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Parametric Optimization in Photochemical Machining of Aluminium Using Taguchi Method

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Abstract. The objective of this study was to investigate the optimal process parameters of photochemical machining on aluminium workpiece. The input parameters considered were etching concentration, etching temperature and etching time. The study revealed their effects over Material Removal Rate, Surface Roughness and Edge Deviation. L_9 Taguchi design was used to formulate the experimental layout. ANOVA and average S/N ratio were performed for the optimal setting of the process parameters. For larger-the-better characteristics the optimal conditions for MRR was obtained at etching concentration of 600g/L, etching temperature of 60˚C and etching time of 8 minutes. For, smaller-the-better characteristics, the optimal setting for surface roughness was obtained at etching concentration of 400g/L, etching temperature of 40˚C and etching time of 4 minutes and for edge deviation obtained at etching concentration of 400g/L, etching temperature of 40˚C and etching time of 8 minutes.

1. Introduction

Unconventional machining processes have been employed for manufacturing of micro size parts like silicon integrated circuits, microfluidic channels, decorative items and copper printed circuit board [1]. A photochemical machining is one of the emerging nonconventional machining processes that produce stress free and burr free flat complex metal parts. The process involves chemical etching through a photo-resist stencil as a method of material removal over selected areas [1]. Using ferric chloride as chemical etchant aluminium was machined at different etching temperature and found that ferric chloride was a suitable etchant for aluminium etching [2]. The selection of etchant is based on the workpiece and selection of machining parameters is based on etchant, etching temperature and etchant time [3]. This selection of efficient etchant is probably the most important parameter in chemical etching of any material. This will enhance the etching rate and produce smooth surface finish [2]. Various characteristics of ferric chloride etchants are studied which are used in industrial photo chemical machining. Although $FeCl_3$ most commonly used as etchant but there is wide variety in grades of $FeCl_3$ [4]. The cost involves for PCM defines standards for industrial etchants and methods to analyses and monitor them [5]. Many researchers had studied the effect of etching time and etchant temperature on the surface finish and rate of etching on PCM of copper, aluminium and Inconel 718 using ferric chloride and cupric chloride as etchants [6, 2, 7].

The objective of the present work is an attempt for finding the feasibility of chemical machining of aluminium by using different concentration of $FeCl_3$ at different etching temperatures and time. Taguchi design approach is used to analysis the responses material removal rate, surface roughness and edge deviation. The effect of process parameters on the machining characteristics has been investigated by ANOVA method and the optimum condition has been predicted using average S/N ratio.

2. Materials and Methods

For the experimentation, aluminium material was used as a workpiece of size 20 mm x 20 mm x 5 mm. After that photo tool was prepared in required shape and size. Photo tool is nothing but a negative film of the image to be produced. The workpiece surface was cleaned to remove dust particles to obtain good surface for adhesion of photo resist masking solution. Masking was applied by immersing into photo resist dip coater followed by drying. The coated specimen is placed under the photo tool and exposed to the ultraviolet source. As Photo resist is sensitive to U.V. radiation therefore a U.V tube exposure unit was used for exposure. Photo tools are generally used in precisely registered pairs, one on the top and one on the bottom, with the material to be machined placed in between which allow the material to be etched from both the side. After U.V. exposure the specimen is dipped into solvent-based developer solution for 60 seconds. This softens the unexposed areas of the photo resist. Then, it is dried and baked for 2 minutes followed by dipping into ferric chloride solution where, the etchant solution dissolves the unexposed masked area to get the required shape and size by removing the material. After that the work sample is cleaned by washing process. Based on the literature survey, some pilot experiments were conducted to select the controllable process parameters such as, concentration (g/L), temperature (˚C) and etching time (min) as tabulated in Table 1 with their different levels.

