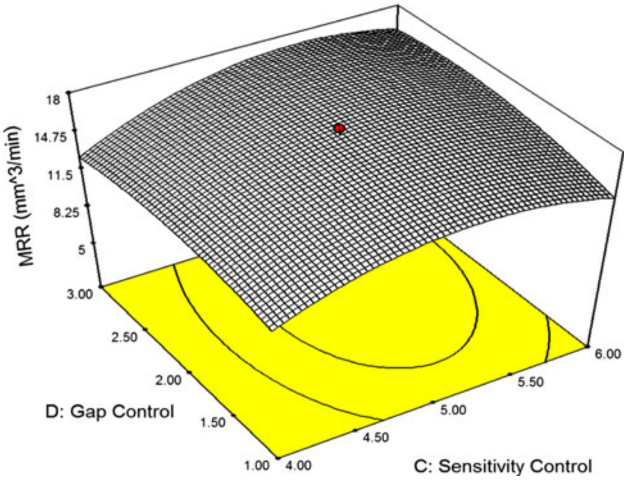

Fig. 8 Combined influence of sensitivity control and gap control on MRR

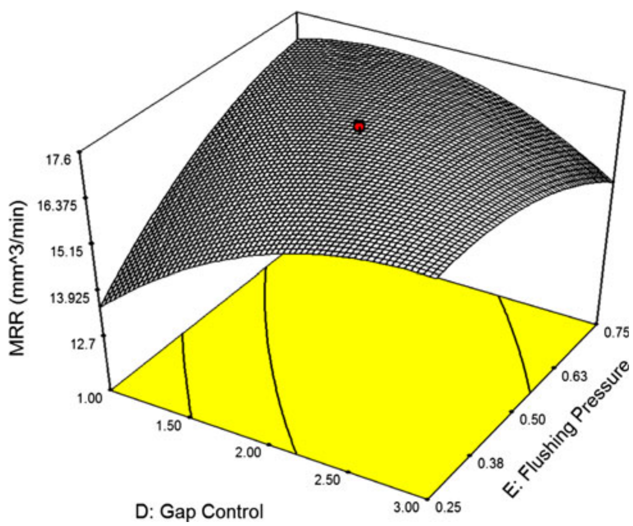

Fig. 9 Typical effects of gap control and flushing pressure on MRR

remains almost the same. This relation indicating the proper gap with sufficient flushing pressure indicates the necessity to flush out the machined derbies on a regular basis to improve the machining performance.

3.2.2 Effect on Surface Finish. The values of the surface roughness parameter for each experiment were obtained from the arithmetic mean of the roughness values of the measurements taken in three parallel directions and in an equidistant distribution over the total area subjected to the EDM process. The combined effects of different process parameters selected for this study are shown in the Fig. 10 to 14.

The interaction between pulse current and duty factor, while machining Inconel 718 is shown in Fig. 10. It is seen that an increase in pulse current resulted in an increased SR value. This is attributed to the fact that larger craters are formed on the surface of the machined workpiece due to higher discharge energy. The combined effects of pulse current and duty factor are more effective, even though, the effect of duty factor on SR is almost insignificant. It is evident from the Fig. 10 that at low

