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Optimization of Ti-5Al-2.5Sn Chemical Milling Process Parameters Using Taguchi Design for Enhanced Performance

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Abstract: One of the nontraditional manufacturing processes is the chemical machining that deals with the removal of material substances using acidic or alkaline chemical solutions. This study aimed to determine the maximum material removal rate (MRR), and minimum surface roughness (SRa) of Ti-5Al-2.5Sn alloy during chemical milling that is possible to achieve by varying the etching chemical milling parameters in terms of time, concentration of the chemical solution [hydrofluoric acid (HF) and nitric acid (HNO_3)], and chemical milling temperature. The Taguchi method based on a statistical design of experiments (DOE) technique with an L_{16} orthogonal array, is efficiently used to obtain the objective of this study and to detect optimal chemical milling parameters for the Ti-5Al-2.5Sn alloy. The experimental results were analyzed using ANOVA analysis to determine the importance of each system parameter on the response variables (MRR and SRa). The optimal process parameters were found to be at a chemical solution concentration of 22.5 HF and 17 HNO_3 , a temperature of 45 °C, and a time of 60 min. These parameters resulted in a maximum MRR of 0.0842 mg/min and a minimum SRa of 0.30 μm . The ANOVA result signalized that the concentration of the etching acids has the most impact on both responses with contribution percentages of 81% and 67% respectively. This takes a look at the efficacy of the Taguchi technique in optimizing chemical milling procedures and offers precious insights for selecting process parameters to attain favored results.

Keywords: Ti-5Al-2.5Sn alloy; material removal rate; chemical milling; Taguchi design; surface roughness

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0 Introduction

When compared to standard machining techniques, non-traditional machining (NTM) method is superior because it can generate surface finishes, dimensional precision, and complicated forms and sizes while minimizing heat and residual tensions^[1]. Chemical energy is used in chemical machining. Instead of using physical force, this technique uses a controlled chemical reaction to precisely form metal into any size or shape. Chemical machining (CHM) predates all other non-traditional machining techniques. This approach eliminates material by using a controlled chemical assault using acids or alkalis, either selectively or simultaneously^[2]. Machining temperature, milling time, milling solution concentration, and etchant type are the main parameters that affect the chemical

milling process and, consequently, the finishing of a chemically machined alloy^[3].

Titanium alloys, known for their resistance to corrosion, fatigue, temperature, and magnetic fields, are the subject of this investigation. These alloys are used in a wide range of industries. Titanium alloys are corrosion-resistant, lightweight, strong, and tough. The Ti-5Al-2.5Sn alloy has a high service temperature of 480 °C (896 °F), superior weldability and fabricability, and a stable microstructure^[4].

El-Awadi et al.^[5] tested stainless steel, copper, and aluminum sheets for metal removal rates (MRRs) at 50 °C. They used etchants (FeCl_3 and $\text{FeCl}_3 + \text{HNO}_3$). They found that copper had the highest MRR, measuring 0.287 mm^3/min , followed by aluminum with 0.738 and stainless steel with 0.224. At this temperature, the concentration of the FeCl_3 solution in each and every metal was 33%. Zogheib et al.^[6] investigated the effect of varying acid milling

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times on the surface roughness and flexural strength of a lithium disilicate-based glass ceramic.

Numerous research studies have investigated the multi-response optimization of process parameters in chemical milling for various alloys using the Taguchi method. The objective of these works is to increase process productivity by decreasing surface roughness and tool wear rates, while simultaneously increasing material removal rates^[7-9].

Using chemical machining of stainless steel 304 by Shather^[7] clarified how machining parameters affect surface roughness. The milling solution consisted of 5 mL HCl + 4 mL HNO₃ + 4 mL HF + 5 mL H₂SO₄ + 82 mL H₂O. The optimal combination of parameters at 3 min, 55 °C, and 10% concentration that obtained by statistical analysis using Taguchi and ANOVA accorded the minimum surface roughness (S_{Ra}). Since the chemical machining process did not alter the crystalline structure, induce stresses, involve mechanical deformation or high temperatures, the hardness of all samples was unaffected. Additionally, the results indicate that increasing machining time increases S_{Ra}.

The study in Ref. [9] used Taguchi's method to analyze the effects of process parameters in metal-assisted chemical etching (M.A.C.E.) of silicon. The parameters included etching time, and etchant concentration, which were analyzed using Taguchi modeling. The data was analyzed using ANOVA, and graph modeling. As well, the study optimized the M. A. C. E. technique for silicon using the primary parameters of temperature, H₂O₂ concentration, HF concentration, and etching time. The results showed that S_{Ra} decreased by 52.5% and MRR increased by 26.7%. The optimal conditions were achieved at 60 °C, with 3.22 M HF, 0.14 M H₂O₂, and an etching time of 90 min.

