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Modeling and optimization of EDM Process Parameters on Machining of Inconel 686 using RSM

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Abstract

This analysis represents the optimization process for MRR, TWR and surface roughness Ra of die sinking EDM on Inconel 686 material by using RSM. Inconel 686 is an advanced corrosion resistance alloy that offers resistance to oxidization in mixed acid environments including those containing halides and other harmful effects of high temperature exposure. A tested Inconel 686 material is taken as a workpiece. For conducting the experiments, four controllable input parameters that is spark current, pulse on time, %duty cycle and voltage have been considered and high conductive aluminum (99.99% aluminum) has been taken as workpiece. Face centered central composite design of response surface methodology is used for designing the experiment using Design Expert software and experiment were performed on it. A total 30 experiments has been carried out for various combinations of process parameters. Various influences of spark current, pulse on time, duty cycle and gap voltage on material removal rate (MRR), tool wear rate (TWR) and surface roughness (Ra) are investigated using Analysis of variance (ANOVA). The model has been developed at 95% confidence level. Spark current, pulse on time, duty cycle and voltage significantly affect the MRR, TWR and surface roughness Ra, this is observed from analysis. The model sufficiency has very satisfactory for MRR, TWR and surface roughness Ra. The comparison of predicted value at the design point and the average prediction error has been evaluated by adequate precision, which is well above 4. The values of R^2 are 0.9222, 0.9402 and 0.8764 for MRR, TWR and Ra consequently. The values of adequate precision are13.5486, 14.7249 and 12.9433 for output characteristics MRR, TWR and Ra. Lack of fit also shows to be insignificant for these experimental values. Aim was to found the significant process parameters that affect the MRR, TWR and Ra.

Key word: EDM, MRR, TWR, Ra and ANOVA.

INTRODUCTION

In manufacturing process EDM stands for electrical discharge machining. In this electro- thermal nontraditional machining process electric energy is utilized to generate electrical spark which produces thermal heat. This thermal heat is the main factor which causing the material removal from workpiece by fusion, evaporation and ablation. The application is best suited for those materials which are characterized by close tolerances of machining that would be extremely difficult or impossible to handle with any other method of machining. EDM has been mainly used for machining difficult to machine and high strength temperature resistance alloys. EDM is widely used in producing dies, punches, molds, finishing parts for aerospace, surgical components and automotive industry [1]. This process is successfully employed for machining electrically conductive material irrespective of their shape, hardness and toughness. During EDM process, the machined shape is mirror of electrode shape. The electrode and workpiece is maintained at some distance called spark gap. High electrode gap erode more workpiece material but it causes poor surface quality of machined surface. EDM properties are relevant to material property and also on design of electrode. The electrode is prepared in two parts electrode tool and holder. This both part is designed and manufactured into one piece of electrode. The electrodes are typically manufactured by traditional cutting process, but complicated shape electrode may be produced by casting, electroforming or metal spraying. In die-sinking EDM process, either fixed electrodes are used or a rotary device works in conjunction with a CNC to control the path of electrode in various EDM profiling. Manufacturing time, cost and performance of EDM electrode is also affected by manufacturing method of electrode. In present days, for manufacturing production tooling out of hardened materials for production of dies and molds EDM is used as a standard technique. Due to high rate of tool wear involved; many electrodes are often required for machining each cavity. Due to high tool wear machining accuracy is affected and it is required to replace tool frequently adding to around 50% of tooling cost. Alternatively use of rapid tooling technique minimizes the electrode development lead-time and reduces the tooling cost considerably. Therefore, design, development and manufacturing of EDM electrode play a very vital role in EDM technology. A lot of published EDM research work relates to parameter optimization for a particular work tool interface or to determine best tool material for a particular work material. Many innovative electrode material and designs have also been tried. The theory of electric discharge machining process has been entrenched by B.R. and N.I. Lazarenko (soviet scientists) in the middle of 1940s in the Technical institute of Moscow during the World War II [2]. The first of two important improvements in EDM process has been carried out by these scientists. RC relaxation circuit makes it feasible to elevate this technique to the category of manufacturing process. In die sinking EDM the machining zone is completely submerged in an insulating liquid like EDM oil, kerosene etc. Being the electrical conductors both tool and workpiece are connected to the two terminal of the electric power sources. The tool is connected at negative terminal (called cathode) and workpiece is connected at positive terminal (called anode). This arrangement of electrode and workpiece is called as straight polarity. An electric field is established between anode and cathode which causes acceleration of electron from cathode to anode due to high voltage difference. When these two electrodes are brought to closer proximity, an electric discharge in form of spark jumped across from cathode to anode due to voltage gap. The effect of working parameters on desired output characteristics like MRR, TWR, machinability and surface roughness have been studied by various researchers. Mohan et al.[3] have studied the effect of spark current, air gap voltage and pulse on time on MRR of a composite material. Fattouh et al. [4] prepared the modeling of the EDM process for maximizing production rate and minimizing cost. To established mathematical relations between principal process parameter and desired response parameter like MRR, TWR, overcut and Ra Response Surface Methodology are used.

