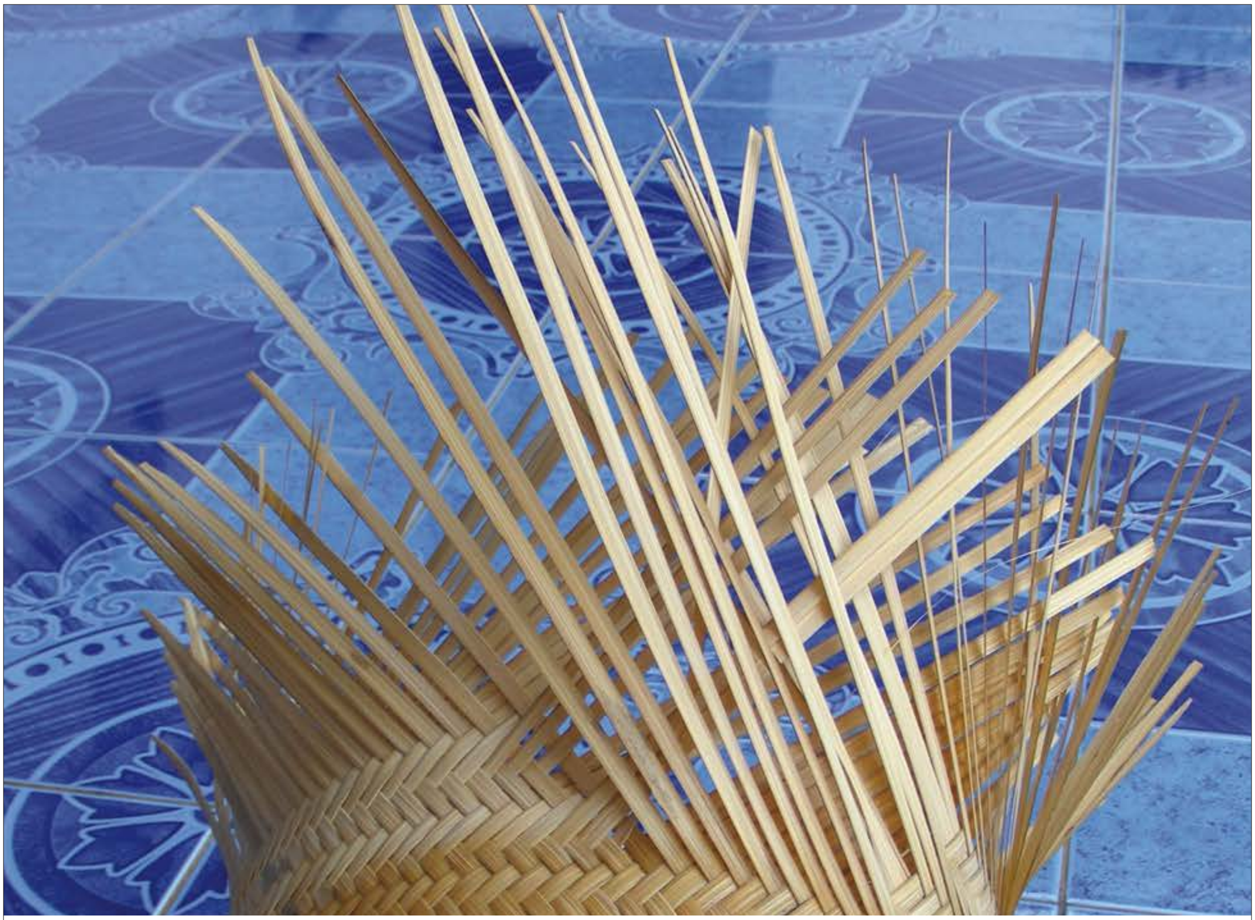

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Modeling and Analysis of Material Removal Rate During Electro Discharge Machining of Inconel 718 under Orbital Tool Movement

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ABSTRACT

In electro discharge machining, it is possible to decouple the size of tool electrode from the desired size of cavity by actuating the tool electrode on orbital trajectory. In present study, experimental investigation based on Taguchi experimental design is carried out to study the effect of orbital parameters along with machine parameters during orbital EDM process. Copper is used as tool electrode for machining of a nickel based superalloy material viz., Inconel 718. The empirical model has been developed using linear regression analysis by applying logarithmic data transformation of non linear equation. The prediction based on the above developed model has been verified with another set of experiments and are found to be in good agreement with the experimental results. Further, analysis of the results has been carried out using signal-noise ratio formulae and ANOVA to identify the significant parameters and their degree of contribution in the process output.

