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ORIGINAL CONTRIBUTION

Generation of Stepped Profiles on Ti6Al4V by Electrochemical Milling

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Abstract Generation of accurate complex-shaped products on various high-strength temperature-resistant (HSTR) alloys such as titanium and nickel alloys is a key feature for many kinds of machine parts widely used in diverse industries starting from biomedical to defence industries. Being free of tool wear, thermal stresses and residual stresses, electrochemical machining has great potential of machining those HSTR metal structures. The process of EC milling is similar to conventional ECM, where the material is removed by a simple geometric tool following a predefined path in a layer-by-layer fashion. EC milling avoids complex electrode design which is often a burden in sinking ECM. In this paper, attempts have been made to investigate the influence of different process parameters on various performance characteristics of EC milling of Ti6Al4V by generating stepped profiles, and then, optimization of process parameters have been done using Taguchi and grey relation analysis (GRA). Experiments were conducted based on Taguchi's L_{27} orthogonal array with five important process parameters, i.e. electrolyte concentration, milling layer depth, feed rate, frequency and duty ratio. From analysis of variance, it was observed that electrolyte concentration and milling layer depth are the significant process parameters that mostly affect the responses. The experimental results show that for successful machining of Ti6Al4V by EC milling process, the optimal parametric combinations are 0.5 M electrolyte concentration, 0.15 mm milling layer depth, 0.04 mm/s feed rate, 5 kHz frequency and 50% duty ratio; and milling layer depth has a major influence on all the responses of EC milling of Ti6Al4V.

Keywords EC milling · Stepped groove feature · Ti6Al4V · Taguchi · GRA

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Introduction

Electrochemical machining has great potential to machine various HSTR metals such as titanium and nickel alloys because in ECM, metal is dissolved in an electrolyte cell by anodic dissolution without any tool wear so that it can machine the metal without depending on their mechanical properties. Electrochemical milling is an advanced process of ECM technique and employed to overcome the burdens of ECM such as the design of complex 3D-shaped tool. EC milling is able to generate any kind of complex surface profiles with a simple geometrical tool on any electrically conducting metal without depending on their mechanical properties. The tool moves along a predefined tool path in a layer-by-layer approach to achieve desired shape over the workpiece surface as in the case of conventional end-milling process. Thus, EC milling can be effectively applied in those areas where 3D surface is very much essential like in aerospace industry for generating air frame, wing and propeller, etc. [1].

Researchers had reported electrochemical milling of Inconel 718 with flow channel structure for rotating tool and showed that the MRR, surface quality and the consistency of the machining gap had been significantly improved with an increased feed rate [2]. During the fabrication of 'L'-shaped features on Ti6Al4V by EC milling, researchers had already investigated the influence of feed rate and frequency on the different machining performances, e.g. width overcut, machining depth, side angle, corner radius and surface roughness using three different combinations of electrolytes [3]. In the field of macro-electrochemical milling, researchers had already fabricated intricate-shaped features by EC milling process using sodium nitrate-based electrolyte [4]. A mathematical model had been derived by the researchers to assume the volumetric material removal for any complex structure generation on Ti6Al4V during EC milling and achieved good correlation with the theoretical predictions after validation [5]. Researchers had already investigated the impact of inner-spraying rotating tool during electrochemical milling of Nimonic-263 alloy [6]. Attempts had been made for optimizing the process parameters in ECM with intervening variables, e.g. MRR, surface quality and overcut had been investigated and concluded that feed rate had more impact than the other parameters on the material removal rate [7]. In EC milling of Ti6Al4V, investigations had already been made using three different electrolytes by varying two process parameters, i.e. feed rate and frequency and corresponding effects on overcut and surface roughness had been studied. Finally, some complicated linear as well as nonlinear profiles had been successfully machined with the suitable range of process parameters [8].

