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Effect of process parameters and optimization for photochemical machining of brass and german silver

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ABSTRACT

This article focuses on parametric optimization for photochemical machining (PCM) of brass and german silver. The aim of the study is to analyze the effect of control parameters on response measures, that is, surface roughness, material removal rate, and edge deviation and optimization of parameters considering different weight percentage for each performance measure. The control parameters have been selected as etchant concentration, etching temperature, and etching time. Using full factorial method of design of experiments, PCM has been carried out using ferric chloride as etchant. Surface roughness and edge deviation should be less, while material removal rate is desired high. For satisfying this multi-objective condition, overall evaluation criteria (OEC) have been formulated by assigning different and equal weight percentage to response measures. The optimized condition for particular OEC is obtained, and analysis of variance (ANOVA) has been performed for observing effect of control parameters on response measures. Surface topography study has been performed using scanning electron microscopy, and material composition analysis has been carried out using energy dispersive spectroscopy. The surface roughness is observed lower for brass, while the edge deviation is found lesser for german silver. The material removal rate is observed higher for brass compared to german silver.

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Brass; german silver; photochemical; machining; MRR; surface; roughness; edge; deviation; OEC

Introduction

For manufacturing of geometrically intricate and precise machine parts, nontraditional machining processes are extensively preferred. Moreover, various nontraditional machining processes have been employed in production of micron-size components and this scenario seems growing day by day. Hitherto, the micro-fabrication methods [1] include micro-electrical discharge machining (μEDM), photochemical machining (PCM), laser machining, electrochemical machining (ECM), and so on. The mostly studied unconventional machining processes are electric discharge machining (50%), laser machining (31%), and electrochemical machining (10%), whereas less studied are abrasive jet machining (6%) and photochemical etching (3%) [2]. Photochemical machining is one of the nonconventional machining processes, which produce stress free and burr free flat complex metal parts [3]. But this process is explored very little by researchers in the latest past. Some of the recent trends of study are discussed as follows.

Two-dimensional simulation model of etching was developed, and the experimental analysis of the process parameters on micro-geometry was investigated [4]. Moreover, single-crystal silicon was tested for three-dimensional anisotropic wet etching using a simulation model [5]. The micro-textures on carbon steel surfaces were fabricated using PCM, and parametric study was carried out [5]. The surface textures were created on sheets of Monel 400 using photochemical machining process. The effect of spinning speed on film of photoresist, and the effect of temperature and etching time on the etched pattern were studied [6]. The chemical machining of copper, aluminum, and Inconel 718 was carried out by many researchers for studying the effect of etching time and etchant temperature on the surface finish and rate of etching. The etchants used were ferric chloride and cupric chloride [7, 8, 9]. The regeneration process for cupric chloride was also investigated [10]. The PCM on OFHC copper was carried out with ferric chloride etchant to observe parametric effect on undercut, surface roughness, and etch factor followed by optimization using gray rational analysis [11]. The optimization of process parameters for undercut and material removal rate was performed by using artificial neural network and gray rational analysis [12, 13]. The process parameter's optimization for PCM of SS316 and SS316L steel was carried out for the prophecy of material removal rate (MRR), surface roughness, and undercut using response surface method and gray rational method. The control parameters considered were concentration, temperature, and time [14, 15, 16]. The different manufacturing alternatives for fabrication of microchannel heat recovery unit were discussed. Photochemical machining was used as a patterning process for producing channels [17].

Nickel silver or german silver is a ternary alloy of copper, zinc, and nickel. Due to its silvery white appearance, it is also

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known as german silver. Because of its hardness, toughness, and resistance to corrosion, it is widely used in marine fittings, plumbing fixtures, name plates, bezels, eyeglass frame, and also for making of ornaments, jewelry, and decorative items.

PCM is one of the most deserving processes for micro-fabrication, but a very less study has been carried out in this area. The PCM is performed on different materials like copper, silicon, aluminum, nickel, and stainless steel to evaluate the effect of temperature, concentration of etchant, and etching time on response measures like etch rate, surface roughness, and depth of etch. To fabricate a particular shape for micro-components, the edge deviation is a prominent measure. In the surface modification of selective masking technique in micro-EDM, an attempt is made to minimize the edge deviation. The effects of control parameters are analyzed by taking into account the results for edge deviation in micro-EDM [18]. Likewise, the edge deviation would also be a significant performance measure for photochemically machined micro-components, but it is not explored for PCM in the present literature. Again, the study on the combined effect of performance measures in PCM is not observed in the literature.

In this article, an experimental study has been carried out on brass and german silver using photochemical machining. The effect of process parameters like etchant concentration, etchant temperature, and etching time on performance measures such as surface roughness, edge deviation, and material removal rate has been investigated. For determining the optimal conditions for desired combinations of performance measures, overall evaluation criteria (OEC) have been formulated for an equal and different weight percentage assigned to each of the performance measure. The surface topography analysis was carried out using optical microscopy and scanning electron microscopy (SEM).

Materials and Methods

Heat sinks, heat recovery units, and microchannels are becoming a significant area of interest in many fields such as MEMS, biomedical, fuel processing, and aerospace. Manufacturing of different components for these applications is promising with PCM. The different materials used for these applications are generally copper and its alloys. Some studies are observed in copper, SS316, SS304, etc., but no significant study is observed for PCM of copper alloys like brass and german silver. Hence, the materials selected for the study are brass and german silver.

