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Investigation of Photo-Chemical Machining on Copper

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ABSTRACT

One of the newer non-traditional machining techniques is photochemical machining (PCM). In addition to PCM, other names for the process include etching, photochemical machining, wet etching, photo etching, photochemical milling, etc. It uses chemical etching through a photo-resist stencil to remove material from specific regions. This method is employed frequently to create flat metal blanks, which can then be shaped into three dimensions if necessary. The work piece of interest is exposed using a photographic mask to create the features, and when negative photo resist is employed, the unexposed UV portion of the work piece material is removed chemically during the etching process [1]. Instead of cutting or burning away metal, the manufacturing process dissolves metal to produce features. Therefore, in the final component of PCM, there are no tensions or flaws that typically result from metal cutting or EDM. This indicates that there are no deformations, residual strains, burrs, or changes in the magnetic characteristics. Hardness, grain structure, or ductility are not altered in the process. Furthermore, regardless of how many components are made, tolerances remain the same because photo tools don't wear out. For the production of small, burr-free, stress-free parts, it can be utilized as an alternative to stamping. The issue of undercut has been introduced in this by smaller and more intricate motifs. Etchant concentration, etching duration, and etchant temperature are the three main parameters that effect undercut. Correct PCM process parameter selection is crucial to enhancing product quality.

1. INTRODUCTION

Some benefits of the method include minimal tool costs, independence from the physical and mechanical qualities of the materials, high precision, etc. The procedure' limitations in work piece material thickness due to undercut (up to 2 mm for most materials, 6 mm for copper) and environmental friendliness are its drawbacks.
In the past thirty years, PCM has been extensively employed in the production of thin, flat, and complicated metal parts (such as lead frames, colour TV masks, sensors, heat plates, and printed circuit boards) in the electronics, precision engineering, and decorative industries. A range of precision parts, including micro fluidic channels, silicon integrated circuits, copper printed circuit boards, decorative objects, micro fluidics, and micro filters, are being produced in large part by the PCM industry. It is primarily employed in the production of micro-components for application in a variety of industries, including electronics, aerospace, and medicine. Additionally, it is employed in the production of micro-filters that are used to purify a variety of liquids as well as flexure bearings and mesh utilised in heat engine regenerators and compressors.
Techniques for chemical and photographic etching are used in PCM procedures. On the photoresist-coated work piece, the chosen portions are exposed by the photographic technique and subsequently machined using a chemical etchant and etching technique. PCM process is carried out in following steps and Figure 1.1 show working of PCM.

Preparation of masters/photo tool

It functions as a PCM tool. The creation of oversized art or paper is the first step. In order to reduce dimensional error, artwork is typically created at a certain magnification factor. Artwork can be created through hand drafting, computer-aided drafting, or precisely coordinating graph plotting. Using a precision reduction camera, the artwork is captured on camera. Multiple image masters are utilised to expose, develop, and etch numerous components in high volume part manufacture. It produces master film with the desired etching design on it. To enable simultaneous exposure from both sides, sets of films are created.

Selection of metal

Because the smoothness of parts' edges reduces as grain size increases, metals should have the smallest possible grain size. It is best to use a metal that is soluble in etchant. A substance should be uniformly thick and flat. Thesurface finish must be homogeneous and free from inclusions, embedded particles, and scratches

Preparation of work piece

Metal surfaces need to be clean and free of impurities in order for metal and photo resist to adhere well. Spraying water on the metal surface of the work piece should be cleared in order to see if each droplet spread out to form a thin layer of water. Film formation indicates thorough cleaning. After rinsing, the piece is dried.

Masking with photo resists

Photo resists offer photosensitive surfaces that withstand etchant action. The photo resist has two masking options: positive and negative. That is exposed to light in a positive acting system area wash away while developing. In a negative system, developing solutions become insoluble on exposed surfaces. Application methods for photo resists include dipping, swirl coating, and spraying. The resists are allowed to air dry before being baked for 15 minutes at a temperature of no more than 120 oC.

