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OPTIMIZATION OF MICROMACHINING PARAMETERS OF CU NANO POWDER ASSISTED DRILLING OF HASTELLOY BY USING RESPONSE SURFACE METHODOLOGY

R.Gobinath
Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamil Nadu, INDIA

P.Hariharan
College of Engineering,Guindy,Chennai, India

Sunil Kumar
Babu Banarasi Das University, Lucknow (U.P.) India

ABSTRACT
In this paper, an attempt was made for enhancing the micromachining characteristics of Hastelloy C276. For drilling holes in the Hastelloy, Copper Nano powder assisted electrochemical micromachining process was used. By fluctuating important electro chemical machining process parameters such as concentration of NaBr electrolyte, machining voltage and concentration of Cu Nano powder, holes were drilled. Using central composite design model, twenty different drilling experiments were conducted. Relationships were developed to establish relationship between the electro chemical drilling process parameters and output responses such as material removal rate and overcut at the interior side. Using analysis of variance, the significance of the developed model was ascertained to a high level of certainty. Using response surface methodology, the micromachining process parameters were optimized. At optimized concentration of Na Br electrolyte of 11.2 g/l, machining voltage of 7.4 V, Cu concentration of3.3 g, highest material removal rate of 0.000196622 and least entry side overcut of 0.208768. As the error obtained in validation experiments were lesser than 4% the optimization model was found to be developed with high predictability. The variations in the hole edges were evaluated by using scanning electron microscopy.
Keywords: Micromachining, optimization, material removal rate, overcut

INTRODUCTION
Electro chemical machining process is being used in precision manufacturing industries for accurately drilling small sized holes. Kumar et al. (2018) conducted electrical discharge micro machining experiments on SS304. Mathematical and statistical tools were used to design an optimization model to predict the variations in micromachining characteristics on the responses. It was observed that the circularity of the machined specimens was more dependent on pulse off duration [1]. Mehrabi et al. (2018) conducted electro chemical machining experiments on B270 glass materials. An attempt was made for enhancement of the machining characteristics by utilizing electrodes of hollow type and increasing the pressure of the electrolyte injection system [2]. Ahn et al. (2004) conducted drilling experiments on 304 stainless steel sheets by using electro chemical micro machining processes. For localization of the electric field, very short pulses were utilized.

Evaluation of the distance of localization on variations in the input voltages, duration of the pulse and its frequency were studied. By controlling the vital parameters, taper free holes were produced [3]. Ghoshal et al. (2015) conducted experiments for enhancing the aspect ratio of electro chemical micro machining process by using vibration assistance. For obtaining appropriate aspect ratio a mathematical model was developed. By generation of microchannel, very high aspect ratio was developed by evaluating the frequencies of the voltage pulses, shape of the micro tools, the machining job thickness and the thickness of the non-conducting layer covered over the tool [4]. Saxena et al. (2018) conducted an exhaustive review on the various electro chemical micromachining methods which were being used all over the world for attaining high precision drilling. An insight about the advancements in the hybrid electro chemical micro machining techniques were elaborately discussed for machining novel and new materials [5]. Patel et al. (2017) conducted experiments by combining pulsed current supply with induced ultrasonic waves in the electrolyte during its flow by using electrode. The base material chosen for drilling holes were 6 series aluminium plate. Stainless steel tubes were used as electrolytes which were coated with Teflon. Using 3D optical profiler, the variations in the rate of removal of the material and the quality of the holes were studied. The variations in the amplitude of the current pulses, frequencies of the pulses, the duration of machining and the amplitude of the generated ultrasonic waves on the machining characteristics were evaluated [6]. Paul et al. (2018) conducted electro chemical machining experiments on borosilicate glass by modifying the tool used. The variations in the machining process parameters on the reductions in radial overcut were evaluated. Significant improvement in circularity of the holes were observed on modifying the tool nomenclature [7]. Chavoshi et al. (2017) conducted an exhaustive review on the latest techniques that are being used in micromanufacturing industries regarding single tooled micromachining that is being done in a sequential process. Effect of incorporation of laser source for enhancement of the micromachining characteristics were studied [8]. Paul et al. (2018) conducted electro discharge machining experiments on Inconel alloy material. The fluctuations in the machining characteristics on addition of Cu in the oil of the dielectric media was observed. The variations in the efficiency of the removal of the material, roughness of the surface and density of the cracks along the surface were observed upon fluctuating the percentage of Cu were ascertained [9]. From study of literature sources, it was found that the study on electro chemical micromachining on Hastelloy was not found. Thus, in this paper an attempt was made to conduct micro drilling experiments using Copper Nano powder assisted electrochemical micromachining process.

MATERIALS AND METHODS

2.1 BASE MATERIALS AND ELECTRO CHEMICAL MICROMACHINING EQUIPMENT

In this research, a nickel-based superalloy such as Hastelloy C276 was used as the base material which was micro drilled. 0.5 mm thickness sheets were used. The chemical composition of the base material was evaluated by using spark spectrometer. By igniting sparks at the various regions, the chemical composition was evaluated. The nominal chemical composition of the base material has been indicated in Table 1.

Table 1. Nominal chemical composition of the base materials (in Wt %).

Material	Co	Cr	Mo	W	Fe	Ni
Hastelloy	2.5	15.5	16.0	4.0	5.5	Balance

The important mechanical properties of the base material are given in Table 2.