Improving S_{Ra} and MRR were the target outcomes of the research using examine CHM approach^[10]. A face-centered central composite design (FCCCD) was used to optimize the etching time, concentration, and temperature. The significance of the parameters was confirmed by analyzing the variance. The optimized settings improved MRR by 17.8% and decreased surface roughness by 52.7% compared to the initial values.

Using a mixed acid FeCl₃, Ibrahim^[8] studied the relation between surface roughness, amount of aluminum alloy material removed, machining

temperature, time, and solution concentration. Three distinct milling solution concentrations were used; 25%, 50%, and 75%. Time, temperature, and etchant concentration have the greatest influence on the finishing of a chemically machined aluminum alloy. Concentration is the most important parameter for maximum MRR and machining time for least surface roughness (S_{Ra}). Machine time, temperatures, and etchant concentration were the most important variables for finishing chemically machined aluminum alloy.

Chemical milling is widely used for the manufacturing of titanium components due to its flexibility and ability to obtain complex components. However, their high final machining costs limit the number of applications for which these materials are feasible. As well as under these conditions, titanium alloys exhibit a high degree of reactivity with oxygen, resulting in the formation of oxide on the metal's surface and an oxygen-enriched subsurface layer^[2, 11]. The alpha-case is a continuous layer that is both hard and brittle, and it has a driving effect on all titanium alloys' significant mechanical properties^[12-13].

Chemical milling was investigated by Deshmukh et al.^[12]. Titanium work surfaces' alpha-case thickness is determined by the test pieces' oxygen concentration, temperature, and heating time. HF acid concentrations between 8% and 9% and etch milling times under 15 min were optimal. The removed alpha-case layer of Ti-6Al-4V alloy at a temperature equal to 980 °C Ti-6Al-4V alloy is thinner than at 1030 °C.

Using chemical milling, Nádai et al^[2] modified the surface roughness of chemically milled titanium materials, especially nanoparticulate titanium discs and Grade 2 titanium discs that were 2 mm thick. The surface that was created was studied utilizing electron microscopy, reflected-light microscopy, and optical stereo. Milling at 30 °C for 30 s with a milling solution of hydrofluoric acid, 12 v/v% nitric acid, and distilled water is the perfect parameter.

Chemical milling with hydrofluoric-nitric acid solutions at 1 : 3 and 1 : 11 molar ratios was used to analyze the behavior of two different titanium alloys Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo^[13]. The rate of corrosion of Ti-6Al-4V was found to be faster than that of Ti-6Al-2Sn-4Zr-2Mo in solutions with a ratio of 1 : 3. Corrosion rates for Ti-6Al-2Sn-4Zr-2Mo were found to be significantly higher in solutions with a ratio of 1 : 11. The observations indicated that the

α -layers corroded more rapidly in both alloys compared to the β -layers. The results showed that the chemical milling behavior of the two alloys tested is controlled by the microscopic corrosion behavior of the individual micro constituents.

Titanium alloy pre-treatment methods are crucial for surface treatment, coating pre-deposition, and surface modification. Vlček^[14] examined how chemical milling affected Ti-35Nb-7Zr-5Ta alloy surface properties and corrosion stability. The chemical milling procedures improved the corrosion stability of the native oxides and suboxides of the alloying elements. According to the research results, other surface parameters may not be as essential as charge transfer during corrosion (roughness, wettability).

The current objectives of this research include determining the optimum value, i. e., the maximum value of the material removal rate (MRR) and minimum surface roughness (SRa), of the Ti-5Al-2.5Sn alloy by varying the chemical milling parameters, including milling time, concentration, and temperature. Evaluate the impact of chemical milling parameters on the rate of material removal and surface roughness, which were investigated and estimated using ANOVA results.

1 Materials and Methods

1.1 Materials and Taguchi Design

In this research, titanium alloy (Ti-5Al-2.5Sn alloy) was used to evaluate the effect of chemical milling parameters. The etchant concentration, immersion time, and temperature of the chemical milling were used as process parameters. All Ti-5Al-