Key words: EDM, Orbital tool movement, orbital radius, orbital speed, Taguchi approach, orthogonal array, S/N ratio, empirical modeling, regression analysis

INTRODUCTION

In recent times, nickel based alloys like Inconel 718 are gaining importance in making of gas turbines, space crafts, rocket motors, nuclear reactors etc. These classes of materials, being strong, light weight and aesthetic in appearance represent an excellent choice specifically for construction of aerospace components (Habeeb *et al.*, 2008). However, nickel based super alloys are among the work materials with the lowest machinability properties. They are specifically designed to retain high strength at elevated temperatures due to which higher cutting forces are encountered as compared to steel. The low thermal conductivity of nickel alloys give rise to high temperatures as compared to steel material is another issue. These lead to difficulty in machining of these alloys using conventional techniques (Shaw, 1997). As a result, EDM process becomes a natural choice for machining of nickel based super alloys. Electro Discharge Machining (EDM) is one of the most successful, profitable and extensively used non conventional machining processes for high degree of dimensional accuracy and economical cost of production of any conductive material irrespective of its hardness. It is particularly advantageous in manufacturing of moulds, dies, automotive, aerospace and surgical components owing to its unique feature of using thermal energy to machine electrically conductive parts regardless of its hardness (Ho and Newman, 2003).

In EDM process, Material removal and its mechanism has been one of the main concerns for several years. Since the development of this process, researchers have explained the material removal mechanism by developing different thermal models by considering relationship between pulse conditions and material removal by solving time dependent heat transfer equations based on various assumptions based on different heat source models (Snoeys and van Dijck, 1971; Snoeys *et al.*, 1972; Erden and Kaftanoglou, 1981; Patel *et al.*, 1989). All of these and most of the many other theoretical models are concerned with die sinking EDM process which shows large discrepancy between the predictions and the experimental results due to simplified and unavoidable assumptions. Many attempts have been made in recent past to develop empirical models for EDM process (Pei-Jen and Kuo-Ming, 2001; Dhar *et al.*, 2007; Doniavi *et al.*, 2008; Sarkar *et al.*, 2008; Chattopadhyay *et al.*, 2009).

However, literature related to the study of EDM process under orbital tool actuation is limited. Most of the reported literature is based on the study of process capabilities of orbital EDM as compared to cavity sinking EDM (Rajurkar and Royo, 1989a, b; Yu *et al.*, 2002; Bamberg *et al.*, 2005; El-Taweel and Hewidy, 2009). These researchers and many others (Rahman *et al.*, 2011) have attempted to work on various grades of steel and very few have attempted to work on superalloy metal. No attempt to develop theoretical and/or empirical model considering orbital tool movement has been reported to the best of the authors' knowledge. The present study is an attempt to bridge this gap. In this paper, a systematic and simplified approach is used for model development and analysis of MRR with various machining parameters and orbital parameters. Taguchi based experimental approach has been employed to design the experimental plan.

ORBITAL EDM

Orbital tool actuation in EDM process helps to decouple the size of the electrode from the size of the feature to be machined. An electrode that is significantly smaller than the cavity to be generated can be actuated on a tool path that will articulate its outer surface on a trajectory equal to the shape of the hole. Hence, a standard electrode can be used to drill a wide range of holes while the increased clearance between the hole and the electrode helps getting the dielectric fluid to the bottom of the hole. The use of a small size of standard electrodes instead of matched electrodes for every single hole size drastically reduces tooling efforts. The improved flushing will reduce recasting of removed material which tends to diminish surface quality (Guitrau, 1997).