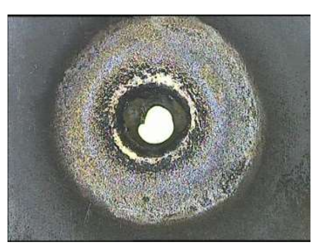
Table 2. Mechanical properties of base material

Material	Yield strength, MPa	Tensile strength, MPa	Elongation, %	Hardness, *HV*
Hastelloy	384	696	53	193

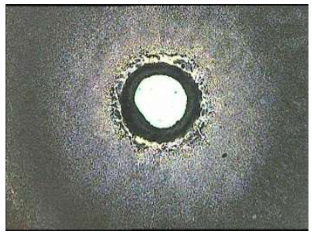
Electro chemical micro machining process was used for drilling holes on Hastelloy by using Na Br electrolyte. Cu powder in micron sizes were procured and its size was reduced to nanometres by using ball milling process. The addition of Cu was done so as to enhance the characteristics of the micro machining process. In this electro chemical micromachining process, Hastelloy material piece of 0.5 mm was used as anode and the tool was set as the anode with Na Br electrolyte enhanced with Cu Nano powder. Dissolution of Hastelloy was made to occur locally so as to enable a hole with shape as a negative mirror image type of the anode. From study of previous literatures, the important electro chemical micro machining process parameters were found to be input voltage, input machining current, the type of electrode used, the concentration of the electrolyte during the machining process, the rate of flow of the electrolytes and the gap between the electrodes. A rigid micro tool having a robust design was used to make a precise hole of 300 µm. By fluctuating the concentration of Na Br, the experiments were conducted.

2.2 Establishment of feasible Electro Chemical Micromachining process parameters.

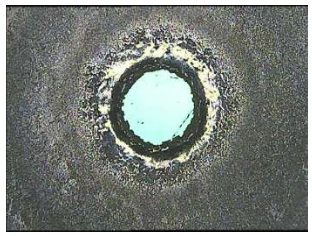
Out of the various process parameters that fluctuate the characteristics of the holes, three important parameters selected for observation were the input voltage in volts, change in concentration of Na Br electrolyte and increase in addition of Cu Nano powder in grams. Other electro chemical micro machining process parameters such as Input Current was maintained constant as 0.75 A and rate of flow of electrolyte was kept at 2.5m/s. The temperature of the electrolyte was maintained at 40°C. the gap between the electrodes was fixed at 10 µm. the machining rate was fixed at 5 µm/min. Experiments were conducted by maintaining two of the process parameters at constant mid-range and the third parameter was fluctuated to identify the variations in the output characteristics. The limit of the process parameters was fixed so as to attain a good drilled hole of good finish without ovality. The important output responses considered in the micro drilling were the rate of material removal and the entry side overcut.



(a) MV < 5 V (b) MV > 5 V


(c) EC < 5 g/l


(d) EC>5 g/l


(e) MP < 1 g

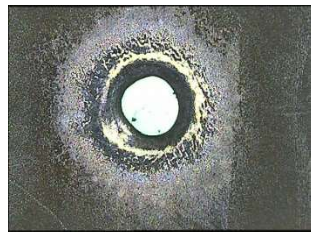

(f) MP > 6 g

Figure 1. Photographs of holes drilled with Electro Chemical Process Parameter values beyond feasible limits.

1. When the input machining voltage was fixed below 5 volts, the rate of dissociation was lesser than required range and the micro machining process was not done properly, resulting in erroneous holes. It is shown in Fig 1 (a).
2. When the input machining voltage was fixed greater than 10 volts, the rate of dissociation in the electrodes were more than necessary and the edges of holes were found to be more defective. It is shown in Fig 1 (b).
3. When the concentration of Na Br solution was fixed lesser than 5 g/l, the micro machining process did not occur properly resulting in defective holes. It is shown in Fig 1 (c).
4. When the concentration of Na Br solution was fixed greater than 15 g/l, excessive dissociation resulted in non-precise holes. It is shown in Fig 1 (d).
5. When the mass of addition of Cu Nano powder was less than 1 gram, the effect of Cu inclusion in enhancing the hole formation was less pronounced resulting in defective machining. It is shown in Fig 1 (e).
6. When the mass of addition of Cu Nano powder was greater than 6 grams, presence of excessive copper Nano particles resulted in formation of excessive chemical reactions resulting in imperfect holes. It is shown in Fig 1 (f).

Thus, within the electro chemical micro machining process parameter values of 5 v to 10 v of input voltage, 5 g/l to 15 g/l of Na Br solution concentration, 1g to 6 g of Cu Nano powder addition, good quality machining was obtained.

2.3 DEVELOPMENT OF CENTRAL COMPOSITE DESIGN MODEL

In this research, as the extent of individual factors were found to be huge, a central composite design model was chosen for obtaining twenty different sets of coded conditions. It was designed with eight points, having five levels. The total number of star points was six and the central points were fixed to be six. The most positive value of the electro chemical micro machining process parameter was coded to be +1.68. The least range of the value was coded to be -1.68. The intermediate values of the process parameters were obtained using the relations developed by Montgomery D C [10].

Table 3 – Range of electro chemical micro machining process parameter values

No	Parameter	Notation	Unit	Levels				
				-1.68	-1	0	1	+1.68
1	Machining Voltage	MV	V	5	6	7.5	9	10
2	Electrolyte concentration (Na Br)	EC	g/l	5	7	10	13	15
3	Mass of Cu Nano powder	MP	g	1	2	3.5	5	6

$J_i = 1.682 [2 J – (J_{max} + J_{min})] / (J_{max} + J_{min})]$ -------------- (1)

In the above given equation, the value of the coded variable J is J_i. From J_{min} to J_{max}, J is made to assume any variable value. The least value is taken as J_{min} and J_{max} is termed to be the highest value. The intermediate values of the feasible process parameters have been indicated in Table 3. The central composite design matrix formed with the twenty conditions are indicated in Table 4.