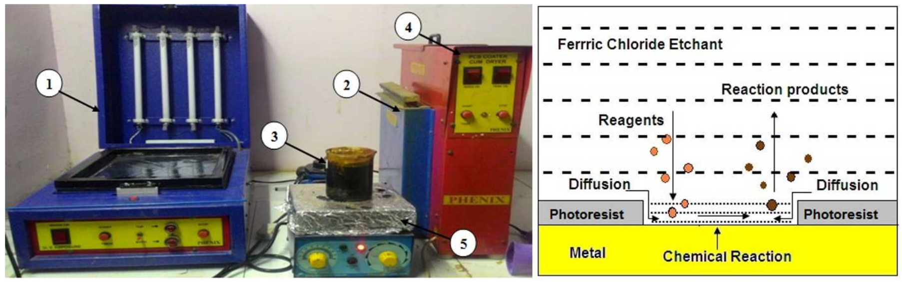
In photochemical machining, the specimen is first cleaned with acetone so that it will be free of contaminants and there will be good adhesion between metal and photoresist. The phototool is the negative film of the image to be produced. Phototools are produced by direct printing of the image from CAD drawings. The photoresist is applied using an immersion process with the help of a photoresist dip coater followed by drying of the specimen. A photoresist is sensitive to ultraviolet (UV) radiation, and therefore, the selectively coated specimen with phototool is exposed to the ultraviolet source using the UV exposure unit. After UV exposure, the specimen is kept in a solvent-based developer. This will remove unexposed areas of the photoresist (wet film negative method). The total development time is about 60 to 90 seconds. The specimen is washed in running water with neutral pH. Then, the next step is etching. Etching is a process in which metal is chemically dissolved by etchant. After etching, cleaning of the specimen is carried out by washing in running water and by using acetone.

For studying the detailed effect of all process parameters on performance measures in PCM, a full factorial design of experiments (DOE) has been selected for experimentation. DOE includes an appropriate selection of process parameters (control factors) and interactions between them. From past study, it has been observed that the different parameters like concentration of etchant, etching temperature, and etching time have an effect on the response measures of PCM [3, 10, 14, 15, 16]. The pilot experimentation has been carried out for deciding the ranges of process parameters. Total three process parameters have been selected for experimentation: etchant concentration, temperature, and etching time. For the temperature below 40°C and etching time less than 7 minutes, no significant results have been observed due to a very less amount of etching. Above 60°C, abrupt surface has been observed because of over etching of the specimen and very fewer changes have been found in response to the etching time greater than 21 minutes. The etchant with concentration above 600 g/L becomes more viscous, which leads to decrease in the rate of etching, and hence has less effect on response measures. Based on the pilot experimentation, the levels of process parameters have been decided. The process parameters selected are etchant concentration with five levels and etchant temperature and etching time with three levels each. For this combination of process parameters, 45 experiments are required to be carried out using a full factorial method. The process parameters (fixed and variable) selected for conducting experimentation are given in Table 1.

Experimentation has been carried out using the experimental setup presented in Fig. 1(a). Ferric chloride ($FeCl_3$) is a universal etchant and generally used for materials like steels, aluminum and its alloys, copper and its alloys, and nickel. It is cheap, providing a high etch rate, and reliable [7]. So, the etchant used is ferric chloride. For each experiment, 500 ml etchant has been used and the temperature has been maintained within the ±1°C. Single-sided chemical etching process has been followed. In photochemical machining, material removal phenomenon takes place by chemical etching process. The

Table 1. Experimental conditions.

Control parameters with their levels		
Control parameters	Level	Values
Concentration (g/L)	5	200, 300, 400, 500, 600
Temperature (°C)	3	40, 50, 60
Time (min)	3	7, 14, 21
Fixed parameters		
Parameters		Values/description
Etchant		Ferric chloride
Specimen thickness		1 mm
Specimen size		20 mm × 20 mm



(a) (b)

Figure 1. (a) Experimental setup of photochemical machining. 1 Ultraviolet (UV) exposure unit. 2 Photoresist coater. 3 Beaker with ferric chloride. 4 Dryer. 5 Hot plate. (b) Etching mechanism of photochemical machining.

photochemical etching mechanism is as shown in Fig. 1(b). It includes three major stages:

a) Ions or molecules from the etchant solution diffused toward the exposed area on the metal surface through the boundary layer.
b) Due to a chemical reaction between etchant and the exposed metal surface, soluble and gaseous by-product formation takes place.
c) A by-product from the surface of the work piece gets diffused through the boundary layer into the etchant solution.

Table 2. Experimental design matrix with response measures and OEC values for brass.