LITERATURE REVIEW

Jegan et al. [5] described the machining of stainless steel AISI202 material with process parameters discharge current, pulse duration and pulse interval. They used GRA approach to optimized the response parameters MRR and SR. GRA was used for multi-objective model to find out the single grey grade. It was found that the discharge current affects the MRR largely followed by pulse duration time and pulse interval time, and proper combination of control factors improves efficiency and product quality.

Ayesta et al. [6] performed machining (narrow slots) on aeronautical alloy C1023 by using EDM with erosion parameters intensity of current, pulse on time and servo voltage. Erosion time (Material removal rate) and electrode wear rate were calculated. They were concluded that for minimum wear of electrode, high intensity of current and high pulse time should be applied. Lower erosion time was found with a high intensity of current and low servo voltage.

Koshy et. al [7] concluded that the machining with rotational tool in disc shape improves MRR and surface roughness because a tangential force acted on outer surface of disc which was responsible for cutting the material and generation of centrifugal force due to rotation, removes the debris particle from the machining area and thus every time a fresh contact has to be done between workpiece and cutter. They also concluded that with increase of speed MRR and surface roughness improves but beyond a limit it has constant effect on MRR and surface roughness.

Li et al. [8] have investigated the effect of TiC (Titanium carbide) in sintered Cu-W (copper tungsten) electrode on EDM performance. The TiC content was varying from 5 to 40 percent in six batches of job, and densification was enhanced by adding Ni because Ni has good solubility with Copper and Tungsten. The relative density initially increases and then decreases by increase in TiC, whereas electrical resistivity first decreases and then increased with increase in TiC. TiC added in tool material showed better performance, the value of SR decreased with increase in relative density and its vice – versa. With 15 percent TiC addition, best EDM obtained i.e. high MRR, better surface finish and low tool wear.

Sanjeev Kumar et al [9] have studied the surface modification phenomenon by electric discharge machining. In this study they have compared various surface modification technics i.e. by conventional electrode, powder metallurgy electrodes, and powder mixed dielectric and other application.

MECHANISM OF METAL REMOVAL

In EDM material is mainly removed by electro discharge erosion caused by sparking in between two electrodes that are separated by a dielectric liquid as shown in figure 1.

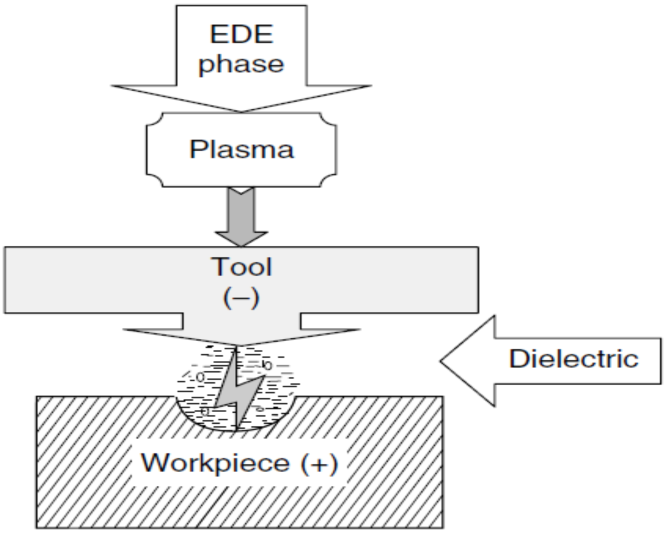

Figure 1. EDM components

The high intensity discharge generates extremely high temperature that melts and evaporates the two electrodes as a result material removal takes place. A series of voltage pulse that's magnitude are ranges from 20 to 120V and frequency of order 5kHz is applied between separated electrodes. The gap between electrodes are maintained typically 0.01 to 0.05mm. The voltage pulses cause the electrical breakdown of dielectric in a channel of radius 10 µm. The breakdown arises due to acceleration of both emitted electron from cathode and stray electron present in the gap towards the anode. This acceleration of electron is due to the applied field. These accelerated electrons when collides with neutral atoms of dielectric, the dielectric atoms gets ionized. These further ionized positive ions and electrons accelerated respectively towards the cathode and anode.