Table 1. Control Parameters with their levels

	Control parameters	Level 1	Level 2	Level 3
A	Concentration (g/L)	400	500	600
B	Temperature(° C)	40	50	60
C	Time (min)	4	6	8

Table 2. Taguchi L_9 matrix with weights of workpiece

Sl. No.	Conc. (g/L)	Temp. (°C)	Time (min)	Trial 1		Trial 2		Trial 3	
				Initial weight	Final weight	Initial weight	Final weight	Initial weight	Final weight
1	400	40	4	1.8939	1.8926	1.9476	1.9468	1.9231	1.9225
2	400	50	6	1.7620	1.7463	1.8832	1.8730	1.8831	1.8772
3	400	60	8	1.9334	1.8790	1.9743	1.9438	2.0303	2.0044
4	500	40	6	1.9670	1.9463	1.7527	1.7490	2.0056	1.9973
5	500	50	8	1.8257	1.7814	1.8685	1.8612	1.8596	1.8473
6	500	60	4	1.9168	1.8923	2.1074	2.0974	1.9211	1.9158
7	600	40	8	1.7648	1.7557	1.9557	1.9427	1.9915	1.9846
8	600	50	4	1.9390	1.9306	1.9723	1.9654	1.8928	1.8908
9	600	60	6	1.8449	1.8184	2.0142	1.9923	1.6964	1.6807

Taguchi’s design is a fractional factorial method is suitable process for parametric optimization. Taguchi’s L9 orthogonal array was selected to carry out the current experimental investigation. Using ferric chloride as etchant, photochemical machining of workpiece was carried out. The effect of input parameters on the material removal rate (MRR), surface roughness (Ra) and edge deviation were studied.

The weight of the workpiece before and after machining are tabulated in table 2. Using optical microscope, edge deviation of desired shape and size were measured machining. The material removal rate was obtained by calculating the volume of material removed and then dividing it by the etching time. After the experimentation, the values of MRR, Ra and ED along with their S/N ratio were measured as tabulated in table 3. Figure 1. shows the machined specimen, measurement of edge deviation and measurement of surface roughness of work samples.

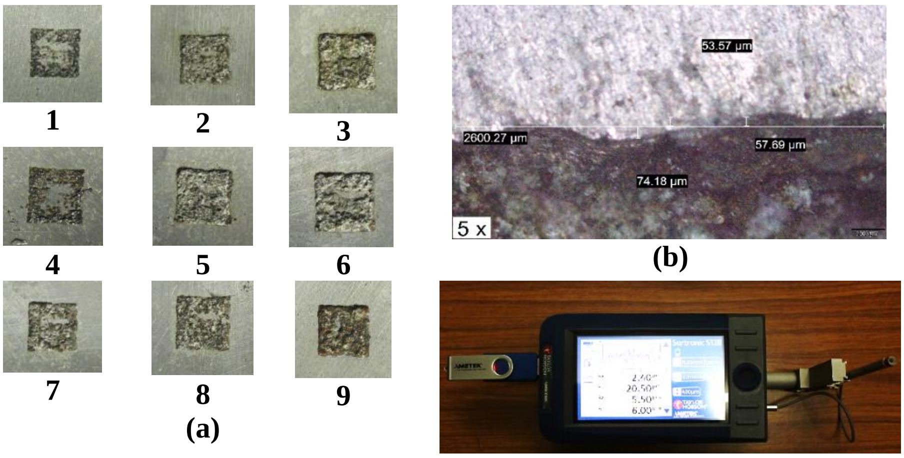

Figure 1. (a) Photo chemically machined sample specimen **(b)** Edge deviation measurement **(c)** Measurement of surface roughness

Table 3. Calculation of MRR Ra and ED along with their S/N ratios

SL. No.	Trial 1			Trial 2			Trial 3			S/N ratio		
	MRR	Ra	ED	MRR	Ra	ED	MRR	Ra	ED	MRR	Ra	ED
1	0.325	1.53	51.28	0.2	0.97	51.28	0.15	0.67	46.47	-14.201	-0.946	-33.93
2	2.617	3.1	65.25	1.57	2.9	61.58	0.983	1.43	62.96	2.766	-8.256	-36.03
3	6.8	2.63	72.12	3.812	3.4	62.04	3.237	2.93	60.89	12.078	-9.558	-36.29
4	3.45	1.37	53.57	0.617	1.3	54.28	1.383	1.57	48.76	-0.326	-3.021	-34.3
5	5.53	2.07	70.06	0.912	3.27	55.86	1.537	2.57	59.75	2.574	-8.561	-35.83
6	6.125	2.57	81.73	2.5	2.07	81.28	1.325	2.53	78.76	5.984	-7.604	-38.13
7	1.137	2.67	57.46	1.625	2.6	55.40	0.862	2.2	48.53	0.795	-7.951	-34.63
8	2.1	2.7	77.84	1.725	2.97	61.36	0.5	1.77	67.77	-1.822	-8.006	-36.82
9	4.417	3.37	79.67	3.65	3.07	62.73	2.617	0.67	64.56	10.420	-8.490	-36.83