Expt. No.	Conc. (g/L)	Temp. (°C)	Time (min)	Ra (μm)	MRR (mm^3/min)	ED (μm)	OEC 1	OEC 2	OEC 3	OEC 4
1	200	40	7	0.115	0.009	30.37	72.70	47.70	70.39	63.60
2	200	40	14	0.153	0.0116	29.12	73.64	50.12	73.31	65.69
3	200	40	21	0.172	0.0137	28.23	**74.63**	52.10	**75.58**	**67.43**
4	200	50	7	0.2864	0.0148	34.25	64.70	44.42	61.07	56.73
5	200	50	14	0.3852	0.0163	32.56	63.71	45.55	63.54	57.60
6	200	50	21	0.4024	0.0181	31.08	65.30	48.00	67.01	60.10
7	200	60	7	0.4536	0.0148	36.48	56.74	39.24	53.49	49.82
8	200	60	14	0.584	0.0197	34.29	56.32	42.54	57.59	52.15
9	200	60	21	0.6376	0.0229	33.41	56.50	44.63	59.61	53.58
10	300	40	7	0.142	0.0152	35.89	67.86	45.31	60.06	57.74
11	300	40	14	0.1714	0.0186	33.16	70.90	49.91	66.53	62.45
12	300	40	21	0.246	0.0219	31.28	71.49	52.79	70.38	64.89
13	300	50	7	0.3168	0.0204	39.56	59.75	41.75	50.91	50.80
14	300	50	14	0.4261	0.0238	37.38	59.54	44.44	54.87	52.95
15	300	50	21	0.4664	0.0287	36.30	60.92	48.04	58.07	55.68
16	300	60	7	0.5123	0.0263	40.94	53.64	40.76	46.56	46.99
17	300	60	14	0.6352	0.0327	38.73	53.97	45.16	51.31	50.15
18	300	60	21	0.6832	0.0379	37.42	55.43	49.07	54.98	53.16
19	400	40	7	0.2385	0.0216	43.16	58.86	39.94	44.84	47.88
20	400	40	14	0.3468	0.0248	41.80	57.74	41.63	46.99	48.79
21	400	40	21	0.3992	0.0273	40.15	58.57	44.13	50.46	51.05
22	400	50	7	0.3873	0.0308	45.29	54.54	41.01	40.70	45.42
23	400	50	14	0.4923	0.0337	44.39	52.94	42.08	41.82	45.61
24	400	50	21	0.5268	0.0389	42.78	55.18	46.54	46.36	49.36
25	400	60	7	0.6125	0.0378	49.54	44.71	37.14	30.04	37.29
26	400	60	14	0.7529	0.0415	47.63	43.27	39.21	32.99	38.49
27	400	60	21	0.7823	0.0468	46.23	45.48	43.59	37.20	42.09
28	500	40	7	0.456	0.0347	44.89	53.93	42.78	41.66	46.12
29	500	40	14	0.593	0.0386	43.17	52.46	44.83	44.33	47.21
30	500	40	21	0.653	0.0426	41.69	53.33	47.96	47.78	49.69
31	500	50	7	0.6852	0.0439	47.83	46.07	41.64	34.45	40.72
32	500	50	14	0.8263	0.0494	45.37	45.77	45.44	39.14	43.45
33	500	50	21	0.8868	0.051	44.34	45.38	46.56	40.86	44.26
34	500	60	7	0.8125	0.0483	50.75	40.09	39.18	27.44	35.57
35	500	60	14	0.9532	0.0535	48.72	39.25	42.32	31.12	37.57
36	500	60	21	1.02	0.0612	47.14	41.18	47.80	35.86	41.61
37	600	40	7	0.568	0.0568	45.65	56.40	54.12	45.18	51.90
38	600	40	14	0.723	0.0603	44.43	53.67	55.08	46.34	51.70
39	600	40	21	0.782	0.0673	43.87	54.54	**59.14**	48.78	54.16
40	600	50	7	0.825	0.0634	48.91	46.45	50.53	35.99	44.32
41	600	50	14	1.06	0.0681	47.13	42.05	51.53	37.40	43.66
42	600	50	21	1.15	0.0756	46.32	42.31	55.66	40.03	46.00
43	600	60	7	1.123	0.0715	51.46	36.37	47.98	28.12	37.49
44	600	60	14	1.48	0.0793	50.29	28.25	48.25	27.18	34.56
45	600	60	21	1.62	0.0877	48.64	28.03	53.03	31.07	37.38

Bold indicates the highest value of all OECs which gives the condition for optimum performance measure.

Table 3. Experimental design matrix with response measures and OEC values for german silver.