When these accelerated ionized particle reach the electrode the give up their kinetic energy in the form of heat and raised the local temperature of electrode more than their boiling point with a very short duration spark typically between 0.1 to

2000 µs. The temperature rises about 8000 to 12000 ^0C. Due to evaporation of the dielectric, the pressure on the plasma channel rises to values as high as 200 atmospheres rapidly, which prevents the evaporation of superheated metal[10]. This pressure drops suddenly at the end of the pulse, which evaporates the superheated metal explosively. Thus metal is removed from the electrode. Now fresh dielectric replaces the older one, flushes the derbies away and quenches the workpiece surfaces, which prevents the defect causing by heat affected. The plasma channel increase in width at the end of EDM process and current density across the inter electrode gap decrease.

EXPERIMENTAL PROCEDURES

Electric discharge machining can machine any conductive material. Material such as heat treated tool steels, super alloys, carbides, heat resistant steels, composites and higher carbon grades are typically used for machining with EDM process. Alloy 686 is a low-carbon, nickel chromium-Molybdenum - tungsten advanced corrosion-resistant alloy that offers outstanding resistance to oxidizing, reducing, and mixed acid environments including those containing halides [11]. The alloy is resistant to seawater and other marine environments. Thus, alloy 686 is widely used in the chemical processing, marine, and air pollution control (flue gas desulfurization) industries. Inconel 686 an alloy of Ni-Cr of size 100mm×50mm×3mm is used as a work piece material.

Table 1. Chemical composition (mass fraction) weight% of the Inconel 686

Components	weight% of the Inconel 686
Nickel(Ni)	59.44
Chromium(Cr)	19.74
Molybdenum(Mo)	15.54
Tungsten(W)	3.31
Iron(Fe)	1.21
Silicon(Si)	0.06
Sulphur (S)	0.02
Carbon (C)	0.01
Phosphorus(P)	0.03
Manganese(Mn)	0.64

Table 2. Properties of Inconel 686

PRODUCT FORM	TENSILE (ksi)	0.2% YIELD (ksi)	ELONGATION (%)	DENSITY (gm/cm^3)
Rod (1.50 inch diameter)	117.5	52.1	56	**8.72**
Plate (0.250inch thick)	106.3	57.9	68	
Sheet (0.125 inch thick)	116.5	61.1	59	

For present experiment Aluminum is selected as the electrode material for machining of Inconel 686 ally because of its appropriate electrical property which is essential property for EDM electrode. Many factors are needed to be taken into consideration while selecting the tool material.

- High electrical conductivity (3.5*10E7 Siemens/meter for Al)
- High thermal conductivity (205 W/m-K for Al)
- Low erosion rate and decent work to tool wear ratio
- Good machinability
- High melting point (660.3 ^0C for Al)
- Higher density (2.7 g/cm^3)

RESPONSE SURFACE METHODOLOGY

The response surface method (*RSM*) is systematic arrangement of statistical and mathematical techniques [12]. This method becomes applicable for the modeling and analysis of real world problems. A desired response can be determined by the interpretation of several input variables and optimized input variables can be evaluated for particular response. RSM was formally developed by G.E.P. Box and K.B. Wilson to model experimental responses which are further emigrated into modeling of numerical experiments [13]. It is assumed that in RSM techniques the errors are random [14]. In Design optimization, the application of RSM is aimed to diminish the cost of lavish analysis methods and their associated numerical noise.

For example, let the MRR in EDM machining is affected by the spark current x_1, pulse on time x_2, % duty cycle x_3 and voltage x_4. Therefore, these variables can vary continuously. The material removal rate, y is the response variable, and it is a function of spark current, pulse on time, % Duty Cycle and voltage. The approximating function of independent linear variables is a first-order model. It can be expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \varepsilon \quad ....(1)$$

Where ε denotes the experimental error term. The variables x_1, x_2 x_3 and x_4 are independent variables where the response y depends on them.

A second order model response function for 4 input variables can by expressed as:

$$\begin{aligned} y &= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 \\ &+ \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 \quad \ldots(2) \\ &+ \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 + \varepsilon \end{aligned}$$

Where ε is a statistical error that is assumed to distribute normally with zero mean and variance s^2. The true response function *f* is generally unknown for most of RSM problems.

For evaluating the useful result for the model functions appropriate experimental design is required for collecting the valuable data. Method of least square techniques is used for estimation of predicted parameters in the model function.

Fitted surface is used for performing the response surface analysis. The response surface designs are types of designs for fitting response surface. RSM has following main objective:

(1) To figure out the topography (maximum, minimum, ridge lines) of the response surfaces

(2) To find the optimal response region. For this purpose its required to move progressively and efficiently in a way that maximum or minimum response can be find so that optimization can be applicable.