Joemars make ZNC EDM with orbit cut mechanism is used in present study. The machine has the capability to control Z-axis movement with precision upto 1 μm. The orbital cut mechanism can control X and Y axis movement independently with same precision.

In present study, orbital movement is actuated along helical path as shown in Fig. 1. Over and above this, the mechanism has a capability to initiate the movement on orbital path at 10 different speeds ranging between 0.04 to 0.36 mm $\sec^{-1}$ at the central point of electrode.

EXPERIMENTAL DETAILS

Workpiece and tool electrode: Inconel 718 is taken as work piece materials and electrolyte copper is taken as electrode material. The properties and compositions of Inconel 718 are summarized in Table 1.

The work piece is cut into the size of 13×13×10 mm. Two work pieces are clamped together as shown in Fig. 2 and hole is drilled at the interface of two polished surfaces of the work piece. The

Table 1: Chemical composition of Inconel 718

C	Cr	Co	Cu	Fe	Mn	Mo	Ni	Nb	Ti	P	S	Si
0.03	17.429	0.236	0.031	19.903	0.046	2.833	52.133	5.042	1.141	0.005	0.004	0.117

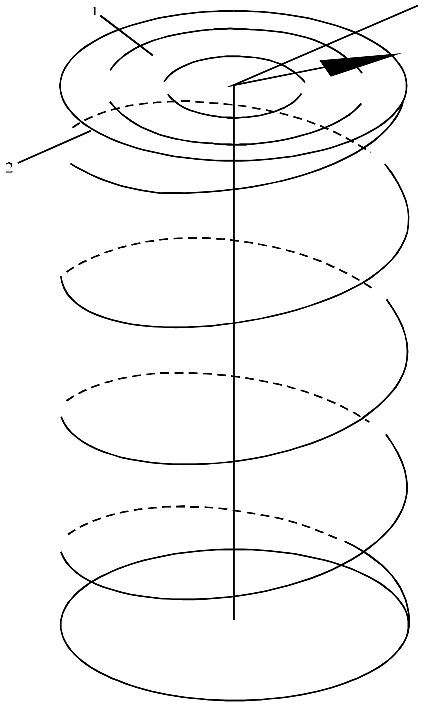

Fig. 1: Helical path traced during orbital tool actuation

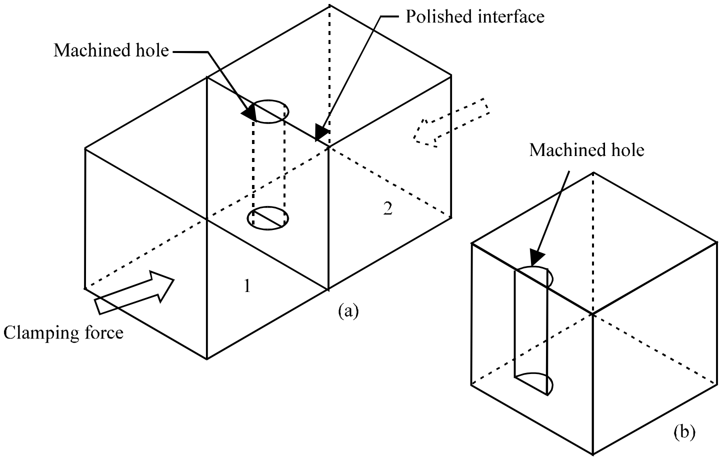

Fig. 2(a-b): Work piece design and method of application

split work piece enables easy separation after machining and hence opens the internal surface for further study.

Copper electrode is fabricated to a length of 20 mm with varying diameter of 5, 6, 7, 8 and 9 mm. Each tool with a specific diameter is given orbital movement at a orbital radius so as to

Table 2: Parameters and their level

Parameter	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Orbital radius R_o	mm	0.50	1.00	1.50	2.00	2.50
Orbital speed S_o	mm s^{-1}	0.05	0.07	0.09	0.11	0.13
Current I	A	9.00	13.00	17.00	21.00	28.00
Gap voltage V_g	V	40.00	55.00	70.00	85.00	100.00
Pulse on time t_{on}	µs	93.00	165.00	240.00	315.00	385.00
Duty factor DF	--	00.40	0.50	0.60	0.70	0.80

split generate a circular hole of 10 mm diameter upto a depth of 10 mm. Commercially available dielectric fluid is used during the experiments.

