

(An ISO 3297: 2007 Certified Organization) Vol. 5, Issue 7, July 2016

# Multi Objective Optimization of Photochemical Machining for ASME 316 Steel Using Grey Relational Analysis

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**ABSTRACT**: Photochemical machining is an engineering production technique for the manufacture of burr free and stress free flat metal components by selective chemical etching through a photographically produced mask. This paper presents the process parameter optimization of Photochemical machining for ASME 316 steel. Sixteen experimental runs based on Design of Experiments (DOE) technique are performed. The channel thickness of 2mm is selected for PCM phototool. The control parameters considered are etchant concentration, etching temperature and etching time. The response parameters were material removal rate (MRR) and surface roughness (Ra). The effect of control parameters on material removal rate and Surface Roughness is analysed using Grey Relational Analysis (GRA) technique and their optimal conditions are evaluated. The maximum material removal Rate and surface roughness are observed at etching temperature of 55°C, etching concentration of 800 gm/litre and 15 minutes etching time. The optimum material removal rate and surface finish obtained are 0.340 mm<sup>3</sup>/min. and 0.58 µm respectively. It is found that etching time and etchant concentration are the most significant factors for optimum material removal rate and surface roughness.

KEYWORDS: Photochemical machining, DOE, material removal rate (MRR), surface roughness (Ra), GRA

### I. INTRODUCTION

Photochemical machining (PCM) is one of the emerging non-conventional machining processes. PCM is also known as etching, photochemical machining, wet etching, photo etching, photochemical milling etc. It employs chemical etching through a photo-resist stencil as a method of material removal over selected areas. This process is used for frequent production of a flat metal blank which in turn can be formed into two dimensional and three dimensional shapes. The features are produced by exposing the work piece of interest through a photographic mask and chemically etching in which the unexposed UV area gets removed from work piece material when photo resist is used [1].

The manufacturing process creates features by dissolving away metal rather than cutting or burning it away. So the stresses and defects that normally arise from metal cutting are absent in the final part of PCM. That means there are no burns, no residual stresses, no changes in magnetic properties, mechanical properties and no deformations. There are no changes in hardness, grain structure, or ductility during the process. Moreover, as photo tools don't wear, tolerances remain the same regardless of how many parts are produced. It can be used as an option to stamping for the manufacturing of small, burn free, stress free parts [2].

The application of PCM has widely been used in the manufacturing of thin, flat and complex metal parts (i.e. lead frames, colour TV masks, sensors, heat plates, printed circuit boards) in electronics, precision engineering and decorative industries in the past thirty years. The PCM industry currently plays a vital role in the production of a variety of precision parts viz. microfluidic channels, silicon integrated circuits, copper printed circuit boards, decorative items, microfluidics and microfilters. It is also used for manufacturing of micro-components in various fields such as



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electronics, aerospace and medical. It is also used for the manufacturing of flexure bearing used in compressors, mesh used in regenerator of heat engine and for micro-filters used for filtration of blood.

The material selected for experimentation is ASME 316 steel. It is very important material used in various applications such as manufacturing of containers used for transport of chemicals, in automobile, in architectural paneling, railings & trim, Heat Exchangers, etc. because of its good electrical and thermal conductivities, good strength and fatigue resistance, high corrosion resistance and ease of fabrication.

### **II.LITERATURE REVIEW**

D. M.Allen [1] explained photochemical machining as the process of chemical etching through a Photoresist stencil as the method of material removal over selected areas.

Dattatray Vishnu Wagh et al. [2] explained the process parameter optimization of photochemical machining on Inconel 600 material .The optimal predicted Material Removal Rate is 0.0029 mm at an etchant concentration of 470 gm/litre and temperature of 55.276°C. The optimal etching time is 32.39 minutes.

A.Fadaei Tehrani et al. [3] developed new etchant for chemical machining of ASME 304 grade material to improve the surface finish during chemical machining. New etchant is a mixture of  $H_2O+HCl+HNO_3+HF+H_2COOH+TEA$ .

Atul R. Saraf et al. [4] investigated machining of Oxygen-Free High Conductivity (OFHC) copper using photochemical Machining (PCM). It was found that etchant temperature and etching time are the most significant factors for minimum undercut and minimum surface roughness.

A.A.G. Bruzzone et al. [5] reported an experimental assessment of a 2D simulation model of etching, where also the role of reaction products dynamics is considered. Furthermore an experimental analysis of the process parameters on micro-geometry is reported.