Expt. No.	Conc. (g/L)	Temp. (°C)	Time (min)	Ra (μm)	MRR (mm^3/min)	ED (μm)	OEC 1	OEC 2	OEC 3	OEC 4
1	200	40	7	0.167	0.007	27.54	71.31	46.31	67.63	61.75
2	200	40	14	0.182	0.0096	25.95	74.30	51.19	72.56	66.02
3	200	40	21	0.195	0.0122	24.16	**77.56**	56.31	**77.96**	**70.61**
4	200	50	7	0.312	0.0129	29.63	68.75	49.59	64.82	61.06
5	200	50	14	0.453	0.0138	25.95	69.36	52.78	71.44	64.53
6	200	50	21	0.567	0.0149	26.84	65.89	51.62	68.60	62.04
7	200	60	7	0.534	0.0154	33.07	60.34	45.93	55.80	54.03
8	200	60	14	0.659	0.0161	31.26	59.24	47.05	58.44	54.91
9	200	60	21	0.761	0.0177	29.84	58.95	49.22	61.13	56.43
10	300	40	7	0.196	0.0124	30.28	70.99	49.87	64.72	61.86
11	300	40	14	0.231	0.0137	28.52	72.76	52.98	68.90	64.88
12	300	40	21	0.257	0.0146	27.11	74.14	55.31	72.19	67.22
13	300	50	7	0.343	0.0149	39.56	58.33	40.90	44.01	47.75
14	300	50	14	0.481	0.0161	37.38	57.59	42.88	47.60	49.35
15	300	50	21	0.613	0.0172	36.3	55.75	43.61	48.80	49.39
16	300	60	7	0.568	0.0168	40.94	51.70	38.67	39.05	43.14
17	300	60	14	0.697	0.0191	38.73	51.96	42.23	43.54	45.91
18	300	60	21	0.815	0.0225	37.42	52.25	46.37	46.92	48.51
19	400	40	7	0.261	0.0151	37.84	62.65	44.19	49.05	51.96
20	400	40	14	0.397	0.0163	35.08	62.60	46.83	53.93	54.45
21	400	40	21	0.475	0.0177	33.49	63.03	49.27	57.20	56.50
22	400	50	7	0.409	0.0182	40.23	57.86	43.49	43.75	48.37
23	400	50	14	0.533	0.0206	38.67	57.61	46.54	46.95	50.37
24	400	50	21	0.626	0.0228	37.01	58.22	49.87	50.68	52.92
25	400	60	7	0.612	0.0219	44.35	50.03	40.90	34.28	41.74
26	400	60	14	0.764	0.0237	42.74	48.66	42.84	36.81	42.77
27	400	60	21	0.841	0.0251	40.92	49.37	45.54	40.60	45.17
28	500	40	7	0.617	0.0211	40.58	53.48	43.91	41.92	46.44
29	500	40	14	0.689	0.0229	38.85	54.50	47.11	45.84	49.15
30	500	40	21	0.758	0.0247	37.23	55.48	50.22	49.56	51.75
31	500	50	7	0.771	0.0261	42.48	50.29	46.11	38.82	45.07
32	500	50	14	0.863	0.0279	40.69	50.81	49.09	42.59	47.49
33	500	50	21	0.935	0.0293	38.17	52.43	52.63	47.98	51.01
34	500	60	7	0.839	0.0285	45.07	47.09	45.42	33.76	42.09
35	500	60	14	0.962	0.0314	43.49	47.22	49.15	37.34	44.57
36	500	60	21	1.048	0.0336	41.24	48.66	53.23	42.46	48.11
37	600	40	7	0.694	0.0323	42.25	56.71	55.44	44.41	52.18
38	600	40	14	0.785	0.0348	40.76	57.38	59.00	47.99	54.79
39	600	40	21	0.861	0.0367	39.17	58.19	**62.12**	51.61	57.30
40	600	50	7	0.897	0.0345	44.14	50.34	53.35	38.84	47.51
41	600	50	14	1.12	0.0374	42.86	47.32	55.34	40.36	47.67
42	600	50	21	1.43	0.0397	41.63	41.40	55.27	40.15	45.60
43	600	60	7	1.38	0.0382	47.08	35.90	48.10	28.00	37.33
44	600	60	14	1.65	0.0426	44.51	33.92	52.77	32.63	39.77
45	600	60	21	1.94	0.0458	42.37	30.14	55.14	35.27	40.18

Bold indicates the highest value of all OECs which gives the condition for optimum performance measure.

Photochemical machining has been carried out for brass and german silver. The design matrix (as per full factorial DOE) for performing experimentation along with recorded response parameters for brass is given in Table 2, while for german silver it is presented in Table 3. After machining, *Ra* has been measured using a Mitutoyo surface roughness tester. The edge deviation and the dimensions have been recorded with RAPID-I Vision 5 microscope. The depth of etch has been measured using the digital micrometer. By calculating the volume of material removed (area×depth of etch) in mm^3 and dividing it by the respective etching time, the material removal rate has been evaluated (in mm^3/min).

Results and Discussion

The performance of photochemical machining of brass and german silver has been evaluated by surface roughness (*Ra*), material removal rate (MRR), and edge deviation (ED). The experimental data analysis has been carried out for determining the effect of concentration, temperature, and time on *Ra*, MRR, and ED.

Surface roughness is a constituent of surface texture. The surface roughness of each specimen of brass and german silver was recorded at three locations, and the average value is taken for analysis. The material removal rate will give the amount of dissolved metal in the etchant. The nonconformity of the edge of the machined component is referred as edge deviation (ED). The edge deviation also recorded at four edges, and the average value is considered for analysis. Analysis of variance (ANOVA) has been used for the prediction of the percentage contribution of process parameters on performance measures. The ANOVA for response parameters is given in Table 4.

The average effect of concentration on *Ra*, MRR, and ED for brass is shown in Fig. 2, and the same for german silver is shown in Fig. 3. When the molecules collide, the reaction occurs. Hence, the higher the number of molecules of reactant (reagents) present per unit volume in the etchant, the greater the chances for reactive collisions to occur. So, increasing the

Table 4. ANOVA for response variables.