Expose to UV Light

In this phase, we add a mask for UV exposure in order to capture images. Depending on the process flow and the desired outcome, the used mask may be positive or negative. The elements that determine proper imaging on the needed workpiece are the light intensity for the specific photo resist, the thickness of the photo mask, the layer of photo resist, and the exposure period. The wavelength of light employed is typically between 300 and 400 nm. The main element affecting proper imaging is exposure time. It is the moment when the work piece is exposed to UV light while wearing a mask. Usually, it lasts between 10 and 30 seconds. Additionally, the side of exposure—either one side or both sides—is a significant effect. Both side exposures appear to take less time to etch and produce a surface polish with less undercutting. The mask should be properly aligned for both side exposures.

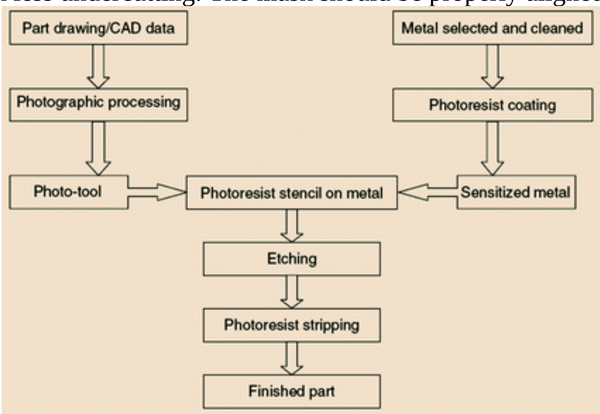


Figure 1.1: Steps in PCM [1]

Image Developing

The image is developed using a highly pure buffered alkaline solution after UV exposure. In this method, photo resist that becomes brittle from UV exposure is removed, and after post-baking, we receive the pattern of the desired image on the work piece material. As a developing solution, sodium carbonate or sodium hydroxide solutions containing 1-2 percent are typically utilised. The most important element in this is the developing time, which typically ranges from 35 to 90 seconds depending on the image quality and photo resist employed.

Etching

During etching, the created and post-baked panel of metal is subjected to hot acid. When metal is exposed to acid, it oxidises and creates a soluble reaction product. Either immersing in an agitated chemical bath or spraying heated acid can be used for etching. The break through happens when the etching has advanced to the point when penetration from each surface has reached halfway through the sheet. Etchant-resistant etching machines can tolerate corrosion. At the base of machines is some that contains the etchant. Etchant temperature is kept consistent with the assistance of a heating element and cooling coil. A conveyor system-equipped etcher enables continuous processing. Batch type machines process one sheet at a time.

2 OBJECTIVES

PCM is a relatively obscure non-traditional machining technique. It is primarily used to make jewellery and decorative items. However, it is currently employed in a number of industries, including aircraft, electronics, and medicine. It can also be utilised for quick prototyping, which eliminates the need for tool or die development. It is used to fabricate tiny elements including microfluidic channels, tiny filters for water and blood filtration, and mesh regenerators that speed up heat removal in stirling engines. These components are excellent for micro engineering. Other methods, such EDM and stamping, can be used to make these parts, but they are more expensive and time-consuming than PCM. In order to calculate blood

In order to discover process parameters like etchant concentration, etching temperature, and etching duration as well as response variables like undercut and surface roughness, the goal of this study is to investigate photo-chemical machining. Additionally, to create microfilters and mesh for regenerators, which are employed in a variety of applications.

The goal of this project is to determine the ideal machining parameters, such as etching duration, etching temperature, and etching concentration of cut, in order to obtain better results while employing copper with a thickness of 30, 50, or 100 m. Based on the literature review, PCM will be used, and the Taguchi method with Grey Relational Analysis will be used to optimise the input parameters. On copper and steel plates with thicknesses of 100 micron and 2000 micron, respectively, micro holes of roughly 300 micron will be cut under ideal machining conditions.

3. LITERATURE REVIEW

There are number of researchers worked on PCM and according to required process parameters and response variables, we are going to study following few papers:

Cakir [3] had studied the copper etching with cupric chloride and regeneration of waste etchant. In this, he observed that cupric chloride is more accepted etchant; because of its high etch rate and easy regeneration properties. In the etching of copper with cupric chloride, the most important etching parameter is etch rate, therefore the investigation was based on the various effects on etch rate. Etchant concentration, additives and etching temperature were examined as an input parameter. It is also important to regeneration/recycle of waste etchant from environmental point of view. Thus, various cupric chloride etchant regeneration processes were investigated.