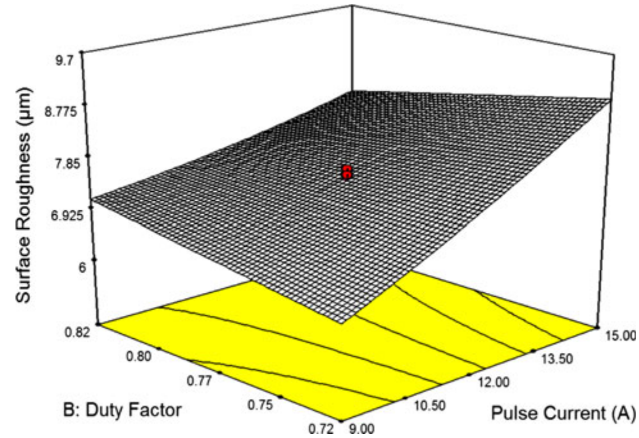

Fig. 10 Influence of pulse current and duty factor on SR

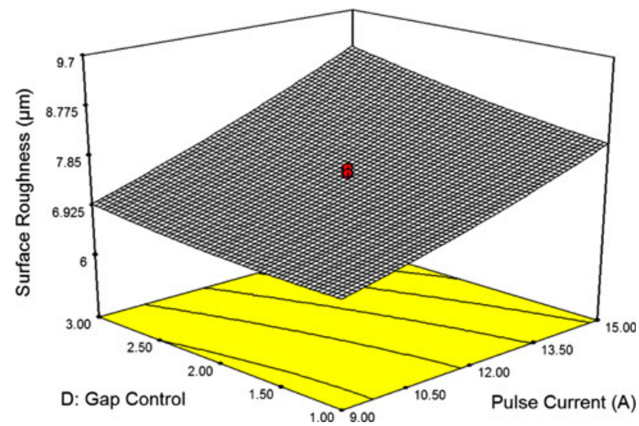

Fig. 11 Combined effect of pulse current and gap control on SR

level of the pulse current and duty factor, the surface finish is better. This is due to the fact that at lower current, material removal is in micro-level, and in the mean while, if the off-time is maximum corresponding to lower duty factor, the dielectric fluid get sufficient time to flush out the machine debris, resulting in lower recast surface and better surface quality.

The response surface resulting from the interaction between the pulse current and gap control during machining Inconel 718 is illustrated in Fig. 11. It is evident from the figure that low inter electrode gap and low pulse current is recommended to obtain better surface finish. At low gap control the spark intensity is low, more uniform and along with the low pulse current, low melting and low material removal results. This leads to better surface quality.

The interaction surface presented in the Fig. 12 reveals that an increasing sensitivity control causes the SR to increase. This is due to the fact that higher energy is acting on the workpiece surface resulting in higher SR. At lower gap control, the arc intensity is low and stable, which leads to improved surface finish. Interaction between gap control and sensitivity control indicates that, at the lowest levels of the gap control and sensitivity, the surface finish is significantly better.

Figure 13 shows the interaction between the duty factor and flushing pressure. Surface roughness increases due to an increase in on-time at higher duty factor. At the combined setting of higher duty factor and higher flushing pressure, on the other hand, the surface quality improves. Higher flushing