3. Results and discussions

The experimental analysis was carried out to observe the effect of process variables on response parameters for optimal condition for high material removal rate, low surface roughness and low edge deviation. The MRR increases with increase in concentration, temperature and time. The maximum MRR was observed at concentration 600 g/L, temperature 60 ℃, and etching time of 8 minutes. The average S/N ratio for MRR are shown in table 4. The ANOVA is presented in table 5. Temperature is the most significant parameter for MRR followed by time. However, the etching concentration has less effect on material removal rate. Based on the average S/N ratio plot, the optimal parameters combination for MRR obtained at etching concentration at 600g/L, etching temperature at 60˚ and etching time at 8 minutes. The parameters that have greater influence on MRR are temperature, time and etchant concentration as shown in figure 2. The temperature has the most dominant effect amongst all other parameters.

Table 4. Ave S/N ratio MRR

Level	Etching Concentration	Etching temperature	Etching time
1	0.2143	-4.577	-3.346
2	2.744	1.173	4.287
3	**3.131**	**9.494**	**5.149**
Delta	2.9167	14.071	8.495
Rank	3	1	2
Optimal setting	3	3	3

Table 5. ANOVA for MRR

Factors	Sum of square	DOF	Mean square	F-Ratio	Percent contribution	Rank
Etching concentration	0.46	2	0.23	0.88	3.09	3
Etching temperature	11.847	2	5.923	22.655	79.53	1
Etching time	2.006	2	1.033	3.951	13.47	2
Other factor	0.522	2	0.261		3.5	
total	14.897	8			3.09	

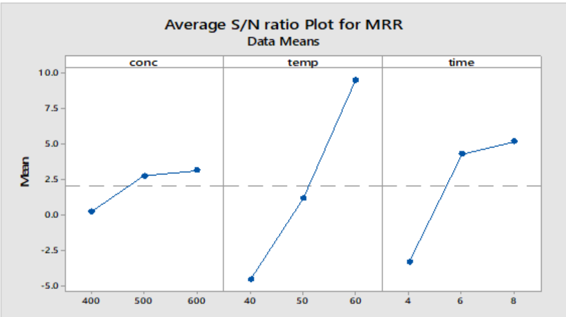

Figure 2. Average S/N ratio plot for MRR

The surface roughness increases with increase in concentration, temperature and time. This is because, as the concentration increase along with temperature then there will be increase in non-uniform material removal that results in increase in surface roughness. The minimum surface roughness observed at concentration 400 g/L, etching temperature 40°C and etching time at 4 minutes. The average S/N ratio values for surface roughness are shown in table 6. From the ANOVA table 7, was observed that etching temperature and etching time contributes more on the variability of surface roughness. However, the concentration had less effect on surface roughness value as compared to other factors. The optimal parameters combination for surface roughness obtained at etching concentration at 400g/L, etching temperature at 40˚ and etching time at 4 minutes. The average S/N ratio plot for surface roughness is plotted in figure 3. The parameters that have greater influence on surface roughness are same as that for MRR. The temperature has the most dominant effect amongst all other parameters.