Parameter selection: The process parameters chosen for the present experiment are: (A) Orbital Radius R_o, (B) Orbital Speed S_o, (C) Current I, (D) Gap Voltage V_g, (E) Pulse ON time t_{on} and (F) Duty Factor DF. These parameters were selected because they can potentially affect Material Removal Rate during EDM operation. The machining conditions and number of levels of the parameters are selected as given in Table 2.

Response selection: MRR (mm^3/min) is calculated by weight difference of the work piece before and after machining using a precision weighing machine (maximum capacity = 300 g, least count = 1 mg).

The Equation used for calculating MRR is as under:

$$\mathrm{MRR} = \frac{(W_{w_i} - W_{w_f})}{\rho_w \times t} \tag{1}$$

where, W_{wi} and W_{wf} are initial and final weights of work piece, respectively; ñ$_w$ is density (g mm^{-3}) of work piece and t is the machining time (min).

The objective of this experimental study is to determine the machining conditions required to achieve maximum Material Removal Rate (MRR) under orbital tool motion in EDM process. Therefore, quality characteristic of larger the better (LB) for MRR is implemented in this study. The S/N ratio (η) is calculated using the Eq.2 given as under:

For LB characteristics:

$$\eta_i = -10\log_{10}\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y_{ij}^2}\right) \tag{2}$$

where, y_{ij} is the response of ith quality characteristics at jth experimental run and n is the total number of repetition of a run.

The experimental plan is designed as per L 25 orthogonal array which considers 6 parameters each at 5 levels. The experimental plan is shown in Table 3. All experimental runs have been conducted twice for effective S/N ratio calculation. The mean and S/N ratio of MRR are also shown in Table 3.

Table 3: L 25 table and observed values

	Experimental plan						MRR ($m\ min^{-3}$)			
	A	B	C	D	E	F	Experimental			
Exp. No.	R_o	S_o	I	V_g	t_{ON}	DF	Trial 1	Trial 2	S/N ratio (η)	Mean value
1	0.5	0.05	9	40	93	0.4	12.889	12.315	22.002	12.602
2	0.5	0.07	13	55	165	0.5	23.629	22.322	27.215	22.976
3	0.5	0.09	17	70	240	0.6	34.905	36.452	31.042	35.679
4	0.5	0.11	21	85	315	0.7	44.465	44.431	32.957	44.448
5	0.5	0.13	28	100	385	0.8	57.472	61.229	35.455	59.351
6	1	0.05	13	70	315	0.8	23.557	23.298	27.394	23.428
7	1	0.07	17	85	385	0.4	20.903	20.551	26.330	20.727
8	1	0.09	21	100	93	0.5	29.518	28.552	29.255	29.035
9	1	0.11	28	40	165	0.6	29.865	26.925	29.030	28.395
10	1	0.13	9	55	240	0.7	15.016	15.764	23.737	15.390
11	1.5	0.05	17	100	165	0.7	22.769	22.073	27.010	22.421
12	1.5	0.07	21	40	240	0.8	25.434	18.442	26.492	21.938
13	1.5	0.09	28	55	315	0.4	29.089	28.831	29.236	28.960
14	1.5	0.11	9	70	385	0.5	9.605	9.617	19.655	9.611
15	1.5	0.13	13	85	93	0.6	14.291	14.213	23.077	14.252
16	2	0.05	21	55	385	0.6	24.893	24.292	27.814	24.593
17	2	0.07	28	70	93	0.7	31.588	31.873	30.029	31.731
18	2	0.09	9	85	165	0.8	11.291	11.466	21.121	11.379
19	2	0.11	13	100	240	0.4	12.137	11.605	21.483	11.871
20	2	0.13	17	40	315	0.5	17.511	17.172	24.781	17.342
21	2.5	0.05	28	85	240	0.5	20.611	21.035	26.370	20.823
22	2.5	0.07	9	100	315	0.6	7.863	7.708	17.824	7.786
23	2.5	0.09	13	40	385	0.7	11.777	12.033	21.513	11.905
24	2.5	0.11	17	55	93	0.8	11.611	11.164	21.124	11.388
25	2.5	0.13	21	70	165	0.4	14.540	14.230	23.157	14.385

EMPIRICAL MODELING OF ORBITAL EDM PROCESS

Empirical expressions have been developed for evaluating the relationship between input and output parameters. The mean output values for MRR are used to construct the empirical expressions.

