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A Study on Process Parameters of Ultrasonic Assisted Micro EDM Based on Taguchi Method

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Experimental investigation of ultrasonic assisted micro electro discharge machining was performed by introducing ultrasonic vibration to workpiece. The Taguchi experimental design has been applied to investigate the optimal combinations of process parameters to maximize the material removal rate and minimize the tool wear. Analysis of variance (ANOVA) was performed and signal-to-noise (S/N) ratio was determined to know the level of importance of the machining parameters. Based on ANOVA, ultrasonic vibration at 60% of the peak power with capacitance of 3300 PF was found to be significant for best MRR. The machining time plays a significant role in the tool wear. The results were confirmed experimentally at 95% confidence interval.

Keywords machining, micro EDM, Taguchi method, tool steels

1. Introduction

In the modern trend of technology, miniaturization is a key word. Systems and devices are increasingly demanded, designed and manufactured at minuscule dimensions. The realization of micro parts calls for optimal machining capabilities. Micro electro-discharge machining (μEDM) is a technology suitable for miniaturized machining of metals and other conductive materials. Material removal in electro discharge machining (EDM) is based on the thermoelectric energy created between a work piece and an electrode submerged in a dielectric fluid. When pulsed power supply is applied between the work piece and the tool electrode that are separated by a specific small gap, called 'spark gap', electrical discharge (spark) occurs. Extremely high temperature generated during the discharge removes material from the electrodes through melting, evaporation and/or spalling. Debris, produced due to machining, is required to be removed to keep the sparking zone clean. Otherwise, the debris concentration will result in abnormal discharges, leading to unstable machining and rough surface. In μEDM, the discharge or spark gap is usually of the order of few micro meters. Removal of gaseous bubbles and debris from such a small gap has been a challenge. The tool rotation facilitates the debris removal due to centrifugal action. Due to fragility and size limitations, conventional flushing techniques such as jet flushing cannot be applied in μEDM. Hence it is required to explore alternate techniques to aid the flushing in μEDM.

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Masuzawa et al. introduced tool withdrawal and 2D vibration (sinusoidal motion of tool) to an EDM process for machining deep holes to increase the flushing effect (Ref 1, 2). Ghoreishi and Atkinson have reported that a combination of rotary and vibratory movements (vibro-rotary) of electrode produces higher material removal (Ref 3). Kremer et al. applied ultrasonic vibrations (20 kHz) to the tool to achieve process improvements (Ref 4, 5). They have reported that the process stability improved due to better slurry circulation caused by the pumping action of the electrode. Moreover, the pressure variation in the gap, caused by the ultrasonic vibration, improved the MRR as larger pressure drop causes lesser resolidification of molten metal. Murthi and Philip have identified cavitation (nucleation, growth, and burst of gaseous bubbles), ultrasonic field forces (radiation force, Stoke's force, Bernoulli's attraction), and acoustic streaming as the factors having pronounced effects in ultrasonic assisted EDM (Ref 6). Their finding is that the debris formed in ultrasonic assisted EDM is solid (rather than hollow) with higher spherodicity. It is reported that there is evidence of collision of particles in the form of dents, splats, attached satellites and cracks. Zhang et al. utilized the combined effect of EDM and ultrasonic machining to machine conductive ceramics by replacing the pulse generator in EDM by a constant DC source and ultrasonic tool vibration (Ref 7, 8). Guo et al. applied ultrasonic vibration in wire EDM (Ref 9, 10). They reported an increase in cutting efficiency, decrease in surface residual stress and reduced probability of rupture of wire. In micro EDM too, it is reported that the introduction of ultrasonic vibration has improved the process performance (Ref 11-14).

The important performance measures in micro EDM are Material Removal Rate (MRR) and Tool Wear (TW). Since the MRR and TW determine the economics of machining and rate of production, it is important to optimize the processes parameters suitably to maximize the MRR and minimize the TW. The objective of the present research is to optimize the process parameters in ultrasonic assisted micro EDM by using Taguchi's design of experiments, which has extensively been used in the past to study the EDM process (Ref 15-18).

2. Role of Ultrasonic Vibration in Micro EDM

Ultrasonic vibration plays dual role in micro EDM. They are (i) Direct contribution to the material removal and (ii) Aiding EDM by facilitating better machining conditions for material removal by EDM. These roles are discussed below.

