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Parametric Optimization for Photochemical Machining of Copper using Overall Evaluation Criteria

Sandeep Sitaram Wangikar[a,b]*, Promod Kumar Patowari[b], Rahul Dev Misra[b]

[a]Department of Mechanical Engineering, SVERI's College of Engineering, Pandharpur, Pandharpur-413304, Maharashtra, India
[b]Department of Mechanical Engineering, National Institute of Technology Silchar, Silchar-788010, Assam, India

Abstract

This paper focuses on parametric effect study and optimization for photochemical machining of copper. The objective of the study is to analyze the parametric effect of concentration of etchant, temperature, and etching time on material removal rate (MRR) and edge deviation (ED). The photochemical machining of copper has been carried out based on Taguchi L9 array using ferric chloride as etchant. The effect of process parameters on output parameters has been studied using Analysis of Variance (ANOVA). The material removal rate should be high while edge deviation is always desired lesser. For achieving this multi-objective condition, overall evaluation criteria (OEC) have been formulated by assigning equal weight percentage to MRR and ED. The optimum condition predicted by OEC is at a concentration of 600 g/L, temperature of 40°C, and 21 minutes etching time

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Keywords: Photochemical machining; copper; Material removal rate; edge deviation; Taguchi method; overall evaluation criteria

1. Introduction

Unconventional machining processes are broadly employed to manufacture geometrically complex and dimensionally accurate machine parts from advanced materials used in industries as diverse as aerospace, electronics and automotive. Moreover, the various unconventional machining processes have been employed in micron-size parts production like microfluidic channels, silicon integrated circuits, copper printed circuit boards and

* Corresponding author. Tel.: +91-9657720923; fax: +91-2186-225082
E-mail address: sandeep.wangikar@gmail.com

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decorative items [1]. The very less studied unconventional machining process is photo-chemical etching [2]. Photochemical machining (PCM) is one of the nonconventional machining processes, which produce stress free and burr free flat complex metal parts [1]. The PCM process is based on the combination of photoresist imaging and chemical machining. Some of the representative studies reported on PCM are discussed below:

A systematic approach for PCM process, the PCM roadmap, and its examples were explained by Allen [1]. The selections of machining parameters in PCM are based on etchant and etching temperature while the selection of etchant is completed by the workpiece material [3]. Allen et al. (2004), studied the characterization of aqueous ferric chloride (FeCl3) etchants used in industrial photochemical machining [4]. Photochemical machining using two different etchants (ferric chloride and cupric chloride) at 50°C has been carried out by Cakir et al. and studied the depth of etching and surface roughness performance [5]. The experimental study concluded that ferric chloride improves the rate of etching whereas cupric chloride helps improving surface quality. Further study was performed to understand the influence of cupric chloride etchant on etching rate [6]. The aluminium was machined by well known chemical etchant, ferric chloride at different etching temperature [7]. Saraf and Sadaiah [8] studied effect of magnetic field on the etch rate of SS316L and also PCM of cardiovascular stent has been carried out [9]. Deepakkumar and Sadaiah conducted the study on Monel 400 using PCM [10]. Response surface method and grey relation method for optimization of the process parameters in SS316L steel etching of PCM process has been used for the prediction of Material Removal Rate (MRR), Surface roughness (Ra) and undercut [11]. The optimization of process parameters for Photo chemical machining of SS316L by using response surface methodology was carried out by Bhasme and Kadam [12]. The process parameter optimization of PCM for ASME 316 steel was presented by Mumbare and Gujar [13]. The surface study of photochemically machined copper microchannel has been carried out [14]. The parametric optimization for photochemical machining of brass and German silver was carried out [15]. The surface roughness study of photochemically machined Inconel 718 was carried out by Misal and Sadaiah [16].

From the literature studied, it can be observed that appropriate study has been reported on photochemical machining of copper. But no substantial study has been reported on parametric optimization for photochemical machining of copper. The photo chemical machining of copper using ferric chloride as etchant has been performed. The effects of etchant concentration, etching temperature with time on material removal rate and edge deviation has been studied. The optimum conditions has been predicted using multi-objective optimization criterion i.e. Overall Evaluation Criteria (OEC).

2. Materials and Methods

2.1. Material

The copper has been used as material in this study. Copper has applications in heat sinks, heat recovery units, molds for microfluidic applications, etc. The specimen size used was 20 mm X 20 mm X 1 mm (thick).