2.5Sn alloy test samples for the current study were cut to 10 mm in height and 20 mm in diameter. Cleaning and masking are important steps in the chemical machining process to remove oil, grease, dust, rust, or any other substance from the surface of the material. The samples were covered with masking material to preserve any components that did not need to be chemically produced. After the samples have undergone the chemical process, the mask material should be easily removable. The epoxy and its hardener in (1 : 1) ratio were utilized for masking the samples, and it took nearly 15 – 16 h to dry then scribing process has been performed for the desired area that should be exposed to chemical milling solution. These samples were subjected to the chemical milling process using milling solution consisting of hydrofluoric acid (HF) and nitric acid (HNO₃) that was added to distilled water in a predetermined ratio. Using the Taguchi technique, based on the theory of experimental design, researchers were able to identify the significance of parameters with their effect on the selected responses i. e. variables. Taguchi methods is the effective technique used to optimize process parameters in a wide range of manufacturing applications such as machining processes^[15-17]. Therefore, in this study, Taguchi method was chosen for the investigation because it is an efficient tool for both the planning and analysis of experiments. Table 1 shows the input CHM parameters with the selected levels. The Taguchi (L₁₆) design (Table 2) has been used for performing the experimental runs of CHM process. To determine etching concentrations, hydrofluoric acid (HF) and nitric acid (HNO₃) were added to distilled water in a predetermined ratio.

Table 1 CHM input parameters required for the experimental work

Level	Cont. (HF+HNO ₃) (%)	Temperature(°C)	Time (min)
Level 1	7.5 HF+100 mL Water	45	15
Level 2	7.5 HF+17HNO ₃ +100 mL Water	50	30
Level 3	15 HF+17 HNO ₃	55	45
Level 4	22.5 HF+17 HNO ₃	60	60

1.2 Chemical Milling Process and Measurement

Chemical milling is the immersion of a part in a chemical bath and the chemical's action on the milled part. The time spent in the chemical bath determines the resulting milling depth^[1]. In chemical milling, hydrogen fluoride and nitric acid solutions are used. Hydrogen fluoride is an odorous, flammable liquid or

gas with no discernible hue. Nitric acid is a common laboratory reagent and a key industrial chemical used in the production of fertilizers and explosives. Handling hydrofluoric acid requires protective equipment due to its high reactivity. The hydrofluoric solution used in this study has a molecular weight of 20.01 g/mol and a density of 1.410–1.420 g/mL.

Hydrofluoric acid and nitric acid mixtures etch titanium well but slowly and produce hydrogen gas. Hydrogen gas from HF alone can cause fires. Milling chemically is slow, and the surface finish may be poor^[18]. Nitric acid accelerates the milling process, eliminates hydrogen gas, and smooths the surface. Therefore, in this study, a mixture of HF and HNO₃ in 100 mL of distilled water was employed at four levels for each input CHM parameter, i.e. (concentrations, temperature, and machining time). The mixture is poured into the beaker on the stirrer apparatus, and an experiment-specific temperature is selected. The samples were submerged for the allotted time, then removed, thoroughly rinsed with distilled water, and dried in dry oven. After machining, the maskant layer will be removed and the weight of the specimens will be measured to detect weight loss. Figs.1(a) and (b) show the experimental setup of chemical milling. Material removal rate (MRR) covers all exposed surfaces, and the substances removed in chemical milling are faster than in conventional machining. The material removal rate was calculated experimentally using the weight difference method before and after chemical milling^[5] in accordance with Eq.(1).

The MRR is defined as:

$$MRR = \frac{W_b - W_a}{t_m} \quad (\text{mg} \cdot \text{min}) \quad (1)$$

where W_b represents the mass of workpiece before

milling process (mg); W_a represents the mass of the workpiece after milling process (mg); t_m represents the milling time (min).

The roughness of the unmasked surface was measured using the roughness tester model TR200 for four zones for each milled sample, and the average has been taken.

Table 2 Taguchi (L₁₆) design for performing experimental runs of CHM process

Runs	Cont (%)	Temperature(°C)	Time(min)
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