In present study the experiments were designed on the basis of Central Composite Design of RSM. The factorial portion of CCD is full factorial design with all combinations of factors at 2 levels (high+1,and Low-1) and composed of 8 Axial/star points and 6 central points (coded level 0) which is midpoint between the high and low levels corresponding to an α value of 2. The face centered CCD involves30 experimental observations at four independent input variables. The experimental layout adopted in this study in the actual form is given in Table 5, which is prepared by Design Expert Software.

The range of input factors spark current, pulse on time, % duty cycle and voltage is taken as per Table 3. given.

Table 3. Various ranges of input factors.

Factor	**Name**	**Units**	**Type**	**Minimum**	**Maximum**	**Coded Low**	**Coded High**	**Mean**	**Std. Dev.**
A	SPARK CURRENT	AMPERE	Numeric	3.00	19.00	-1 ↔ 7.00	+1 ↔ 15.00	11.00	3.64
B	PULSE ON	μ S	Numeric	100.00	500.00	-1 ↔ 200.00	+1 ↔ 400.00	300.00	90.97
C	DUTY CYCLE	% RATIO	Numeric	8.00	12.00	-1 ↔ 9.00	+1 ↔ 11.00	10.00	0.9097
D	VOLTAGE	VOLTS	Numeric	40.00	80.00	-1 ↔ 50.00	+1 ↔ 70.00	60.00	9.10

Table 5. Experimental layout and Experimental value on corresponding points

			Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3
Std	Run	Space Type	A:spark current	B:pulse on time	C:% duty cycle	D:voltage	MRR	TWR	Ra
			Ampere	μsec	ratio	volt	mm^3/min	mm^3/min	μm
26	7	Center	11	300	10	60	8.942	2.254	12.3
29	14	Center	11	300	10	60	9.035	2.693	12.7
27	17	Center	11	300	10	60	9.022	2.222	12.68
25	18	Center	11	300	10	60	10.398	2.469	11.8
28	19	Center	11	300	10	60	8.601	2.083	12.5
30	27	Center	11	300	10	60	8.792	2.263	14.1
20	4	Axial	11	500	10	60	10.103	2.47	13.9
18	6	Axial	19	300	10	60	11.396	2.546	13.6
23	9	Axial	11	300	10	40	6.212	1.235	14.3
22	11	Axial	11	300	12	60	12.079	1.975	12.7
19	12	Axial	11	100	10	60	2.042	1.444	9.2
24	13	Axial	11	300	10	80	10.608	2.16	11.7
21	16	Axial	11	300	8	60	8.376	2.415	12.2
17	25	Axial	3	300	10	60	5.213	0.168	4.5
13	1	Factorial	7	200	11	70	6.467	0.607	10.5
11	2	Factorial	7	400	9	70	7.243	0.78	8.5
8	3	Factorial	15	400	11	50	10.448	2.053	14
1	5	Factorial	7	200	9	50	4.128	0.296	8.2
6	8	Factorial	15	200	11	50	8.083	1.666	13.7
15	10	Factorial	7	400	11	70	8.549	1.346	9.7
9	15	Factorial	7	200	9	70	6.322	0.665	10.7
12	20	Factorial	15	400	9	70	14.417	2.315	13.4
2	21	Factorial	15	200	9	50	6.952	2.315	11.5
14	22	Factorial	15	200	11	70	12.309	2.469	12.7
7	23	Factorial	7	400	11	50	6.307	1.44	9.6

			Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3
Std	Run	Space Type	A:spark current	B:pulse on time	C:% duty cycle	D:voltage	MRR	TWR	Ra
4	24	Factorial	15	400	9	50	11.265	2.397	12.5
10	26	Factorial	15	200	9	70	10.321	2.279	13.2
3	28	Factorial	7	400	9	50	4.077	1.235	8.9
5	29	Factorial	7	200	11	50	2.638	0.3703	9.2
16	30	Factorial	15	400	11	70	14.264	2.48	15.3

Table 6. Fit summary for MRR model

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	0.0368	0.8105	0.7527	
2FI	0.9512	0.0212	0.7692	0.6192	
Quadratic	**0.0317**	**0.0493**	**0.8496**	**0.5839**	**Suggested**
Cubic	0.0101	0.6334	0.9633	0.7764	Aliased

Calculations for MRR

Table 6 shows the fit summary for the material removal rate in which highest lack of fit p-value is selected as model for evaluation. From this information it is clear that quadratic model should be selected for the further calculation in which lack of fit p-value is 0.0493.

F-value of calculated quadratic MRR is 12.70 which entails given quadratic representation for MRR is valuable. A chance in variation is 0.01% in F-value for MRR which is caused by noise. The probability (p-values) 0.0500 which is less than F-value indicates that model term is significant. Probabilities which are greater than 0.1000 entails insignificance terms. Significance F-value for Lack of Fit with respect to pure error is 4.77 for model. A chance of 4.93% is in variation of F-value of Lack of Fit which is only caused by noise. ANOVA table for the diminished quadratic model shows Spark current, pulse on time and second order of voltage has significant effect on MRR which is shown in Table 7.