From the literature survey, it can be found out that till date very limited research works have been carried out in EC milling on Ti6Al4V. Thus in this paper, investigation will be carried out to determine the influence of the five most significant process parameters on important performance characteristics of EC milling during generation of stepped profiles on Ti6Al4V. Moreover, with the help of single as well as multi-objective-optimized techniques, most suitable combinations of those process parameters and their appropriate range will be searched out. Finally, based on the outcomes of the multi-objective-optimized technique, more accurate stepped profiles will be fabricated on Ti6Al4V to confirm the effectiveness of the used technique.

Experimental Set-up

To perform EC milling operation, a suitable experimental set-up needs to be utilized which will permit the tool to move along predesigned path for generating desired shapes. In Fig. 1, a schematic diagram of experimental EC milling set-up has been shown. The developed set-up mainly consists of several sub units, e.g. mechanical machine unit, power supply unit, electrolyte supply unit and control unit.

A tool attachment unit which is attached to the *Z*-axis of the stage has been developed in-house. The electrolyte supply system includes two submerged pumps, electrolyte tank, two nozzles, filter unit, control valves and a pressure gauge. Used electrolyte is kept in a storage tank and for the time being sludge is precipitated at the bottom of the tank after that fresh electrolyte is kept in another storage tank and supplied through a filter as shown in Fig. 1. The electrolyte pressure can be adjusted by the control valve, and the actual pressure can be measured and displayed by the pressure gauge. The electrolyte is constantly circulated through the system to ensure optimal machining condition.

Experimental Planning

EC Milling Strategy

In the present research work, step groove has been generated to study the effects of various three-dimensional features, and then, design of experiments have been done for the generation of effective step groove. The machined profiles have been generated by moving the tool along a predefined path as shown in Fig. 2a, b.

To check the quality of the three-dimensional effects of step groove, five responses have been selected for the machined profile, e.g. side angle (S_a), step angle (S_t), radius of curvature of step (R_{oc}), effective depth (E_d) and surface roughness (R_a). In Fig. 2c, the schematic diagram of obtained profile, desired profile and various responses are shown. Side angle (S_a) is the angle between the sidewall of the obtained profile and sidewall of the desired profile. Similarly, step angle (S_t) is the angle between the base of upper step of obtained profile and the base of the upper step of desired profile and both are expressed in 'degree'. A curvature was formed in the junction of the two steps as shown in the figure, termed as radius of curvature (R_{oc}) and expressed in 'mm'. Effective depth (E_d) is the difference of depths of upper step and deeper step of the machined profile. Various geometric parameters of the EC milled pockets have been measured by Formtracer Extreme SV-C4500, a contact-type contour-measuring machine made by Mitutoyo, Japan. Surface quality (R_a) of the machined profile have been measured by Surftest SJ-210, a portable surface roughness tester made by Mitutoyo, Japan, and expressed in micron. During measurement, measuring force, cut-off length and sampling length have been set at 0.75 mN, 0.25 mm and 10 mm, respectively. Tip radius of stylus and tip angle are 2 μm and 60°, respectively.

Experimental Design

Experimental investigations have been carried out to demonstrate the effects of machining parameters on the various responses of EC milling. For this experimentation, a cylindrical tool of SS-310 with the diameter of 1.5 mm and a rectangular flat plate of titanium alloy Ti6Al4V with