N.D Misal et al. [6] used ANOVA technique and grey based taguchi method for optimization of process parameters in copper etching. PCM process was used for the prediction of undercut and Material Removal Rate. The optimal material removal rate was 0.127 mm<sup>3</sup> /min and 0.279 mm<sup>3</sup> /min and undercut 0.002 mm and 0.006 mm in ANNOVA and grey relational method respectively.

David M. Allen et al. [7] explained various characteristics of ferric chloride etchants that are used in photochemical machining process.

Haydar A.H. Al-Ethari et al. [8] performed experimental design by taguchi method for optimization of chemical machining parameters on cold worked stainless steel-420 metal. The optimal parameters are 60% previous cold working, etching time 2 minutes at an etching temperature of 45° C.

D. M. Allen et al. [9] explained the use of regeneration system of oxygen-hydrochloric acid for ferric chloride etchants used in photochemical machining.

Saraf et al. [10] has studied optimization of Photochemical Machining for SS304. The minimum undercut (Uc) was observed at the etching temperature of 60°C, etching concentration of 600 gm/litre and 30 minutes etching time. It was found that etchant temperature and etching time are the most significant factors for undercut.

Cakir et al. [11] investigates on chemical etching of Cu-ETP copper. Copper is chemically etched with two different etchants (ferric chloride and cupric chloride) at 50°C. 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.

### III. DESIGN OF EXPERIMENTS

Design of Experiments (DOE) refers to planning, designing and analysing an experiment so that valid and objective conclusions can be drawn effectively and efficiently. In performing a designed experiment, changes are made to the input variables and the corresponding changes in the output variables are observed. The input variables are called resources and the output variables are called response. In the present investigation the input parameters are etching time, etching temperature, etchant concentration and the response variables are material removal rate (MRR) and surface roughness (Ra). Taguchie's  $L_{16}$  orthogonal array design is used to conduct the experimental runs and to evaluate optimum response variables.



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#### Table I. Input Parameters and Their levels

	Levels				
Process Parameter	1	2	3	4	
Time (min.)	15	20	25	30	
Temperature ( <sup>0</sup> C)	40	45	50	55	
Concentration (gm/litre)	500	600	700	800	

The total numbers of experiments performed are 16.Table I. shows input parameters and their levels. The time for experimentation is taken in the range of 15 minutes to 30 minutes, the temperature in the range of  $40^{\circ}$ C to  $55^{\circ}$ C and concentration 500 to 800gm/litre. The 4 Level four factors are chosen for experimental work. After selecting the factors and their levels the next step is to form an orthogonal array.

Experimental	Time	Temperature	Concentration
No.	(min.)	(°C)	(gm/lit)
01	15	40	500
02	15	45	600
03	15	50	700
04	15	55	800
05	20	40	600
06	20	45	500
07	20	50	800
08	20	55	700
09	25	40	700
10	25	45	800
11	25	50	500
12	25	55	600
13	30	40	800
14	30	45	700
15	30	50	600
16	30	55	500

#### Table II. Taguchie's L16 Orthogonal Array

Table II..Shows Taguchi's  $L_{16}$  Orthogonal array. The orthogonal array design is also called as matrix design. The orthogonal arrays provide a test to see whether the above selections can successfully achieve the goal of experimentation or not, also this design matrix provides a test to see whether interactions are large compared to the main effects.

### IV. EXPERIMENTAL PROCEDURE

The first step in photochemical machining includes the production of the required shape on a photographic film or glass plate, termed the photo-tool. Computer-aided design (CAD) creates the required part shape design, which is used as the primary image for the photo-tool. The sheet metal is chemically cleaned to remove dust, dirt, oil, grease and other foreign materials from the workpiece and to provide maximum surface for adhesion of Photoresist .The metal is then coated with a light-sensitive Photoresist film. The Photoresist will adhere to the part surface and act as a stencil resist protecting the surface during etching. The resist laminated, or coated, metal is then placed under the photo tool and exposed, in a vacuum, to an ultraviolet light source. This transfers the image precisely onto the resist. Most often,



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photo-tools are used in precisely registered pairs-one on the top, one on the bottom, with the material to be machined sandwiched in between. This permits the material to be etched from both sides, thus minimizing undercutting of the Photoresist and producing straighter sidewalls. Next step is developing the metal in the developer solution either by dipping into the developer solution or spraying. Each Photoresist has its own developing solution, such as water, alkaline solution, hydrocarbons, or solvents. The developed and imaged metal workpiece passes through the acid etch spray or dip where the etchant solution dissolves the exposed area to get the required shape as that of phototool. After etching process, Protective resist is removed from machined parts with chemicals or with mechanical techniques along with chemicals.

