Comparision of Design of Experiments and Gray Rational Analysis of Photochemical Machining

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Abstract: Photochemical machining (PCM) is one of the least well-known nonconventional machining processes. The measure of performance is undercut (UC) and material removal rate (MRR). In this paper, Analysis of Variance (ANOVA) technique and grey-based Taguchi method for optimization of the process parameters in copper etching of PCM process were used for the prediction of Material Removal Rate (MRR) and undercut (Uc). The data used for prediction, derived from experiments conducted in etching operation of PCM process according to the principles of Design of Experiment (DoE) method. The input factors considered in the experiments were time, temperature, and concentration of etching process where copper was used as substrate. By comparing both techniques it was found that the optimal PCM process parameters for ANOVA are Temperature 47°C, Concentration 800gm/liter, and Time 5 minute and for gray rational are temperature 47^{o}c, time 5 minute and concentration 700 gm/liter. The optimum material removal rate was 0.127 mm^3/min and 0.279 mm^3/min and undercut 0.002 mm and 0.006 mm in ANOVA and gray rational respectively.

Keyword: PCM, Grey rational analysis, Taguchi, undercut, MRR, DoE.

I. INTRODUCTION

Photochemical machining (PCM) is one of the non-conventional machining processes that produce burr free and stress free flat complex metal components (D.M. Allen et. al, 2004). It is controlled dissolution of work-piece material by contact of strong chemical solution. It is useful for components with relatively low geometric complexity and high feature size. It is mainly used for manufacturing of jewelry, electronics parts, and decorative items, aerospace and medical applications. It employs chemical etching through a photo-resist stencil as method of material removal over selected areas. Therefore, it is very important that the proper selection of PCM process parameter to improve product quality. In this, paper the use of grey-based Taguchi method to optimize the PCM process parameter with consideration of multiple output parameters such as MRR and Undercut is reported. The Taguchi method is a systematic application of design and analysis of experiment for improving of product quality. The gray relational analysis is a multiple performance characteristics in the Taguchi method for the optimization of process parameters. The theory of grey analysis was developed and presented by Deng in 1982. The grey rational theory converts a multiple response process optimization problem into a single response optimization using maximization of overall grey relational grade (J.L. Lin, 2002). The grey rational theory has been successfully used in various fields, including industry, agriculture, economics and civil engineering. It can be successfully used to solve problems that are uncertain or which involve systems with incomplete information (Tong et al., 2006). David et al. (2004) has studied Characterization of aqueous ferric chloride etchants used in industrial photochemical machining. Fecl3 most commonly used as etchants. But there is wide variety in grades of Fecl3. Defining standards for industrial etchants and methods to analyze and monitor them Rajkumar et al. (2004) have investigated the Cost of photochemical machining in which they gave the cost model for PCM. David et al. (1983) have study manufacture of stainless steel edge filters: an application of electrolytic Photo polishing and stated the two methods for manufacturing of edge filter Professor David et al. (2004) gave the PCM as the state of the art, the PCM Roadmap and its examples. Jonathan et al. (1995) have studied Direct printing of etch masks under computer control in which all the stages of photo-processing and mask making. David et al. (1983) gave the surface textures and process characteristics of the electrolytic photo etching of annealed AlSl 304 stainless steel in hydrochloric acid. As observed from past literature, no systematic study has been reported so far to analyze the interaction effects of process parameters on etching process of PCM. It depends on experience of operator and optimal set of parameter required for process is not calculated, it is taken only by experience. The study is necessary to investigate the performance in different ranges, and to find the global optimum parameters. It is necessary to find out single optimum parameters setting to satisfy the requirements of excellent etching quality. In this paper attempt is made to finalize optimum parameters by ANOVA as well as gray rational analysis.

II. DESIGN OF EXPERIMENTS

In this study, experiments were designed on the basis of the experimental design technique which refers to the planning 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 process parameters on performance characteristics. It determines the process parameter conditions for optimum response variables. During experimentation, a large number of experiments have to be carried out as the number of machining parameters increases. Design of experiments involves proper selection of variables (input factors) and their interactions. The use of statistically derived full factorial design gives the number of experimental runs, to be carried out without affecting the quality of the analysis. Therefore, the full factorial design method was used to determine optimal machining parameters for maximum material removal rate and minimum undercut with less etching time. The 3k full factorial design consists of all combinations of the k factors taking on three levels. These are high, medium and low levels of factors. Accordingly to 33 full factorial designs, 27 experiments were planned as per the selected design with one replication. The present investigation studied the results of the effects of Concentration, Time and Temperature on the volumetric metal removal rate and undercut during the PCM process of copper material. Input parameters and their levels are shown in Table 1. Table 2 shows experimental design matrix with coded and un-coded values of 33 Full Factorial design.