Table 7. ANOVA Table for MRR

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	257.11	14	18.36	12.70	< 0.0001	significant
A-spark current	124.64	1	124.64	86.22	< 0.0001	
B-pulse on time	52.43	1	52.43	36.26	< 0.0001	
C-% duty cycle	5.75	1	5.75	3.98	0.0646	
D-voltage	50.42	1	50.42	34.88	< 0.0001	
AB	2.33	1	2.33	1.61	0.2234	
AC	0.0001	1	0.0001	0.0001	0.9931	
AD	0.6131	1	0.6131	0.4241	0.5248	
BC	0.0392	1	0.0392	0.0271	0.8714	
BD	0.0964	1	0.0964	0.0667	0.7997	
CD	0.3114	1	0.3114	0.2154	0.6493	
A^2	0.9772	1	0.9772	0.6759	0.4239	
B^2	15.30	1	15.30	10.58	0.0054	
C^2	2.34	1	2.34	1.62	0.2228	
D^2	0.7232	1	0.7232	0.5002	0.4902	
Residual	21.69	15	1.45			
Lack of Fit	19.63	10	1.96	4.77	0.0493	significant
Pure Error	2.06	5	0.4116			
Cor Total	278.79	29				

Determination coefficient R^2 entails about the integrity of model fitness. Calculated value of R^2 is 0.9222 for the quadratic model for MRR. This value of R^2 entails that 92.22% experimental data conforms the predicted model report. The model is unable to explain only 7.78% of total variation. R^2 value varies between 0 and 1 which indicates the compatibility of Model. Adjusted R^2 value is 0.8496 is high value which also entails the high significance of model term for MRR. A greater precision ratio than 4 is useful which entails about the signal to noise ratio. The precision ratio value 13.549 entails an adequate signal.

The regression equation for MRR in form of actual factor is represented in eq. 3. This equation is a second order model which is able to predict a point on nonlinear contour of MRR.

$$MRR = 14.81118 + 0.255885A + 0.048794B - 6.32886C + 0.169748D$$
$$+0.000954AB - 0.000656AC + 0.004894AD + 0.000495BC - 0.000078BD$$
$$+0.013950CD - 0.011797A^2 - 0.000075B^2 + 0.292000C^2 - 0.001624D^2$$
..(3)

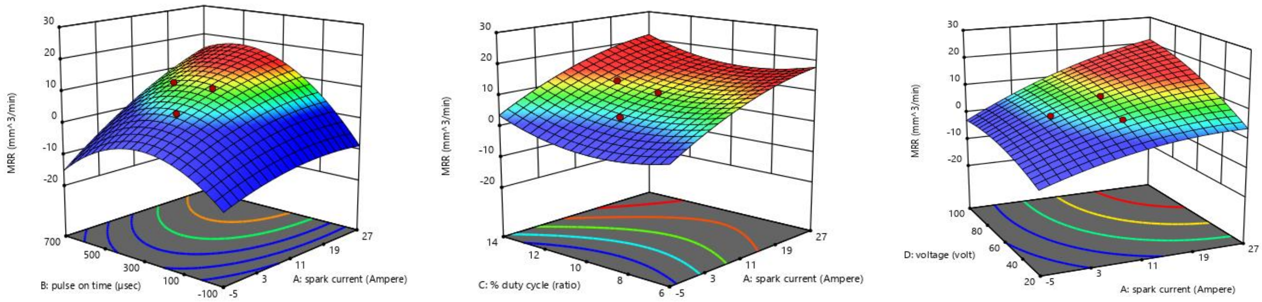

Figure 2. Surface plots for MRR V\s. input variable

Table 8 Fit summary for TWR model

Source	Sequential p-value	Lack of Fit p-value	Adjusted R²	Predicted R²	
Linear	< 0.0001	0.0383	0.6603	0.6025	
2FI	0.6547	0.0292	0.6338	0.4382	
Quadratic	**0.0002**	**0.2859**	**0.8844**	**0.7138**	**Suggested**
Cubic	0.7759	0.0845	0.8500	-2.2916	Aliased

From figure 2 it is clear that MRR increases continuously with increase in spark current because at the increased value of spark current strong sparks were generated which produces high temperature causing more material melting and evaporation. Value of MRR starts decreasing after 300µs when further increase in pulse on time. MRR varies very few till 10% duty cycle after this MRR increases with increasing slope with increase in duty cycle. This is due to at lower value of duty cycle there occurs a heat loss which does not contribute in Material removal process. With respect to voltage, MRR increase initially but after 60 volts it starts decreasing.

