Experimental Investigation of PCM on Inconel 600 Using Response Surface Methodology

Dattatray Vishnu Wagh[1], Prof.D.R.Dolas[2]
[1]M.E.(Mfg) Student, Department of Mechanical Engineering
[2]Associate Professor, Department of Mechanical Engineering
MGM's Jawaharlal Nehru Engineering College,Aurangabad, Maharashtra, India.
E-mail - wagh.dattatray@gmail.com

Abstract— Photochemical machining (PCM) is one of the non-conventional machining processes that produce burr free & stress free flat complex metal components. In the present work optimization of process parameters for Photochemical machining of Inconel 600 by using response surface methodology. Mathematical models have been developed to study the effect of input parameters on Undercut from the results of the experiments. The predictive models' analyses were supported with the aid of the statistical software package-Design Expert (DE 9). The different input parameters such as etching time, etchant concentration and etchant temperature were set during the photochemical machining. Design of Experiment was done by Face centered composite design method by having 20 experiments to see the effect on etching of Inconel 600. Minimum Undercut was observed at the etching temperature 55.276^{0}C, etchant concentration 470.781 gm/lit and 55.276 min etching time. The optimum material undercut was found 0.0029 mm.

Keywords — Photochemical machining (PCM), Undercut, Response surface methodology (RSM), Face centered composite design, Inconel 600.

I. INTRODUCTION

Photochemical machining (PCM) is one of the least well known non-conventional machining processes. Photochemical machining basically removes material by chemical action. Application of the process frequently produces a flat metal blank which in turn can be formed into a three dimensional shape if need be. The features are produced by exposing the work piece of interest through a photographic mask and chemically etching away areas that disappear the features of interest. The method is relatively modern and became recognized as a manufacturing process about fifty years ago [1]. The manufacturing process creates features by dissolving away metal rather than cutting or burning it away. So the stresses and defects that normally arise from metal cutting or EDM are absent in the final part. That means there are no burrs, no residual stresses, no changes in magnetic properties, and no deformations. There are no changes in hardness, grain structure, or ductility during the process. Moreover, because photo tools don't "wear," tolerances stay the same regardless of how many parts are produced. In addition, it is possible to precisely control the "Z" (depth) dimension. The application of photochemical machining has increased widely in the precision engineering, electronics, medical and decorative industries as well as in the micro component manufacturing industry. The increasing application of photochemical machining as an option to stamping for the manufacturing of small, burr free, stress free parts and the inevitable trend towards ever smaller and more complex designs has brought the problem of undercut. Fig. 1, show Undercut is the difference between the final width of the etched feature across the top (B) and the width of the developed resist line (A). The factors affecting undercut are grouped into three broad areas, etchant concentration, etching time and etchant temperature. 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 process parameters of PCM on Inconel 600 with consideration of output parameter such as Undercut is reported. RSM is frequently employed to obtain the optimum parameter setting following analysis of variance (ANOVA) for identifying significant factors.

In the literature, David et al. [2] has studied Characterization of aqueous ferric chloride etchants used in industrial photochemical machining process. $Fecl_3$ 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. [3] have explained the Cost of photochemical machining in which they gave the cost model for PCM. Saraf et. Al. [4] has studied optimization of photochemical machining of OFHC copper by using ANOVA. Saraf and Sadaiah et. Al. [5] have investigated optimization of photochemical machining of SS304. Cakir O, et. Al. [6] found that ferric chloride (FeCl3) 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. To improve the product quality proper selection of PCM process parameter is very important. Inconel 600 (nickel-chromium alloy) is a typical engineering material for applications which have need of resistance to corrosion and heat. Inconel 600 has excellent mechanical properties and having desirable combination of high strength and good workability. The chemical composition of Inconel 600 is shown in Table I. The high nickel content in Inconel 600 alloy gives the resistance to corrosion by many organic and inorganic compounds. Chromium confers resistance to sulfur compounds & oxidizing conditions at high temperatures or in corrosive solutions. The adaptability of Inconel 600 has led to its utilize in a variety of applications involving temperatures from cryogenic to above 1000°C. The alloy is used extensively in the chemical industry for its strength and corrosion resistance. The alloy's strength and oxidation resistance at high temperatures make it useful for many applications in the heat-treating industry. In the aeronautical field, Inconel 600 is used for a variety of engine and airframe components which must withstand high temperatures.

