Application of Box Behnken Design to Model Crater Size Generated during Micro-EDM of NI-X Alloy

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***Abstract*—This paper aims to implement Box Behnken experimental design along with response surface methodology for modelling the effect of machining parameters on the crater sizes during micro-EDM of Ni based alloy using carbide tools. The Box-Behnken design was exploited to design the experimental design array using the machining parameters, such as capacitance, voltage and tool rotational speed. Blind micro-holes were machined on the surface of Ni alloy. An important machining performance parameter crater size was observed and calculated using scanning electron microscope (SEM) image, and the mathematical model was developed by the Minitab software to predict the crater size. In addition, response surface plots were generated from the model using GNU Plot to show the effect of operating parameters and their interactions on performance parameter. The predicted values from the mathematical model were in good agreement with the experimental measurement of crater sizes. This study concludes that Box-Behnken design and response surface methodology could efficiently be applied to generate a model for calculating crater size created during micro EDM when the discharge energy is not so low.**

***Index Terms*— Micro-EDM, Nickel (Ni) alloy, Crater size, Micro hole, Box Behnken design**

I. Introduction

Nickel (Ni) alloys are known for their high temperature and corrosion resistance characteristics which make their application inevitable in the aerospace and aircraft industries. Despite of these beneficial properties, Ni alloys impose significant challenges during the machining process due to its low thermal conductivity [1]. Conventional machining of Ni-based alloys is limited by the fact that low thermal conductivity leads to heat accumulation on the tool rake face, which accelerates tool wear and deteriorate the surface finish. Furthermore, the work hardening characteristics and thermal affinity of Ni alloys towards the cutting tools cause welding between the tool and workpiece, and make the machining of Ni-alloys even harder [2]. In order to avoid, all these limitations associated with conventional machining of Ni alloy, non-conventional machining, such as, electro-discharge machining (EDM) has been exploited in the industry since several years. With the miniaturization of the product, and increased demand for micro scale parts and components, micro-EDM becomes popular recently because of its capabilities to fabricate micro-holes and other complex micro-features. The major advantage of micro-EDM process over mechanical micromachining processes is that it is considered as a non-contact machining process which is free from chatter, vibration and cutting forces [3-5]. Micro-EDM has been found to be useful in particular for the applications having restrictions on dimensional accuracy and complex geometries. In the micro-EDM process, the material is removed by electro-thermal discharge energy which comes in the form of sparks. The material is removed by each single spark in the form crater. Therefore, the crater sizes are dependent on the discharge energy and other machining parameters of micro-EDM. The crater size also defines the surface roughness of the machined surface.

There have been several research studies done on the machinability of different Ni alloys using both macro and micro scale EDM. Many of the studies on micro-EDM of Ni based alloy focused on investigating the effect of machining parameters on the surface integrity, material removal rate, and tool wear ratio [6-8]. There have been few studies that focused on the fabrication of micro-structures on the Ni alloys using the micro-EDM process [9, 10]. In addition, there have been few studies on the development of hybrid machining processes combining micro-EDM with other micromachining processes in ordert o improve the machinability of Ni alloy in micro-EDM [11] Besides experimental studies, statistical analysis has also been carried out to optimize the machining parameters and to study the influence of various parameters on micro-EDM performance [12]. Although there have been several studies on machining of blind and through micro-holes using micro-EDM, very

