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Multi Response Optimization of Process Parameters in PCM of Inconel 600 Using Desirability Function Approach of RSM

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Abstract: An attempt has been made to apply the multi response optimization using desirability function concept for optimizing the etching conditions (etchant concentration, etchant temperature and etching time) on machining responses i.e. material removal rate, surface roughness, undercut and etch factor while photochemical machining of Inconel 600. The etching performance for Inconel 600 has been evaluated with different condition as per Face Central Composite Design of Response Surface Methodology. The mathematical models for each response have been developed using second order regression analysis. Key parameters and their interactive effect on each response have also been presented in graphical contours. The optimization of parameters has been done for machining with this non-conventional process using the desirability function concept with a target of high etchant concentration and etchant temperature. The aim is to maximize the responses i.e. material removal rate (MRR), etch factor and minimize the response i.e. surface roughness, undercut. Using this criteria, the optimum condition has been arrived for maximum MRR with etchant temperature 65^0C, etchant concentration 700 gm./lit and etching time 70 min. Using the same procedure, the desirability function values of surface roughness, undercut and etch factor comes around 94%, 91% and 77% respectively.

Keywords—PCM, MRR, surface roughness, RSM, Face central composite design, Inconel 600.

I. Introduction

The advancement of technology causes to the development of many hard to cut materials like nickel alloys due to their strength, high hardness, toughness, brittleness and low machining properties. Various machined components want dimensional accuracy and high surface finish, complex shape and special size which cannot be accomplished by the conventional machining processes.

Moreover, the increase in residual stresses and temperature generated in the work piece due to traditional machining processes may not be acceptable. These requirements have led to the improvement of non- traditional machining processes, one of which is the Photochemical machining (PCM). Photochemical machining process is a precision contouring of metal into any shape, size or form without using of physical force, by a controlled chemical reaction. Material is etched by microscopic electrochemical cell action, as occurs in chemical dissolution or corrosion of a metal. A PCM system setup was developed for carrying out in-depth research for achieving satisfactory control of PCM process parameters. David et al. [1]presented Characterization of aqueous ferric chloride etchants used in industrial photochemical machining process. $Fecl_3$is most commonly used as etchants. But there is wide variety in grades of $Fecl_3$. Defining standards for industrial purpose etchants and methods to analyze and monitor them. Rajkumar et al. [2] explained the Cost of photochemical machining in which they gave the cost model for PCM. Saraf et Al. [3] carried out experiments for optimization of photochemical machining of OFHC copper by using ANOVA. He investigated optimization of photochemical machining of SS304. Cakir O, et Al. [17] found that ferric chloride ($FeCl_3$) was a suitable etchant for aluminum etching. From literature, it is found that no statistical study has been reported to investigate the interaction effects of input parameters on etching process of Inconel 600. Table 1 shows Chemical composition of Inconel 600. Recent changes in society demands us to introduce more and more micro-parts into various types of industrial products. For example, the fuel injection nozzle for automobiles, several regulations arising from environmental problems has forced manufacturers to improve the design of compact, accurate, and efficient nozzles. Inspection of internal organs of human body and surgery without pain are universally desired.To improve the product quality proper selection of PCM process parameter is very important.

In this paper we used Response surface methodology(RSM) to optimize the PCM process parameters with consideration of multiple output parameters such as MRR, Surface roughness(Ra), Undercut and Etch factor are reported. RSM is frequently employed to obtain the optimum parameter setting following analysis of variance (ANOVA) for identifying significant factors.

In this paper, the mathematical models for MRR, surface roughness, undercut and etch factor have been developed using second order regression analysis. The multi objective optimization of parameters has also been done for etching with this non-conventional machining inserts using the desirability function concept with a target of high etchant temperature and etchant concentration. The aim is to minimize the responses i.e. surface roughness and undercut.

Table 1.Chemical composition of inconel600

Ni	Cr	Nb	Mo	Ti	Al	Si	S	Fe
75	14.2	3.06	0.15	0.2	0.4	0.95	0.013	7

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II. Experimental Procedure

The experiments were performed according to the Face central composite design which is a kind of response surface methodology. It is well known that response surface methodology or RSM is a collection of mathematical andstatistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. First, the material is cleaned to remove the oil, grease, dust, rust or any substance from the surface of material that would provide good adhesion of the photo resist. PCM process beings from engineering drawing or sketch that defines the precise characteristics of the part. The utilize CAD system and laser plot technology to generate an exact images of your part on a set of photographic films, called a photo tool. Depending upon size of the part, the photo tool may contain from one to several thousand exacting images of the part. The photo tool is used to transfer the images of your part photographically to sheet of clean flat metal which has been coated on both sides with photosensitive, etchant resistive polymer called photo resist. Then the chemical etching operation is carried out in etchant machine. The thickness of specimen was 0.3 mm and cut at 20mmX20mm dimension. $FeCl_3$ chemical etchant was prepared. The amount of etchant for each experiment was 100ml. Single sided chemical etching was conducted. The measurements of thickness were carried out by digital micrometer (± 0.001 mm). Fig.1. shows schematic representation and photo of experimental setup.