The functional relationship between a dependent output parameter viz., MRR with the input independent parameters viz., orbital radius, orbital speed, current, gap voltage, pulse ON time and duty factor can be postulated using the following Eq. 3:

$$Y = A(X_1)^a(X_2)^b(X_3)^c(X_4)^d(X_5)^e(X_6)^f \tag{3}$$

where, Y is a dependent parameter viz., MRR; X1, X2, X3, X4, X5 and X6 are independent parameters viz., orbital radius, orbital speed, current, gap voltage, pulse ON time and duty factor; a,b,c,d,e and f are power indices of the respective terms and A is a constant.

The above non linear Eq. 3 can be converted into linear form by logarithmic transformation of Eq. 4 as under:

$$\text{Log } Y = \text{Log } A + a.\log(X_1) + b.\log(X_2) + c.\log(X_3) + d.\log(X_4) + e.\log(X_5) + f.\log(X_6) \tag{4}$$

The above Eq. 4 can be rewritten as under:

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 \tag{5}$$

where, $\hat{y}$ is the true value of the dependent machining output on a logarithmic scale; x_1, x_2, x_3, x_4, x_5 and x_6 are the logarithmic transformations of the different input parameters; $\boldsymbol{\beta}_0$, $\boldsymbol{\beta}_1$, $\boldsymbol{\beta}_2$, $\boldsymbol{\beta}_3$, $\boldsymbol{\beta}_4$, $\boldsymbol{\beta}_5$ and $\boldsymbol{\beta}_6$ are the corresponding parameters to be estimated.

Gauss Newton algorithm has been used to estimate the parameters of the above first order model using the data shown in Table 3. The developed empirical model for MRR is given below:

$$\text{MRR} = 0.549\left[\frac{I^{0.885}.V^{0.203}T_{on}^{0.058}.DF^{0.335}}{r_o^{0.479}.S_o^{0.103}}\right] \tag{6}$$

The predicted MRR for each experiment have been calculated and verified for the closeness between actual and predicted values. The adequacy of the empirical model presented in Eq. 6 is checked and validated by the mean error (E_{mean}), Standard deviation (σ_{dev}) or Root mean square error and average percentage error (E_{avg}) which, are given as under:

$$E_{mean} = \frac{1}{n}\sum_{i=1}^{n}(X_i - X) \tag{7}$$

$$\sigma_{dev} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \mu)^2} \tag{8}$$

where:

$$\mu = \frac{1}{n}\sum_{i=1}^{n}X_i$$

$$E_{avg} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - X}{X_i}\right)\times 100 \tag{9}$$

where, X_i is the ith result obtained from the model and X is the corresponding experimental result, n is the total number of observations considered in present case i.e., 25.

The value of E_{mean} is found to be -0.042 and the value of E_{avg} (%) is found as 0.46%. These values show that the model is very well suited for predicting MRR in EDM during orbital tool actuation.

Further, the observations of M.R.R. for Inconel 718 are checked for existence of any objectionable data points which may be rejected using Chauvenet's criterion (Taylor, 1997) which, states that "An observation may be rejected if the probability of obtaining the particular deviation from the mean is less than 1/2n".

Based on Chauvenet's criterion, it is found that there is no observation in AISI 304 required to be rejected. However, one observation in Inconel 718 is rejected. Hence, the revised standard deviation comes out to be 9.41 which, are better than the standard deviation shown in Table 4.