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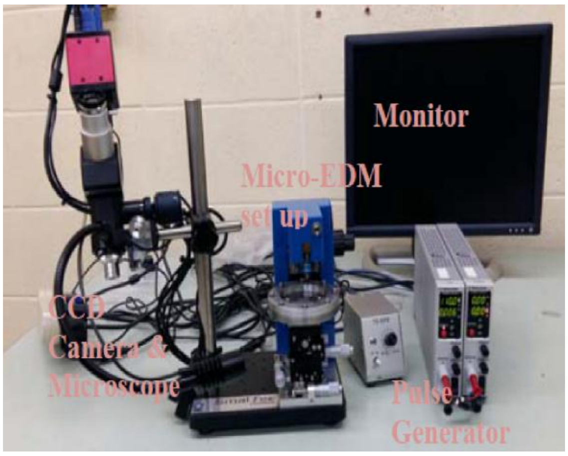
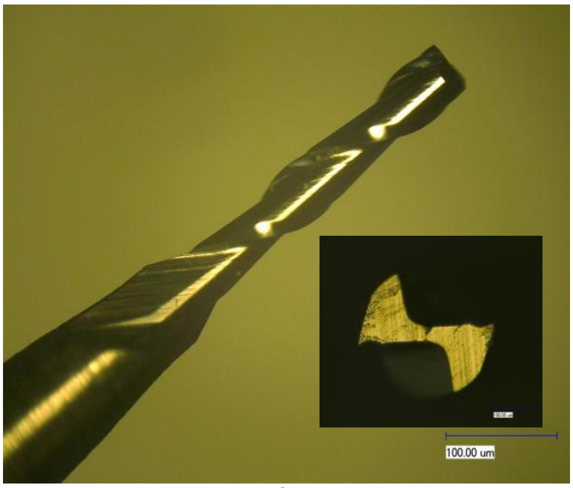
few studies attempted to machine micro holes on Ni -based alloy using carbide micro end mill, which could provide better gap conditions for EDM debris removal due to the tool geometry. In addition, very few studies focused on modeling the crater sizes generated during micro-EDM, which plays an important role in determining the roughness of the machined surface. Therefore, in this study, Box Behnken design using three levels of machining parameters was used to design and conduct experiment on Ni-X alloy. The crater size on the machined surface was measured for each experiment using SEM, and analyzed as a function of voltage, capacitance and tool rotational speed. The aim of this study is to establish functional relationship between micro-EDM input variables and generated crater size on the machined surface.



(a)



(b)

Figure 1. (a) Experimental set up, and (b) commercial carbide tool as electrode.

II. Experimental Details

A desktop micro-EDM machine tool manufactured by SmalTech was deployed in this study to carry out the experiments. The experimental setup and tool electrode (carbide end mill) used in this study are shown in Fig. 1. The experimental details used in this study are provided in Table I. Using experimental condition from Table I, a series of blind micro-holes of 30µm depth were machined on Ni workpiece using tungsten carbide milling tools. Resistor–capacitor (RC)-type pulse generator included in the EDM machine provides the required discharge energy for micro-EDM. In RC-type pulse generator, this discharge energy is calculated as half of the product of capacitor and voltage. Therefore, voltage and capacitor were the core electrical parameters varied in this study. After conducting the experiments; Ni samples were cleaned using ethanol, normal tap water, and deionized water sequentially in order to analyse the machined surface using SEM. Finally, the images of the craters on the machined surface were captured using SEM techniques and was measured in-situ from the images. The Box-Behnken design with coded values for crater sizes are presented in Table II.

TABLE I. Level of Variables Chosen for the Design

Variables	symbol	Coded variable level		
		Low	Center	High
		-1	0	+1
Capacitance(pF)	X_1	30	1000	4700
Voltage	X_2	60	85	110
Tool Rotation(RPM)	X_3	1000	2000	3000

TABLE II. Box-Behnken Design with Coded Values for Crater Size

Run no	Actual coded level of variables			Crater size	
	X_1	X_2	X_3	Experimental	Predicted
1	-1	-1	0	0.272	1.383
2	+1	-1	0	9.81	8.504
3	-1	+1	0	0.392	1.7
4	+1	+1	0	15.67	14.56
5	-1	0	-1	0.38	-1.412
6	+1	0	-1	7.87	7.263
7	-1	0	+1	0.53	-0.098
8	+1	0	+1	8.18	9.97
9	0	-1	-1	0.58	1.260
10	0	+1	-1	1.41	1.896
11	0	-1	+1	0.59	0.104
12	0	+1	+1	6.52	5.84
13	0	0	0	4.84	4.84
14	0	0	0	4.84	4.84
15	0	0	0	4.84	4.84

III. Response Surface Methodology

Response surface methodology is basically an optimization tool which consist of collection of statistical and mathematical methods based on the fit of polynomial equation to the experimental data. This method is especially useful for empirical modelling and evaluating problems relevant to engineering. Using this technique, it is quite possible to optimize not only the response surfaces which is effected by various input variables but also to quantify the relationship between input parameters and achieved response surface.

The design procedure related to response surface methodology can be described as below.

(a) Firstly, it is required to design a series of experimental runs for adequate and reliable measurement of the desired response variable.
(b) Secondly, a mathematical model representing second order polynomial response surface fitting best curve is developed.
(c) Thirdly, with the help of this derived model, the optimal combination of experimental input variables to produce maximum or minimum responses will be determined.
(d) Finally, direct and interactive influence of input variables can be represented using three dimensional plots.