2.1 Direct Contribution to the Material Removal

Phenomenon such as cavitation caused by ultrasonic vibration, directly removes the material. Ultrasonic waves are the stress waves transmitted from one mass to another by direct contact between the masses. Ultrasonic cavitation is the formation of bubbles or cavities in liquids during the low-pressure portion of a wave cycle. These bubbles may contain either the gases coming out of the solution in the liquid under reduced pressure or vapors of the liquid itself. Extremely high stresses associated with the formation and collapse of these cavitation bubbles cause material removal by fracture. The intensity of these stresses is a function of the vapor pressure of the liquid, the gas content of the liquid and the adhesive forces between the liquid and the surface. In addition to these stresses, formation and collapse of the cavitation bubbles also produce free chemical radicals that can erode even very tough materials. Hence ultrasonic vibration can remove material from both brittle and ductile materials. During this time material is also removed by melting and evaporation due to electric discharges caused by EDM. The simultaneous material removal by EDM and ultrasonic vibration provides hybrid nature to the entire process.

2.2 Facilitating Better Machining Conditions for Material Removal by EDM

Material removed by EDM and ultrasonic vibration form undesirable debris. Pumping action of the ultrasonic vibration improves the motion of dielectric fluid in the inter electrode gap. This provides better debris removal and minimization of arcing. As a result the performance of the micro EDM process increases.

3. Experimental Work

3.1 Materials

The work material used is A2 tool steel of size 12 mm×24 mm×2.5 mm with measured hardness of 54 HRC. The specimens were ground to get a flat surface. Tungsten with a diameter of around 200 μm and Common wealth 185 were used as a tool electrode and dielectric. Sizing of the tool was done on the machine using the built-in Wire Electrical Discharge Grinding (WEDG) unit.

3.2 Machine

The experiments were conducted using the commercial Panasonic MG-ED72W micro EDM. An ultrasonic vibration system having a peak power of 45 W was used in the experiments. The work piece was ultrasonically vibrated using a fixture as shown in the Fig. 1. A piezo-electric transducer of 40 kHz frequency with 10 μm maximum amplitude of vibration in feed direction (Z-axis) was used to vibrate the work

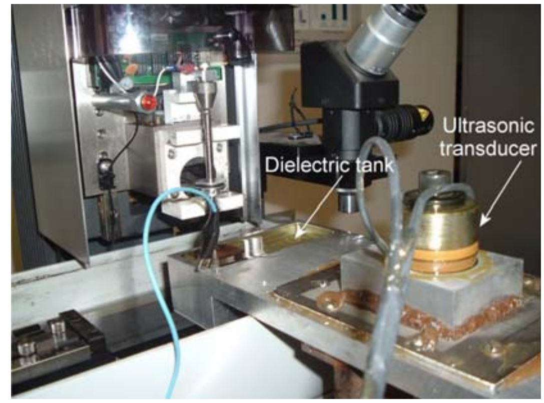

Fig. 1 Experimental setup

piece. A variable transformer was used to vary the power input to the generator, which in turn controls the amplitude of piezo-electric transducer.

4. Taguchi Approach

Taguchi method is very effective to deal with response influenced by multi-variables. This method focuses on minimizing the effect of causes of variation. The process performs consistently on target and is relatively insensitive to uncontrollable factors. In comparison with a traditional full factorial design of experiments, Taguchi's methods in general, provide a significant reduction in the size of experiments, thereby speeding up the experimental process (Ref 19-21). Two important tools used in Taguchi design are orthogonal arrays and signal-to-noise (S/N) ratios. Orthogonal arrays (OAs) were originally developed by Taguchi to control experimental error. OAs are constructed in such a way that, for each level of any one factor, all levels of other factors occur an equal number of times thereby giving a balanced design. Orthogonal arrays allow researchers or designers to study many design parameters simultaneously and can be used to estimate the effects of each factor independent of the other factors. Therefore, the information about the design parameters can be obtained with minimum time and resources. The signal-to-noise ratio is a quality indicator by which one can evaluate the effect of changing a particular design parameter on the performance of the process. Figure 2 shows the procedure and steps of Taguchi parameter design (Ref 19).

4.1 Selection of Quality Characteristics

There are three types of quality characteristics in the Taguchi methodology, viz. smaller-the-better, larger-the-better, and nominal-the-best. The objective of this research was to determine the machining conditions required to achieve (a) maximum Material Removal Rate (MRR) (b) minimum Tool Wear (TW) in UV assisted micro EDM process. Therefore, quality characteristic of larger-the-better for MRR and smaller-the-better for TW were implemented in this study.