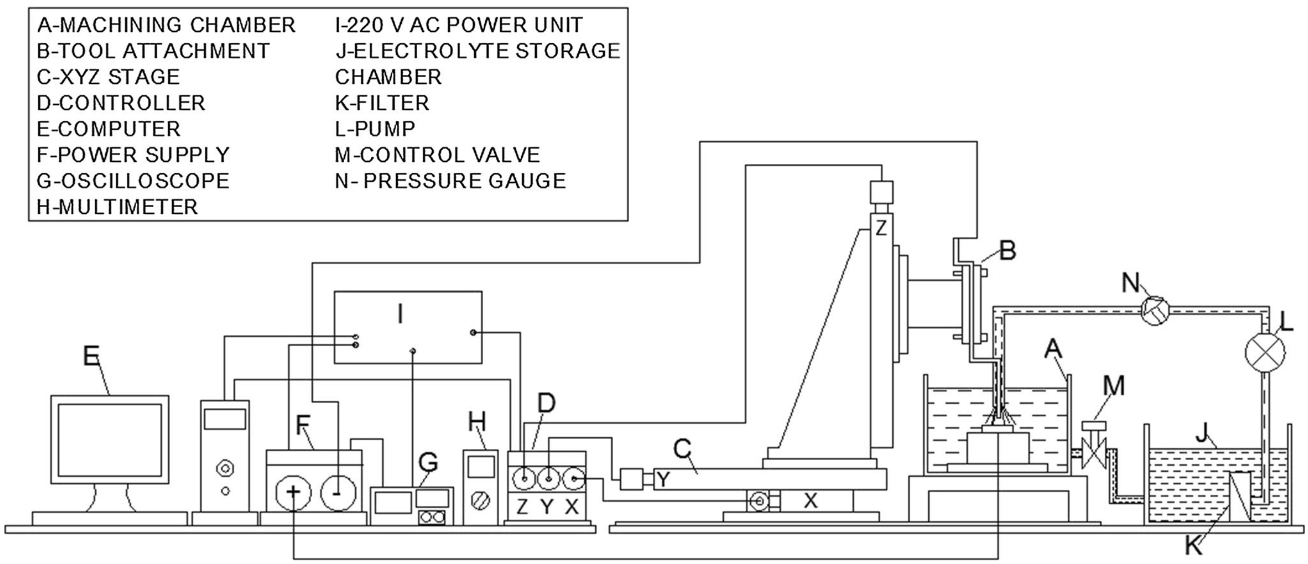

Fig. 1 Schematic diagram of experimental set-up of EC milling

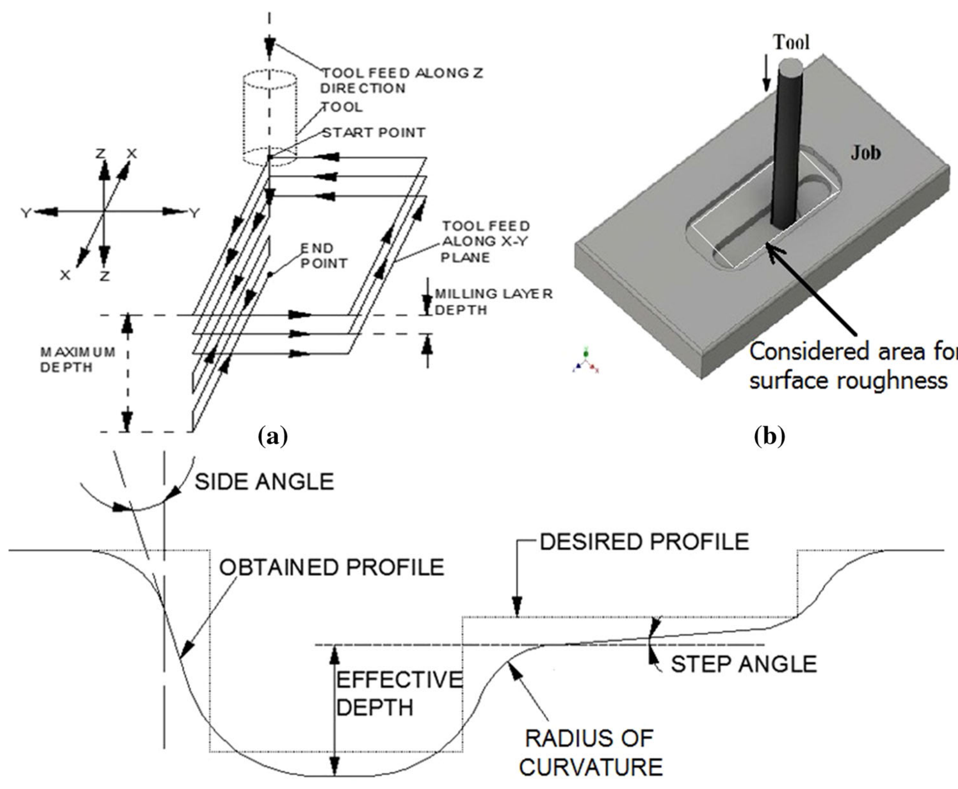

Fig. 2 **a** Tool travel path, **b** isometric view of machined profile and **c** various measured responses of EC milling