Parameter	DOF	Sum of Sqrs. (*S*)	*F*-ratio (F)	Percent *P* (%)
		For brass		
		(a) Surface roughness (*Ra*)		
Concentration	4	2.94150	118.91	43.84
Temperature	2	1.58891	128.46	47.36
Time	2	0.29518	23.86	8.80
Error	36	0.22264		
Total	44			100
		(b) Edge deviation (ED)		
Concentration	4	1561.51	1419.89	71.45
Temperature	2	240.55	437.47	22.01
Time	2	71.44	129.91	6.54
Error	36	9.90		
Total	44			100
		(c) Material removal rate (MRR)		
Concentration	4	0.0161183	694.84	78.79
Temperature	2	0.0015848	136.64	15.49
Time	2	0.0005849	50.43	5.72
Error	36	0.002088		
Total	44			100
		For german silver		
		(a) Surface roughness (*Ra*)		
Concentration	4	3.73990	68.20	46.02
Temperature	2	1.77895	64.89	43.79
Time	2	0.41397	15.10	10.19
Error	36	0.49350		
Total	44			100
		(b) Edge deviation (ED)		
Concentration	4	1184.61	132.16	60.39
Temperature	2	297.32	66.34	30.31
Time	2	91.17	20.34	9.29
Error	36	80.67		
Total	44			100
		(c) Material removal rate (MRR)		
Concentration	4	0.0035073	1040.10	77.79
Temperature	2	0.0003839	227.69	17.03
Time	2	0.0001169	69.32	5.18
Error	36	0.0000303		
Total	44			100

concentration of reactants generally leads to increase in the rate of reaction. Thus, at 200 g/L etchant concentration, less number of molecules will collide on the surface of metal as well on the edge, which results in less diffusion at the surface, and this gives less material removal, good surface finish, and edge finish, that is, less *Ra* and ED. As the concentration increases from 200 g/L to 600 g/L, the reagents increase in proportional amount in etchant. As more reagents present in the etchant, the reactive collision with increased frequency at the surface may occur. This will lead to improved diffusion and hence better material removal rate, but produces an uneven surface and edge and hence gives higher *Ra* and ED. The area available for reactive collision at the edge is very less as compared to the surface. ED increases slightly because reactive collisions occur at higher concentration (greater than 400 g/L). It can be noted from Table 4 that concentration has the highest contribution for MRR, followed by ED, and somewhat less contribution for *Ra*, for both brass and german silver.

The influence of average temperature on *Ra*, MRR, and ED for brass is shown in Fig. 2(a), (c), and (e), respectively, and the same for german silver is shown in Fig. 3(a), (c), and (e), respectively. Chemical reactions take place when molecules collide with one another in a dynamic way. The movement of molecules is governed by temperature because the temperature is a measure of the kinetic energy present in molecules. The molecules react only when they have an adequate amount of energy for a reaction. The molecular energy level will increase with the increase in the temperature of a solution causing more collisions between particles, which leads to a better rate of reaction. Generally, etching rate increases with an increase in temperature [9, 19]. As the temperature increases from 40°C to 60°C, the molecular energy level may increase reactive collisions of the molecules on the surface, which leads to better diffusion. So, a higher amount of material will be removed from the surface as well as edges, resulting in uneven surface and edges. This leads to better MRR and higher *Ra* and ED for an increase in temperature. For brass and german silver, temperature has the highest contribution for surface roughness, followed by ED, and slightly less for MRR as given in Table 4.

Figures 2(b), (d), (f) and 3(b), (d), (f) demonstrate the effect of average etching time on *Ra*, MRR, and ED for brass and german silver, respectively. The etching time has slightly less effect on performance measures. If the reagents collide on the surface for less time, then lesser diffusion will occur. This leads to lower material dissolution in the etchant, which, in turn, gives low MRR but good surface finish (less *Ra*). The collision of reagents on the specimen surface for the higher time will enhance the diffusion and material removal rate. But the surface obtained may be uneven due to collisions for a longer time resulting in higher *Ra*. This gives a continuous increase in MRR as well as *Ra* with time. These results for MRR and *Ra* are analogues to that of the results for chemical machining of copper (Cakir et al. [6]).

The area available for the collision of molecules is less at the edge of the specimen. For the etching time of 7 minutes, less time is available for collisions and simultaneously diffusion as compared to the etching time of 14 and 21 minutes. Hence lesser amount of material at the edge is dissolved in etchant producing an uneven edge, that is, higher ED. With increase in time (to 14 and 21 minutes), which causes continuous attack of molecules on the small area, material removal at the edge is increased compared to that at 7 minutes. This results in somewhat smoother edge and thus lower ED. The dissolution of material at the edge increases with an increase in time, and the edge becomes smoother. Thus, less ED is observed at 21 minutes as compared to 7 and 14 minutes. The etching time has very less contribution on response measures as compared with concentration and temperature. Time has the highest contribution for *Ra* followed by ED, and less contribution for MRR, for brass and german silver as presented in Table 4.

The input parameters have the simultaneous effect on response measures. If there are more than one response measures in experimentation, then the analysis of a single response measure at a time will not give better outcome. So, there is a need of multi-objective optimization considering all response measures in the analysis, and it will predict the best condition among the experiments. The overall evaluation criteria (OEC) have been formulated for multi-objective optimization to satisfy three responses of each sample. The relative weight percentage of the individual criterion of evaluation is decided. 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 response measures X and Y