Calculations for TWR

Table 8 shows the fit summary for the tool wear rate in which highest lack of fit p-value is selected as model for evaluation. From this information it is clear that quadratic model should be selected for the further calculation in which lack of fit p-value is 0.2859.

F-value of calculated quadratic TWR is 16.85 which entails given quadratic representation for TWR is valuable. A chance in variation is 0.01% in F-value for TWR which is caused by noise. The probability (p-values) 0.0500 which is less than F-value indicates that model term is significant. Probabilities which are greater than 0.1000 entails non significance terms. Insignificance F-value for Lack of Fit with respect to pure error is 1.72 for model. A chance of 28.59% is in variation of F- value of Lack of Fit which is only caused by noise. ANOVA table for the diminished quadratic model shows Spark current, pulse on time and second order of voltage has significant effect on TWR which is shown in Table 9.

$$TWR = -15.43086 + 0.793944A + 0.013917B + 0.964405C + 0.166818D$$
$$-0.00367AB - 0.022270AC + 0.001649AD + 0.000647BC - 0.000099BD \quad (4)$$
$$+0.009854CD - 0.017891A^2 - 0.000014B^2 - 0.076757C^2 - 0.002011D^2$$

The regression equation for TWR in form of actual factor is represented in eq. 4. This equation is a second order model which is able to predict a point on nonlinear contour of TWR.

Table 9. ANOVA table for TWR

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	16.33	14	1.17	16.85	< 0.0001	significant
A-spark current	10.65	1	10.65	153.87	< 0.0001	
B-pulse on time	1.23	1	1.23	17.75	0.0008	

Source	Sum of Squares	df	Mean Square	F-value	p-value	
C-% duty cycle	0.0222	1	0.0222	0.3213	0.5792	
D-voltage	0.3797	1	0.3797	5.48	0.0334	
AB	0.3442	1	0.3442	4.97	0.0415	
AC	0.1270	1	0.1270	1.83	0.1957	
AD	0.0696	1	0.0696	1.01	0.3319	
BC	0.0669	1	0.0669	0.9664	0.3412	
BD	0.1554	1	0.1554	2.24	0.1549	
CD	0.1554	1	0.1554	2.24	0.1549	
A^2	2.25	1	2.25	32.46	< 0.0001	
B^2	0.5092	1	0.5092	7.35	0.0161	
C^2	0.1616	1	0.1616	2.33	0.1474	
D^2	1.11	1	1.11	16.03	0.0012	
Residual	1.04	15	0.0692			
Lack of Fit	0.8046	10	0.0805	1.72	0.2859	not significant
Pure Error	0.2340	5	0.0468			
Cor Total	17.37	29				

Determination coefficient R^2 entails about the integrity of model fitness. Calculated value of R^2 is 0.9404 for the quadratic model for TWR. This value of R^2 entails that 94.04% experimental data conforms the predicted model report. The model is unable to explain only 5.98% of total variation. R^2 value varies between 0 and 1 which indicates the compatibility of Model. Adjusted R^2 value is 0.8844 is high value which also entails the high significance of model term for TWR. A greater precision ratio than 4 is useful which entails about the signal to noise ratio. The precision ratio value 14.7249 entails an adequate signal.