5 mm thickness have been chosen for the tool and the job material, respectively. Based on the studies available on machining of Ti6Al4V and with the help of pilot experimentations, proper range of these process parameters have been selected [3]. Due to the formation of oxide layer, titanium machining is very difficult and high-accuracy machining cannot be possible with any single electrolyte; thus, two electrolytes should be mixed such a way that problem encounteres due to the individual electrolyte can be overcome. It has been seen that sludge produced during machining using NaCl + $NaNO_3$ electrolyte is insoluble, non-sticky and lighter. So, this sludge is easily flushed away from the machined zone; hence, excellent surface finish has been obtained using NaCl + $NaNO_3$ electrolyte [3]. The fixed and variable process parameters are depicted in Tables 1 and 2, respectively.

Table 1 Fixed process parameters [3]

Parameters	Value
Initial inter electrode gap (mm)	0.5
Feed rate along '*Z*'-axis (mm/s)	0.02
Input current (A)	12
Type of current	Square pulse
Input DC voltage (V)	20

Table 2 Variable process parameters

Parameters	Level 1	Level 2	Level 3
(A) Electrolyte concentration (M)	0.5	0.75	1
(B) Milling layer thickness (mm)	0.15	0.175	0.2
(C) Feed rate (mm/s)	0.03	0.04	0.05
(D) Frequency (kHz)	5	7.5	10
(E) Duty ratio (%)	30	40	50

One of the popular single-objective optimization techniques is the Taguchi method, and another effective multi-object optimization technique is grey relation analysis (GRA) method. Both the techniques have been employed in this experimentation to obtain more influencing process parameters with their appropriate level for various responses to generate accurate 3D-stepped groove profile on Ti6Al4V. On the basis of input factors and their levels, 27 experiments have been conducted.

Results and Discussion

After the completion of experiments according to L_{27} array, measurements have been taken for all the performance characteristics. All the experiments have been repeated for three times and averaged. The average value of performance characteristics is listed in Table 3.

Analysis Based on *S*/*N* Ratios of Taguchi Method and Determination of Optimal Parametric Combinations

After obtaining the data for all performance characteristics, these have been further processed to calculate *S*/*N* ratios for analysing effects of process parameter on performance characteristics and also to determine optimal parameters setting [9].

S/*N* ratio graphs for each performance characteristics have been plotted as shown in Fig. 3. From the graphs, each performance characteristic and its corresponding optimum parametric condition has been obtained. The peak points of the graph for each process parameter indicate the optimum level of that process parameter for corresponding performance characteristics. As Taguchi analysis is a single-objective optimization technique, thus, it optimizes one response at a time and offers one particular combination of parameter settings without considering other responses. For example, for minimizing step angle, a combination of high concentration of electrolyte, higher feed rate and moderate value of milling layer depth are needed, whereas, with the combination of low concentration of electrolyte, moderate feed rate and lower value of milling layer depth, radius of curvature can be minimized. Table 4 reveals all the process parameters with the optimum parametric combination obtained by the Taguchi method.

ANOVA Test Results for Performance Characteristics

In this investigation, the analysis of variance (ANOVA) has been performed to determine which machining parameter has more significant effect on machining performance characteristics and also to find out the percentage of contribution of the machining parameters on the responses [9].

The higher the '*F*' value, the more significant the effect on the performance characteristics. From the table of standard '*F*' values, it has been seen that the '*F*' values of electrolyte concentration, milling layer depth and feed rate fall in the confident interval of 97.5% [10]. Table 5 depicts '*F*' ratio and percentage of contribution for all the responses. It is seen from '*F*' ratio and percentages of contribution in Table 5 that all the responses are mostly dependent on the concentration of electrolyte, feed rate and milling layer depth as in EC milling material removal takes place by means of controlled ionic electrochemical reaction in between anode and electrolyte in the machining gap. Hence, electrolyte concentration has more impact on surface roughness than the feed rate, and ANOVA results in Table 5 also reveal the same.