Surface response can be articulated as a function of all the measurable variables.

$$y = f(x_1, x_2, x_3, \ldots \ldots \ldots x_k) \tag{1}$$

here, y is the output of the system and x_i are the variables.

The actual purpose of this method is to optimize the response output variable by assuming the independent variables as continuous but controllable parameters during the experiment with insignificant errors. Later on, functional relation between input parameters and response variables will be deduced by suitable approximation. In general, a second order polynomial model is used for such case.

$$y = \alpha_0 + \sum_{i=1}^{k} \alpha_i x_i + \sum_{i=1}^{k} \alpha_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \alpha_{ij} x_i x_j + \varepsilon \tag{2}$$

Here, $x_1, x_2, \ldots x_k$ are the input variables which influence the response variable output y. $\alpha_0, \alpha_{ii}, \alpha_{ij}$ are the unknown parameters and ε is considered as random error. Now the coefficient α can be determined using least square method. Therefore, equation (2) can be rewritten again as below in the matrix form.

$$Y = aX + \varepsilon \tag{3}$$

Here, Y represents the matrix to be measured, X represents the matrix of variables that are independent. The matrix a and ε represent basically coefficient and errors. The solution of equation (3) also can be determined using matrix approach as below.

$$b = (X'X)^{-1}X'\ Y \tag{4}$$

Here, X ' represents the transpose of the matrix X and $(X'X)^{-1}$ represents the inverse of the matrix $X'X$.

In this paper, Box-Behnken design is chosen to establish the relationship between the response output and independent variables. Being second order polynomial design, Box Behnken is mainly based on three level of incomplete factorial design which is rotatable. Due to this special arrangement of Box-Behnken design levels, the number of design points increases at the same rate as with the increase of number of polynomial co-efficient. In case of three factors, this design can be built in such way that three blocks of four experiments consist of a full two factor factorial design while keeping the third factor level at zero. This design method will determine the number of experiments according to following equation [13].

$$N = k^2 + k + c_p \tag{5}$$

Here, K represents number of experimental factors, C_p represent the replicate number of the central points.

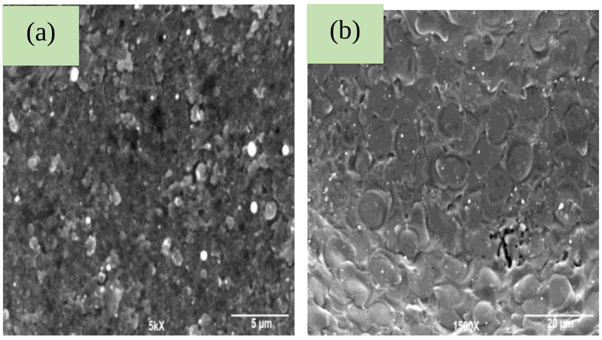
This design can be considered as spherical revolving design which can be viewed as cube and consists of a central point and the middle points of the edges. Nevertheless, it also can be viewed as three interlocking 2^2 factorial design and a central point. For three level three factorial Box-Behnken experimental design, a total of 15 experimental runs are required as can be seen in Table I. The empirical model looks like as follows.