Table 6. Ave S/N ratio **Ra**

Level	Etching Concentration	Etching temperature	Etching time
1	**-6.253**	**-3.973**	**-5.519**
2	-6.396	-8.274	-6.589
3	-8.149	-8.551	-8.69
Delta	1.896	4.578	3.171
Rank	2	1	3
Optimal setting	1	1	1

Table 7. ANOVA FOR **Ra**

Factors	Sum of square	DOF	Mean square	F-Ratio	Percent contribution	Rank
Etching concentration	0.164	2	0.082	0.572	5.44	3
Etching temperature	1.636	2	0.818	5.703	54.24	1
Etching time	0.928	2	0.464	3.234	30.77	2
Other factor	0.286	2	0.143			
total	3.016	8				

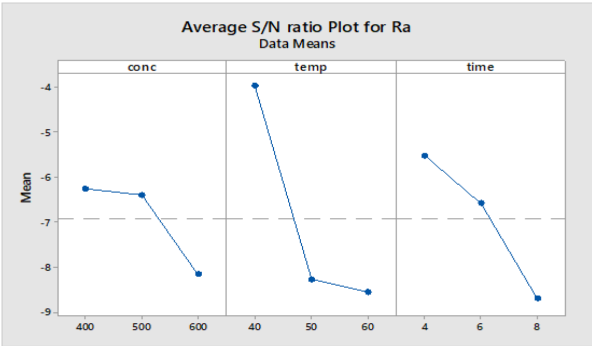

Figure 3. Average S/N ratio plot for Ra

The edge deviation increases with increase in etching concentration and etching temperature but, decreases with increase in etching time. The minimum edge deviation observed at etching concentration 400 g/L, etching temperature 40°C and etching time of 8 minutes. The average S/N ratio value for ED are shown in table 8. From the ANOVA table 9 was observed that etching temperature is the most significant parameter on the variability of edge deviation. However, the etching time and etching concentration had less effect on edge deviation. The optimal parameters combination for surface roughness was obtained at etching concentration at 400g/L, etching temperature at 40˚ and etching time at 8 minutes. The average S/N ratio plot for edge deviation is plotted in figure 4. The parameters that have greater influence on edge deviation in the decreasing order of importance is same as that for MRR and surface roughness. The temperature has the most dominant effect amongst all other parameters.

Table 8. Ave S/N ratio **ED**

Level	Etching Concentration	Etching temperature	Etching time
1	**-35.42**	**-34.287**	-36.293
2	-36.087	-36.227	-35.72
3	-36.093	-37.083	**-35.583**
Delta	0.673	2.796	0.71
Rank	3	1	2
Optimal setting	1	1	3

Table 9. ANOVA for **ED**

Factors	Sum of square	DOF	Mean square	F-Ratio	Percent contribution	Rank
Etching concentration	51.058	2	25.529	0.914	6.78	3
Etching temperature	579.082	2	289.541	10.371	76.92	1
Etching time	66.841	2	33.42	1.197	8.88	2
Other factor	55.832	2	27.916			
total	752.815	8				

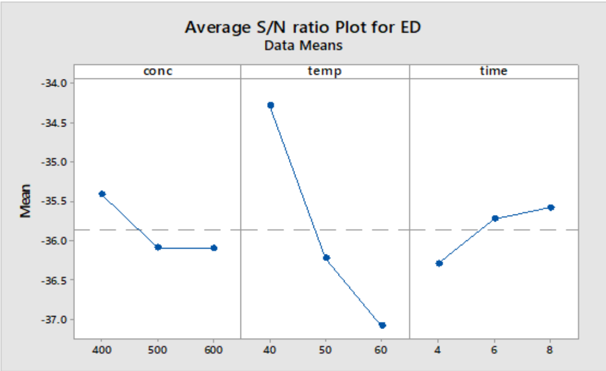

Figure 4. Average S/N ratio plot for ED

4. Conclusions

Based on the results obtained, the following inferences were drawn.

- MRR increases with increase in concentration, temperature and time respectively.
- Surface roughness increases with increase in concentration, temperature and time respectively.
- The edge deviation increases with increase in concentration and temperature but decreases with increase in etching time.
- The optimal parameters combination for MRR obtained at etching concentration at 600g/L, etching temperature at 60˚ and etching time at 8 minutes.
- The optimal parameters combination for surface roughness obtained at etching concentration at 400g/L, etching temperature at 40˚ and etching time at 4 minutes.
- The optimal parameters combination for edge deviation obtained at etching concentration at 400g/L, etching temperature at 40˚ and etching time at 8 minutes.
- From ANOVA it was observed that for MRR, surface roughness and ED temperature is the most significant factor followed by time while machining Aluminium work piece.

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