Table 4: Adequacy check of empirical model

Criteria	Inconel 718
E_{mean}	-0.042
E_{avg} (%)	0.46
σ_{dev}	11.64
No. of rejected readings	1.00
Revised σ_{dev}	9.41

Table 5: ANOVA for MRR of Inconel 718

Factor	Degree of freedom	Sum of squares	Mean square	F	p-value
A: Orbital radius	4	164.127	41.032	24.01	<0.001
B: Orbital speed	4	$7.563^{\#}$	1.8907	--	--
C: Current	4	247.788	61.9470	36.25	0.000
D: Gap voltage	4	$7.381^{\#}$	1.8453	--	--
E: Pulse ON	4	$5.564^{\#}$	1.3910	--	--
F: Duty factor	4	18.972	4.7430	2.78	0.078
Error	0				
Total	24	451.395	18.8083		
Pooled error	12	20.508	1.709		

Thus, it can be noted that the proposed empirical model also fits well with the observations recorded during Taguchi approach based experiments. This is evident from very less average error found in the models.

ANALYSIS OF VARIANCE (ANOVA)

The basic idea behind analysis of variance is to breakdown total variability of the experimental results into components of variance and then to assess their significance by comparing them with the residuals. The F-test is carried out to compare the variance attributed to a particular factor effect with the variance attributed to the residual (Montgomery, 1997). Standard values of F can be obtained from standard tables of statisticians depending on the desired confidence level. If the calculated F ratio values exceed the standard values, then the contribution of the respective input parameter is considered to be significant. In present case, analysis of variance has been carried out based on the theory proposed by Phadke (1989).

The main effect plot for MRR of Inconel 718 is shown in Fig. 3 and the ANOVA table for MRR of Inconel 718 is given in Table 5.

From Fig. 3, it is found that best MRR is obtained at minimum orbital radius of 0.5 mm. In present study, variation in orbital radius is taken in such a way that final dimension of the generated cavity remains same. Thus, when orbital radius increases, there is reduction in tool diameter. It is observed that as the orbital radius increases (i.e., tool electrode diameter reduces), there is sharp reduction in MRR. When orbital radius is more, there is relatively more open space available between the circumference of tool and cavity being generated. Thus, the side gap across periphery is not uniform which results in to reduction in effective sparks occurring around the electrode cylindrical surface. Further, there is improvement in flushing due to large space available between tool and workpiece surfaces. This results in faster removal of eroded particles. This reduces the occurrence of secondary sparks which generally contribute in high MRR during cavity sinking EDM.

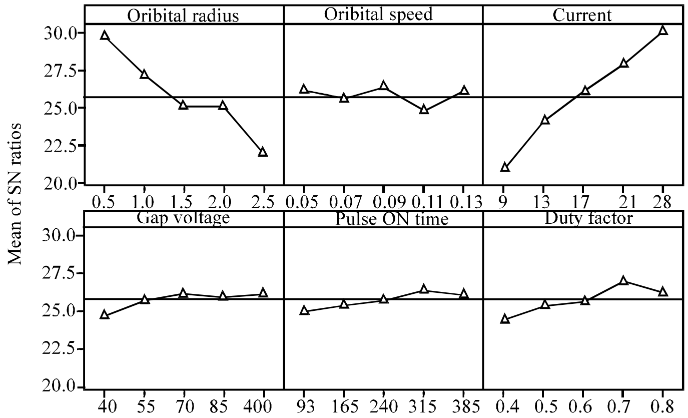

Fig. 3: Main effect plot for MRR of Inconel 718

From the Table 5, it is found that current is the single most significant parameter that affects MRR followed by orbital radius. Thus, it can be seen that just as cavity sinking EDM, current remains the most significant parameter in orbital EDM. Orbital radius proves to be more significant parameter than any other machining parameters which lead to the fact that orbital radius can greatly affect MRR.

CONCLUSION

Attempt has been to study the effect of orbital parameters viz., radius and speed during EDM process by carrying out experiments based on Taguchi approach. Empirical model has been developed for predicting MRR which matches well with the experimental results. Thus, it can be used for MRR prediction in selected range of process parameters.

The significance of parameters involved has been checked through ANOVA technique. It is found that current along with orbital radius have significant effect on MRR.

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