2.2 Experimental Procedure

The metal surface must be free of contaminants so that there will be good adhesion between metal and photoresist. Cleaning of the surface is carried out by solvent like trichloroethylene or acetone to remove traces of grease or oil. After cleaning, the metal plates are washed in running water. A photo tool is nothing but a negative film of the image to be produced. Nowadays photo tools are generated by direct printing of the image from CAD drawings. Photo resists application is carried out by using an immersion process with the help of a photo resist dip coater followed by drying of the specimen. The coated specimen is generally exposed to the ultraviolet source in contact with photo tool. Photo resist is sensitive to U.V. radiation & therefore an U.V tube based, U.V exposure unit can be used for exposure. After UV exposure, the specimen is kept in a solvent based developer. This will remove unexposed areas of the photo resist (Wet film negative method). The total development time is about 60 to 90 seconds. The specimen should be washed in running water with neutral pH. Process in which metal is chemically dissolved by etchant, their relative importance depends on the process parameters, such as temperature and dilution of the etchant solution. The cleaning of the specimen is carried out by washing in running water and by using acetone.

2.3 Selection of Parameters

Many parameters affect the performance of PCM process. Based on the survey of literature and some preliminary experiments, the input parameters (control parameters) has been chosen. These control parameters have been varied in a range during the experiments to study their effect on the performance measured. The input parameters along with their range of experimentation are mentioned in Table 1. Along with the input parameters, there are some parameters which also have an effect on the performance of the photochemical machining. In order to study the effect of input parameters on the PCM process, these parameters are kept constant during the experimentation like specimen size, etchant (ferric chloride), photoresist, etc.

Table 1 Control Parameters with their levels

Control Parameters	Level 1	Level 2	Level 3
Concentration (g/L)	400	500	600
Temperature (° C)	40	50	60
Etching Time (min)	7	14	21

The performance of any photochemical machining process is stated by the undercut, material removal rate, etch factor, edge deviation. The output parameters considered for the experimentation are as follows.

- Material Removal Rate (MRR): The higher value of MRR represents better etching performance. The material removal rate can be calculated from the depth of cut and the area etched.
- Edge Deviation (ED): The non conformity of the edge of machined component is referred as Edge deviation. It is an important parameters for microfluidic applications.

2.4 Taguchi Design of Experiments

Taguchi's fractional factorial method is used to optimize the process input parameters. For the combination of above mentioned parameters (Table 1), using Taguchi L-9 array, only 9 experiments are required to be performed. The PCM was performed on copper by using Taguchi L-9 array with two replications. Thus total 27 experiments has been carried out.

2.5 Experimentation

The experimental study for photochemical machining of copper was carried out in beakers, using the immersion etching method. The experimental setup is as shown in figure 1. The effect of input parameters on the material removal rate MRR (mm^3/min) and edge deviation (µm) has been studied. The measurements for edge deviation of the specimen after photochemical machining has been carried out with Leica Optical Microscope and RAPID I Vision 5 microscope. The material removal rate has been calculated by calculating the volume of material removed and then dividing it by the etching time. Figure 2 (a) shows the photochemically machined sample specimen and Figure 2 (b), (c), (d), and (e) show the edge deviation measurement of a sample specimen for all four sides.

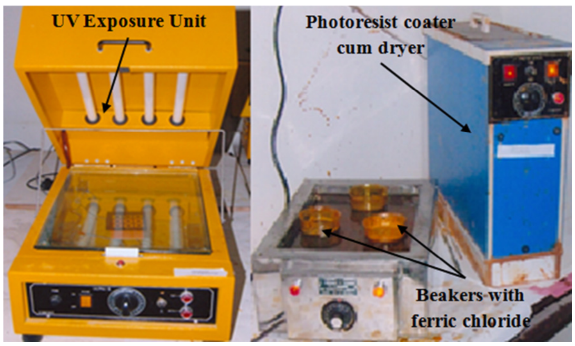

Fig. 1. Photo chemical Machining set-up.