Saraf et al. [4] has studied optimization of photochemical machining of OFHC copper by using ANOVA. The control parameters considered were the etchant concentration, etching temperature and etching time. The response parameters were Undercut (Uc) and the Surface roughness (Ra).The effects of control parameters on undercut and surface roughness were analyzed using Analysis of Variance (ANOVA) technique and their optimal conditions were evaluated. An optimum surface roughness was observed at an etching temperature of 55°C, an etching concentration of 600 gm/litre and 15 minutes etchings time. The minimum undercut (Uc) was observed at the etching temperature of 45°C, etching concentration of 600 gm/litre and 15 minutes etching time. It was found that etchant temperature and etching time are the most significant factors for undercut.

Hardeep Singh et al. [5] had done experimental investigation of chemical etching on EN-5 steel using nitric acid. The experimental investigation analyses the influence of etching conditions on material minimum overcut area during chemical etching process. ANOVA is employed to investigate the influence of time, temperature and concentration on minimum undercut area of the material. The experiments was conducted by varying the parameters of etching process like temperature from 20^0C to 30^0C, Time from 2 hours to 6 hours and concentration 10% to 30%. Taguchi is used as design of experiments. Results were analyzed using Taguchi, ANOVA and parametric optimization is done for minimum undercut area of material. From the experimentation, it is concluded that for etching of EN-5 steel optimum machining condition for minimum undercut area with Time (2 hours), Temperature (20^0C), and Concentration (10%).

Wagh et al. [7] studied experimental investigation of PCM on Inconel 600 using Response Surface Methodology. They had done 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 model's analyses were supported with the aid of the statistical software package-Design Expert. 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 55^0C, etchant concentration 470.781 gm/lit and 55.276 min etching time. The optimum material undercut was found 0.0029 mm.

Cakir et al. [8] investigate on chemical etching of Cu-ETP copper. Copper is chemically etched with two different etchants (ferric chloride and cupric chloride) at 50^0C. The effects of selected etchants and machining conditions on the depth of etch and surface roughness was investigated. By experimental study, they found that ferric chloride produced the fastest chemical etch rate, but cupric chloride produced the smoothest surface quality.

Tehrani and Imanian [9] investigated a new etchant for the chemical machining of Stainless Steel 304. Their investigation aimed at reducing pitting problem and obtaining better surface finish in chemical machining of SS304. A new etchant is introduced for chemical machining of SS 304. Results present good surface finish without any pitting while high machining rate is achieved. The etchant tested in several temperatures and different depths of machining and the results are compared with other etchants. New etchant is a mixture of H2O + HCl + HNO3 + HF + H2COOH + TEA. Scan electron microscope (SEM) and roughness tests were employed to observe the surface topography.

Allen and Almond [10] studied characterization of aqueous ferric chloride etchants used in industrial photochemical machining. Ferric chloride ($FeCl_3$) is the most commonly used etchant for PCM but there is a great variety in the grades of the commercial product. In an ideal world, to maintain a constant rate of etching and hence control of part dimensions dependent on etch time, the etchant composition would be constant. Unfortunately, in the real world, the etchant composition changes continuously. As an *n*-valent metal (M)is dissolved into solution, etchant is consumed and the by-products of ferrous chloride ($FeCl_2$) and metal chlorides (MCl_n) are generated, i.e.

$$nFeCl3 + M \rightarrow nFeCl2 + MCln$$

Thus, for quality control of PCM, this creates a specific demand for data relating to the composition of the etchant as it changes. The demand covers characterization of the new etchant, its degradation with use and the etchant resulting from its in situ chemical regeneration.

4. METHODOLOGY

Hands on experiments are performed to verify the machine capability, range for the selected process parameter. Hands on experiments are done randomly at extreme condition i.e., higher temperature, concentration and etching time also slower range. Based on the hands-on experiments, the constant parameters for trial experiments are selected. After finalizing the values for parameters, experiments are performed according to design of experiments (DoE).