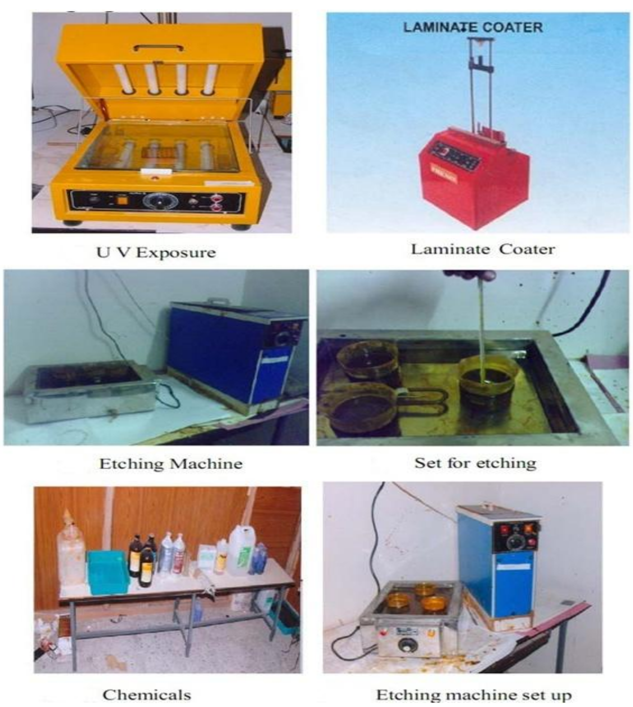

Fig. 1. Experimental setup

III. Methodology of Investigation

An experiment is a series of tests, calledruns; in this paper we have explained photo chemical etching of Inconel 600.Response surface methodology method was used to determine optimal machining parameters for maximum material removal rate, etch factor and minimum surface roughness, undercut with less etching time.Response surface methodology (RSM) is a collectionof mathematical and statistical techniques forempirical model building. By careful design ofexperiments, the objective is to optimize a response(output variable) which is influenced by severalindependent variables (input variables).

III.1 Response Surface Methodology (RSM)

Changes are made in the input variables in order to identify the reasons for changes in the output response. Originally, RSM was developed to model experimental responses (Box and Draper, 1987), and then migrated into the modeling of numerical experiments. The difference is in the type of error generated by the response. In physical experiments, inaccuracy can be due, for example to measurement errors while in computer experiments numericalnoise is a result of incomplete convergence ofiterative processes, round-off errors or the discreterepresentation of continuous physical phenomena.In RSM, the errors are assumed to be random. Theresponse can be represented graphically, either in thethree-dimensional space or as contour plots that helpvisualize the shape of the response surface. Contoursare curves of constant response drawn in the x_i, $x_j$plane keeping all other variables fixed.

Each contourcorresponds to a particular height of the responsesurface. With this technique, the effect of two ormore factors on quality criteria can be investigatedand optimum values are obtained. In RSM designthere should be at least three levels for each factor. The design expert (DE 9) software wasused to develop the experiment plan for RSM. Table 2 shows the level of input variables.

Table 2. Input parameters and their levels

Input Parameter	Level 1	Level 2	Level 3
Concentration (gm./lit)	300	500	700
Time (min)	30	50	70
Temperature (^{0}C)	55	60	65

III.2 Face centered compositedesign

In this paper, experiments were designed on the basis of the experimental design technique which refers to theplanning of experiments, collection and analysis of data with near-optimum use of available resource (D.C.Montgomery). It is an experimental method designed and developed for evaluating the effects of processparameters on performance characteristics. It determines the process parameter conditions for optimum responsevariables. During experimentation, a large number of experiments have to be carried out as the number ofmachining parameters increases. Design of experiments involves proper selection of variables (input factors) and their interactions. In this paper we have used Face centered composite design (FCCD),where FCCD requires 20 number of runs to cover all possible combination of the three input variable with three level of each input variable which consist of 8 factorial points with its origin at the center, 6 star points fixed axially at a distance from the central point to generate the quadratic values & 6 replicates of the centre point. The centre point have vital role since it represents a set of experimental conditions at which six independent replicates were run. The deviation between them reflects the variability of all design. It was used to estimate the standard deviation. In this model each input variable was investigated at three levels. The present research work studied the results of the effects of input parameters such as Concentration, Time and Temperature on the MRR, surface roughness, undercut and etch factor during the PCM process of Inconel 600 material. Table 3 shows experimental plan & result with Face centered composite design