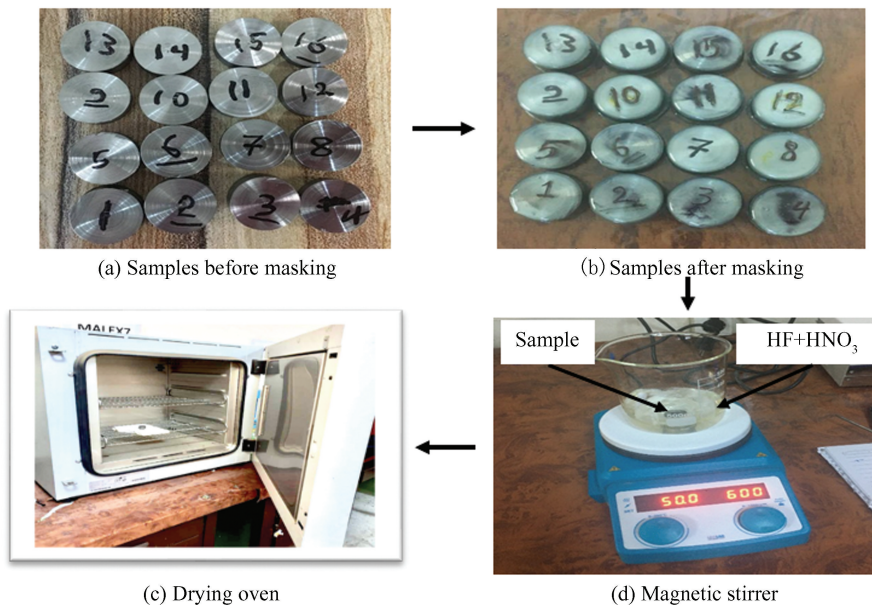


Fig. 1 Experimental setup of chemical milling

1.3 Analysis of Variance (ANOVA)

ANOVA is a statistical method for determining the significance of parameters in the selected responses. Minitab 17 created an ANOVA table to determine which parameters were controlled for this research. According to the ANOVA analysis, the distribution of treatment data can be clarified to determine if it is normal or not. Assuming the distribution of treatment data was normal, the specimens were selected at random and independently. Specimens were independent^[19-20].

The signal-to-noise ratio (S/N) of Taguchi is the logarithm of the desired output responses. The optimization ratios depend on the quality of the product or process^[21].

The standard S/N ratios are nominally better (NTB), smaller better (STB), and higher better (HTB)^[22-23]. In this study, the proper aim for MRR was selected as higher better (HTB) with the applicable S/N Eq. (2) while surface roughness (SRa) was calculated using the applicable S/N

Eq. (3) i.e. smaller better (STB). S/N depends on the response aim (i.e. minimum or maximum) is the ratio of the standard deviation to the mean. The objective function of optimization experiments that are orthogonal are well-balanced^[21].

$$\frac{S}{N} = -10 \log \frac{1}{n} \left(\sum \frac{1}{z_i^2} \right) \quad (2)$$

$$\frac{S}{N} = -10 \log \frac{1}{a} \left(\sum z_i^2 \right) \quad (3)$$

where a is the repetitions number; z_i is the data of experiment.

2 Results and Discussion

Chemical milling machining (CHM) was performed depending on Taguchi L_{16} using Minitab17 software to look for the machinability of the Ti-5Al-2.5Sn alloy in terms of surface roughness (SRa) and material removal rate (MRR). The results of MRR and SRa are presented in Table 3.

Table 3 Predicted and measured roughness and material removal rate

Exp. run	Time (E_t) (min)	Temp. (T) (°C)	Cont (%) (HF + HNO ₃)	ΔW (mg)	MRR (g/min)	SRa (μm)
1	15	45	7.5 HF	0.3943	0.0262	1.94
2	30	50	7.5 HF	0.5332	0.0177	2.53
3	45	55	7.5 HF	1.0610	0.0235	2.04
4	60	60	7.5 HF	1.1886	0.0198	1.86
5	30	45	7.5 HF +17 HNO ₃	0.5168	0.0172	1.59
6	15	50	7.5 HF +17 HNO ₃	0.2012	0.0134	1.90
7	60	55	7.5 HF +17 HNO ₃	0.5537	0.0092	1.51
8	45	60	7.5 HF +17 HNO ₃	0.3550	0.0078	1.89
9	45	45	15 HF + 17 HNO ₃	1.8148	0.0403	0.84
10	60	50	15 HF + 17 HNO ₃	1.0115	0.0168	1.30
11	15	55	15 HF + 17 HNO ₃	0.2234	0.0148	1.28
12	30	60	15 HF + 17 HNO ₃	0.4642	0.0154	2.21
13	60	45	22.5 HF +17 HNO ₃	5.0573	0.0842	0.30
14	45	50	22.5 HF +17 HNO ₃	0.2857	0.0063	0.41
15	30	55	22.5 HF +17 HNO ₃	0.5338	0.0177	1.05
16	15	60	22.5 HF +17 HNO ₃	0.8120	0.0541	0.98

2.1 Material Removal Rate

The experimental data were analyzed to determine how chemical milling parameters (machining temperature, concentrations, and milling time) affect

material removal rate (MRR). DOE based Taguchi design was used to analyze all experiment data. All sixteen experiments used Ti-5Al-2.5Sn alloy as a workpiece. The difference in workpiece weight before

and after chemical milling (ΔW) indicates to the material removal rates (MRR). Table 3 presents the material removal rate values according to the runs of Taguchi design and based on Eq. (2). Fig. 2 shows residuals that are positioned near to the straight line, which corresponds and this designates to the regular distribution of the attained outcomes and normal error

distribution. The comparison between measured and predicted values depends on the material removal rate design model and regression Eq.(4) as shown in Fig.3. The measurements match the forecasts.