TABLE I. CHEMICAL COMPOSITION OF INCONEL 600

Ni	Cr	Mn	C	Cu	Si	S	Fe
72	14-17	1	0.15	0.50	0.50	0.015	6-10

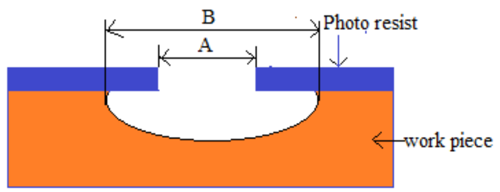

Fig. 1. Undercut

II. EXPERIMENTAL DESIGN WITH MULTIVARIATE

Response surface methods (RSM) are powerful process optimization tools in the arsenal of statistical design and analysis of experiment. Response surface methodology (RSM) is a sequential form of experimentation used to find out or optimize output response variables made up of mathematical-statistical model of many number of input variables [7]. RSM was used in this study to check the effect of different input variables on Undercut during the PCM process of Inconel 600 material, where Face centered composite design (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. At the same time, the number of runs for a complete replicate of the design increases as the number of input variables increases. The model was developed with the responses and their optimization was done using ANOVA to estimate the statistical parameters by using response surface methodology. In this paper optimization process is based on three major steps first performing the statistically designed experiments then evaluating the coefficients in a mathematical model and finally predicting the response. Fig. 2, shows FCCD structure for three input variables.

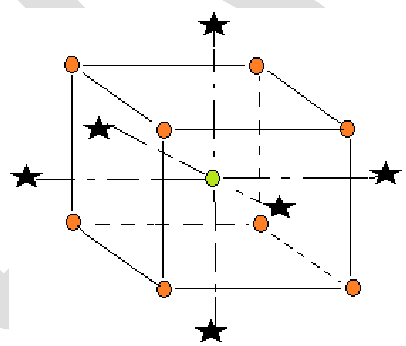

Fig. 2. Face centered composite design for three factors

The present reserch work studied the results of the effects of input parameters such as Concentration, Time and Temperature on the undercut during the PCM process of Inconel 600 material. Input parameters and their levels are shown in Table II. Table III shows experimental design matrix with coded and un-coded values of Face centered composite design

TABLE II. 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

TABLE III. EXPERIMENTAL LAYOUT PLAN FOR FACE CENTERED COMPOSITEDESIGN OF EXPERIMENTS

Ex No.	Coded Value			Un-Coded Value		
	A	B	C	Conc. (gm/lit)	Time (min)	Temp. (^{0}C)
1	-1	-1	-1	300	30	55

2	1	-1	-1	700	30	55
3	-1	1	-1	300	70	55
4	1	1	-1	700	70	55
5	-1	-1	1	300	30	65
6	1	-1	1	700	30	65
7	-1	1	1	300	70	65
8	1	1	1	700	70	65
9	-1	0	0	300	50	60
10	1	0	0	700	50	60
11	0	-1	0	500	30	60
12	0	1	0	500	70	60
13	0	0	-1	500	50	55
14	0	0	1	500	50	65
15	0	0	0	500	50	60
16	0	0	0	500	50	60
17	0	0	0	500	50	60
18	0	0	0	500	50	60
19	0	0	0	500	50	60
20	0	0	0	500	50	60