4.1 Final Experiments for Copper

After successfully completing trial experiments on photo chemical machine, positive and negative points are considered for main experiments and parameters for final experiments are decided.

4.1.1 Experiment Details

- Work piece material : Copper
- Thickness : 100 micron
- Etchant Solution : Ferric Chloride ($FeCl_3$)
- Machine : Photo Chemical Machine supplied by Venice Electronics Pune.
- The values of the selected machining parameters, three parameters with three levels of each parameter are as shown in Table 4.1.

4.1.2 Design of Experiments

Design of experiments is a method of designing experiments, in which only selected number of experiments are to be performed. Table 4.1 shows process parameter and their value at different level.

Table 4.1: Process Parameters and Their Levels for Final Experiments for Copper

Process Parameter	Levels		
	1	2	3
Temperature (^{0} C)	40	50	60
Concentration (gm/litre)	500	600	700
Time (min)	4	6	8

There are three parameters with three levels of each parameter and then the total number of experiments to be performed is 3^3= 27 experiments. On the basis of these 27 experiments, the significance and optimal levels of each parameter is obtained. After performing all experiments, the values of response variables are fed to software for analysis. Analysis is done using Minitab software.
Orthogonal array used to perform final experiments and the results are as shown in Table 4.2.

Table 4.2: L27 (3^3) Orthogonal Array used for Experiments with Results for Copper

Final Experiments	Concentration (gm/litre)	Temperature (^{0}C)	Time (min)	Undercut (µm)	Ra (µm)
F_1	500	40	4	25	0.26
F_2	500	40	6	35	0.48
F_3	500	40	8	40	0.83
F_4	500	50	4	35	0.52
F_5	500	50	6	45	1.02
F_6	500	50	8	50	1.24
F_7	500	60	4	40	0.78
F_8	500	60	6	45	1.42
F_9	500	60	8	60	1.66
F_{10}	600	40	4	30	0.58
F_{11}	600	40	6	35	0.78
F_{12}	600	40	8	45	1.02
F_{13}	600	50	4	35	1.04
F_{14}	600	50	6	40	1.34
F_{15}	600	50	8	55	1.78
F_{16}	600	60	4	45	1.32
F_{17}	600	60	6	50	2.03

F_{18}	600	60	8	55	2.32
F_{19}	700	40	4	30	0.84
F_{20}	700	40	6	35	1.22
F_{21}	700	40	8	40	1.34
F_{22}	700	50	4	40	1.02
F_{23}	700	50	6	50	1.56
F_{24}	700	50	8	55	1.66
F_{25}	700	60	4	45	1.52

5. ANALYSIS AND DISCUSSION

After performing all experiments, the values of response variables are fed to software for analysis. Analysis is done using Minitab software. This chapter deals about the results obtained from the software and its analysis. Analysis of experimental results is carried out using Minitab-16 software. Here undercut and surface roughness are two response variables. Hence analysis of undercut and surface roughness is carried out separately for each work piece.

5.1 Analysis of Undercut (µm)

Analysis of variance (ANOVA) for undercut (micron) is given in Table 5.1. These values are obtained from Minitab 16 software. It shows that time and temperature is the significant parameters for undercut.

Table 5.1: ANOVA for Undercut (µm) for copper

Source	DF	Seq. SS	Adj. SS	Adj. MS	F ratio	P
Concentration	2	50.00	50.00	25.00	2.57	0.101
Temperature	2	1050.00	1050.00	525.00	54.00	0.000
Time	2	1105.56	1105.56	552.78	56.86	0.000
Error	20	194.44	194.44	9.72		
Total	26	2400.00				
S = 3.11805 R-Sq = 91.90% R-Sq(adj) = 89.47%						