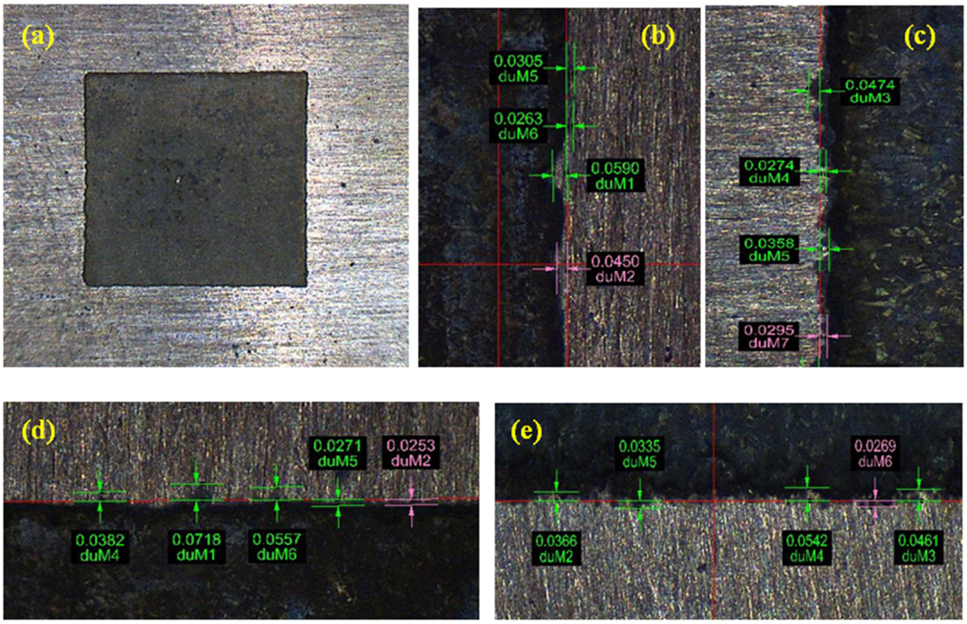

Fig. 2.(a) Photochemically machined sample specimen.; (b), (c), (d), and (e) Edge deviation measurement for all four sides of a sample specimen.

3. Results and Discussion

The performance of PCM process for copper has been analyzed by studying the material removal rate (MRR), and edge deviation (ED). The Taguchi L9 design matrix along with response parameters is given in table 2. The analysis of experimental data has been performed using Analysis of Variance (ANOVA) for studying the parametric effect.

3.1 Parametric effect on Material Removal Rate (MRR)

The effect of process parameters on MRR is represented using Main Effect plots as shown in figure 3 (a). The MRR increases with increase in concentration from 400 g/L to 600 g/L. The increase in MRR means the rate of reaction is increased. The MRR also increases with increase in temperature and etching time. The maximum MRR observed at concentration 600 g/L, temperature 60°C, and etching time of 21 minutes. The ANOVA summery data is presented in Table 3. Concentration is the most significant parameter for MRR followed by temperature.

Table 2 Taguchi L9 matrix with output parameters and OEC values

Sr. No.	Conc. (g/L)	Temp. (°C)	Time (min)	ED(µm)	MRR (mm^3/min)	OEC
1	400	40	7	51.23	0.0018	50.28
2	400	50	14	52.69	0.0029	52.60
3	400	60	21	54.88	0.0040	51.77
4	500	40	14	51.24	0.0033	64.86
5	500	50	21	52.63	0.0043	67.84
6	500	60	7	60.24	0.0041	23.29
7	600	40	21	52.07	0.0057	**84.98**
8	600	50	7	58.06	0.0054	48.42
9	600	60	14	59.69	0.0067	53.03