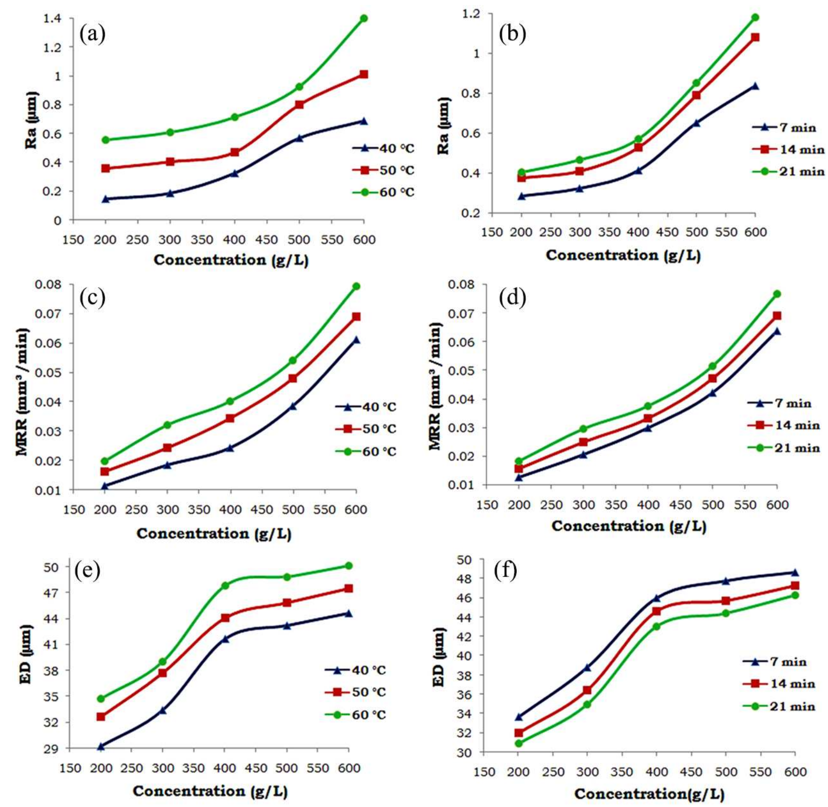


Figure 2. For brass—(a) The average effect of concentration and temperature on surface roughness. (b) The average effect of concentration and time on surface roughness. (c) The average effect of concentration and temperature on material removal rate. (d) The average effect of concentration and time on material removal rate. (e) The average effect of concentration and temperature on edge deviation. (f) The average effect of concentration and time on edge deviation.

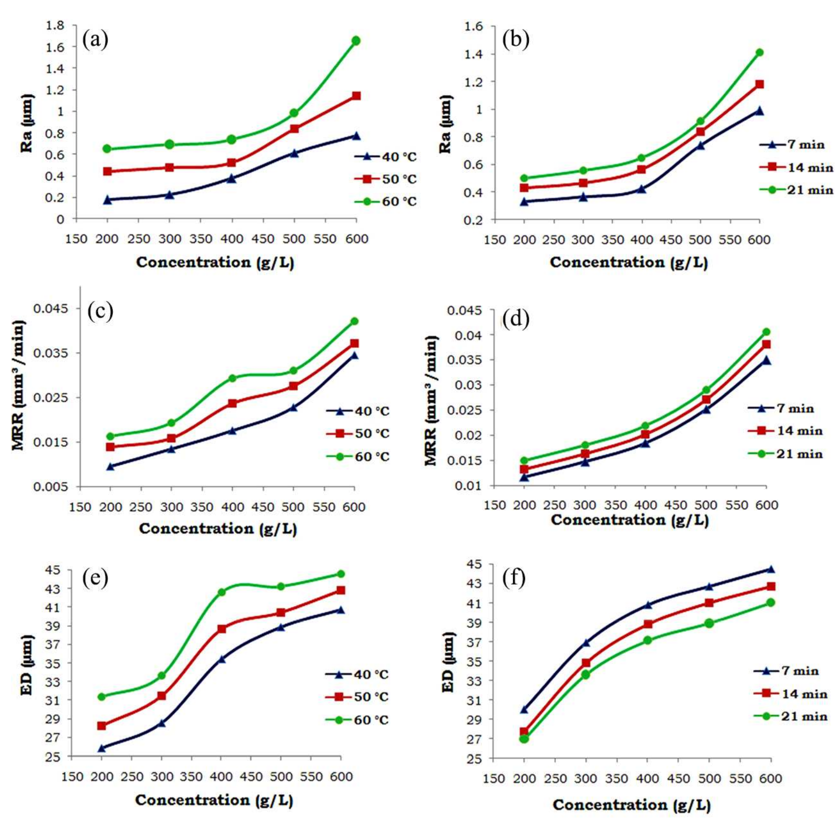


Figure 3. For german silver—(a) The average effect of concentration and temperature on surface roughness. (b) The average effect of concentration and time on surface roughness. (c) The average effect of concentration and temperature on material removal rate. (d) The average effect of concentration and time on material removal rate. (e) The average effect of concentration and temperature on edge deviation. (f) The average effect of concentration and time on edge deviation.

Table 5. Parameters and their weight percentage for OEC.