Table1. Input parameters and their levels

Factor / parameter	Level l	Level 2	Level 3
Temperature (^{o}C)	47	55	60
Concentration (gm/lit.)	600	700	800
Time (Min.)	5	10	15

Table 2 Experimental layout plan for full factorial design of experiments (FFD)

Expt. No	Coded value			Un-coded value		
	A	B	C	Temp.	Conc.	Time
1	1	1	1	47	600	5
2	1	1	2	47	600	10
3	1	1	3	47	600	15
4	1	2	1	47	700	5
5	1	2	2	47	700	10
6	1	2	3	47	700	15
7	1	3	1	47	800	5
8	1	3	2	47	800	10
9	1	3	3	47	800	15
10	2	1	1	55	600	5
11	2	1	2	55	600	10
12	2	1	3	55	600	15
13	2	2	1	55	700	5
14	2	2	2	55	700	10
15	2	2	3	55	700	15
16	2	3	1	55	800	5
17	2	3	2	55	800	10
18	2	3	3	55	800	15
19	3	1	1	60	600	5
20	3	1	2	60	600	10
21	3	1	3	60	600	15
22	3	2	1	60	700	5
23	3	2	2	60	700	10
24	3	2	3	60	700	15
25	3	3	1	60	800	5
26	3	3	2	60	800	10
27	3	3	3	60	800	15

3.0 Experimental Procedure

PCM process begins from engineering drawing or sketch that defines the precise characteristics of final part. The CAD system and laser plot technology are to be utilize to generate an exact image of final part on a set of photographic films, nothing but Photo-tool. The Photo-tool is used to transfer the images of final part photographically on a clean sheet of flat metal. The flat metal should coat with photo-resist which is photosensitive, etchant-resistant polymer on both side. The coating is done on only on that part opposite to film. The result of this process is a final component as per image on sheet of metal. The machining is done on that part which is not covered with photo-resist. The sheet is then sprayed with a heated etching solution. The metal not covered by the photo-resist is dissolved, leaving precisely. Metal with exposed and developed photo resist Metal etched nominal dimensions. The copper with chemical composition 99.90% copper, 0.005% Pb and 0.001% Bi was selected for experimentation. It was electrolytic tough pitch high conductive copper with hardness 55 HV. The thickness of specimen was 0.8mm and cut at 20mmX20mm dimension. $FeCl_3$ chemical etchant was prepared at 3.76M. The amount of etchant for each experiment was 100ml. Single sided chemical etching was conducted. The chemical etching period was 25 min in total and the measurements were completed after 5 min intervals. The measurements of thickness were carried out by mitutoyo micrometer (± 0.001 mm). Fig 1 shows schematic representation and photo of experimental setup.

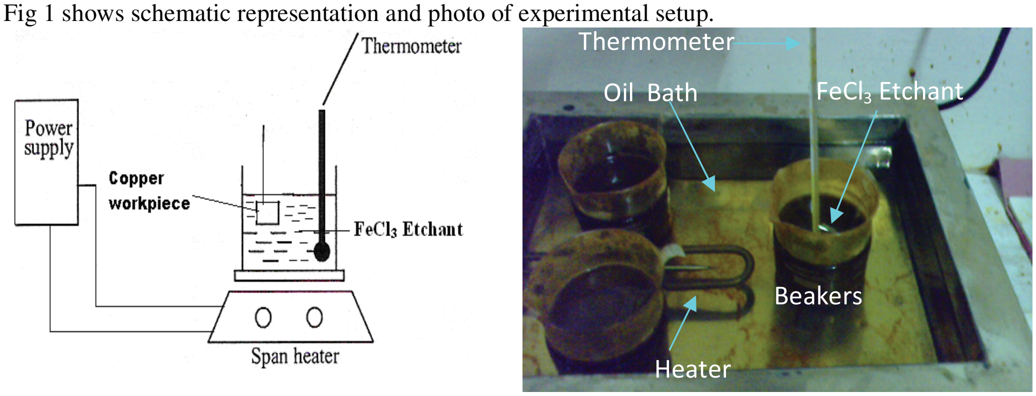

Fig. 1: experimental Set-up for etching (a) schematic representation (b) photo

IV. Result and Discussion

Grey relational analysis ranks the experiments based on the increasing order of their grey relational grade (GRG). The present investigation is focused on the improvement of maximum material removal rate and minimum undercut in PCM process.