The work piece material for this experimental work is ASME 316 steel. The ferric chloride (FeCl<sub>3</sub>) is used as an etchant. The size of work piece taken for the experiment is 20X50X2 mm. The 2mm channel thickness is used for phototool. UV exposure time is 15 seconds .The developing time is 90 seconds.

Table III. Chemical Composition of ASME 316 Steel
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Contents	C	Р	Cr	Mn	S	Si	Ni	Ν	Fe
% limit	0.08	0.045	16-18	2.0	0.03	0.75	10-14	0.10	balance

The chemical composition of ASME 316 steel is given in the Table III. The main constituents in ASME 316 steel are Cr 16-18%, Ni 10-14 %, Mn 2% and balance is ferrous. The carbon is on lower side. ASME 316 steel is soluble in the FeCl3 etchant .The material is available in the market in the form of flat sheets. .The experimental set up of photochemical machining is as shown in Fig.1



Figure 1. (a) PCM Coater cum Photo Resist Dryer, (b) Both Side Exposures, (c) Easy Etcher, (d) Chemicals Used

Fig.1 shows the experimental set up of photochemical machining. It consists of Photoresist tank in which Photoresist can be fed manually. The second equipment in the PCM set up is air drying unit in which heating coils are provided for air drying. Next is easy etcher with 15 litres etchant capacity next equipment is ultra violet light exposure unit with the facility of one sided exposure and both side exposure. The different chemicals used in PCM are Developer solution, FeCl<sub>3</sub> solution and liquid Photoresist.



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#### V. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental data analysis is done by using gray relational method. This theory of grey relational analysis was developed and presented by Deng in 1982. In grey relational analysis, experimental data i.e. measured features of quality characteristics of the product are first normalized ranging from zero to one. This process is known as grey relational generation. Next, based on normalized experimental data, grey relational coefficient is calculated to represent the correlation between the desired and actual experimental data. Then overall grey relational grade is determined by averaging the grey relational coefficient corresponding to selected responses. The overall performance characteristic of the multiple response process depends on the calculated grey relational grade. This approach converts a multiple-response- process optimization problem into a single response optimization, with the objective function is overall grey relational grade. The grey relational analysis table of this experiment is shown in Table IV.

	Response Variables		Normal Distribution		Grey Relational Coefficient			
Exp. No.	MRR (mm3 /min))	Surface Roughness (µm)	MRR (mm3 /min)	Surface Roughness (µm)	MRR (mm3 /min)	Surface Roughness (µm)	Grey Relational Grade	Rank
01	0.140	0.580	0.217	1.000	0.390	1.000	0.695	3
02	0.220	2.250	0.565	0.729	0.535	0.648	0.592	5
03	0.307	2.760	0.943	0.646	0.898	0.586	0.742	2
04	0.340	3.200	1.087	0.575	1.211	0.540	0.875	1
05	0.170	2.960	0.348	0.614	0.434	0.564	0.499	8
06	0.115	2.860	0.109	0.630	0.359	0.575	0.467	9
07	0.275	3.420	0.804	0.539	0.719	0.520	0.620	4
08	0.235	3.580	0.630	0.513	0.575	0.507	0.541	6
09	0.172	3.960	0.357	0.451	0.437	0.477	0.457	10
10	0.240	4.260	0.652	0.403	0.590	0.456	0.523	7
11	0.100	4.500	0.043	0.364	0.343	0.440	0.392	12
12	0.128	5.380	0.165	0.221	0.375	0.391	0.383	13
13	0.213	5.940	0.535	0.130	0.518	0.365	0.441	11
14	0.137	6.620	0.204	0.019	0.386	0.338	0.362	14
15	0.107	6.720	0.074	0.003	0.351	0.334	0.342	15
16	0.090	6.740	0.000	0.000	0.333	0.333	0.333	16

Table IV.GRG Analysis

According to the experimental design Table IV and GRG it is clearly observed that experiment no.4 is highest grey relational grade. Therefore experiment no.04 is the optimum process parameter setting for maximum MRR and minimum surface roughness simultaneously (best multi performance characteristics) among the sixteen experiments. The optimum condition for PCM performance for both material removal rate and surface roughness was found for 15 minutes time, temperature of 55°C and at etchant concentration of 800 gm/litre.