Confirmation Test of the Outcomes at Optimal Parametric Settings

After the determination of optimal parametric setting, grand mean of all *S*/*N* ratios for each response has been determined followed by the predicted *S*/*N* ratio at optimum parameter; and 2σ values have been calculated. After the determination of grand mean *S*/*N* ratio, predicted *S*/*N* ratio for the machining at optimum parameter setting followed by the value of 2σ of all the responses has been determined. Confirmation test result for all the responses are shown in Table 6 [8].

Table 3 Experimental results according to L_{27} array

Exp. no.	Radius of curvature (mm)	Side angle (°)	Step angle (°)	Surface roughness (micron)	Effective depth (mm)
1	3.3699	42.4053	24.7796	0.99600	0.486233
2	2.3406	39.9085	27.3060	0.94870	0.702967
3	1.8136	40.0388	21.9270	0.85900	0.612000
4	1.6098	41.4197	18.7383	1.34100	0.522367
5	1.4106	41.0100	19.2384	1.02480	0.451133
6	5.4911	49.1392	15.2247	0.92600	0.346500
7	0.4033	41.0366	11.4999	1.96640	0.553100
8	2.0177	43.6879	15.1673	1.03150	0.528700
9	0.5694	38.3317	13.1418	0.86220	0.522967
10	1.2473	43.3190	23.2296	1.00380	0.434567
11	3.5512	51.3875	18.2966	0.73240	0.466433
12	0.8110	56.1301	10.4224	1.09930	0.458100
13	3.6684	56.1720	14.2655	0.98925	0.300633
14	2.7040	48.8449	13.7077	1.44180	0.316267
15	4.2658	53.8465	14.4849	0.94100	0.210067
16	25.9605	54.4857	22.5658	0.87860	0.556000
17	17.8076	59.8734	16.1764	0.75350	0.448200
18	4.7306	56.5440	21.0858	0.90310	0.512767
19	4.3402	55.9704	11.7850	0.79575	0.298567
20	3.1475	48.7448	14.4615	0.99375	0.542067
21	2.3006	50.3857	14.9931	0.96180	0.604000
22	15.8343	53.0883	16.9138	0.90375	0.406133
23	7.4685	55.9314	17.4072	1.10230	0.372733
24	3.1823	53.9843	15.5002	1.42330	0.287300
25	0.6268	52.7027	16.3611	1.04500	0.414800
26	2.0050	34.9130	11.1886	0.85960	0.440300
27	1.5168	59.8864	10.0204	0.95860	0.453033

From Table 6, it has been also observed that prediction error value of all responses lie in between their corresponding 2σ values. As Taguchi experimentation is only valid when all the prediction errors at the optimal parameter setting lie in between their corresponding 2σ values, it can be stated that Taguchi experimentation is truly valid for this experimentation.

Multi-objective Optimized Condition Based on GRA

In the previous section, single-objective optimization technique has been done considering single response at a time and optimized process parameters with their optimum levels have been found. But, in practical situation, all the responses are needed to be considered at a time. So, in this experimentation, final desired performance characteristics have been achieved at minimum side angle, minimum step angle, minimum surface roughness, and minimum radius of curvature and maximum effective depth of the step profile. The response table according to the Taguchi method is used to calculate the average grey relational grade for each level of the process parameters.

Taking entire grey relational grade, graph is plotted against the experiment number in Fig. 4. From the figure, it has been clearly seen that the 26th experiment has the highest grey relational grade. Thereby, it signifies that the 26th experiment is the most optimal process parameters for achieving minimum side angle, step angle, radius of curvature, surface roughness and maximum effective depth for the generation of step groove among all 27 experiments.