						Weightage			
Sr. No.	Parameter	Material	Worst	Best	QC	OEC 1	OEC 2	OEC 3	OEC 4
1	Surface roughness, Ra	Brass	1.62	0.115	S	50	25	25	33.33
		german silver	1.94	0.167					
2	Material removal rate, MRR	Brass	0.0089	0.0877	B	25	50	25	33.33
		german silver	0.0070	0.0458					
3	Edge deviation, ED	Brass	51.46	28.23	S	25	25	50	33.34
		german silver	47.08	24.16					

with weight percentages W_x and W_y is as given in Eq. (1) [20]. The QC for X is 'smaller is the best' (QC = S) and for Y is 'bigger is the best' (QC = B).

$$OEC = \left(1 - \frac{X - Xmin}{Xmax - Xmin}\right)Wx + \left(\frac{Y - Xmin}{Ymax - Ymin}\right)Wy \quad (1)$$

The objective of the analysis is to find out process parameters, which correspond to higher MRR with low *Ra* and ED values. For satisfying these objectives simultaneously, different OECs have been formulated as OEC1, OEC2, OEC3, and OEC4 for different weight percentages of *Ra*, MRR, and ED, as presented in Table 5. In OEC1 and OEC3, *Ra* and ED have higher weight percentages, while MRR has been assigned greater weight percentage in OEC2. The OEC4 has been formulated by assigning equal weight percentage to *Ra*, MRR, and ED.

Tables 2 and 3 show the values of OEC1, OEC2, OEC3, and OEC4 along with the process parameters for brass and german silver, respectively. The higher value of all OECs is highlighted in the same table, which gives the condition for optimum performance measure. For brass and german silver, experiment number 3 (concentration 200 g/L, temperature 40°C, time 21 min) gives the optimized condition for OEC1 and OEC3. By giving equal weight percentage to *Ra*, MRR, and ED (OEC4), again experiment number 3 is in the optimum condition. For OEC2, experiment number 39 (concentration 600 g/L, temperature 40°C, time 21 min) gives the optimum condition.

The scanning electron microscopy (SEM) images of brass and german silver specimens at the optimum conditions, that is, for experiment number 3 and for experiment number 39, are shown in Fig. 4(a), (b), (c), (d) and (e), (f), (g), (h), respectively. Detection of material composition on the surface of photochemically machined brass and german silver specimens was performed using energy-dispersive X-ray spectrometry (EDS). Figure 5(a) and (b) presents the EDS analysis of brass and german silver. The surface roughness of brass is less as compared to german silver for the same parameters. At 200 g/L concentration, less number of reagents will collide on the surface. As shown in Fig. 4(a), (b), (e), and (g), the diffusion starts at grain boundaries characterized by inter-granular corrosion. Then, the diffusion progresses within the grain, that is, trans-granular corrosion [Fig. 4(b), (d), (g)]. The dendrite structure is observed for brass at this concentration [Fig. 4(b)]. At 600 g/L concentration, due to reactive collision of reagents, during the diffusion process, voids are formed in brass as shown in Fig. 4(c). Due to the presence of nickel in good amount, german silver has better corrosion resistance. This will not

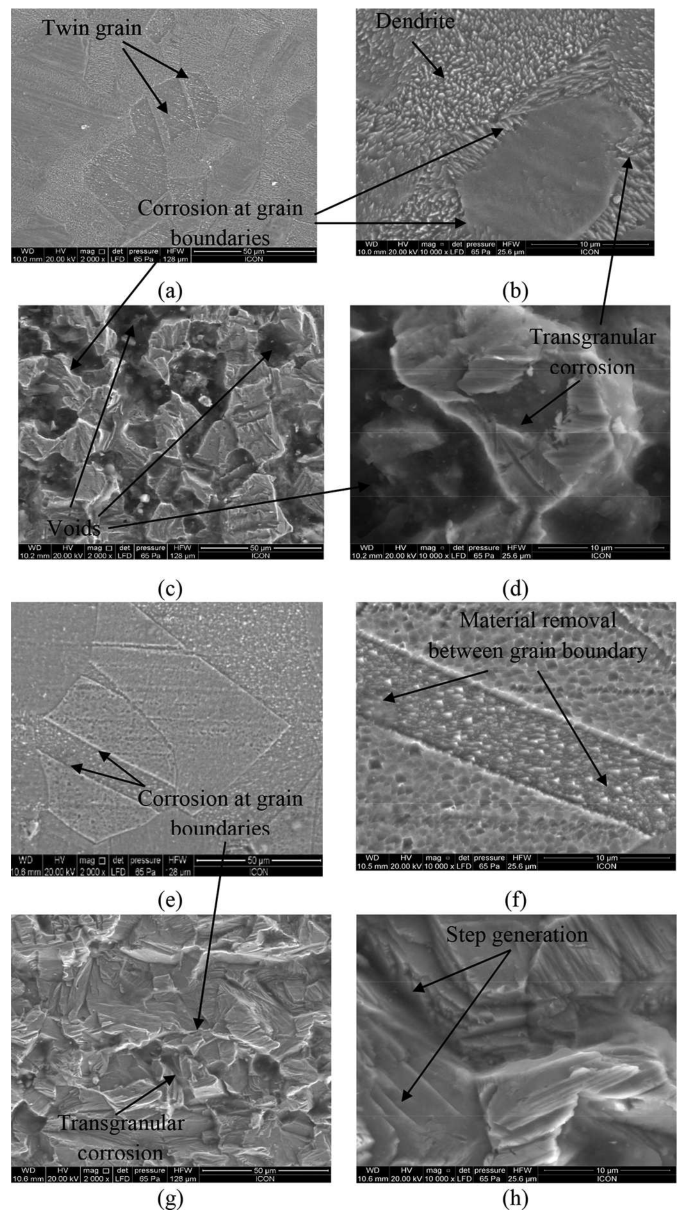
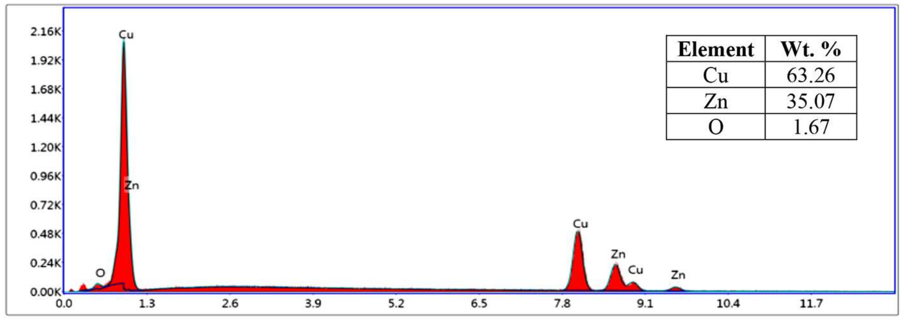
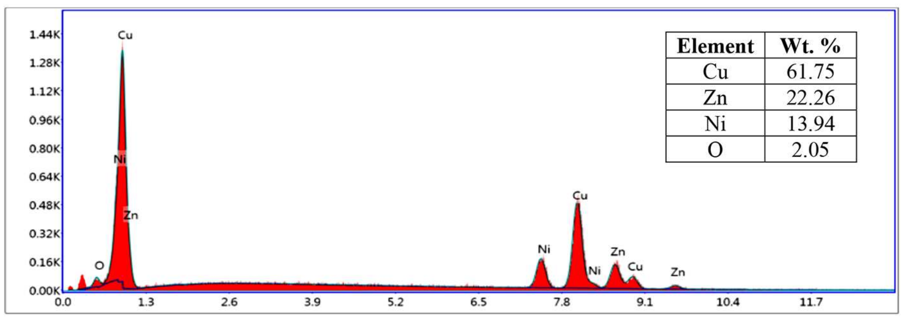