Table 4 – Central composite design matrix and experimental results

No	Coded factor value			Actual factor value			MRR grams	Entry Side Overcut
Run	MV	EC	MP	MV	EC	MP		
				V	g/l	g		
1	0	-1.68	0	7.50	5.00	3.50	0.000186204	0.403418
2	-1	-1	1	6.01	7.03	4.99	0.000187384	0.391362
3	0	1.68	0	7.50	15.00	3.50	0.000192829	0.317574
4	-1	-1	-1	6.01	7.03	2.01	0.000173428	0.452851
5	0	0	0	7.50	10.00	3.50	0.000196615	0.231489
6	1	-1	-1	8.99	7.03	2.01	0.000185021	0.379064
7	0	0	1.68	7.50	10.00	6.00	0.000195432	0.436454
8	0	0	-1.68	7.50	10.00	1.00	0.000182182	0.292979
9	0	0	0	7.50	10.00	3.50	0.000195668	0.223296
10	-1	1	1	6.01	12.97	4.99	0.000192829	0.358736
11	0	0	0	7.50	10.00	3.50	0.000197088	0.206894
12	1	1	1	8.99	12.97	4.99	0.0001907	0.469248
13	0	0	0	7.50	10.00	3.50	0.000196378	0.198695
14	1	-1	1	8.99	7.03	4.99	0.000202769	0.45695
15	0	0	0	7.50	10.00	3.50	0.000196851	0.219194
16	-1.68	0	0	5.00	10.00	3.50	0.000187624	0.39956
17	0	0	0	7.50	10.00	3.50	0.000196615	0.22739
18	-1	1	-1	6.01	12.97	2.01	0.000194485	0.301177
19	1	1	-1	8.99	12.97	2.01	0.000187624	0.288879
20	1.68	0	0	10.00	10.00	3.50	0.000194722	0.440553

Twenty sets of holes were drilled with the electro chemical micro machining process parameter values indicated in Table 4.

3. RESULTS AND DISCUSSIONS

3.1 Establishing empirical relations and analysis by using ANOVA

During the Electro chemical micro machining process, the responses were measured in terms of rate of removal of material (MRR) characteristics were measured in terms of material removal rate and overcut.

$$MRR = \frac{Wa - Wb}{T} \quad \text{------------------ (1)}$$

W_a = Weight before machining of work piece in Mg
W_b = Weight after machining of work piece in Mg
T = machining time in seconds

$$Entry\ Side\ Overcut = \frac{\text{Entry side diameter} - \text{Exit side diameter}}{2} \quad \text{-------------- (2)}$$

The responses were recorded in the form of Material Removal Rate (MRR) in grams and Entry Side Overcut in mm. These were related to the three important Electro Chemical Micro Machining process. The relationship was established as per the methods indicated by Paventhan [11].

Material Removal Rate in electro chemical micro machining = f {MV, EC, MP} -- (3)

Entry Side Overcut in electro chemical micro machining = f {MV, EC, MP} ------------ (4)

The response surface two models of material removal and entry side overcut is represented to be a polynomial regression equation having second order [11]

$G = a_0 + \Sigma a_i x_i + \Sigma a_{ii} x_i^2 + \Sigma a_{ij} x_i x_j$ ------------------------------ (5)

For the process parameters such as the input voltage in volts (MV), change in concentration of Na Br electrolyte (EC) and increase in addition of Cu Nano powder in grams (MP)

Table 5 – Results of ANOVA analysis of material removal rate of the electro chemical micro machining process

Source	Sum of squares (SS)	DOF	Mean square (MS)	F value	p-value Prob>F	Note
Model	15142.23	9	1682.47	568.96	< 0.0001	Significant
MV	1170.88	1	1170.88	395.96	< 0.0001	
EC	1038.49	1	1038.49	351.19	< 0.0001	
MV	4015.60	1	4015.60	1357.96	< 0.0001	
MV EC	2888.00	1	2888.00	976.64	< 0.0001	
MV MV	162.00	1	162.00	54.78	< 0.0001	
EC MV	2048.00	1	2048.00	692.57	< 0.0001	
MV2	955.73	1	955.73	323.20	< 0.0001	
EC2	1624.89	1	1624.89	549.49	< 0.0001	
MV2	1965.72	1	1965.72	664.75	< 0.0001	
Residual	29.57	10	2.96			
Lack of fit	8.24	5	1.65		0.8402	Not significant
Std. Dev		1.72		R^2	0.9981	
Mean		-608.10		Adj R^2	0.9963	

C.V. %	0.28	Pred R^2	0.9936
PRESS	96.36	Adeq precision	101.002

Table 6 – Results of ANOVA analysis of entry side overcut of the electro chemical micro machining process

Source	Sum of squares (SS)	DOF	Mean square (MS)	F value	p-value Prob>F	Note
Model	0.17	9	0.019	129.19	< 0.0001	Significant
MV	1.850×10^{-3}	1	1.850×10^{-3}	12.67	0.0052	
EC	0.012	1	0.012	82.87	< 0.0001	
MV	0.018	1	0.018	123.16	< 0.0001	
MV EC	1.415×10^{-3}	1	1.415×10^{-3}	9.69	0.0110	
MV MV	8.593×10^{-3}	1	8.593×10^{-3}	58.84	< 0.0001	
EC MV	6.134×10^{-3}	1	6.134×10^{-3}	42.01	< 0.0001	
MV^2	0.072	1	0.072	491.40	< 0.0001	
EC^2	0.035	1	0.035	241.88	< 0.0001	
MV^2	0.037	1	0.037	256.68	< 0.0001	
Residual	1.460×10^{-3}	10	1.460×10^{-4}			
Lack of fit	6.649×10^{-4}	5	1.330×10^{-4}	0.84	0.5756	Not significant
Std. Dev		0.012		R^2	0.9915	
Mean		0.33		Adj R^2	0.9838	
C.V. %		3.61		Pred R^2	0.9635	
PRESS		6.247×10^{-3}		Adeq precision	30.778	

Pitting potential/ Mass loss = { $a_0 + a_1$ MV+ a_2 EC + a_3 MP+ a_{12} MV* EC+ a_{13} MV * MP+ a_{23} EC * MP + $a_{11}MV^2$ + a_{22} EC^2 + a_{33} MP^2}-------------------------- (6)

a_0 is considered to be the average of all the responses used in this research analysis. a_1, a_2, …, ca be considered to be the other coefficients of regression which were corelated and compared with the factor components in the linear form, squared and the interaction form [12].