In addition to that previous calculation, to attain more accurate optimized parameters setting, further calculations are required with the help of Taguchi method. Using Taguchi method, from the L_{27} array, average grey relational grades for each level of step groove parameters are determined. Average grey relational grade of parameters and their corresponding levels are calculated and listed on Table 7. For each level of the process parameters, the

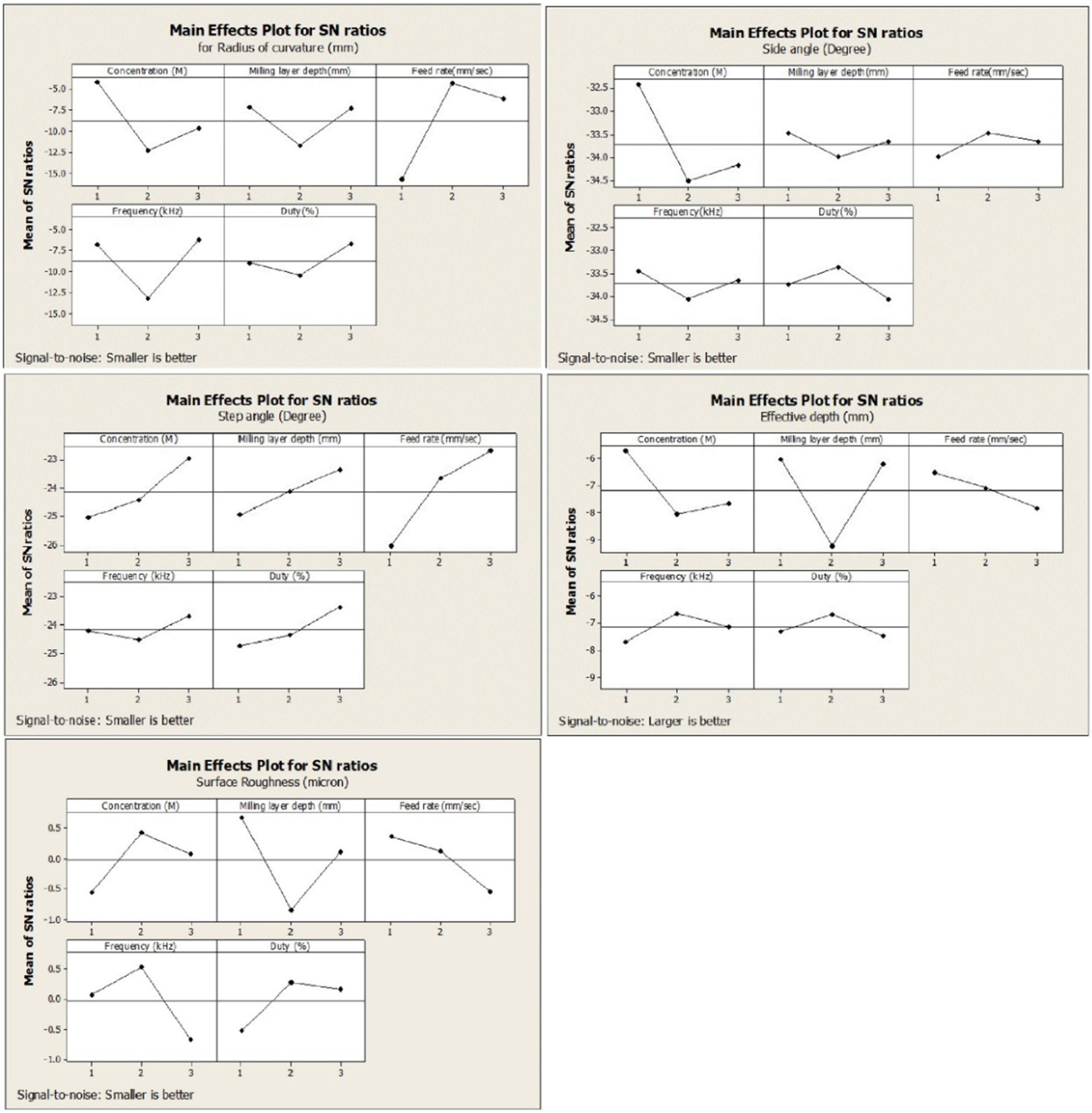

Fig. 3 Effects of process parameters on various responses of EC milling

highest value indicates the optimum level of those parameters and highlighted in the table. For each process parameter, the difference between highest average grey grades and the lowest grey grade have been determined. Considering all the responses at a time, the highest value of this difference indicates highest impact.