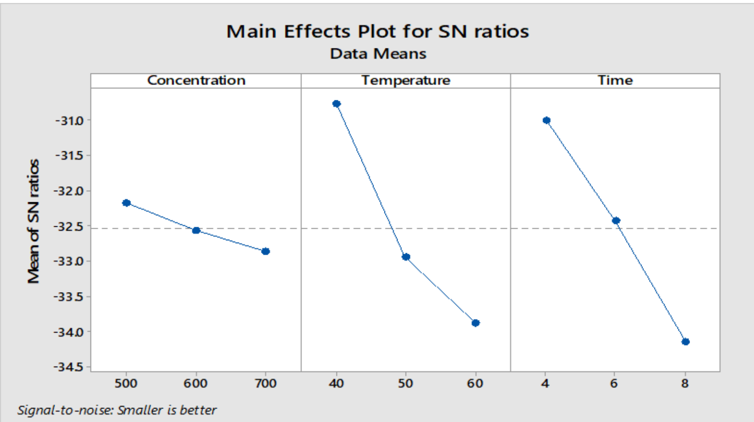
Unusual Observations for Undercut

Obs.	Undercut	Fit	SE Fit	Residual	St Resid.
26	45.0000	50.5556	1.5876	-5.5556	-2.07

R denotes an observation with a large standardized residual.

Analysis of variance (ANOVA) for material undercut (micron) is given in Table 5.1, these values are obtained from Minitab 16 software. Time is most significant parameter affecting undercut with F value 56.86 and second significant parameter is temperature with F value 54.00

The relationship between undercut and other parameters is as shown in graph 5.1. Highest value of undercut is observed at concentration 700 gm/litre, Temperature 60^0 C and time 8 minute. Whereas lowest value of undercut is observed at concentration 500 gm/litre, temperature 40^0 C and time 4 minute.



Graph 5.1: Main Effects Plot (SN Ratios) for Undercut (micron) for Copper

From the main effect plot in graph 5.1, it indicates that as time and temperature increases then undercut goes on increases due to faster chemical reaction at high temperature for longer period. Similar tends are observed by Atul Saraf [6].

5.2 Analysis of Surface Roughness (µm)

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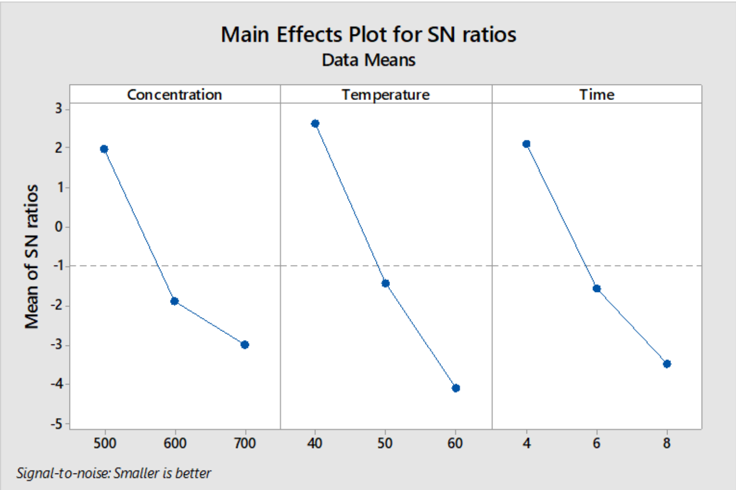
Surface roughness of photo chemical machined components was measured by using surface roughness tester. The determined surface roughness (R_a) value is shown in Table 5.2.

Table 5.2: ANOVA for SR (µm) for Copper

Source	DF	Seq. SS	Adj. SS	Adj. MS	F ratio	P
Concentration	2	1.5600	1.5600	0.7800	42.05	0.000
Temperature	2	3.3456	3.3456	1.6728	90.19	0.000
Time	2	2.1991	2.1991	1.0995	59.28	0.000
Error	20	0.3710	0.3710	0.0185		
Total	26	7.4757				
S = 0.136192 R-Sq = 95.04% R-Sq(adj) = 93.55%						

Analysis of variance (ANOVA) for surface roughness (µm) is given in Table 5.2. These values are obtained from Minitab 16 software. Temperature is most significant parameter affecting surface roughness (µm) with F value 90.19. Time is second most significant parameter affecting surface roughness (µm) with F value 59.28.
The relationship between surface roughness and other parameters is as shown in graph 5.2. Smaller surface roughness is observed at concentration 500 gm/litre, temperature 40^0 C and time 4 minute. Whereas higher surface roughness at concentration 700 gm/litre, temperature 60^0 C and time 8 minute.



