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Effect of Tool Electrode Tip Shape on Machining Rate and Overcut in Electrochemical Micromachining (EMM)

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ABSTRACT: This paper presents the studies on the effect of tool electrode tip shape on machining rate and overcut in Electrochemical Micromachining (EMM). An L_{18} mixed orthogonal array based on Taguchi technique has been used, signal to noise (S/N) ratio, analysis of variance and F-test values have been calculated. Based on these analyses, the significant process parameters affecting the machining rate and accuracy have been identified. The optimum process parameters that result in higher machining rate and lower overcut have been found out and confirmation tests carried out to validate the prediction. The confirmation test results shows 72.59% and 48.75% improvement of machining rate and overcut respectively with respect to the initial parametric setting. In-depth studies have also been made to examine the influence of various process parameters on the overcut through SEM micrographs of machined micro-hole.

KEYWORDS: Taguchi Technique; Machining rate; Overcut; Electrochemical micromachining.

1. INTRODUCTION

Electrochemical micromachining (EMM) is one of the non-conventional micromachining processes. In EMM, the workpiece material is removed by the anodic dissolution process in electrolytes under an electric field. Since EMM has many advantages such as high machining efficiency, absence of tool wear, stress free, absence of burrs, better surface quality and capacity to machine complex shapes it has been successful in the manufacture of various micro-parts and devices [10].

Drilling of micro-holes is a basic feature found in many industrial parts such as miniature oil sprayers, miniature oil atomizers, miniature mixers and ink jet nozzles [3]. In electrochemical machining, ion dissolution is the major mode for material removal and therefore, the dissolution products produced during machining is to be flushed out properly from the machining area in order to increase the machining rate and minimize the overcut as well as avoid micro sparks. This also holds well in EMM.

Researchers have found several ways of improving the machining rate and accuracy[10-15]. One of the approaches for improving the machining rate and accuracy of the micro hole is properly refreshing the electrolyte in the inter-electrode gap. The influence of rotational cathode tools on EMM have experimentally studied and found that the rotational tool electrode produces micro-hole with high aspect ratio and lower overcut [5]. Wang et al. (2010) have used wedge-shaped electrodes for drilling inclined holes. The use of wedged electrode have improved the machining accuracy and process stability. The semi-cylindrical tool electrode with ultrasonic vibrations produces micro-hole with higher accuracy and machining rate [14]. The effect of micro-helical tool in electrochemical micro-drilling is studied. This study reveals that the accuracy of the micro- hole is improved using the micro- helical tool [10]. The accuracy and



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material removal rate is also improved by using vibrating tool electrode. The tool vibration in the range of 150-200 Hz provides better machining.

Ahn et al. (2004) have found that the bottom shape of the tool affects the machinability. The use of round ended tools show good machinability due to the easiness of electrolyte supply. The use of reciprocal motion between the tool and the workpiece to pump and enhance the circulation of the electrolyte improves ECM machining accuracy. The amplitude of the tool vibration is the most effective parameter affecting ECM accuracy [4]. The generic aspects of tooling design for the ECM process are studied. Based on the study, it is concluded that the electrolyte flow should be as unrestricted as possible, all electrode edges should have shape of curvature and tool has to be insulated [13].

Based on these literatures, it is quite evident that although proper flushing of the inter electrode gap (IEG) is vital for increasing machining rate and minimizing overcut, not much research has been carried out to achieve proper flushing. Taking this issue into consideration, this research focuses on studying the effect of two tool electrode tip shapes and other parameters on the machining rate and overcut. Analysis based on Taguchi method has been carried out to obtain significant process parameters and their optimal combination level for effective micro-hole generation in 304 stainless steel. Although Munda et al. (2010) have investigated the effect of EMM process parameters, but the Taguchi method has not been used in EMM process optimization. Considering these requirements, the different process parameters levels have been identified and an L_{18} mixed orthogonal array is used in determining the optimal combinations of process parameters to maximize the machining rate and minimize the overcut. In addition, further study has been carried out to examine the influence of process parameters on overcut with the help of scanning electron microscope (SEM) micrographs.

II. EXPERIMENTAL SET-UP

The EMM set-up used in the study has been fabricated in- house. The electrolyte supply and cleaning system consist of a pump and filter. A pulsed power supply of 20 V and 30 A with the capability for varying voltage, current and pulse width was used.

The basic tool electrode is made up of stainless steel of diameter 452 μ m and tip shapes were selected based on the experimental study [11]. The tool electrode tip shapes has been chosen from the three tip shapes namely flat electrode, truncated cone and conical with rounded tip shape. Sodium nitrate (NaNo₃) was used as an electrolyte. The electrolyte is allowed to flow with low pressure so that fresh electrolyte is circulated by the electrolyte supply system into the machining chamber. Some of the process parameters like tool electrode tip shape, machining voltage, pulse-ontime and electrolyte concentration greatly influence the micromachining performance.