4.2 Selection of Parameters

In Taguchi method, process parameters which influence the process are separated into two main groups: control factors and

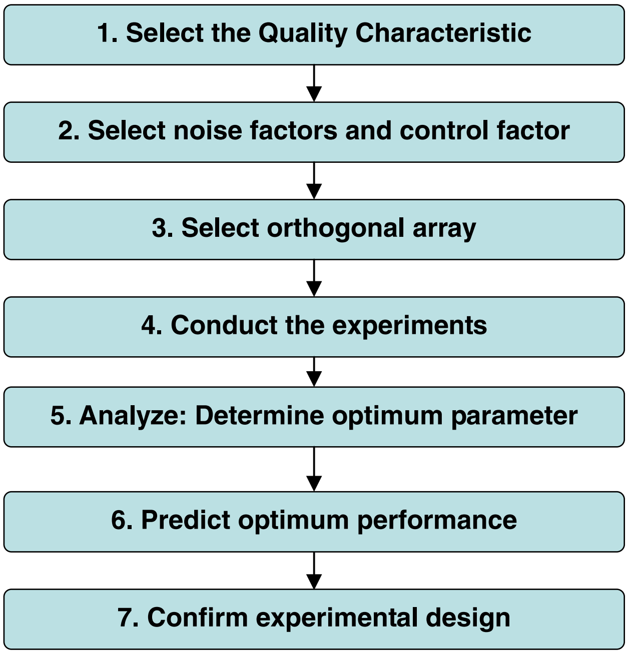

Fig. 2 Procedure and steps of Taguchi parameter design (Ref 19)

Table 1 Machining parameters used in experiment

Machining parameter	Level 1	Level 2	Level 3
A: Capacitance (PF)	3300	1000	...
B: % of peak power vibration	0	30	60
C: Feed Rate (μm/s)	1	3	5
D: Machining Time (min)	10	20	30

noise factors. The control factors are used to select the best conditions for stability in design of manufacturing process, whereas the noise factors are special variables that affect system function which are either uncontrollable or too expensive to control. The process parameters chosen for the experiment are: (A) Capacitance, (B) % of peak power used for ultrasonic vibration, (C) Feed Rate and (D) Machining Time. These parameters were selected because they can potentially affect MRR and TW (response function) performance in micro EDM operation and considered to be controllable factor. The machining conditions and number of levels of the parameters are selected as given in Table 1.

4.3 Selection of Orthogonal Array

The optimal process parameters are determined by analyzing the characteristic data acquired by using Orthogonal Arrays (OA). The total number of degrees needs to be computed to select an appropriate orthogonal array for the experiments. The degrees of freedom are defined, as the number of comparisons that needs to be made to determine which level is better. Since each three-level parameter has two degrees of freedom (number of levels−1), the degrees of freedom (DOF) required for three parameters, each at three levels, is 6 ($3\times(3-1)$). The DOF for two-level parameter is 1, i.e., (2–1) with total DOF as 7, Taguchi's OAs are selected on the basis of the condition that the total DOF of the selected OA must be greater than or equal to the total DOF required for the experiment (Ref 21). Hence an

Table 2 Experimental design using L_{18} orthogonal array

Exp. No	A	B	C	D	MRR, mm^3/min	Tool Wear, mm
1	1	1	1	1	0.000500046	0.039
2	1	1	2	2	0.000414534	0.1508
3	1	1	3	3	0.000427997	0.2882
4	1	2	1	1	0.001165085	0.079
5	1	2	2	2	0.000746397	0.2693
6	1	2	3	3	0.00136257	0.2435
7	1	3	1	2	0.000905843	0.1376
8	1	3	2	3	0.00130557	0.3883
9	1	3	3	1	0.002057524	0.1423
10	2	1	1	3	0.000855838	0.2468
11	2	1	2	1	0.001763868	0.1164
12	2	1	3	2	0.001345486	0.2689
13	2	2	1	2	0.000975833	0.1843
14	2	2	2	3	0.001153642	0.3059
15	2	2	3	1	0.002444251	0.1027
16	2	3	1	3	0.000928207	0.2553
17	2	3	2	1	0.001445989	0.059
18	2	3	3	2	0.001222457	0.2738

L_{18} OA ($2^1\times3^3$) was selected for this study. The layout of this L_{18} OA is shown in Table 2.