Graph 5.2: Main Effects Plot (SN ratios) for SR (µm) for Copper

From the main effect plot shown in graph 5.2 indicates that with increases in temperature and time surface roughness is increased. This is because, as the temperature increases then there will be increase in un-uniform material removal results into increase surface roughness.

5.3 Grey Relational Analysis of Copper

The grey relational analysis of Copper is shown in Table 5.3. The grey relational grades are obtained by averaging the grey relational coefficients of two response variables. The ranking to the experiments is given according to value of the grey relational grade. Rank one is given to that experiment having largest value of grey relational grade. The experiment having smallest value of grey relational grade is ranked as number twenty-seven.

5.4 Analysis for Grey Relation Grade (GRG) of Copper

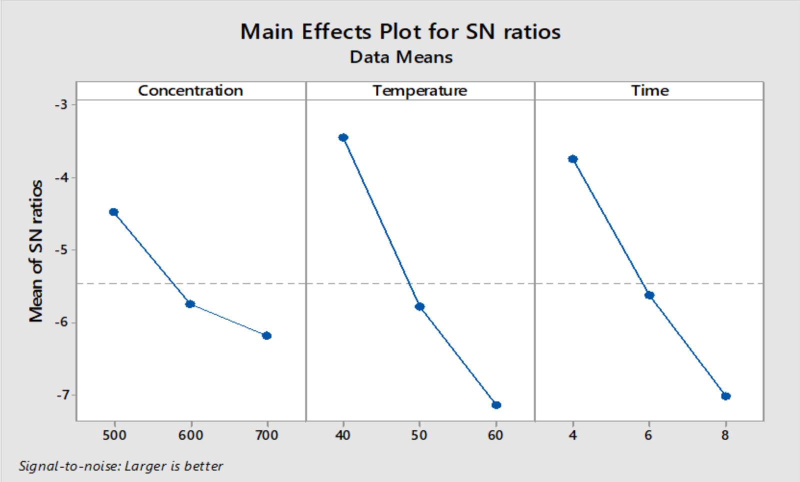
The Table 5.5 is obtained by doing ANOVA of GRG. ANOVA is used to identify the statistical significance of individual parameter on a particular response. The F ratio values in this table indicate the significance of process parameters. Here Time and temperature is the most significant parameter.

Table 5.5: ANOVA for GRG of Copper

Source	DF	Adj. SS	Adj MS	F ratio	P
Concentration	2	0.0687	0.0343	16.72	0.00
Temperature	2	0.2685	0.1342	65.32	0.00
Time	2	0.2091	0.1045	50.87	0.00
Error	20	0.0411	0.0020		

Total	26	0.5875				
S=0.0453 R-sq.=93.00% R-sq.(adj.)= 90.90% R-sq.(pred.)= 87.25%						

The values of parameters at which the SN ratios of GRG are larger are shown in graph 5.3. Here these values of parameters give best results of response variables. While the lower most values in the plot indicate the values of parameters for worst case results. Here Concentration 500 gm/litre, temperature 40^0 C and time 4 minute is best result.



Graph 5.3: Main Effects Plot (SN ratios) for GRG for Copper

6. CONCLUSION

The conclusions below are reached based on experimental data received during copper material photochemical machining utilising L27 orthogonal array.

- The analysis of experimental results indicate that time, temperature have a significant influence on undercut and surface roughness during photo chemical machining of copper.
- Lowest undercut is observed at concentration 500 gm/litre, temperature 40^0 C and time 4 minute for copper.
- Better values of surface roughness are obtained concentration 500 gm/litre, temperature 40^0 C and time 4 minute for copper.
- Multiple response variable optimization is performed using grey relational analysis indicates that concentration 500 gm/litre, temperature 40^0 C and time 4 minute are optimum conditions for undercut and SR (25 µm and 0.26µm) for copper.
- Different materials, including Inconel 600, glass, aluminium alloy, titanium alloy, etc., can be used for photo chemical machining.
- You can employ a variety of etchants, including hydrofluoric acid, cupric chloride, and alkaline etchants.

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