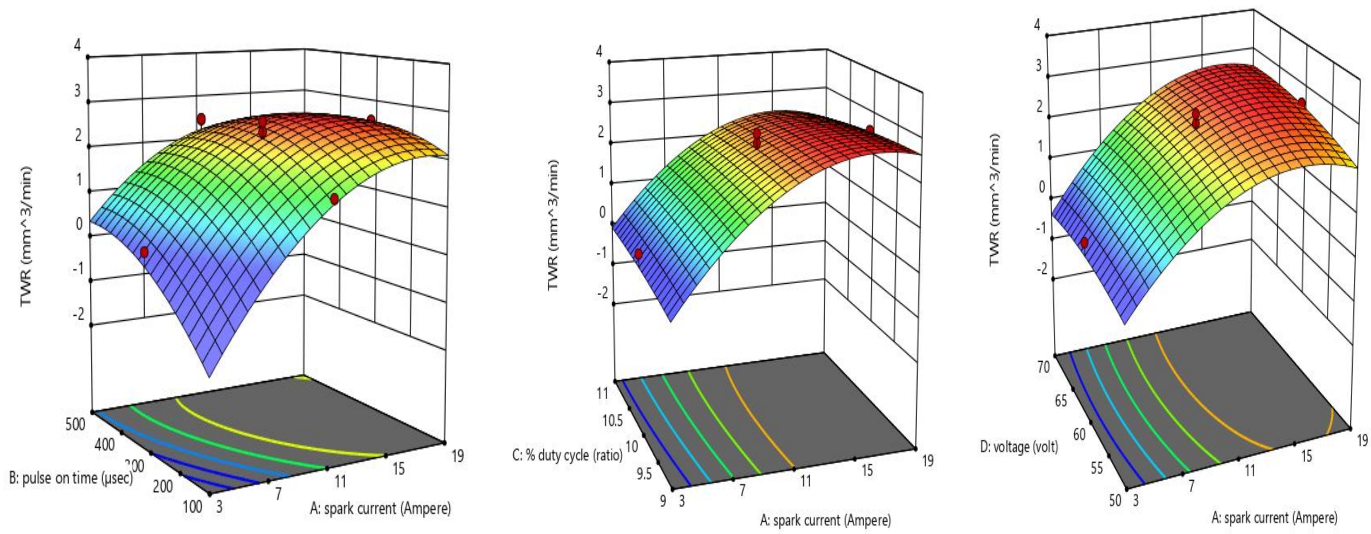

Figure 3. Surface plots for TWR V\s. input variable

From figure 3 it is clear that TWR increases continuously with a higher slope than MRR value with the increase in spark current because at the increased value of spark current strong sparks were generated which produces high temperature causing more melting and evaporation of aluminum than Inconel 686. Value of TWR starts decreasing after 300µs when further increase in pulse on time. TWR decreases with increase in duty cycle. This is due to at lower value of duty cycle there occurs a heat loss which does not contribute in tool wear process. With respect to voltage, TWR increase initially but after 60 volts it starts decreasing.

Calculations for surface roughness Ra

Table 10 shows the fit summary for the surface roughness in which highest lack of fit p-value is selected as model for evaluation. From this information it is clear that quadratic model should be selected for the further calculation in which lack of fit p-value is 0.1315.

F-value of calculated quadratic Ra is 7.60 which entails given quadratic representation for Ra is valuable. A chance in variation is 0.02% in F-value for Ra which is caused by noise. The probability (p-values) 0.0500 which is less than F- value indicates that model term is significant. Probabilities which are greater than 0.1000 entails non significance terms. Insignificance F-value for Lack of Fit with respect to pure error is 2.83 for model. A chance of 13.15% is in variation of F- value of Lack of Fit which is only caused by noise. ANOVA table for the diminished quadratic model shows Spark current, pulse on time and second order of voltage has significant effect on Ra which is shown in Table 11.

Determination coefficient R^2 entails about the integrity of model fitness. Calculated value of R^2 is 0.8764 for the quadratic model for Ra. This value of R^2 entails that 87.64% experimental data conforms the predicted model report. The model is unable to explain only 12.36% of total variation. R^2 value varies between 0 and 1 which indicates the compatibility of Model. Adjusted R^2 value is 0.7610 is high value which also entails the high significance of model term for Ra. A greater precision ratio than 4 is useful which entails about the signal to noise ratio. The precision ratio value 12.9433 entails an adequate signal.

Table 10 Fit summary for Ra model

Source	**Sequential p-value**	**Lack of Fit p-value**	**Adjusted R^2**	**Predicted R^2**	
Linear	< 0.0001	0.0664	0.6371	0.5395	
2FI	0.9376	0.0401	0.5617	0.3422	
Quadratic	**0.0095**	**0.1315**	**0.7610**	**0.3683**	**Suggested**
Cubic	0.0317	0.8085	0.9162	0.7358	Aliased

Table 11. ANOVA Table for Ra

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	139.99	14	10.00	7.60	0.0002	significant
A-spark current	100.86	1	100.86	76.63	< 0.0001	
B-pulse on time	5.61	1	5.61	4.26	0.0568	
C-% duty cycle	3.23	1	3.23	2.45	0.1383	
D-voltage	0.0600	1	0.0600	0.0456	0.8338	
AB	2.25	1	2.25	1.71	0.2107	
AC	0.3600	1	0.3600	0.2735	0.6086	
AD	0.0225	1	0.0225	0.0171	0.8977	
BC	0.4900	1	0.4900	0.3723	0.5509	
BD	0.4225	1	0.4225	0.3210	0.5794	
CD	0.5625	1	0.5625	0.4274	0.5232	
A^2	23.96	1	23.96	18.20	0.0007	
B^2	2.63	1	2.63	2.00	0.1780	
C^2	0.1962	1	0.1962	0.1491	0.7048	
D^2	0.0768	1	0.0768	0.0584	0.8124	
Residual	19.74	15	1.32			
Lack of Fit	16.77	10	1.68	2.83	0.1315	not significant
Pure Error	2.97	5	0.5936			
Cor Total	159.73	29				

$$Ra = -17.10654 + 1.19755A + 0.005346B + 2.24583C + 0.188062D$$
$$+0.000937AB + 0.037500AC - 0.000937AD + 0.001750BC - 0.000162BD$$
$$-0.018750CD - 0.058411A^2 - 0.000031B^2 - 0.084583C^2 + 0.000529D^2 \qquad \text{………} \qquad \text{……5}$$

The regression equation for Ra in form of actual factor is represented in eq. 5. This equation is a second order model which is able to predict a point on nonlinear contour of Ra.