From Table 7 and Fig. 4, it has been cleared that the highest difference has been obtained in the case of milling layer thickness. In GRA, the higher value of difference between the highest and the lowest average grey-grade coefficients leads to higher influence considering all the responses at a time. So, it signifies that milling layer thickness has the most significant effect on machining performance for the generation of step groove. According to Table 7 and Fig. 4, the rank of influence on machining performance for the generation of step groove is as follows B > A > C > E > D. Furthermore, optimized process parameters are determined from Table 7 by taking the highest value of each parameter for all the levels; and it has

Table 4 Optimum parameter level

Process parameters	Electrolyte concentration (A) (M)	Milling layer thickness (B) (mm)	Feed rate (C) (mm/s)	Frequency (D) (kHz)	Duty ratio (E) (%)
Radius of curvature (R_{oc})	0.5	0.15	0.04	10	50
Side angle (S_a)	0.5	0.15	0.04	5	40
Step angle (S_t)	1	0.2	0.05	10	50
Effective depth (E_d)	0.5	0.15	0.04	7.5	40
Surface roughness (R_a)	0.75	0.15	0.03	7.5	40

Table 5 ANOVA test results

Parameters	'F' ratio					Percentage of contribution				
	R_{oc}	S_a	S_t	E_d	R_a	R_{oc}	S_a	S_t	E_d	R_a
Concentration (M)	4.58	10.86	3.95	4.92	0.61	20.95	77.70	21.40	27.42	15.47
Milling layer depth (mm)	1.9	0.58	2.17	10.21	1.44	8.69	4.12	11.77	56.88	36.49
Feed rate (mm/s)	10.26	0.63	10.08	1.38	0.55	46.97	4.53	54.67	7.67	13.97
Frequency (kHz)	4.09	0.87	0.58	0.87	0.89	18.74	6.25	3.14	4.85	22.45
Duty (%)	1.01	1.03	1.66	0.57	0.46	4.63	7.37	9.00	3.16	11.59
Total						100	100	100	100	100

Table 6 Confirmation test results

Responses	Optimal condition		Prediction error	2σ value
	Predicted result	Experimented result		
Radius of curvature (mm)	0.4912	0.5210	0.5440	± 9.862
Side angle (°)	36.797	44.0383	1.5537	± 1.765
Step angle (°)	9.4770	10.3139	0.7330	± 2.786
Effective depth (mm)	0.7070	0.7030	0.0437	± 2.890
R_a (micron)	0.7656	0.9141	1.5397	± 3.313

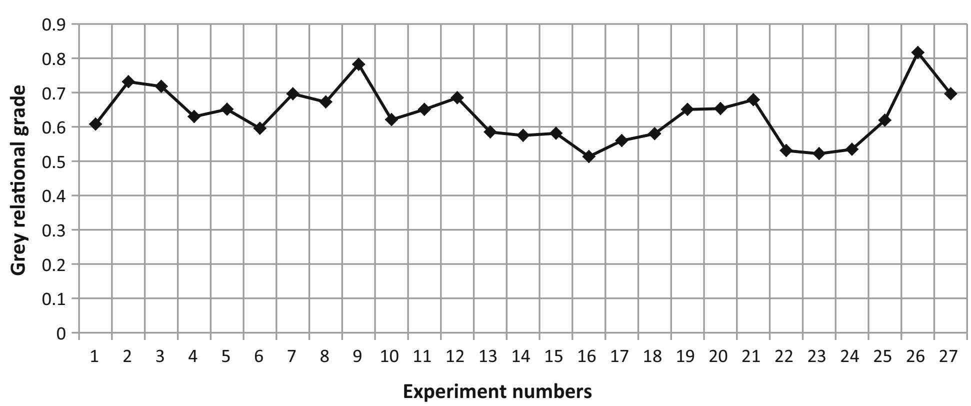

Fig. 4 Grey-grade coefficient for all experiments

been cleared that the most optimum process parameter setting is A_1 B_1 C_2 D_1 E_3 for the generation of step groove.