III. EXPERIMENTAL PROCEDURE

In this research work experiments were performed according to the Face Centered Composite design (FCCD) which is a kind of response surface methodology. Work piece first chemically cleaned to remove oil, grease, dust, rust or any substance from the surface so the photo resist can adhere. Deep the prepared work piece in photo resist for some minutes. Then it is hanged till extra photo resist drops fall into tank. After photo resist apply keep work piece into dryer for four minute. Select circular shape having dimensions 8 mm cut this section on black color radium & stick this section on the transparence paper with suitable distance so photo tool is ready to use. Exposed photo tool and masked work piece together in such way that the work piece should be above the photo tool. If both side exposing is carried out match corner to corner of photo tool and work piece. Expose this photo tool and masked work piece for five minute. Rinse the work piece in developer for some time till visibility of figure on work piece. For confirmation it is dipped into dye where visibility is increased or it can be seen by naked eye. Wash it in running water. Then the chemical etching operation is carried out in etching machine, adjust the time and temperature as per experiment planning. The thickness of specimen was 0.3 mm and cut at 20mmX20mm dimension. $FeCl_3$ chemical etchant was prepared. 100 ml amount of $Fecl_3$ was prepared for each run. In this paper single sided photochemical etching was conducted. The measurements of Undercut were carried out by Tool maker's Microscope (± 0.001 mm). Fig. 3, shows schematic representation of Photochemical machining experimental setup.

Fig. 3.Experimental setup of Photochemical machining

IV. RESULT AND DISCUSSION

A. Statistical Analysis

Although additional trials are required to fully confirm the results, the actual and the predicted undercut during the PCM process of Inconel 600 material are shown in Fig. 4, Actual values are the experimentally performed response data for a certain experiment and the predicted values are measured from the RSM design. This plot explains the effectiveness of the developed mathematical model. The difference between the actual and predicted values shown in Table IV. It is clear that model provided values are quite close to the experimental values.

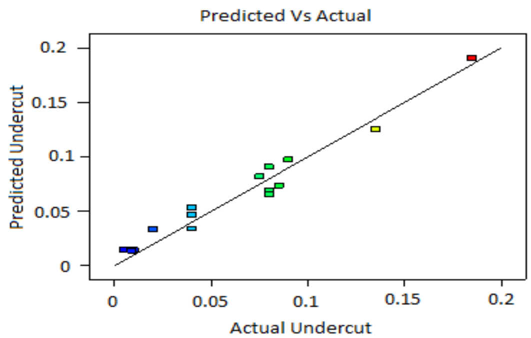

Fig. 4.The actual and predicted plot of Undercut of Inconel 600.

TABLE IV. EXPERIMENTAL DESIGN FOR THE ACTUAL AND PREDICTED RESPONSE.

Ex No.	Un-Coded Value			Response Undercut (mm)		
	Conc. (gm/lit)	Time (min)	Temp. (^{0}C)	Actual Values	Predicted values	Residual
1	300	30	55	0.075	0.082	-0.007
2	700	30	55	0.080	0.066	0.014
3	300	70	55	0.040	0.034	0.006
4	700	70	55	0.040	0.053	-0.013
5	300	30	65	0.19	0.19	00
6	700	30	65	0.085	0.074	0.011
7	300	70	65	0.080	0.069	0.011
8	700	70	65	0.040	0.034	0.006
9	300	50	60	0.040	0.034	0.006
10	700	50	60	0.040	0.047	-0.007
11	500	30	60	0.009	0.014	-0.005
12	500	70	60	0.080	0.090	-0.01
13	500	50	55	0.040	0.034	0.006
14	500	50	65	0.005	0.015	-0.01
15	500	50	60	0.020	0.033	-0.013
16	500	50	60	0.040	0.034	0.006
17	500	50	60	0.14	0.13	0.01
18	500	50	60	0.040	0.034	0.006
19	500	50	60	0.090	0.097	-0.007
20	500	50	60	0.01	0.014	-0.004