From GRC values of MRR and UC, grey relational grade (GRG) is obtained. The GRG values for all eight experiments are show in Table 3.

Table 3 GRG calculation

Sr. No	GRC of UC	GRC of MRR	GRG
1	1.0000	0.3377	0.6689
2	1.0000	0.3333	0.6667
3	0.5021	0.5868	0.5444
4	0.9835	0.3900	0.6867
5	0.9835	0.3620	0.6727
6	0.4296	0.5894	0.5095
7	0.9675	0.5069	0.7372
8	0.9675	0.4312	0.6993
9	0.3754	0.5949	0.4852
10	0.9835	0.3620	0.6727
11	0.9675	0.3620	0.6647

12	0.4630	0.5894	0.5262
13	0.5021	0.5150	0.5086
14	0.4630	0.4356	0.4493
15	0.4007	0.5922	0.4964
16	0.4630	0.6539	0.5585
17	0.4007	0.4581	0.4294
18	0.3531	0.5977	0.4754
19	0.5484	0.3768	0.4626
20	0.4630	0.3924	0.4277
21	0.4296	0.5908	0.5102
22	0.4630	0.7003	0.5817
23	0.4296	0.5256	0.4776
24	0.3754	0.5949	0.4852
25	0.4007	1.0000	0.7003
26	0.3754	0.5894	0.4824
27	0.3333	0.5991	0.4662

Condition seven is optimum at Temperature =47°C, Concentration=800gm/liter, and Time=5 minute

According to the experiment design, it is clearly observed from Table 2 that the PCM process parameters setting of experiment no.7 has the highest grey relational grade. Therefore, experiment no.7 is the optimal process parameters setting for maximum material removal rate (MRR) and minimum undercut (UC) simultaneously (i.e. the best multi-performance characteristics) among the twenty-seven experiments. In other words, the optimum condition for PCM performance for both material removal rate (MRR) and undercut (UC)) was found for Temperature =47°C (level-1), Concentration=800gm/liter (level-3), and Time=5 minute (level-1) combination. As listed in Table 4, the difference between the maximum and the minimum value of the grey relational grade of the photochemical machining parameters is as follow: 0.1198 for time, 0.1196 for temperature and 0.0307 for concentration.

Table 4 Response table for grey relational grade

Photochemical machining parameters	Average grey relational grade by factor level			Max - Min	Rank
	Level	Level 2	Level 3		
Temperature, °C	0.6301	0.5313	0.5104	0.1196	1
Concentration, gm/liter	0.5716	0.5409	0.5593	0.0307	2
Time, Min.	0.6197	0.5522	0.4999	0.1198	3

The most significant factors affecting PCM performance characteristics are determined by comparing these values. This comparison will give the level of significance of the input factors over the multi-performance characteristics. The most effective controllable factor was the maximum of these values. Here, the maximum value among 0.1198, 0.1196 and 0.0307 is 0.1198. The value indicates that the time has the strongest effect on the multi-performance characteristics among the selected PCM process parameters. On the other hand, the significant role of every input factor can be obtained by examining these values. The order of importance of the controllable factors to the multi-performance characteristics in the PCM process, in sequence can be listed as: factor C (time), A (temperature) and B (concentration), (i.e. 0.1198>0.1196 > 0.0307). The factor time (0.1198) was the most effective factor to the performance of the PCM process.

5.3 Analysis of Variance of Grey Relational Grade (GRG)

The main effects plots for grey relational grade and the analysis of variance (ANOVA) are show in Fig. 4 and Table 6 respectively. It is observed from the ANOVA that the time and temperature has significant effect on the variability of the performance characteristics of Photochemical Machining of copper. Temperature and time is found statistically significant at 99% confidence interval respectively.
In this study, Taguchi grey relational analysis was employed to optimize the PCM In this study, Taguchi grey relational analysis was employed to optimize the PCM process parameters for multi-performance characteristics that include material removal rate and undercut in copper etching.