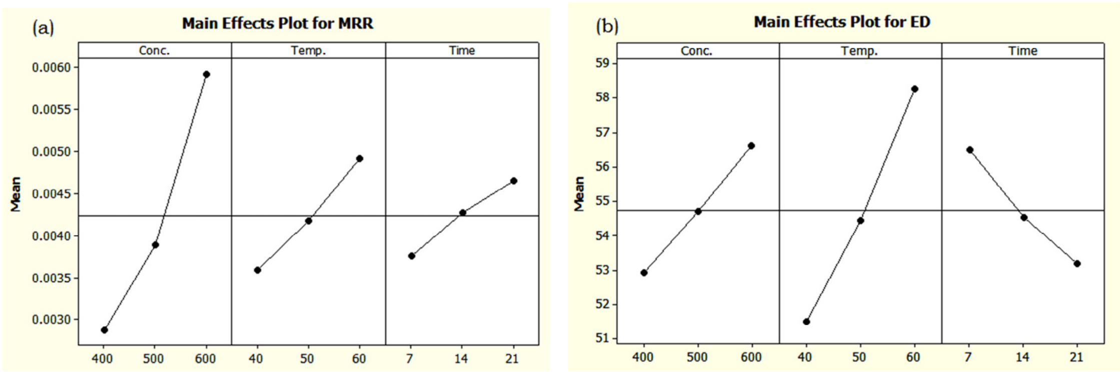

Fig. 3. (a) Main effect plot for MRR.; (b) Main effect plot for ED.

Table 3 ANOVA for MRR and ED

Parameter	DOF	Seq SS	F ratio	P value
Material Removal Rate (MRR)				
Concentration	2	0.0000144	1090.40	0.001
Temperature	2	0.0000026	199.50	0.005
Time	2	0.0000012	91.96	0.011
Error	2	0.0000000		
Edge Deviation (ED)				
Concentration	2	20.275	57.59	0.017
Temperature	2	68.801	195.43	0.005
Time	2	16.681	47.38	0.021
Error	2	0.3522		

3.2 Parametric effect on Edge Deviation (ED)

Fig. 3 (b) presents effect of process parameters on ED using Main Effect plots. The ED increases with increase in concentration and temperature. As the etching time increases, the ED decreases. The edge deviation is always preferred lesser. The lesser ED observed at concentration 400 g/L, temperature 40°C, and etching time of 21 minutes. From the ANOVA summery data for ED (Table 2), it can be noted that temperature is the most significant parameter for ED. The concentration and etching time have lesser effect on ED.

3.3 Optimization using Overall Evaluation Criteria (OEC)

The control parameters have the simultaneous effect on MRR and ED. From the parametric effect (Fig. 3 (a) and(b)) it can be observed that the control parameters are different for higher MRR and Lower ED. So, it is required to formulate a multi-objective optimization considering MRR and ED which will give the best condition among the experiments. The overall evaluation criteria (OEC) have been formulated for multi-objective optimization to satisfy two performance parameters. The relative weight percentage of the individual criterion of evaluation presented in table 4. For OEC, the different criteria with quality characteristics (QC) are normalized and weighted with 'bigger is the best' (QC = B). The calculation of OEC for the MRR and ED, X and Y with weight percentages W_x and W_y is as given in Eq. (1) [17]. The QC for X is 'bigger is the best' (QC = B) and for Y is 'smaller is the best' (QC = S) [18].

$$OEC = \left(\frac{X\text{-}X_{min}}{X_{max} - X_{min}}\right)W_x + \left(1 - \frac{Y\text{-}Y_{min}}{Y_{max} - Y_{min}}\right) W_y \quad (1)$$

Table 4 Parameters with weight percentage for OEC

Sr. No.	Parameter	Material	Worst	Best	Weights
1	Material removal rate, MRR	Copper	0.0018	0.0067	50
2	Edge deviation, ED	Copper	51.23	60.24	50

The OEC values along with the process parameters is shown in Tables 2. The higher value OEC is highlighted in the table, which gives the condition for optimum performance parameter. Experiment number 7 (concentration 600 g/L, temperature 40°C, time 21 min) gives the optimized condition for the considered output parameters.

4. Conclusions

The photochemical machining of copper has been carried out using Taguchi L9 array design matrix using ferric chloride as etchant and analysis has been carried out using ANOVA. Etchant concentration, temperature and etching time have been taken as the control parameters. The main conclusions based on the study are as given below

- The material removal rate increases with increase in concentration, temperature and etching time. The edge deviation increases with increase in concentration and temperature but decreases with increasing etching time.
- Concentration is the most significant parameter for material removal rate while temperature is significant parameter for edge deviation.
- The maximum MRR observed at concentration 600 g/L, temperature 60°C, and etching time of 21 minutes while lesser ED observed at concentration 400 g/L, temperature 40°C, and etching time of 21 minutes.
- Overall evaluation criteria (OEC) have been formulated for deciding the optimum parametric condition.
- The optimum condition predicted by OEC is at concentration of 600 g/L, temperature of 40°C, and 21 minutes etching time.

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