4.4 Analysis and Discussion of Experimental Results

In the Taguchi method, a loss function has been defined to gauge the deviation between the experimental value and desired value of a performance characteristic. The loss function is further transformed into a signal-to-noise ratio (S/N ratio). Three categories of performance characteristics are usually used in the analysis of the S/N ratio, i.e., the lower-the-better, the higher-the-better, and the nominal-the-best. In this article, the lower TW and the higher MRR are the indication of better performance. Experiments were replicated twice and randomized to minimize the bias from both between experiments and within experiment error. During the experiments, ultrasonic generator was switched on and the desired value is set in the controller before the machining is commenced. With the first machining spark, a stopwatch was activated and readings of the machine's *Z*-axis movement were recorded. TW was measured by electrical contact at a reference point on the workpiece before and after machining. Material Removal Rate (MRR) was obtained by calculating the volume of material removed per unit time. The actual depth of the machined part is not the same as the feed (*Z*-axis) due to the electrode wear. The actual depth is the difference between the designed depth (feed) and the change in the length of the electrode due to wear.

Analysis on MRR: The MRR is a 'higher the better' type of quality characteristic. So, the 'higher the better' type of response was used to calculate the S/N ratio and is given by (Ref 19-21)

$$L_{ij} = 1/n\sum_{i=1}^{n} 1/y_{ij}^2 \qquad \text{(Eq 1)}$$

where L_{ij} is the loss function of the *i*th performance characteristic in the jth experiment.

The corresponding S/N ratio is given by

$$\eta_{ij} = -10\log(L_{ij}) \qquad \text{(Eq 2)}$$

The S/N ratios were computed for MRR for each of the 18 trials given in Table 2. The greater η_{ij} value corresponds to a better performance. The values of S/N ratios of MRR for each parameter at levels 1, 2, and 3 are calculated from Table 2 and are given in Table 3. The analysis of S/N ratio reveals that the optimal performance for the MRR was obtained at capacitance 3300 PF (Level 2), 60% of peak power vibration (Level 3), 5 μ/s (Level 3) and 10 min (Level 1). To determine which factor significantly affected the performance characteristic, analysis of variance (ANOVA) was performed. The ANOVA result for S/N data of MRR is given in Table 4. The ANOVA table decomposes the variability of MRR into contributions due to various factors. Here the contribution of each factor is measured having removed the effects of all other factors. The *P*-values test the statistical significance of each of the factors. Since *P*-values of Factor A and B are less than 0.05, these factors have a statistically significant effect on MRR at the 95% confidence level. This could be attributed to the fact that higher discharge energy leads to higher MRR and better alternating pressure variation was generated in the dielectric with 60% of peak power vibration. During the narrow phase of the gap between electrode and the work piece, the ultrasonic vibration results in widened gap which leads to larger pressure drop resulting in higher removal rate because of less debris concentration on the gap.

Percent contribution (ρ%) indicates the relative power of a factor to reduce variation. For a factor with a higher percent contribution, a small variation will have a great influence on the performance. The percent contribution of the machining parameters on the MRR shown in Table 4, reveals that ultrasonic vibration and feed rate have the maximum and minimum influence on MRR.

4.5 Analysis on TW

The TW is a 'lower the better' type of quality characteristic. So, the 'lower the better' type of response was used to calculate the S/N ratio and is given by

$$L_{ij} = 1/n\sum_{i=1}^{n} y_{ij}^2 \qquad \text{(Eq 3)}$$

where L_{ij} is the loss function of the *i*th performance characteristic in the *j*th experiment.

The corresponding S/N ratio is given by Eq 2. The greater η_{ij} value corresponds to a better performance. The values of S/N ratios of TW for each parameter at levels 1, 2, and 3 are calculated from Table 2 and are given in Tables 5.

The analysis of S/N ratio reveals that optimal performance for the TW was obtained at 1000 PF (Level 1), No vibration (Level 1), 1 μ/s (Level 1) and 10 min (Level 1). The ANOVA result for S/N data of TW is given in Table 6. The ANOVA table decomposes the variability of TW into contributions due to various factors. Here the contribution of each factor is measured having removed the effects of all other factors. The *P*-values test the statistical significance of each of the factors. Since *P*-values of Factor D are less than 0.05, it has statistically significant effect on TW at the 95% confidence level. The percent contribution of the machining parameters on the TW shown in Table 6 reveals that machining time, feed rate influence the TW compared to others.