By using design expert software which is a statistical and mathematical analysis tool, the coefficients that were related to the significance of the developed model was validated by using student t test and p test methods. Using analysis of variance, the level of significance of the developed electro chemical micro machining model was ascertained. The ANOVA analysis of the material removal rate of the electro chemical micro machining process is indicated in Table 5 and the ANOVA analysis of the entry side overcut of the electro chemical micro machining process is indicated in Table 6. For evaluating the significance of the developed model ANOVA analysis was conducted. The ANOVA analysis result of Pitting potential variations are indicated in Table 5 and ANOVA results of response model of mass loss in salt spray test is shown in Table 6.

It could be found that for the probability values of the F value which was found to be lesser than 0.005, a very appreciable and high level of significance of the developed model could be ascertained. In the designated terms where the values were found to be greater than 10, the model was found to be insignificant. The coefficients of the important electro chemical micro machining process were used for the prediction of empirical relationships between the input process parameters and the output responses.

$MRR = +1.965 \times 10^{-4} + 2.19 \times 10^{-6} MV + 2.063 \times 10^{-6} EC + 4.057 \times 10^{-6} MP - 4.496 \times 10^{-6} MV \times EC + 1.065 \times 10^{-6} MV \times MP - 3.786 \times 10^{-6} EC \times MP - 1.927 \times 10^{-6} MV^2 - 2.512 \times 10^{-6} EC^2 - 2.763 \times 10^{-6} MP^2$ -------------- (7)

$ESOC = +0.22 + 0.012\, MV - 0.030\, EC + 0.036\, MP + 0.013\, MV \times EC + 0.033\, MV \times MP + 0.028\, EC \times MP + 0.071\, MV^2 + 0.050\, EC^2 + 0.051\, MP^2$ ----------- (8)

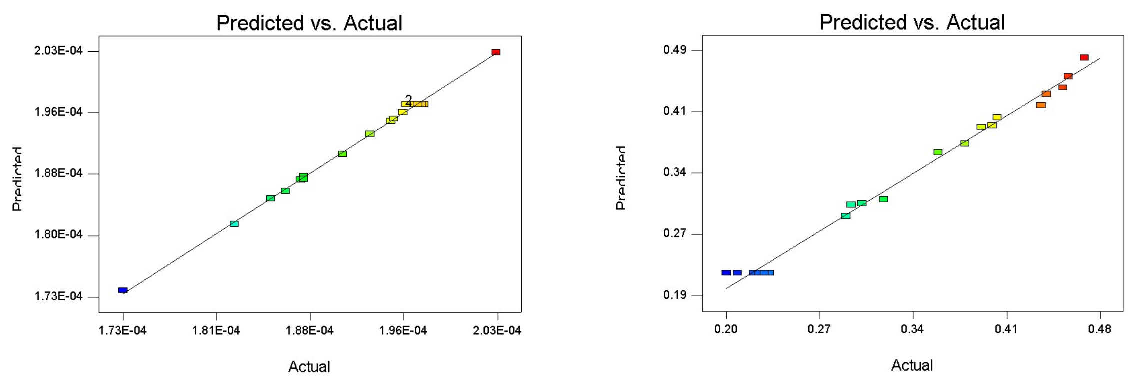


Figure 2 (a) Scatter plot for predicted and actual values of (a) material removal rate, (b) entry side overcut.

The values of fit for the developed model has been indicated in Table 5 and Table 6. The coefficient used for identification of the coefficient values has been indicated by R^2. For the purpose of observing the goodness of fit, for the electro chemical micro machining model, the coefficient of determination can be used. By evaluation of the developed material removal rate and entry side overcut models, it was found that only lesser than five percent of the values were left unexplained [16]. Also, it was found that the determination coefficient was found to be very high. This indicates very high level of significance of the developed model. Between the adjusted value of the coefficient of determination and predicted R squared value, an acceptable level of agreement was witnessed. Fig 2 (a) shows the scatter plot between the predicted and actual values of Material removal rate values and Fig 2 (b) shows that for entry side overcut.

Upon utilizing mathematical and statistical evaluation strategies, the correlation between the important electro chemical micro machining process parameters with material removal rate and entry side overcut.

Response surface methodology (RSM), which is a renowned mathematical and statistical evaluation technique, was used in this research for the purpose of optimization of the micro machining process parameters. For fetching the desired dependent variable, the factors of the independent variables were manipulated using this technique.