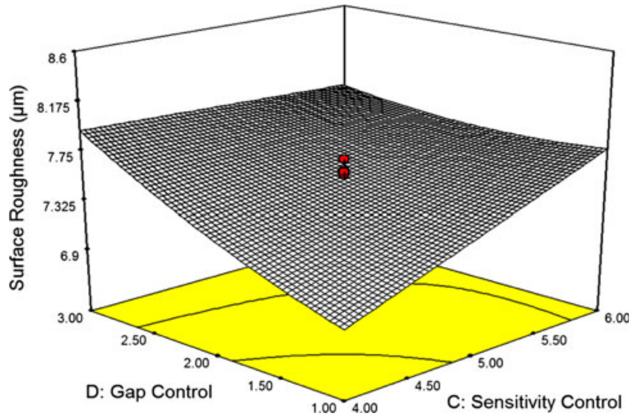

Fig. 12 Interaction of gap control and sensitivity control on SR

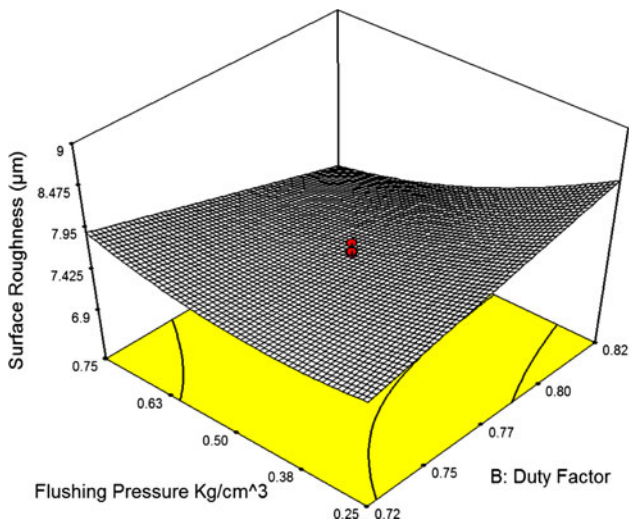

Fig. 13 Combined influence of duty factor and flushing pressure on SR

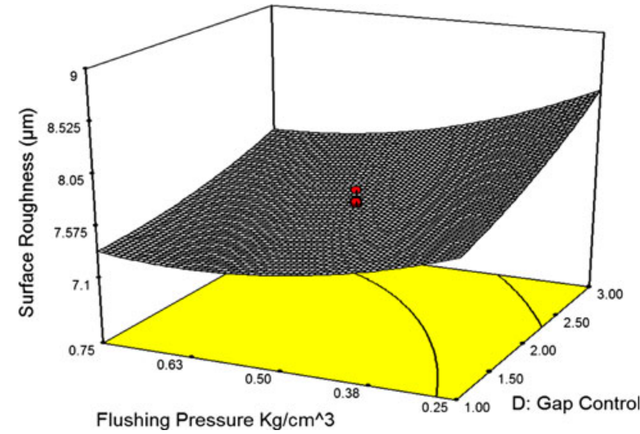

Fig. 14 Combined influence of gap control and flushing pressure on SR

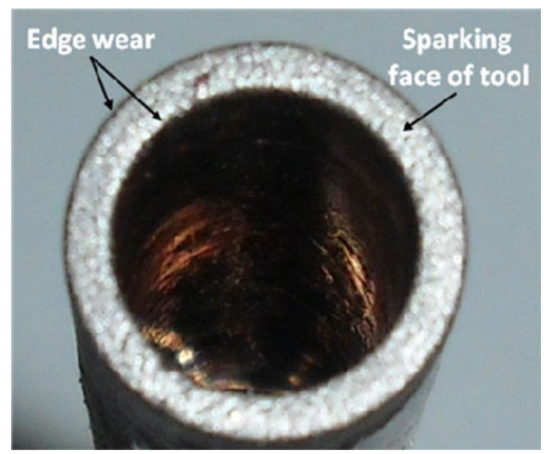

Fig. 15 A hollow copper tool face after electric discharge machining of Inconel 718

pressure facilitates better flushing of the machined debris even at lower off-time. This is desirable for optimum SR as well as MRR.

Lower flushing pressure results in poor surface quality due to inadequate flushing to drive out the machined debris during the off-time. This is evident in Fig. 14 corresponding to lower flushing pressure. As the flushing pressure increases, the SR also increases. The combined effect of the gap control and flushing pressure shows that at a lower level of gap control with higher flushing pressure, the surface finish is better. Figure 14 also illustrates that at higher flushing pressure, the influence of gap control on surface quality is not significant.

3.2.3 Effect on Tool Wear. In EDM process, the tool wear is another important issue with respect to the effects of the process parameters. It is necessary to study effects of process parameters on tool wear to obtain accurate and desired shape of a job which directly influences the machining economics. Tool wear was observed to be increasing with increasing pulse current in the present investigation. It was also observed that there is a change in the form of the tool edge in terms of rounding-off and deposition of a thin layer workpiece material on the tool while machining of Inconel 718. Figure 15 shows a typical photograph of an eroded face of copper tool end with a deposited layer. Figure 16(a) micrograph of the copper tool face shows the clear evidence of edge rounding. During the off-time of duty cycle electrolyte flushes away the debris containing possible hard carbides and microchips of the Inconel super alloy under pressure. The sharp edges of the relatively soft copper tool get smoothened/rounded owing to the continued abrasion by this debris. Further, it is also observed that higher pulse current, duty factor, and sensitivity control levels results in higher edge erosion as can be seen in Fig. 17(a). Figure 16(b) and 17(b), on the other hand, clearly shows the deposition of rich nickel-based workpiece material on the sparked area of the tool face. The thickness of this thin layer varies with the pulse current and flushing pressure. At higher pulse current, the thickness of the layer is high due to erratic discharges that causes the temperature to increase to a very high value, melts higher volume of the workpiece, and also soften the tool. The debris gets solidified due to the flowing dielectric fluid and gets deposited on the face of the tool in the form a thin sputtered layer. This layer also acts as a protective layer for further tool wear at low pulse current, but at higher pulse current this layer frequently gets remelted and causes an increase in the tool wear.