The orthogonal array (OA) is selected based on the degrees of freedom (DOF) [9]. In this study, an L_{18} mixed orthogonal array is used. This array has 4 columns and 18 rows and it can handle one, two-level process parameter and three, three-level process parameters. Each of the experiments has been conducted twice. Machining rate and overcut are the two responses considered in this study. In EMM, higher machining rate and lower overcut are desired. Therefore, the machining rate is the higher-the-better performance characteristic and the overcut is the lower-the-better performance characteristics.

III. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

3.1. Signal-to-Noise (S/N) ratio

In the Taguchi Technique, the S/N ratio is used to determine the deviation of the performance characteristic from the desired value. To obtain optimal machining performance, the maximum machining rate and minimum overcut are desired. Therefore, the higher-the-better machining rate and lower-the-better overcut should be selected. The loss function is further transformed into an S/N ratio.

Signal-to-Noise ratio for larger-the-better performance characteristic can be expressed as [7] :

$$\eta = -10\log\left[1/n\sum_{i}^{n} Y_{i}^{-2}\right]$$

(1)



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Signal-to-Noise ratio for smaller-the-better performance characteristic can be expressed as:

$$\eta = -10\log\left[1/n\sum_{i}^{n} Y_{i}^{2}\right]$$
⁽²⁾

Where η : S/N ratio, Y_i : the *i*th result of the experiment; n: the repeated number of the *i*th experiment. The experimental results for the machining rate, overcut and its S/N ratio are shown in Table 3. The S/N ratios are estimated based on Eq. (1) and (2).

3.2 Determination of optimal machining parametric combination for machining rate

Orthogonal experimental design helps to separate out the effect of each machining parameter at different levels. For example, the mean of the S/N ratio for the tool electrode tip shape at levels 1 and 2 can be calculated by averaging the S/N ratios for experiments 1-9 and 10-18, respectively. The mean of the S/N ratio for each level of the other machining parameters can be computed in a similar manner. The mean of the S/N ratio for each level of the machining parameters is summarized in the Table 4. Based on the Table 4, an optimal combination of process parameter for higher machining rate is truncated cone tip shape (level 2), machining voltage of 8 V(level 1), pulse on-time of 15 ms (level 3) and electrolyte concentration of 0.29 mole/l (level 2). The total mean of all 11 values were calculated and is presented in Table 4.

3.3 Effect of parameters on machining rate

Figure 3 shows the S/N ratio graph for machining rate and the total mean of the S/N ratio is indicated in dashed line. Based on the figure the machining rate increases linearly and maximum for the truncated tool tip shape when compared with the conical tip shape.

Figure 3 confirms that the machining rate increase sharply as pulse on-time increases from 10 to 15 ms. For a frequency of 50 Hz, pulse off-time decreases with increase in pulse on-time. When pulse off-time decreases, the time for renewing the electrolyte becomes shorter. This results in improper flushing of dissolution products. The improper flushing causes micro spark, which leads to higher material removal.



Figure 3 S/N ratio graph for machining rate



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Table 4 S/N response table for machining rate

Symbol	FACTORS	S/N ratio response				
Symbol		Level 1	Level 2	Level 3	Maximum	
А	Tool electrode tip shape	-17.5511	-14.0)309	-14.0309	
В	Machining voltage	-14.8604	-17.1465	-15.57	-14.8604	
С	Pulse-on-time	-17.5282	-16.6369	-13.208	-13.208	
D	Electrolyte concentration	-17.7179	-14.0322	-15.623	-14.0322	
				Total Mean	-15.8095	

3.4 Determination of optimal machining parametric combination for overcut

According to the Table 5, the optimal combination of process parameter for lower overcut is, conical with rounded tool tip (level 1), machining voltage of 9 V (level 2), pulse on-time of 7.5 ms (level 1) and electrolyte concentration of 0.35 mole/l (level 3). Larger values of the S/N ratio in the graph (or in the S/N ratio table) indicate that the smaller is the variance of the performance characteristics around the desired value. Figure 4 shows the S/N ratio graph for the overcut. The dashed line shows the mean S/N ratio.

3.5 Effect of parameters on overcut

The effects of electrolyte concentration on overcut are shown in the Figure 4. Based on the figure the overcut decreases sharply with increase in electrolyte concentration. The S/N ratio curve of overcut, it is observed that the micro-hole has a lower overcut at machining voltage of around 9 V, however, with increase in machining voltage, overcut is also found to increase. If the machining voltage is too large (i.e., at 10 V), large quantity of workpiece material is removed.