Table 3. Experimental plan & result

Sr no	Temp ^{0}C	Conc gm/lit	Time min	MRR gm/min	Ra µm	Uc mm	Etch factor
1	60	500	50	0.04	2.3	0.08	0.61
2	60	300	50	0.04	1.4	0.16	0.31
3	60	500	30	0.06	1.8	0.02	1.4
4	55	300	30	0.02	1.6	0.08	0.2
5	65	500	50	0.05	2.3	0.18	0.28
6	60	500	50	0.04	2.3	0.08	0.61
7	55	300	70	0.04	2.0	0.16	0.26
8	60	500	50	0.04	2.3	0.08	0.61
9	65	700	70	0.06	2.4	0.17	0.35
10	60	500	50	0.04	2.3	0.08	0.61
11	55	500	50	0.03	2.8	0.04	1.12
12	60	500	70	0.05	2.8	0.08	0.92
13	60	700	50	0.05	2.2	0.18	0.30
14	55	700	30	0.03	2.1	0.16	0.17
15	65	300	30	0.02	1.7	0.27	0.07
16	55	700	70	0.06	2.3	0.37	0.17
17	65	700	30	0.04	2.2	0.01	4.8
18	65	300	70	0.07	2.1	0.15	0.42
19	60	500	50	0.04	2.3	0.08	0.61
20	60	500	50	0.04	2.3	0.08	0.61

III.3Modeling of Material removal rate (MRR), Surface Roughness, Undercut and Etch factor

The Material removal rate (MRR), Surface Roughness, Undercut and Etch factor were studied by performing 20 trials. The result of the trials is reported in the completed design layout Table 3.The adequacy and significance of the regression model is tested using ANOVA method. Test for significance on individual model coefficients and test for lack-of-fit is also estimated. By selecting the backward elimination procedure the terms that are not significant were eliminated and following equations (1-4) were obtained in the actual factors:

For material removal rate is:

MRR=0.069+0.0012*Temperature+0.000025*Concentration+0.00055*Time (1)

For surface roughness is:

Surface Roughness (Ra) = +28.73774 -1.02213 * Temperature +0.013388 * Concentration +0.017973 * Time +8.00000E-006 * Temperature * Concentration -3.50000E-005 * Temperature * Time -1.18125E-005 * Concentration * Time +8.47818E-003 * Temperature^2 -1.20761E-005 * Concenreation^2+9.88636E-006*Time^2 (2)

For etch factor is:

Etch factor = -5.58141 +0.041695 * Temperature -0.025945 * Concentration +0.36552 * Time +5.96706E-004 * Temperature * Concentration -5.20081E-003 * Temperature *Time-1.51852E-004*Concentration*Time (3)

For undercut is:

Undercut = +2.16227 -0.098032 * Temperature +1.10801E-003 * Concentration +0.021680 * Time -6.62500E-005 * Temperature * Concentration -3.12500E-004 * Temperature * Time +1.28125E-005 * Concentration * Time +1.21818E-003 * Temperature^2 +2.26136E-006 * Concenreation^2 -7.38636E-005*Time^2 (4)

IV.Result and Discussion

IV.1 Optimization of Responses

In the present study, desirability function optimization of the RSM has been employed for all the responses. During the optimization process the aim is to find the optimal values of etching parameters in order to maximize the values of MRR, etch factor and minimize undercut as well as surface roughness during the photochemical machining of Inconel 600. As the material removal rate mainly depends upon Etchant concentration, etchant temperature and etching time so the condition for Etchant concentration, etchant temperature has been put maximum with etching time in range. The optimal solutions for each response are reported in Tables below in the decreasing desirability level. From the Table 4, it can be concluded that etchant temperature65^{0}C, etchant concentration 700 gm./lit and etching time 70 minis the optimum condition with 90% desirability level for maximum material removal rate (MRR). Using the above optimized condition, the desirability function values of surface roughness, undercut and etch factor has been depicted in Table 5-7.