The independent factors are represented in quantitative manner according to the following equation

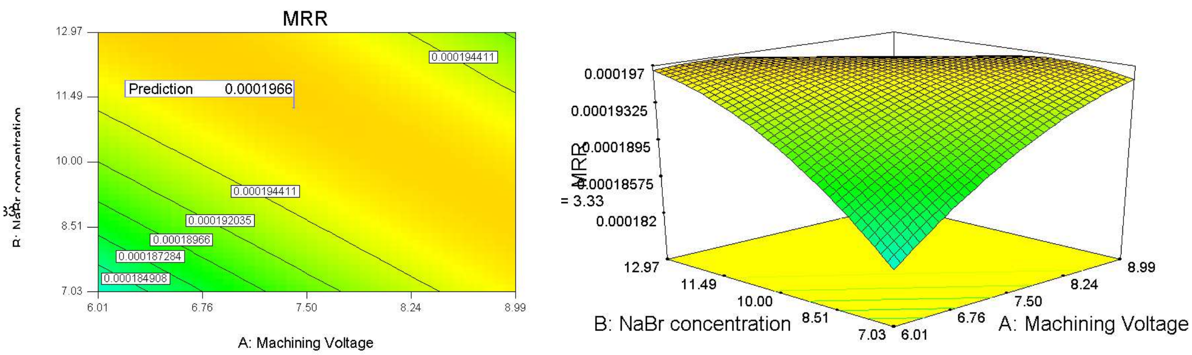
P = Φ (X_1, X_2, ….. X_k) + er ----------------------------(8)

In the above equation, P is termed as the response. X_1, X_2……, are termed as the quantitative factors. The response surface of the equation is indicated by Φ. During the experimentation procedure, the error obtained is attributed to be er. The most appropriate response surface was developed for two variables which could be different and independent. In many cases, the exact value of the response surface could be identified. In some cases, when the value of the response surface could not be identified, approximation could be done. As the degree of the polynomial gets higher and higher, the clarity gets better, but the experimentation cost would drastically increase.19].

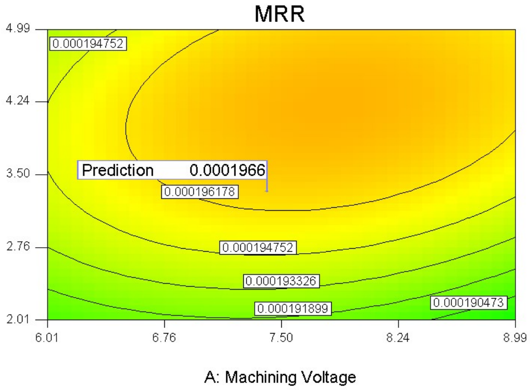
In this research, response surface methodology was used for optimization of the input voltage in volts, change in concentration of Na Br electrolyte and increase in addition of Cu Nano powder in grams, for enhancing the material removal rate and reducing the entry side overcut. Using a proper combination of the three important electro chemical micro machining process parameters, the maximum possible material removal rate and minimum possible entry side overcut was achieved. The three important process parameters were formed to be the surface on which the appropriate fitting was done. The changes and fluctuations in the responses could be clearly identified by using geometric contours. Circular shapes were used for identification of interdependence of the variables. Elliptical shapes of contours indicate interactions in between the process parameters. By evaluation of the contours, the optimal region could be identified. The contour patterns are found to be simple while plotting first order models. As the order of the models increases, the complexity of the pattern also increases. Characterization of the response surface was done by identifying the stationary spot. By characterizing the stationary point, it could be identified as maximum, minimum or saddle spot. Using design expert software, the contour plots were generated. By characterizing the contours, identification of the optimal values was done. Circularity indicates independence of the input process variables and the elliptical shapes were used to identify factor interactions [18].

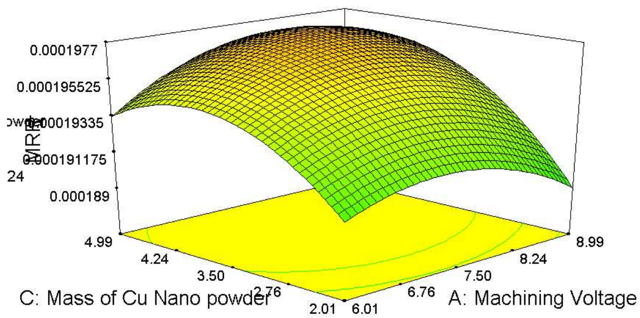
Two of the values of the process parameters were identified at the middle and plotted, while the third is plotted in the surface in the form of material removal rate and entry side overcut were traced. From the surface plots, the optimal points were identified. The contours and surface plots for material removal rate maximization model is indicated in Figure 3 and contours and surface plots for entry side overcut minimization model is indicated in Figure 4.

Figure 3 shows the contour and surface plots for maximization model of material removal rate. Figure 3 (a) shows the contour plots for electrolyte concentration and machining voltage. Figure 3 (b) shows the contour plots for mass of Cu Nano powder vs Machining voltage. Figure 3 (c) indicates contour plot for mass of Cu Nano powder vs Electrolyte concentration.

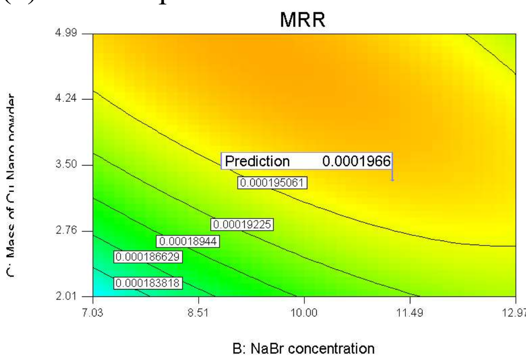


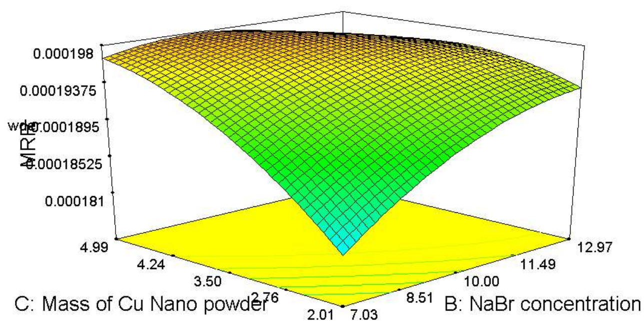
(a) Contour plot EC vs MV (d) Surface plot EC vs MV