Three-dimensional plots were drawn by using the response surface methodology to investigate the effects of the time, concentration and temperature factors on the undercut during the PCM process of Inconel 600 material. Fig. 5, indicates Undercut along with temperature and time and it is clear that with increasing time Undercut increases but almost no effect with increasing temperature. Fig. 6, indicates Undercut first decreases as concentration increases up to concentration 500 gm/lit but then increases, up to at 700 gm/lit concentration it reaches to 0.011 mm. Fig. 7, shows Undercut along with temperature and concentration and it is clear that with increasing concentration Undercut increases but almost no effect with increasing temperature. Based on the ANOVA results obtained in Table V, time and temperature were found to have significant effects on Undercut of Inconel 600. With the help of this statistical model we have tried to find out the significant and non-significant terms in the variables (Table V), so non-significant terms are omitted in the developed mathematical model. Actual values were calculated through response surface data for a particular run & the predicted values were evaluated from the model and were generated by using the approximating functions. The fair correlation coefficients might have resulted by the insignificant terms in Table V, and most likely due to different variables chosen in wide ranges with a limited number of tests as well as the nonlinear effect of the investigated parameters on process response.

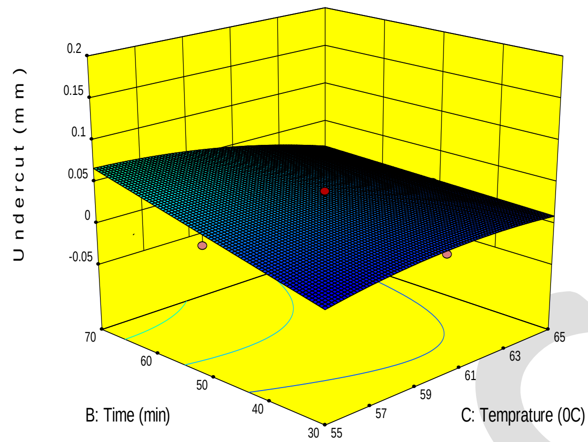

Fig. 5. The combined effect of time and Temperature on Undercut

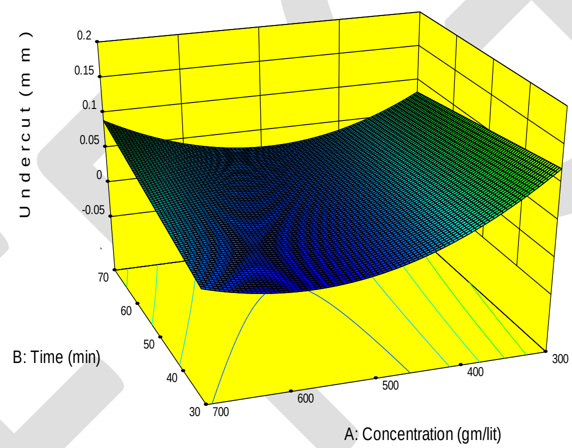

Fig. 6. The combined effect of time and concentration on Undercut

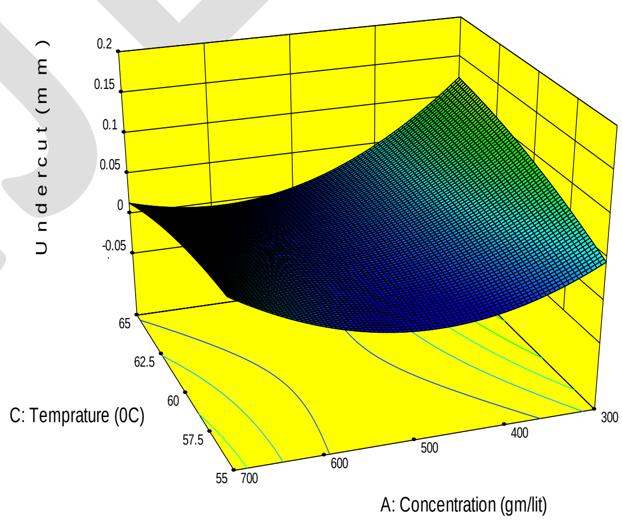

Fig. 7. The combined effect of temperature and concentration on Undercut

TABLE V. ANALYSIS OF VARIANCE TABLE FOR UNDERCUT (MM)