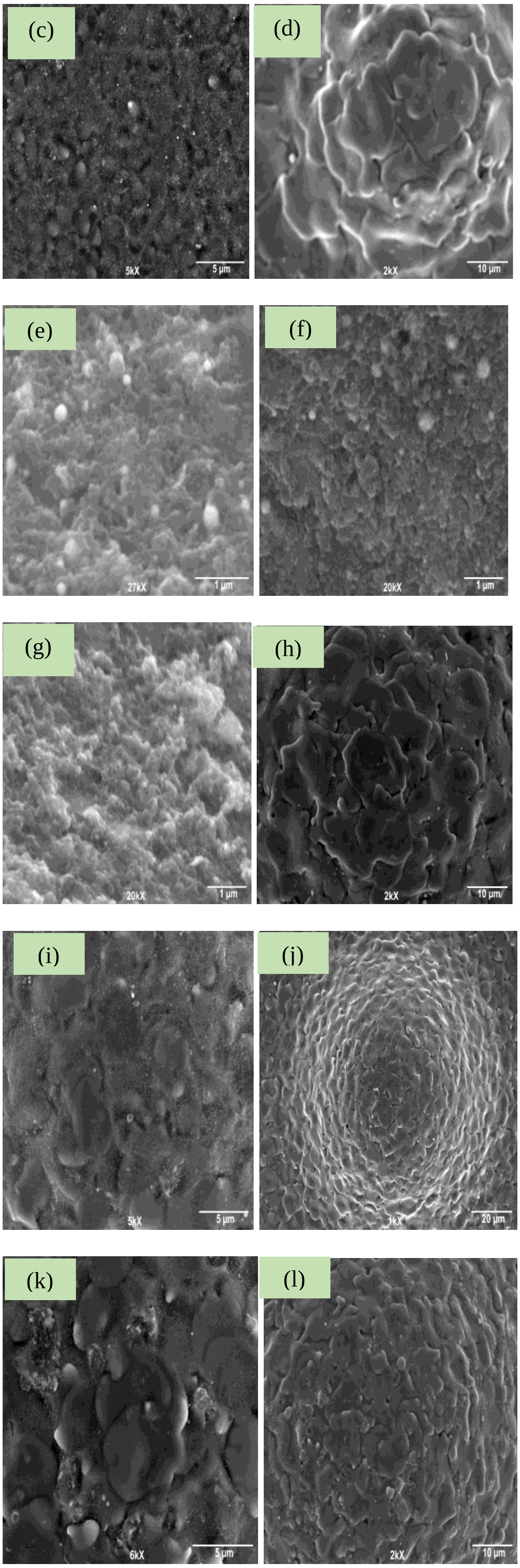
$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_{11} x_1^2 + \alpha_{22} x_2^2 + \alpha_{33} x_3^2 + \alpha_{12} x_1 x_2 + \alpha_{23} x_2 x_3 + \alpha_{13} x_1 x_3 \tag{6}$$

Here, y represents predicted response variables, α_0 represent constant for the model; x_1, x_2, x_3 represent independent input variables, $\alpha_1, \alpha_2, \alpha_3$ represent linear co-efficient, $\alpha_{12}, \alpha_{23}, \alpha_{31}$ represent cross product co-efficient and $\alpha_{11}, \alpha_{22}, \alpha_{33}$ represent quadratic co-efficient. The co-efficient α_i and α_{ij} will be computed using experimental results by Minitab software.

IV. Results & Discussion

Box Behnken design using three levels for three factors has been implemented in this study. Calculated experimental values of crater sizes using this design table and their predicted values are provided in Table II. From these experimental values provided in the Table II, second order response function for prediction of crater size can be constructed using Minitab software. The second order response equation is a function of the machining parameters capacitance, voltage and tool rotation.





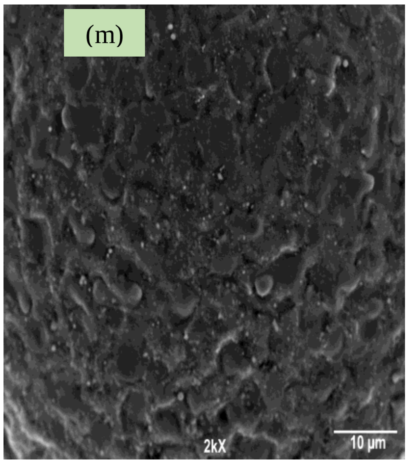


Figure 2. Scanning electron microscope images under different experimental conditions (a)Run 1 (b) Run 2 (c) Run 3 (d) Run 4 (e)Run 5(f) Run 6(g)Run 7 (h) Run 8(i) Run 9 (j) Run 10 (k) Run11 (l) Run 12 (m) Run 13

Estimated Regression equation for crater size is given below.

$$Y=4.84+4.9955X_1+1.593X_2+0.697X_3+1.831X_1*X_1-0.134X_2*X_2-2.431X_3*X_3+0.1435X_1*X_2+0.40X_1*X_3+1.275X_2*X_3 \quad (7)$$