(b) Contour plot MP vs MV (e) Surface plot MP vs MV





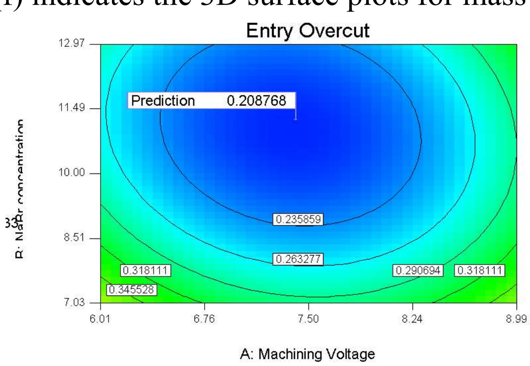
(c) Contour plot MP vs EC (f) Surface plot MP vs EC

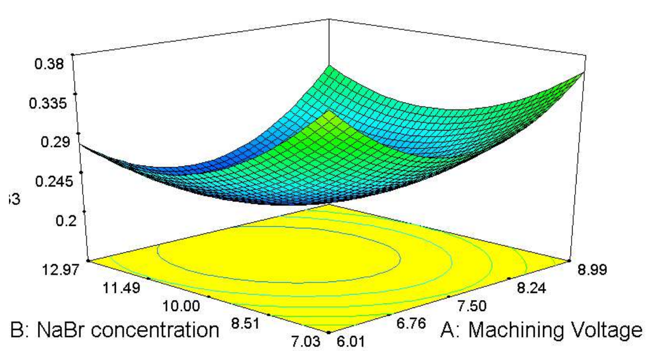
Figure 3 - The contours and surface plots for material removal rate maximization model

Figure 3 (d) indicates the 3D surface plot for electrolyte concentration and machining voltage. Figure 3 (e) shows the 3D surface plots for mass of Cu Nano powder vs Machining voltage. Figure 3 (f) indicates the 3D surface plots for mass of Cu Nano powder vs Electrolyte concentration.

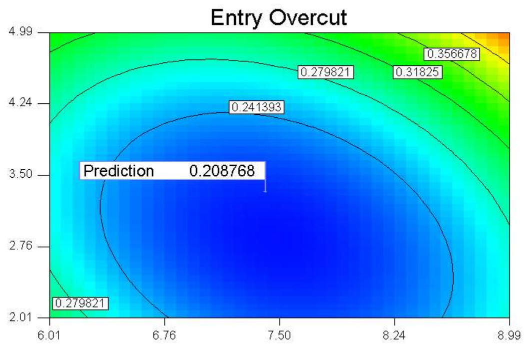
Figure 4 shows the contour and surface plots for minimization model of entry side overcut. Figure 4 (a) shows the contour plots for electrolyte concentration and machining voltage. Figure 4 (b) shows the contour plots for mass of Cu Nano powder vs Machining voltage. Figure 4 (c) indicates contour plot for mass of Cu Nano powder vs Electrolyte concentration. Figure 4 (d) indicates the 3D surface plot for electrolyte concentration and machining voltage.

Figure 4 (e) shows the 3D surface plots for mass of Cu Nano powder vs Machining voltage. Figure 4 (f) indicates the 3D surface plots for mass of Cu Nano powder vs Electrolyte concentration.

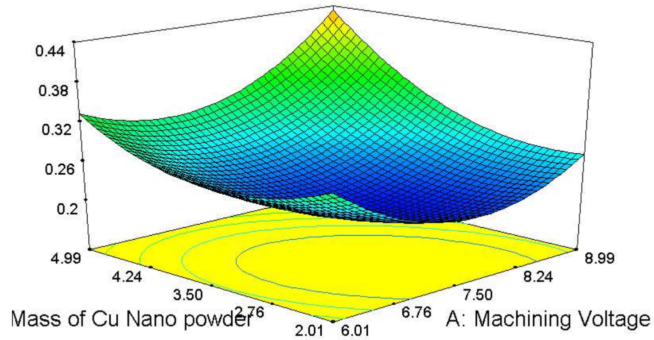




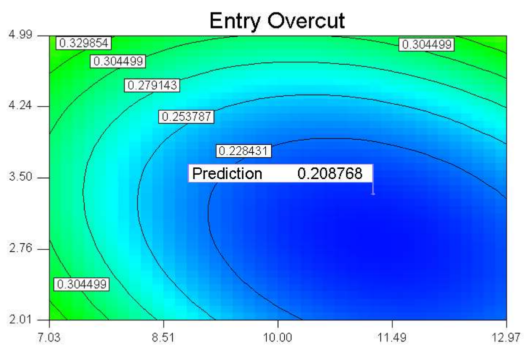
(a) Contour plot EC vs MV (d) Surface plot EC vs MV