Source	**SS**	**df**	**MS**	**F-value**	**p-value Prob.>F**	
Model	0.036	9	3.95E-3	25.66	< 0.0001	significant
A	1.22E-4	1	1.22E-4	0.80	0.3933	
B	3.80E-3	1	3.80E-3	24.70	0.0006	
C	9.21E-4	1	9.21E-4	5.99	0.0344	
AB	5.25E-3	1	5.25E-3	34.12	0.0002	
AC	8.77E-3	1	8.77E-3	57.02	< 0.0001	
BC	1.95E-3	1	1.95E-3	12.69	0.0052	
A^2	9.88E-3	1	9.88E-3	64.21	< 0.0001	
B^2	5.68E-9	1	5.68E-9	3.69E-5	0.9953	
C^2	3.05E-4	1	3.05E-4	1.99	0.1890	
Residual	1.53E-3	10	1.53E-4			
Lack of Fit	1.53E-3	5	3.07E-4			
Pure Error	0.000	5	0.000			
Cor Total	0.037	19				

B. Development of Regression Model Equation

Face centered composite design was used to develop correlation between the undercut during the PCM process of Inconel 600 material to concentration, temperature and time. Experimental error was determined by using 20 experiments at the center point. Associate to the sequential model sum of squares, the models were selected based on the F-value. The independent input variables of the model were significant so that the models were not aliased and the quadratic model was taken as proposed by the software Design Expert (DE9). Based on quadratic model, experiments were planned to obtain 20 trials plus a star configuration (0, ±1) and their duplicates at the center point. Table IV shows the design of experiment, together with the experimental results. The minimum undercut was found to be 0.0029mm. Regression analysis was performed to fit the response function of undercut. The mathematical model expressed by Eq. 1, where the variables fill their coded values, represents the Undercut (Y) as a function of concentration (A), time (B) and Temperature(C).

$$\text{Undercut} = 0.0034+0.0035A+0.019B-0.0096C+0.026AB - 0.033AC-0.016BC+0.06A^2-0.000045B^2-0.011C^2 \quad (1)$$

C. Optimization by Response Surface Modeling

The main purpose of this study was to find out the optimum process parameters to minimize undercut during the PCM process of Inconel 600 material from the developed mathematical model equations. Design Expert (DE9) software package was used to optimize quadratic model equation within the experimental range. The optimum Undercut conditions determined for PCM process on Inconel 600 materials shown in Table VI.

TABLE VI. OPTIMIZATION RESULT OF PCM OF INCONEL 600

Desirability	Temp. (°C)	Time (min)	Conc. (gm/lit)	Undercut(mm)
1	55.276	32.39	470.781	0.0029

V. CONCLUSIONS

The response surface methodology based on three variables, face centered composite design was used to determine the effect of time (ranging 30-70 min), concentrations of etchant (ranging 300– 700 gm/lit) and temperature (55-65 ^{0}C) on the Undercut during the PCM process of Inconel 600 material. The regression analysis, statistical significance and response surface were applied using Design Expert Software for forecasting the responses in all experimental areas. Quadratic models were developed to show a relationship between variables and the responses. Through analysis of the response surfaces derived from the models, role of time was found to have the most significant effect on Undercut. Process optimization was carried out and the experimental values acquired for the Undercut during the PCM process of Inconel 600 material are found to agree satisfactorily with the values predicted by the models. Since experimentally obtained and model predicted values are residual which shows the effectiveness of model, based on the designed experiment. The optimal predicted Undercut 0.0029 mm of Inconel 600 was obtained as Ferric chloride concentration, time and temperature of etching and these were found to be 470.781gm/lit, 32.39 min and 55.276 ^{0}C respectively.

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