$$MRR = 0.00154 + 0.00662Cont\% - 0.00504T + 0.00186E, \quad (4)$$

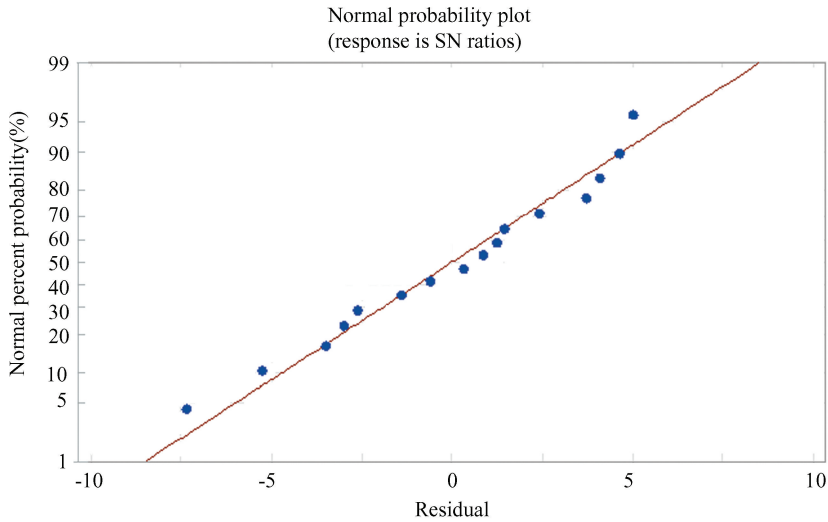


Fig.2 Normal probability plot of MRR

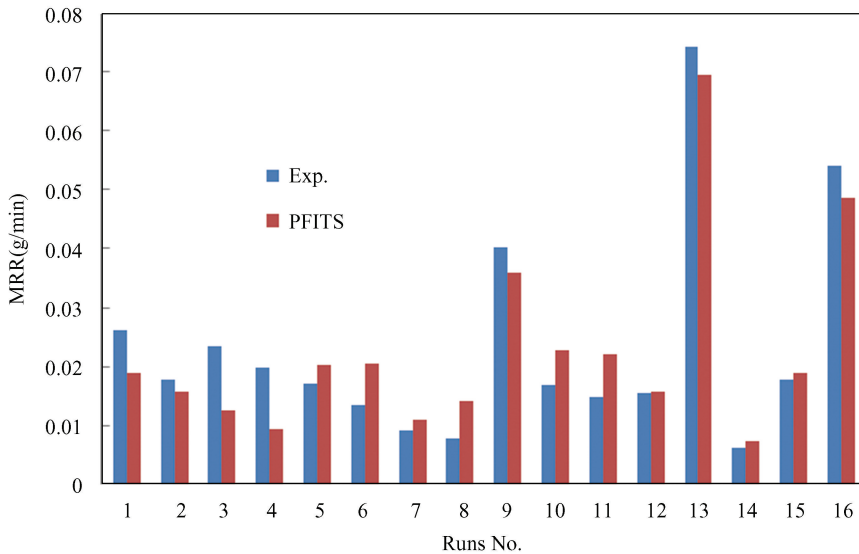


Fig.3 Comparison between experiment and predicted values of MRR

The optimum process parameters to obtain maximum temperature on MRR for machined specimens are depicted in Fig.4. In this graph, the MRR for the machined specimens increased as the temperature (T) decreased, indicating that the effect of temperature has an inverse relationship with the MRR. In other words, a decrease in machining temperature causes an increase in corrosion rate due to

a powerful oxidizing agent and an increase in ion mobility. The graph demonstrates that the MRR increases as the temperature decreases from 45 to 60 °C, with temperature having the least impact of the selected variables.

The MRR for the machined specimens increased as the concentration percentage (cont.%) increased from 7.5% to 22.5% HF + 17% HNO₃ as depicted in

the graph. In chemical etching milling, the removal rate of etching is directly proportional to the etching concentration and the surrounding areas to be machined. The concentrations of etchant chemical milling solutions are proportional to the amount of hydrogen ions in the chemical etchant. Higher etchant concentrations or ion hydrogen concentrations

facilitate substrate chemical milling process. This applies to all types of alkaline and acidic chemical etchants. In addition, hydrofluoric and nitric acids, which form a highly acidic solution, are frequently used to etch titanium alloys. The greater the acid concentration, the more metal is removed as indicated in the previous study^[8].