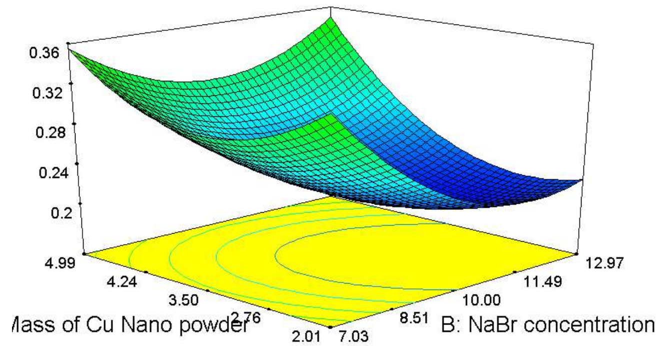
(b) Contour plot MP vs MV



(e) Surface plot MP vs MV



(c) Contour plot MP vs EC



(f) Surface plot MP vs EC

Figure 4 - Contours and surface plots for entry side overcut minimization model

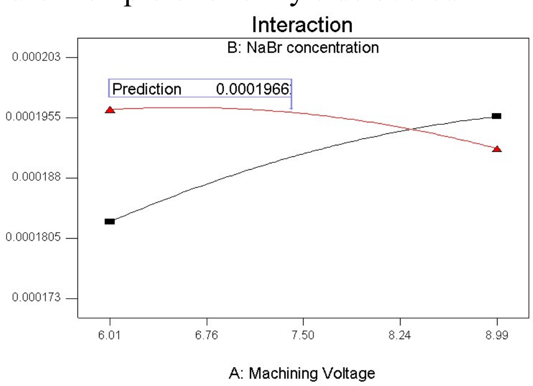
On evaluation of the developed contours and surface plots for optimization of the electro chemical micro machining process parameters, it was observed that for an initial increase of the values of process parameters, the material removal rate was found to increase initially. When the process parameters were increased beyond a certain extent, the material removal rate was found to reduce. Also, on increasing the values of process parameters for a certain extent, the entry side overcut was found to reduce. On further increasing the process parameter values beyond a certain extent, the entry side overcut was found to reduce. It was found that with optimized electro chemical micro machining process parameters such as machining voltage of 7.4 V, Na Br concentration for 11.2 g/l, mass of Cu Nano powder concentration of 3.3 g, maximum possible material removal rate of 0.000196622 g and minimum entry side overcut of 0.208768 mm was predicted. The optimized model was validated with validation experiments. Three experiments were conducted with the optimized set of parameters. It was found that the error difference between the predicted and actual values were found to be less than 3 %. Thus, it could be attributed that the model was developed with very high level of predictability

Table 7 -Validation experiments and results

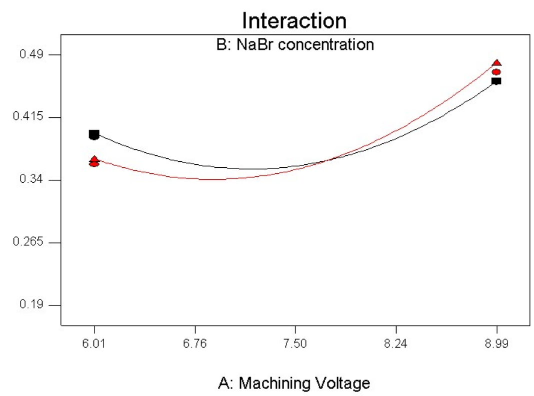
Exp No	Material Removal Rate		Error %
	Predicted	Experimental	
1	0.000196622	0.000196649	+0.21
2		0.000196312	-0.31

3		0.000196551	-0.13
	Entry Side Overcut		
	Predicted	Experimental	
1	0.208768	0.208792	0.19
2		0.208785	0.12
3		0.208697	-0.12

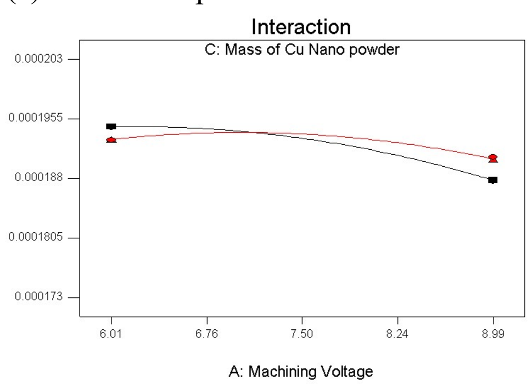
Figure 4 indicates the interaction plots for Material removal rate. Figure 4 (a) indicates interaction between Machining Voltage and Na Br concentration for MRR. Figure 4 (b) indicates the interaction between Machining Voltage and Mass of Cu Nano powder for MRR. Figure 4 (c) indicates interaction between Na Br concentration and Mass of Cu Nano powder for MRR. Figure 4 (d) indicates interaction between Machining Voltage and Na Br concentration for ESOC. Figure 4 (e) indicates the interaction between Machining Voltage and Mass of Cu Nano powder for ESOC. Figure 4 (f) indicates interaction between Na Br concentration and Mass of Cu Nano powder for ESOC. Figure 5 (a) indicates the perturbation plots for material removal rate. Figure 5 (b) indicates the perturbation plots for entry side overcut.