From figure 4 it is clear that Ra increases continuously with a higher slope than MRR value with the increase in spark current because at the increased value of spark current strong sparks were generated which produces high temperature causing more melting and evaporation of material and produces rough surfaces. Surface roughness starts decreasing after 300µs when further increase in pulse on time. Surface roughness increases with increase in duty cycle. This is due to at lower value of duty cycle there occurs a heat loss which does not contribute in material removal process. With respect to voltage, Surface roughness increase initially but after 60 volts it starts decreasing.

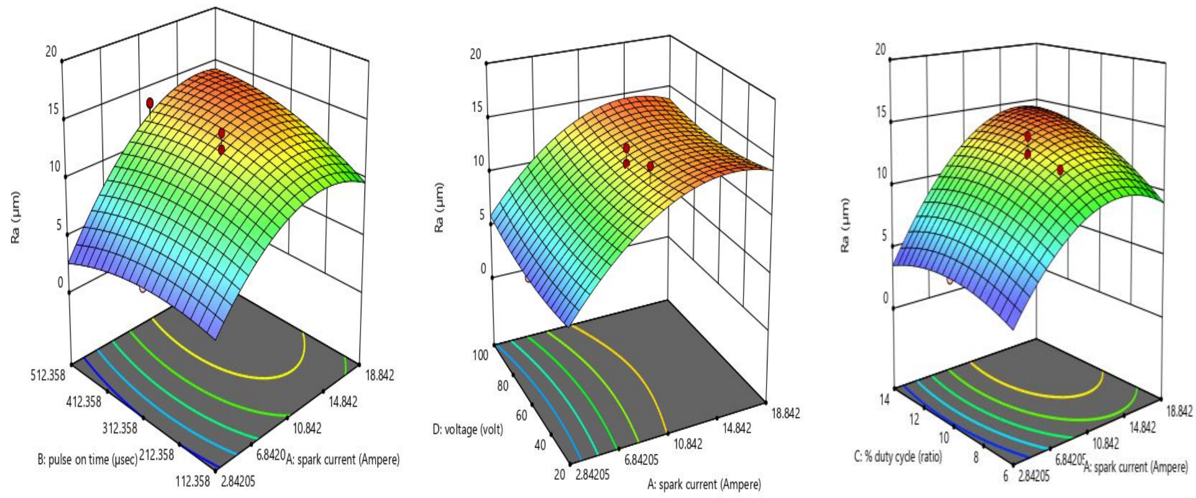

Figure 4. Surface plots for TWR V\s. input variable

RESULTS

The optimum parameter for combined setting is spark current 7.000 Ampere, pulse on time 400.000µs, % duty cycle 9.000 and voltage 70.000 which selected out of 100 possible solution depending on desirability value. For prediction and Verification of the optimal settings confirmation experiments were carried out. The results of confirmation experiments relate good with the predicted optimal settings. It has been found an error of 5.68%, 14.58% and 9.87% for MRR, TWR and surface roughness Ra respectively, which confirms excellent reproductively of experimental conclusion.

CONCLUSION

In the present study effect of input variable spark current, pulse on time, % duty cycle and voltage are measured on machining response MRR, TWR and Ra of Inconel 686 material using an aluminum electrode for an EDM process. The experiments were conducted under various levels of the input parameters. The models for MRR, TWR and Ra were developed using regression analysis of input output relationships of independent variables in response surface methodology. The trend of MRR, TWR and Ra were predicted satisfactorily for the response surface plots of individual Model. It is stated from the investigation that central composite design gives the powerful result of experimental values by plotting experimental diagram and statistical mathematical models, by which an experimenter can perform the experiments efficiently and economically.

The developed second order model for these variable entails that the input parameter spark current, pulse on time, %duty cycle and voltage significantly affects the MRR, TWR and Ra. The MRR increase throughout the range, but TWR and Ra first increases than starts decrease after some times with respect to spark current. MRR, TWR and Ra firstly increase and start decreasing after some time with respect to pulse on time at a specified value. A combined optimum value of MRR=7.638 $mm^3/\min$, TWR=1.076 $mm^3/\min$ and Ra=9.183µm is found with a combination of spark current=7A, pulse on time= 400µs, % duty cycle=9 and voltage=70V with experimental range.

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