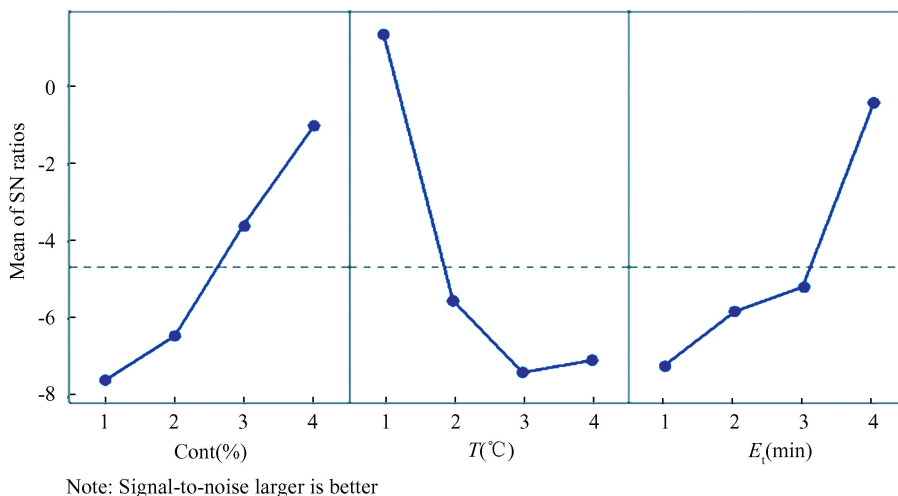


Fig.4 Main effect plot for S/N ratio for MRR

The effect of milling time (E_t) on the rate of material removal from workpieces is depicted in Fig.4. The MRR increases as the milling time increases for all machined workpieces, as depicted in this graph. As the corrosion rate increases over time, the MRR increases from 15 to 60 min as the milling time increases.

The objective of response (MRR) is the larger-is-better rule which is used to measure the performance characteristic in this graph. So, the optimum chemical process parameters that can be suggested to obtain the optimal material removal rate from Fig.4 are ($Cont\%_4 T_1 E_{t4}$) i.e. at concentration level 4, milling temperature level 1, and milling time level 4. Thus, the maximum rate of material removal using HF and HNO₃ acids was 0.0842 mg/min for experimental run number 13 at operating conditions of machining temperature (45 °C), concentrations (22.5 HF +17 HNO₃) %, and milling time (60 min). The figure illustrates the average signal-to-noise ratios for each parameter in terms of characteristic response. The larger-is-better rule is used to measure the performance characteristics in this graph. In addition,

Fig. 4 suggests that the optimal material removal rate can be obtained at concentration level 4, milling temperature level 1, and milling time level 4.

The results of the analysis of variance (ANOVA) for the rate of material removal from specimens are presented in Table 4 according to the Taguchi design. The table illustrates the relationship between quantity of material removed from a specimen and the three chemical milling parameters: temperature, concentration, and chemical milling time. The F -values demonstrate that concentration has an effect of 65.05% , temperature of 5.67 °C, and time of 8.10 min respectively. It appears that the chemical milling solution concentration is most important parameter with percentage of contribution (PCR) 81%, followed by milling duration with PCR equal to 10% and then machining temperature at PCR 7%. Among the chosen variables, chemical milling temperature had the least effect on the MRR, which increases as the temperature drops from 45 to 60 °C. This may be due to the difficulty of installing the magnetic stirrer device used to measure temperature during experimental work.

Table 4 Analysis of variance for SN ratios MRR

Source	Cont%	$T(^{\circ}\text{C})$	$E_t(\text{min})$	Residual error	Total
DF	3.000	3.000	3.000	6.000	15.000
Seq SS	563.910	49.110	70.210	17.340	700.580
Adj SS	563.910	49.110	70.210	17.340	–
Adj MS	187.971	16.372	23.404	2.890	–
F	65.050	5.670	8.100	–	–
P	0	0.035	0.016	–	–
PCR(%)	81	7	10	2	100

The response is displayed in Table 5 according to the maxim “larger is better”. This table explains the relative impact of each parameter on the rate at which material is removed. The rankings in Table 5 indicate the extent to which each parameter contributed to the overall response. The concentration, which is ranked first among the parameters, has the greatest effect, followed by the etching chemical milling time and then the machining temperature, which are ranked second and third, respectively. The following is confirmation of the arrangement in this Table: Etching at higher concentrations has the greatest impact, followed by etching for longer durations and at higher temperatures. It is possible to make educated guesses regarding the effect of various parameters on surface roughness. One of the most important parameters that determine surface roughness is the rate of material removal. When there are more, the material rate is lower and there are more roughness values.