Table 6 ANOVA of grey relational grade (GRG)

Source of variance	DF	Sq. SS	Variance (MS)	F	P value
Temperature	2	0.0735	0.0368	6.51	0.007
Concentration	2	0.0043	0.0022	0.38	0.688
Time	2	0.0650	0.0325	5.75	0.011
Error	20	0.1130	0.0057	--	--
Total	26	0.2558	--	--	--
S = 0.0751704 R-Sq = 55.82% R-Sq (adj.) = 42.57%					

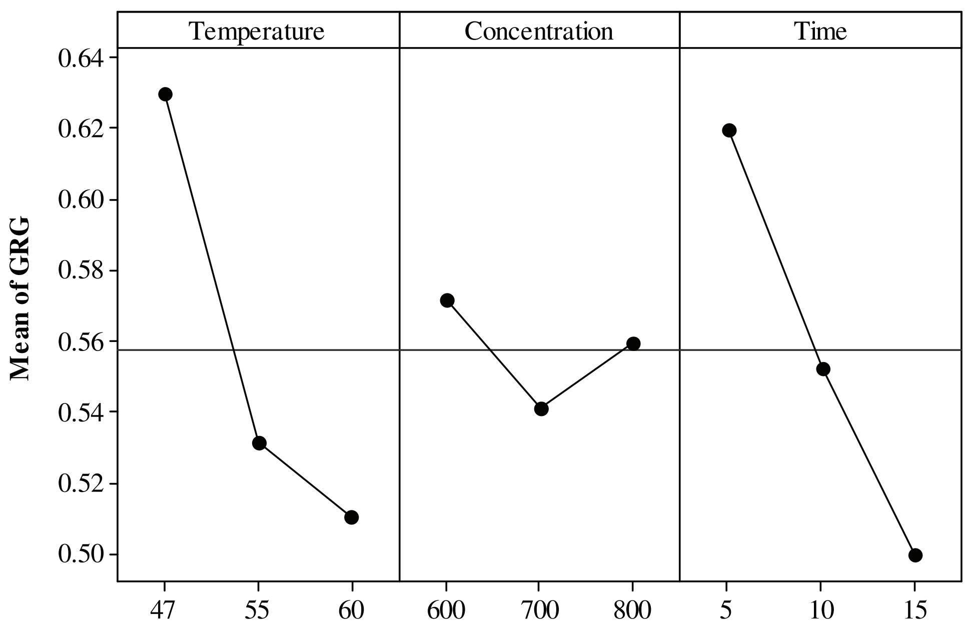

Fig. 4 Main effect plots for grey relational grade

It is found that the largest value of grey relational grade which corresponds to better process performance was obtained for the following parameter combination: Temperature 47°C, Concentration 800gm/liter and Time .5 minute. The main effect plot shows that time and temperature has linear dependence on the variation in grey relational grade value. The temperature has higher contribution to the variability of GRG over the selected range. As the temperature increases from 47°C to 55°C, there is a significant decrease in the GRG value from 0.63 to 0.53 and from 55°C to 60 there is slight change in GRG value from 0.53 to 0.49. The second higher contribution is time decreases from 5 to 15 min; there is a sudden decrease in the GRG value from 0.62 to

0.50. The concentration has very less effect as compare to other parameters and it shows the changing nature that is from 600 to 700 the GRG values decrease from 0.57 to 0.54 and from 700 to 800 the GRG values slightly increases from 0.54 to 0.56. For the low input factor level the GRG values are at highest level and for high input factor level the GRG values are at low levels. This is noticed that the for high GRG values low input factors are significant. These values are the recommended levels of input machining parameters that gives the optimum value of multi-performance characteristics. The most influential factor observed from the graph is temperature. The order of importance of the input factors to the multi-performance characteristics is temperature, time and concentration. Experimental results have shown that the material removal rate and undercut in photochemical machining of copper can be improved effectively through the proposed approach. This study indicated that the grey relational analysis approach is a robust way to obtain optimal parameters from the multiple quality characteristics.

V. Conclusion

The gray-based Taguchi method is used to determine the optimal input parameter levels of photochemical machining of copper with the multi-performance characteristics has been given in this paper. A gray relational analysis gives the single performance characteristic for MRR and UC in terms of gray relational grade.

- The conditions of experiment number seven, Temperature at 47°C, Concentration 800gm/liter, and Time 5 minute is optimum for MRR and UC.
- The time has the most effecting parameter in photochemical machining of copper amongst the selected process parameters.
- The order of importance of controllable factors effecting multi-performance characteristics in the photochemical machining of copper are in sequence can be listed as: factor C (time), A (temperature) and B (concentration), (i.e. 0.1198>0.1196 > 0.0307).
- It was found that the improvement of 6.08% is observed in the grey relational grade between predicated and experimental values.
- As per ANOVA time (P=0.007) and temperature (P=0.011) are the most effecting parameters.
- From main effect plot it is observed that time has linear variation. As time increases GRG decreases. Temperature shows gradual decrease from 47 to 55 and from 55 to 60 less decrease was observed.

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