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	Time (min.)	Temperature (°C)	Concentration (gm. /lit.)
Level -1	0.7260	0.5231	0.4717
Level-2	0.5316	0.4858	0.4539
Level-3	0.4385	0.5239	0.5254
Level-4	0.3697	0.5331	0.6148
(Max-Min)	0.3563	0.0473	0.1608
Rank	1	3	2

Table V. Response Table for Grey Relational Grade (GRG)

The response table for grey relational analysis is shown in Table V. The difference between the maximum and the minimum value of the grey relational grade of the photochemical machining parameters is as 0.3563 for time, 0.0473 for temperature and 0.1608 for concentration.

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 them is 0.3563. 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 time, concentration, temperature (i.e. 0.3563>0.0473>0.1608). The factor time (0.3563) was the most effective factor to the performance of the PCM process.



Figure 2. Workpiece Material after Photochemical Machining

The fig.2 shows the actual workpiece after performing the experiments .There are 16 no of workpieces for 16 experimental runs. Table VI shows results obtained by doing ANOVA of GRG on Minitab-16 software. 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 higher value of F-ratio indicates the most influencing parameter among the all input factors. The p-value gives the probability that the test statistic will take on a value that is at least as extreme as the observed value of the statistic when null hypothesis is true .thus p-value conveys the information about the weight of evidence against null hypothesis. It is observed from the ANOVA that the etching time and etchant concentration has significant effect on performance characteristics of photochemical machining of ASME 316 steel. The time and concentration is found statistically significant at 99% confidence interval respectively.



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Source	DF	Seq. SS	Adj. SS	Adj. MS	F ratio	Р
Time	3	0.286952	0.286952	0.095651	84.64	0.000
Temperature	3	0.005264	0.005264	0.001755	1.55	0.295
Concentration	3	0.062627	0.062627	0.020876	18.47	0.002
Error	6	0.006780	0.006780	0.001130		
Total	15	0.361623				
S = 0.0336159 R-Sq = 98.13% R-Sq(adj) =95.31%						

Table VI. ANOVA for Grey Relational Grade

Fig.2 shows the main effect plot for grey relational grade. Here the uppermost 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. According to the graph we can evidence that the response variables are optimum at Concentration 800 gram per litter, temperature 55°C and time 15 minute. The etching time has higher contribution to the variability of GRG over the selected range. and etching temperature has lower contribution. The most important factor observed from GRA is Etching time. The order of sequence as per importance is Etching time, etchant concentration and etchant temperature.



Figure 3. Main effect plot of grey relational grade

It is seen from main effect plot that etch rate at the start of process is high but as PCM proceeds the rate of etch decreases due to the fact that the flow of etchant through the workpiece is not smooth as it was at the start of process. The rate of etching can be increased by increasing the concentration of the etchant. The etching temperature has no effect on MRR but increases surface roughness.

#### VI. CONCLUSION

From the experimental work based on grey relational analysis following conclusions are drawn for photochemical machining of ASME 316 steel.

- The etching time and etchant concentration are the most influencing parameters that affects the performance of photochemical machining of ASME 316 steel. The order of importance is etching time, etchant concentration and etching temperature.
- The results shows that the optimal process performance for material removal rate and surface finish is obtained at Concentration 800 gram per litter, temperature 55°C and time 15 minute.
- From the experimental work for photochemical machining of ASME 316 steel the maximum material removal rate and minimum surface roughness obtained are 0.340 mm<sup>3</sup>/min. and 0.58 μm respectively.



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• From the main effects plot it is observed that as the etching time increases GRG decreases due decrease in rate of etching, as the etchant concentration increases the GRG increases and etching temperature has less effect on GRG.

### VII. FUTURE SCOPE

Further study can be taken out with the following future scope

- Optimum Process parameters and their Comparisons among the different grades of materials such as SS304, inconel, copper, SS 304, SS 316, and Aluminium etc. can be made.
- Effect of addition of HCl, HNO3 and other elements can be taken for analysis.
- Effect of undercut on process performance of PCM can be studied.

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