Table 5 Response for Signal to Noise Ratios

Level	Cont(%)	$T(^{\circ}\text{C})$	$E_t(\text{min})$
1	–5.3022	0.2666	–3.7741
2	–6.1775	–3.0275	0.7703
3	2.5848	1.7300	1.0648
4	8.2538	0.3898	1.2979
Delta	14.4313	4.7574	5.0720
Rank	1	3	2

2.2 Surface Roughness

Surface roughness refers to deviations in the surface texture and it is often quantified by measuring the average roughness height (SRa), which is the arithmetic mean of the surface deviations from the mean line. This study found that the concentration and temperature of the chemical milling solution have a significant effect on the surface roughness of the machined specimens. Table 3 presents the surface

roughness value according to Taguchi design runs. Fig.5 depicts the data points that fall along a straight line on the probability plot, indicating that the data is normally distributed. Fig.6 depicts that the comparison between measured and predicted values depends on the average surface roughness and regression Eq. (5); it indicates that the predicted values are close to the experimental values, which would suggest a good agreement between the two.

$$\text{SRa} = 2.551 - 0.4537 \text{ Cont\%} + 0.1638 T - 0.1397 E_t \quad (5)$$

Fig.7 depicts the effect plot for the signal-to-noise ratios in terms of characteristic responses that can help visualize the optimum chemical milling parameters (Cont%, T , and E_t) to obtain best surface finish. The main effect plot for SN ratio (SRa) shows that the concentration of the chemical milling solution has a significant effect on the surface roughness of machined workpieces, and increasing the concentration leads to a smoother surface finish. As the concentration expands from level 1 to level 4, the SRa goes down. In addition, the SRa value at level 1 is the highest (6.3503 μm), and the SRa value at level 4 is the lowest (4.4884 μm). The main effect plot for T also shows that as the temperature increases, the SRa slightly decreases, indicating that higher temperatures lead to smoother surfaces. The effect of milling time (E_t) is relatively small, while the effect of temperature (T) is more pronounced. The longest milling time and due to the effect of the concentration of solution on the temperature, it can be obtained the lowest roughness. Thus, the optimum chemical milling parameters are at (cont%₄ T_1 E_{t4}) i.e. the optimal process parameter settings are a higher concentration of the chemical milling solution (Cont%), a lower machining temperature (T), and a longer etching time (E_t) that will result in a smoother surface finish.