Using this function, within the range of our experimental design, crater size was predicted. Fig. 2 shows the SEM images of the craters on the machined surfaces of Ni-alloy at different experimental conditions. As can be seen from Table II, predicted values of crater sizes are in good agreement with the experimental values measured from SEM analysis, which also indicates a good fit (R^2 value of 95% Fig. 3). However, at the lowest setting of parameters, the predicted values for crater size are scattered from the measured values. For better understanding of this Box Behnken model, predicted model is represented by surface response graph, as shown in Fig. 4. Fig. 4(a) shows the effect of capacitance and voltage on the crater size. This figure demonstrates good agreement for both the center and highest values of voltage and capacitance. However, for the lowest values of the voltage and capacitance, this model makes some overestimation. Fig. 4(b) shows the effect of capacitance and tool rotation on the crater size. As per the model, predicted crater sizes show underestimation for the lowest values of capacitance and tool rotation. As can be seen from the Fig. 4(c), lowest values of tool rotation and voltage show overestimated values of crater size. All these results reveal the fact that with the lower setting of electrical parameters and tool rotation, prediction of crater sizes is not very accurate. However, with the higher settings of parameters, prediction of crater sizes becomes more accurate.

V. Conclusions

This paper investigates the application of Box Behnken design and response surface plot to predict the crater sizes generated during the micro-EDM of Ni-x alloy. With three levels of voltage, capacitance and tool rotation as input variables, and using Box Behnken design, mathematical model for crater size has been derived using Minitab software. The model was verified by comparing the predicted crater sizes with the experimentally measured values. It was found that with the lowest settings of input variables, predicted values were not very accurate due to generation of very small size craters, however, for higher input parameters the model seems in good agreement with the experimental values. Response surface plots showed the combined effects of input variables on the crater size.

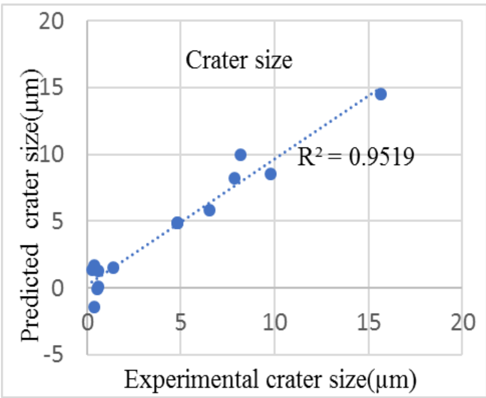
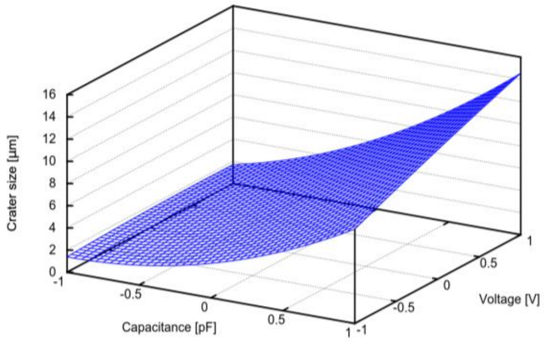
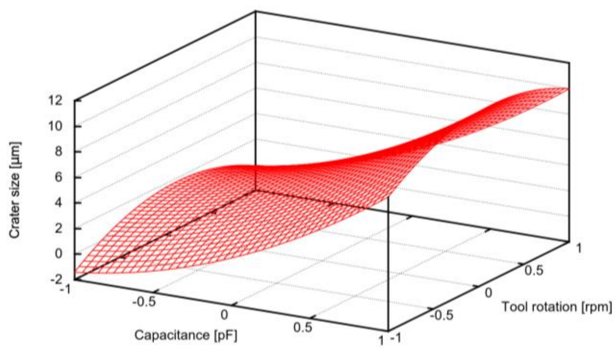


Figure 3. Experimental results vs predicted results.



(a)



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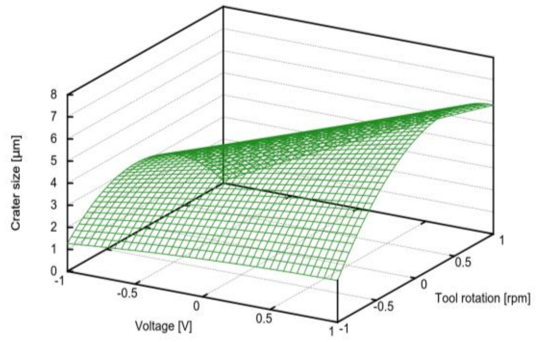

(c)

Figure. 4. Response surface plot of crater size (a) combined effect of voltage and capacitance (b) combined effect of tool rotation and capacitance (c) combined effect of voltage and tool rotation.

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