Table 4. Optimization Result on material removal rate (MRR)

Sr no	Temp (^{0}C)	Conc (gm./lit)	Time (min.)	MRR	Desirability	Remarks
1	65	700	70	0.065	0.900	Select
2	64.9	699.8	70	0.065	0.899	
3	65	697.5	70	0.065	0.899	

Table 5. Optimization Result on Surface roughness

Sr no	Temp (^{0}C)	Conc (gm./lit)	Time (min)	Ra (µm)	Desirability	Remarks
1	57.22	302.516	30.4	1.479	0.947	Select
2	62.23	301.849	33.4	1.475	0.924	
3	61.47	302.531	30.8	1.424	0.911	

Table 6. Optimization Result on Undercut

Sr no	Temp (^{0}C)	Conc (gm./lit)	Time (min)	U_c (mm)	Desirability	Remarks
1	59.42	554.39	30.60	0.009	0.912	Select
2	60.41	523.03	30.03	0.009	0.901	
3	59.29	496.19	30.06	0.00	0.897	

Table 7. Optimization Result on Etch factor

Sr no	Temp (^{0}C)	Conc (gm./lit)	Time (min)	Etch factor	Desirability	Remarks
1	65.00	700.00	30.00	3.752	0.778	Select
2	64.96	700.00	30.00	3.741	0.776	
3	65.00	698.36	30.00	3.739	0.775	

Desirability 3-Dplots were first drawn keeping input parameters in range and material removal rate and etch factor at maximum. Likewise plots were made for surface roughness, and undercut independently keeping their values at minimum level. Figure 2 shows the three dimensional response surface, optimized bar histograms and ramp graphs for overall desirability of the entire responses i.e. material removal rate (MRR), surface roughness, undercut and etch factor.

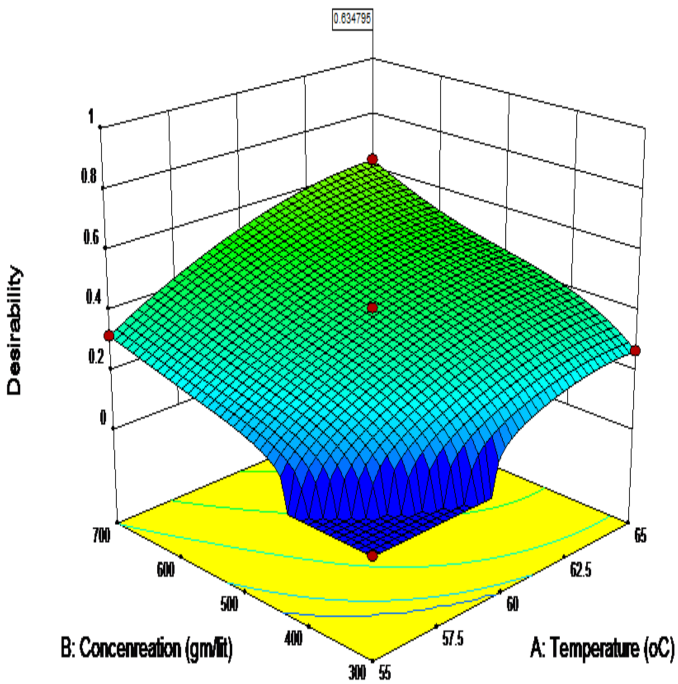

Fig. 2. 3-D surface plot of composite desirability for all responses Desirability

V. Conclusions

In this paper, desirability function optimization was employed for this RSM study, where the main criterion had been set for photochemical machining of Inconel 600. Concept of desirability in combination with RSM has also been used for simultaneous optimization of response characteristics of conflicting nature. The optimal sets of process parameters for multi response optimization with maximum desirability of the selected performance measures were found as per the assumed models. As the material removal rate mainly depends upon etchant temperature and etchant concentration so the condition for etchant temperature and etchant concentration has been set maximum while etching time has been set as per the experimental range. Using this criteria, the optimum condition has been arrived for maximum MRR with etchant temperature 65^{0}C, etchant concentration 700 gm./lit and etching time 70 min. Using the same procedure, the desirability function values of surface roughness, undercut and etch factor comes around 94%, 91% and 77% respectively. From this estimation, it can be concluded that this photochemical machining of Inconel 600 can be used for etching of corrosive resistance material with etchant concentration 650-700 gm./lit with high etchant temperature and mediumetching time. From the above research findings, it has also been shown that the developed etching of Inconel 600 can be a good alternative for high productive machining and ensuring minimum tool failure as well as maximum tool life.

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