Figure 4. (a), (b) SEM images of brass specimen for 200 g/L concentration at different magnifications. (c), (d) SEM image for brass specimen for 600 g/L concentration at different magnifications. (e), (f) SEM image for german silver specimen for 200 g/L concentration at different magnifications. (g), (h) SEM image for german silver specimen for 600 g/L concentration at different magnifications.



(a)



(b)

Figure 5. (a) EDS analysis of brass. (b) EDS analysis of german silver.

allow the molecules to form voids. Hence, due to combined inter-granular and trans-granular corrosion [Fig. 4(g)], step-like structure is observed as shown in Fig. 4(h), which leads to a rougher surface in german silver. The material removal rate of brass is higher than that of german silver. In brass, the zinc content is 35%, and hence, while etching, the leaching of zinc from the alloy, that is, dezincification, occurs, which will give higher MRR. In german silver, nickel inhibits dezincification and improves the corrosion resistance of alloy. Hence, lesser MRR is noted for german silver. Also, in german silver, less material is removed at the edges of the specimen, which leads to less edge deviation as compared to that of brass.

The study is useful for producing components of brass and german silver. It is also helpful for fabrication of microchannels, which can be used in microreactors, heat recovery units, etc. The molds required for fabrication of polydimethylsiloxane (PDMS) microchannels can be effectively produced from brass and german silver using PCM.

Conclusions

This experimental study has been performed using full factorial design of experiment for photochemical machining of brass and german silver. The process of PCM has been discussed by taking into account the effect of process parameters like concentration, temperature, and time on response measurers such as surface roughness, material removal rate, and edge deviation. Based on the results obtained, the following conclusions have been drawn.

- The concentration has a noteworthy effect on surface roughness, material removal rate, and edge deviation, followed by temperature; however, etching time has a lesser effect on response measures.
- The surface roughness and material removal rate increase with an increase in concentration, temperature, and time. The average surface roughness (*Ra*) lies in the range of 0.12 µm to 1.62 µm for brass while 0.17 µm to 1.94 µm for german silver.
- Surface roughness and material removal rate increase, but edge deviation decreases, with an increase in time. The range of edge deviation for brass and german silver is from 28.23 µm to 51.46 µm and from 24.16 µm to 47.08 µm, respectively.
- For deciding the parameters for optimum performance measures, overall evaluation criteria (OEC) have been formulated. The combined effect of multiple performance measures has been studied by formulating different OECs considering equal and different weight percentage for performance measures.
- The optimum condition predicted by OEC considering high weightage to surface roughness and edge deviation is at 200 g/L concentration, 40°C temperature, and 21 min etching time. The same optimum condition has been obtained by considering equal weight percentage for all three performance measures. When higher weightage is given to material removal rate in OEC, the optimum condition is at 600 g/L concentration, 40°C temperature, and 21 min etching time.
- The surface topography has been studied using scanning electron microscopy, and the material composition at various locations of machined surface has been analyzed using energy-dispersive X-ray spectrometry. This shows that there is no significant change in material composition and hence the structure after machining.

- The material removal rate of brass is found greater as compared to that of german silver. The edge deviation is found less for german silver, while surface roughness is observed less for brass.

Finally, the data generated through this study will act as a good archive, which can be used for further analysis and investigation by many researchers.

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