Figure 4 S/N ratio graph for overcut



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Table 5 S/N response table for overcut

Symbol	FACTORS	S/N ratio response				
Symbol		Level 1	Level 2	Level 3	Maximum	
А	Tool electrode tip shape	-31.4604	-36.1	3672	-31.4604	
В	Machining voltage	-36.8342	-30.6789	-34.8736	-30.6789	
С	Pulse-on-time	-32.4921	-34.2008	-35.0486	-32.4921	
D	Electrolyte concentration	-35.6042	-37.6987	-28.4389	-28.4389	
				Total Mean	-33.9726	

3.6 Analysis of variance (ANOVA)

The S/N values determined from the experimental observed values were statistically studied by ANOVA to investigate the effects of each machining parameter on the observed values and to clarify which machining parameters significantly affecting the observed values. In addition, the F-test named after fisher can also be used to determine which process parameters have a significant effect on the performance characteristic [Montgomery DC., 1997]. Usually, the change of the process parameter has a significant effect on the performance characteristic when the F value is large. Based on the table 6 the calculated F-values of the ANOVA for machining rate reveals that the tool electrode tip shape and pulse on-time have significant effect on machining rate. From the ANOVA test, it is also clear that tool electrode tip shape and pulse on-time have a high percentage of contribution on different machining criteria compared to other parameters. Table 7 shows the results of F-values for overcut. From the results of F-test, it can be found that machining voltage and electrolyte concentration is the most significant machining parameter which affects the overcut. From the ANOVA test, it is evident that machining voltage and electrolyte concentration have a high percentage of contribution on a high percentage of contribution compared to other parameters.

IV. CONFIRMATION TEST

The use of confirmation test is to validate the conclusions drawn during the analysis phase. The predicted or estimated S/N ratio of machining rate and overcut can be calculated as

$$\eta = \eta_m + \sum_{i=1}^{q} (\eta_i - \eta_m) \tag{3}$$

Where η_m is the total mean of the S/N ratio, q is the number of significant parameters, η_i is the mean of the S/N ratio at the optimal level. Table 8 shows the S/N ratio of the predicted machining rate and the actual machining rate. The increase of the S/N ratio from the initial machining parameters to the optimal machining parameters is 15.45 dB, which means that the machining rate is increased. So, the parameter combination suggested for the higher machining rate is tool electrode tip shape at level 2 (truncated cone tip), machining voltage at level 1 (8 V), pulse on-time at level 3 (15 ms), and electrolyte concentration at level 2 (0.29 mole/l). Table 9 shows the comparison of S/N ratio of the predicted overcut with the actual overcut. The increase of the S/N ratio from the initial machining parameters to the optimal machining parameters is 19.44 dB and therefore the overcut is reduced by 48.75%. Table 8 shows the improved S/N ratio for the overcut. The parameter combination suggested for the lower overcut is tool electrode tip shape at level 1(conical with rounded), machining voltage at level 2 (9V), pulse-on-time at level 1(7.5 ms), and electrolyte concentration at level 3.



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Table 6 Results of ANOVA for machining rate

Symbol	Factor	Sum of Squares	Degrees of Freedom	Mean square (variance)	F ₀ - value	Contribution (%)
А	Tool electrode tip shape	55.764	1	55.764	32.629	24.09
В	Machining voltage	55.149	2	27.574	16.134	23.82
С	Pulse-on-time	62.433	2	31.216	18.265	26.97
D	Electrolyte concentration	41.007	2	20.503	11.997	17.71
E	Error	17.0920	10	1.709		7.384
Т	Total	231.446	17			100.00

Table 7 Results of ANOVA for overcut

Symbol	Factor	Sum of Squares	Degrees of Freedom	Mean square (variance)	F value	Contribution (%)
А	Tool electrode tip shape	108.347	1	108.347	7.989	11.65
В	Machining voltage	382.05	2	191.02	14.084	41.11
С	Pulse-on-time	20.348	2	10.174	0.750	2.18
D	Electrolyte concentration	282.967	2	141.483	10.432	30.44
Е	Error	135.622	10	13.562		14.59
Т	Total	929.342	17			100.00



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Table 8 Confirmation test table for machining rate

	Initial levels of machining parameters	Optimal combination levels of machining parameters	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_2B_1C_3D_2\\$	$A_2B_1C_3D_2$
S/N ratio of machining rate in dB	-21.281	-8.7045	-5.831

Table 9 Confirmation test table for overcut

	Initial levels of machining parameters	Optimal combination levels of machining parameters	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_1B_2C_1D_3$	$A_1B_2C_1D_3$
S/N ratio of overcut in dB	-39.877	-21.1561	-20.433

VI. CONCLUSIONS

Experiments were conducted for studying the influence of tool tip shape in EMM on 304 stainless steel. The machining parameters considered for the experiments are tool tip shape, machining voltage, pulse-on-time and electrolyte concentration.

Based on the conducted experiments the optimal parametric combination for higher machining rate are truncated cone tip, at machining voltage of 8 V, pulse-on-time of 15 ms, and electrolyte concentration of 0.29 mole/l.

The optimal parameter combination suggested for the lower overcut are conical with rounded tip, machining voltage of 9 V, pulse-on-time of 7.5 ms, and electrolyte concentration of 0.35 mole/l.

Based on the F- value analysis, tool electrode tip shape is one of the significant parameter affecting the machining rate and its contribution is 24.09%.

The most significant parameter that affects the overcut is machining voltage and its contribution is 41.11%.

The improvement of machining rate and overcut from the initial machining parameters to the optimal machining parameters are about 72.59% and 48.75%.

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