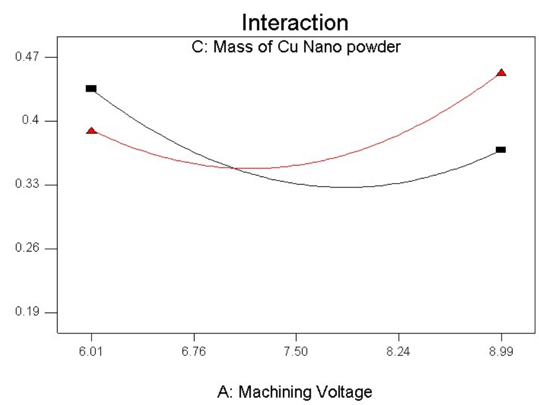
(a) Interaction plot EC vs MV



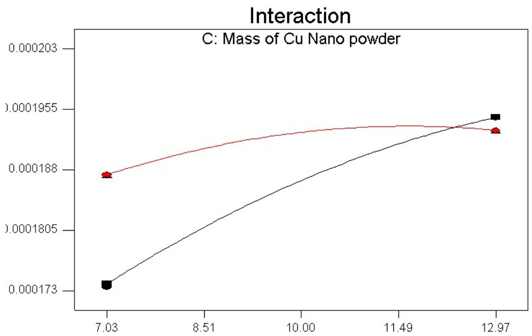
(d) Interaction plot EC vs MV

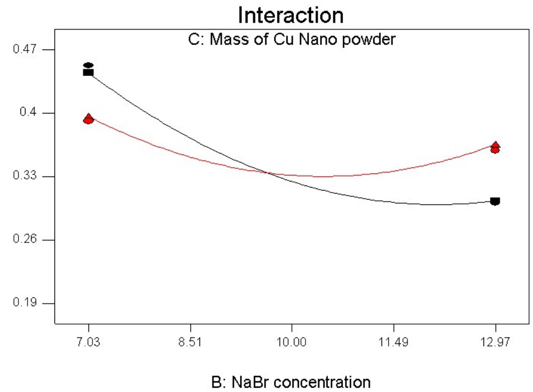


(b) Interaction plot MP vs MV



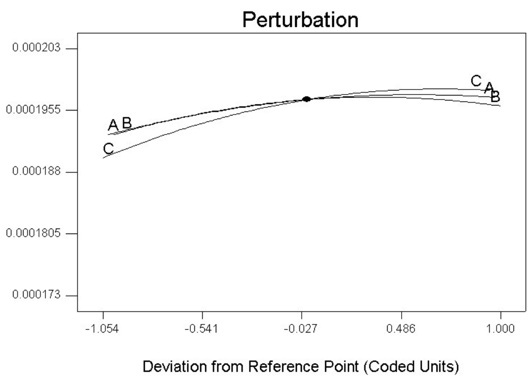
(e) Interaction plot MP vs MV

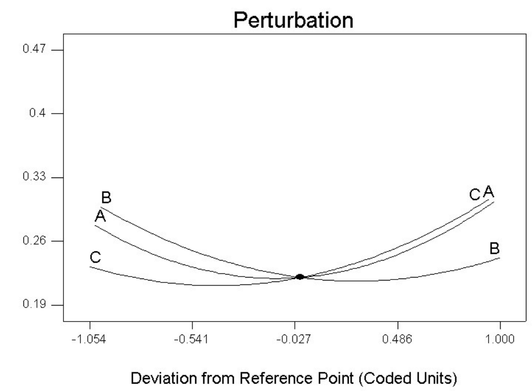




(c) Interaction plot MP vs EC (f) Interaction plot MP vs EC

Figure 4. Interaction plots

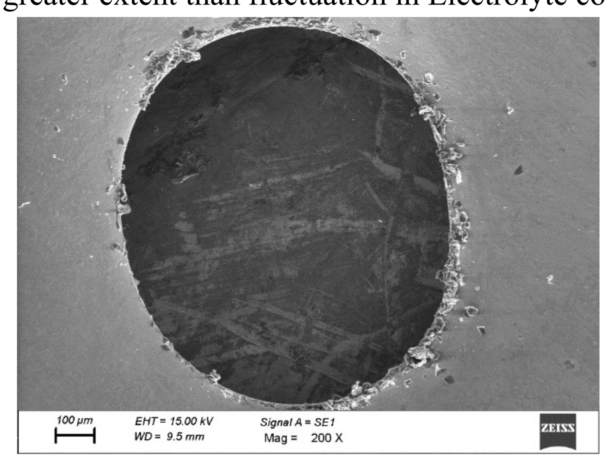


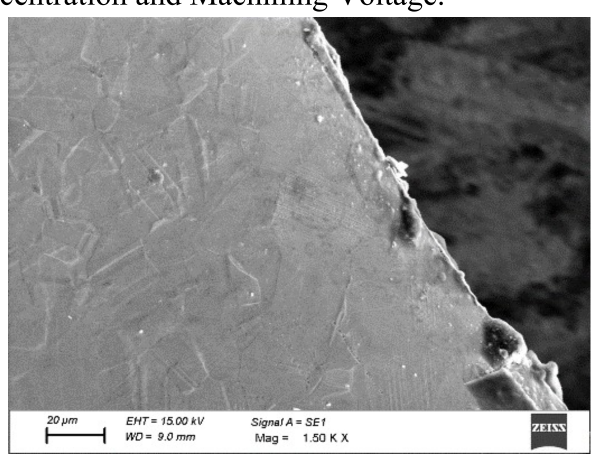


(a) Perturbation plots for MRR (b) Perturbation plots for ESOC

Figure 5. Perturbation plots

By evaluation of the perturbation and interaction plots, it was found that, the effect of variations in the amount of addition of Cu Nano powder had greater effect on fluctuations in material removal rate and entry side overcut. It was observed that out of the three important electro chemical micro machining process parameters, Cu Nano powder addition was found to fluctuate the responses to a greater extent than fluctuation in Electrolyte concentration and Machining Voltage.





(a) (b)

Figure 6. SEM Micrographs of specimen machined under optimum conditions.

The SEM micrograph of the Hastelloy specimen machined under optimum electro chemical micro machining characteristics has been indicated in Figure 6. Figure 6 (a) indicates the holes drilled with very minimal ovality and distortion under 200 x magnification. The edges of the drilled hole with more or less clear boundary with certain disruptions in certain regions is indicated in Figure 6.2 (b)

CONCLUSIONS

In this paper, precise holes in Hastelloy material were drilled by using electro chemical micro machining process and the following conclusions were drawn.

1. Using a central composite design model, empirical relationships were developed between the important micro chemical machining process parameters and output responses.
2. Using Analysis of variance, the significance of the developed model was ascertained.
3. Using response surface methodology, the optimized electro chemical micro machining process parameters such as machining voltage of 7.4 V, Na Br concentration for 11.2 g/l, mass of Cu Nano powder concentration of 3.3 g, maximum possible material removal rate of 0.000196622 g and minimum entry side overcut of 0.208768 mm was predicted.
4. Interaction and perturbation plots indicated that the rate of addition of Cu Nano powder fluctuated the output responses to a greater extent than the Na Br concentration and Machining voltage.

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