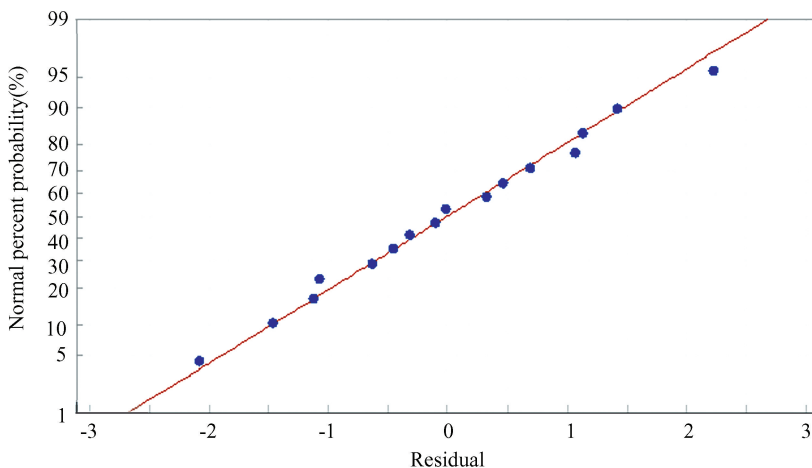


Fig.5 Normal probability plot of SRA

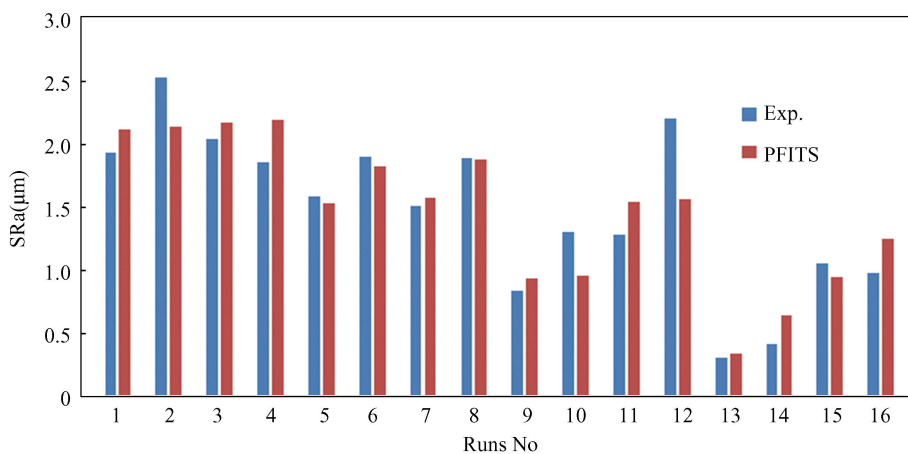
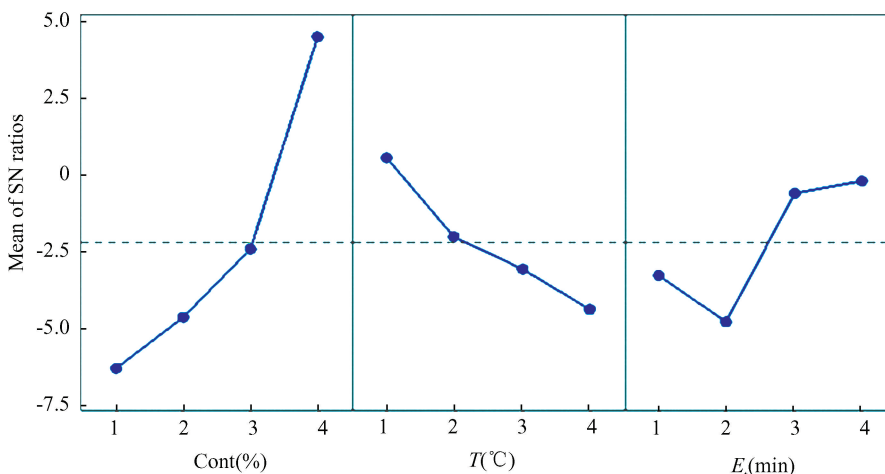


Fig.6 Comparison between experiment and predicted values of SRA



Note: Signal-to-noise larger is better

Fig.7 The main effect plot for SN ratio (SRA)

According to the Taguchi design, the results of the analysis of variance (ANOVA) for the average roughness height (SRA) are presented in Table 6. The

positions in Table 7 indicate the contribution of each parameter to the overall response. It can be seen that the concentration (Cont%) has a big effect on the

roughness of the surface (SRa) with PCR 67%. The SRa value at levels 2 and 3 goes down gradually. The effect of time (E_t) on SRa is statistically significant with an F-value of 5.98 at PCR equal to 15%. The effect of temperature (T) is relatively small compared to the other parameters, such as concentration (Cont%) and milling time. The ANOVA results show that the F-value for T is 5.34 with PCR is 13%,

Table 6 Analysis of variance for SN ratios for SRa

Source	Cont(%)	T ($^{\circ}$ C)	E_t (min)	Residual error	Total
DF	3.000	3.000	3.000	6.000	15.000
Seq SS	272.610	52.880	59.200	19.800	404.500
Adj SS	272.610	52.880	59.200	19.800	-
Adj MS	90.871	17.627	19.734	3.301	-
F	27.530	5.340	5.980	-	-
P	0.001	0.039	0.031	-	-
PCR%	67	13	15	5	100

Table 7 Signal to Noise Ratios for SRa

Level	Cont(%)	T ($^{\circ}$ C)	E_t (min)
1	-6.3503	0.5470	-3.3250
2	-4.6779	-2.0430	-4.8505
3	-2.4491	-3.0850	-0.6158
4	4.4884	-4.4080	-0.1978
Delta	10.8387	4.9550	4.6527
Rank	1	2	3

3 Conclusions

From the experimental work, the following can be observed:

1) The Taguchi method was used to predict MRR values with high accuracy.

2) The Material removal rate is directly proportional to both concentration rate and milling time. However, the MRR increases as the temperature decreases.

3) The surface roughness directly decreases with a proportional increase of both concentration rate and milling time. However, the SRa decreases as the temperature decreases.

4) The concentration of the chemical milling solution has the greatest influence on the responses (MRR and SRa), followed by duration of the milling process and machining temperature. The result indicated that the contribution percentages of the concentration of the etching acids on the both

which is significant but lower than obtained for Cont% and E_t . The rankings in Table 7 indicate the extent to which each parameter contributed to the overall responses. The concentration, which is ranked first among the parameters, has the greatest effect, followed by the temperature machining and then chemical milling time which are ranked second and third, respectively.

responses (MRR and SRa) is 81% and 67% respectively.

5) The optimal combination of chemical milling process parameters for achieving higher material removal and a smoother surface finish is a higher concentration of the chemical milling solution, a low temperature, and a longer milling time, i. e., a concentration of (22.5 HF + 17 HNO₃), milling temperature of 45 $^{\circ}$ C, and 1 h (60 min). These parameters resulted in a maximum MRR of 0.0842 mg/min and a minimum SRa of 0.30 μ m.

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