Machining has been done at the optimum parameter combination at A_1 B_1 C_2 D_1 E_3, i.e. the profile has been

Table 7 Difference of average grey-grade coefficient

Process parameters	Levels			Difference between highest and lowest grey grades of the parameter
	1	2	3	
Concentration (M)	**0.675990**	0.594468	0.633511	0.081522
Milling layer depth (mm)	**0.666247**	0.578225	0.659497	**0.088022**
Feed rate (mm/s)	0.588529	**0.662796**	0.652644	0.074266
Frequency (kHz)	**0.658890**	0.612431	0.632648	0.046459
Duty (%)	0.605855	0.647992	**0.650122**	0.044266

Highest values have been highlighted in bold

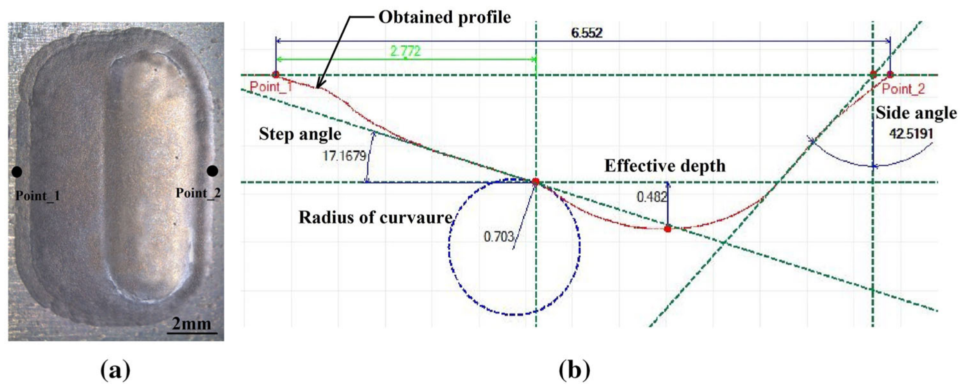

Fig. 5 Image of machined profile at optimum parameters based on GRA analysis. **a** Photographic view and **b** form data acquired by contour-measuring machine

machined at 0.5 M electrolyte concentration, 0.150 mm milling layer depth, 0.04 mm/s feed rate, 5 kHz frequency of pulsed voltage, 50% duty ratio of pulsed voltage. After the experiments on these optimal parametric combination, performance characteristics, e.g. radius of curvature of step has been found as 0.703 mm, side angle as 42.52°, step angle, effective depth and surface roughness have been found as 17.17°, 0.482 mm and 0.94 µm, respectively.

Attempt has been made to fabricate stepped groove profile at the optimum parameter settings based on GRA analysis. Figure 5 depicts the photographic image and machined profile at the optimal parameter settings based on GRA analysis. From Fig. 5a, b, it has been clearly seen that the step of the profile is prominent and surface roughness quality has also been found to be excellent.

Conclusions

In this study, the performance of the EC milling process has been successfully investigated considering different aspects of the process during machining of Ti6Al4V. After analysing the experimental outcomes, the following conclusions can be drawn:

1. It can be stated from all the experimentations that the EC milling set-up is suitable to perform EC milling process effortlessly and able to generate 3D complex shape on any HSTR alloys.
2. From Taguchi analysis, it has been seen that electrolyte concentration, milling layer depth and feed rate have major influence, while frequency and duty ratio are the less-influencing factors considering all the responses individually.
3. As all the prediction errors at the optimal parameter setting lie between the corresponding 2σ values, it can be concluded that Taguchi experimentation is valid and should be quite acceptable in the practical field.
4. It is concluded from grey relational analysis that milling layer depth has a major influence on all the responses of EC milling for the generation of stepped groove on Ti6Al4V.
5. From grey relational analysis, considering all the responses at a time, the most suitable process parameters have been obtained as 0.5 M electrolyte concentration, 0.15 mm milling layer thickness, 0.04 mm/s feed rate, 5 kHz frequency and 50% duty ratio.

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