The crack propagation on the tool and workpiece is a common phenomenon in the EDM process due to the effect of thermal stresses on the newly formed layer by cooling. The

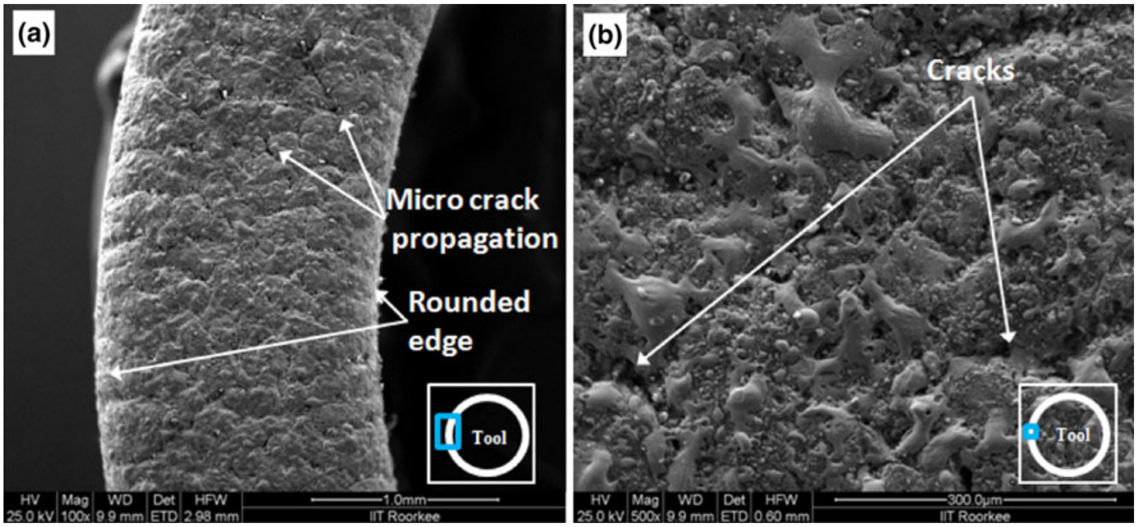

Fig. 16 Analysis of tool face: (a) FESEM micrographs of a typical tool face; (b) a zoomed view of tool face; [insets: schematics of the tool end views] (conditions: pulse current 9 A, duty factor 0.72, sensitivity control 4, gap control 1, and flushing pressure 0.75 kg/cm^2)

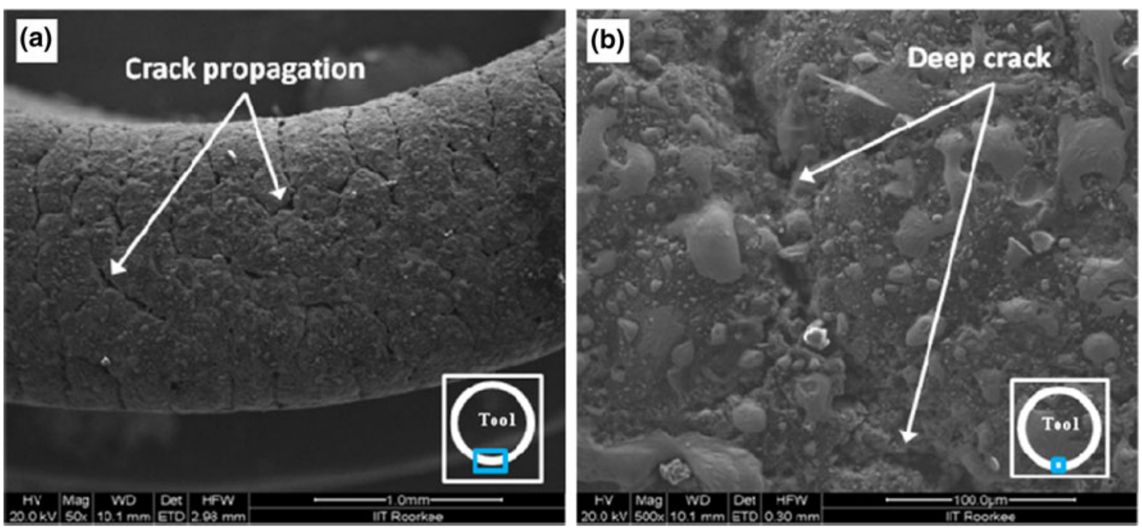

Fig. 17 Analysis of tool face: (a) FESEM micrographs of a typical tool face. (b) A zoomed view of tool end face; [insets: schematics of the tool end views] (conditions: pulse current 18 A, duty factor 0.77, sensitivity control 5, gap control 2, and flushing pressure 0.5 kg/cm^2)

width and propagation of the crakes were highly influenced by the value of the pulse current. At low pulse current (9 A), the width and length of the cracks were less (Fig. 16a, b) compared to those (Fig. 17a, b) at high pulse current (18 A). This is due to the fact that at higher pulse current, the rapid heating and cooling cycles induces higher level of thermal stresses on the tool face leading to deep and wide cracks.

4. Conclusions

In this study, the influence of some significant EDM process parameters like pulse current, duty factor, sensitivity control, gap control, and flushing pressure on material removal rate and surface quality while machining the Inconel 718 has been investigated. Experimentations were planed and conducted according to the central composite design of response surface methods, with half replication for five variables. Mathematical models were developed using regression analysis. Influence of the major process parameters on tool wear has been briefly discussed. Following major conclusion were drawn from this study.

- The most influential factors on MRR are the pulse current, duty factor, and the interaction effect of both. Therefore, to obtain high values of MRR while machining Inconel 718, higher level setting of pulse current and duty factor is suggested.
- Sensitivity control largely influences the MRR. Optimum setting of this parameter could result in better MRR with average surface quality.
- The value of MRR decreases, as would logically be expected, with increasing duty factor. However, when it

comes to combined effect with gap control, good MRR can be achieved with both the parameters set at higher values.

- It is necessary to set proper flushing pressure while EDMing Inconel 718 due its high thermal resistance. Very high or low settings of flushing pressure leads to lowering the MRR as well as surface quality.
- Higher flushing pressure facilitates better flushing of the machined debris even at lower off-time. This is desirable for optimum SR as well as MRR.
- Surface finish while EDMing the Inconel 718 is majorly influenced by pulse current, duty factor, and gap control factors. Interaction effect between the pulse current and gap control at higher level decreases the surface quality significantly.
- In order to obtain better surface finish while machining the Inconel 718, lower level setting of pulse current, gap control, and sensitivity control and moderate flushing pressure process parameter values are suggested.
- Pulse current and duty factor have the highest influence interactively on MRR yielding a wide range from 14.4 to 22.6 mm^3/min, while pulse current remains the most contributing factor with approximate changes in the MRR and SR of 48% and 37%, respectively, for the extreme values considered.
- Tool wear, thickness of the sputtered layer, and crack propagation on the tool were highly influenced by higher pulse current.
- The EDM tool wear is primarily caused by the continued abrasion of the hard debris in addition to the discharge-associated erosion. Edge smoothening in case of hollow tool does take place on the both the outer and the inner sides of the tool owing to the continuous flow path of the debris laden electrolyte.

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