4.6 Estimation of Optimum Performance Characteristics

The optimum value of performance characteristics is predicted at the selected levels of significant parameters. The estimated mean of the response characteristic (MRR and TW) can be computed as follows:

$$\eta_{\text{predicted}} = T + \sum (\eta_i - T) \qquad \text{(Eq 4)}$$

where T is the overall mean of process parameter, η_i is the average value of significant factor.

The estimated mean of the response characteristic (MRR) can be computed as follows:

$$\eta_{\text{predicted}} = A_2 + B_3 - T \qquad \text{(Eq 5)}$$

where T is the overall mean of MRR, A_2 is the average value of MRR at second level of capacitance, and B3 is the average value of MRR at the third level of ultrasonic vibration. Similarly the estimated mean of the response characteristic for TW was calculated using the Eq 4 was found to be

$$\eta_{\text{predicted}} = D_1 \qquad \text{(Eq 6)}$$

Table 3 η for MRR

	Mean by factor level, db		
Machining parameter	**Level 1**	**Level 2**	**Level 3**
A	−61.32	−57.86	
B	−62.48	−58.29	−58.00
C	−61.29	−59.75	−57.72
D	−57.09	−61.16	−60.52

Table 5 η for TW

	Mean by factor level, db		
Machining parameter	**Level 1**	**Level 2**	**Level 3**
A	15.95	14.96	
B	16.28	15.08	15.01
C	17.69	14.93	13.74
D	21.70	11.77	9.37

Table 4 ANOVA for MRR

Source	Sum of Squares	DF	Mean Square	*F*-Ratio	*P*-Value	ρ%
Main effects						
A: Capacitance	53.69	1	53.6978	5.97	0.0347	17.03%
B: % of peak power vibration	75.54	2	37.719	4.2	0.0475	23.96%
C: Feed Rate	38.51	2	19.2548	2.14	0.1684	12.21%
D: Machining Time	57.47	2	28.7357	3.19	0.0846	18.23%
Residual	89.96	10	89.996			28.54%
Total (Corrected)	315.186	17				

Table 6 ANOVA for TW

Source	Sum of squares	DF	Mean square	*F*-Ratio	*P*-Value	ρ%
Main effects						
A: Capacitance	4.3294	1	4.3294	0.57	0.4666	0.85%
B: % of peak power vibration	6.0848	2	3.0424	0.4	0.4	1.19%
C: Feed Rate	49.3237	2	24.6619	3.26	0.0812	9.68%
D: Machining Time	374.437	2	187.219	24.77	0.0001	73.45%
Residual	75.5937	10	7.55937			14.83%
Total (Corrected)	509.769	17				

Table 7 Confirmation Experiment for MRR

	Optimal machining parameters	
	Predicted	**Experimented**
Level	A2B3C3D1	A2B3C3D1
MRR	0.001535	0.001168
S/N ratio	−56.27	−58.6505

Table 8 Confirmation Experiment for TW

	Optimal machining parameters	
	Predicted	**Experimented**
Level	A1B1C1D1	A1B1C1D1
TW	0.07702	0.0360
S/N ratio	21.70	28.87

where D_1 is the average value of TW at first level of machining time. The insignificant factors are not considered for estimation since it is less effective on S/N ratio.

Predicted optimal MRR and TW by substituting the values of terms in Eq 4 from Table 3 and 5 are −56.27 db and 21.70 db, respectively.

The 95% confidence interval of confirmation experiments (CI_{CE}) was computed by using the following equations:

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e) v_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \text{(Eq 7)}$$

where $F_{\alpha}(1, f_e)$ is the *F*-ratio at a confidence level of $(1-\alpha)$ against DOF one, f_e is error degree of freedom, v_e is error variance which is the ratio of the total variation of non-significant factors to the total degrees of freedom of its factors, R is the number of repetitions and n_{eff} is given by

$$n_{eff} = \frac{N}{1 + \left(\begin{array}{r}\text{Total DOF associated with the} \\ \text{estimate of mean response}\end{array}\right)} \quad \text{(Eq 8)}$$

From Eq 3 and 4 CI_{CE} is calculated for MRR and TW. The predicted optimal range for the confirmation run is

$$\text{Mean MRR/TW} - CI_{CE} < \text{MRR/TW} < \text{Mean MRR/TW} + CI_{CE}$$

The 95% confidence interval of the predicted MRR mean is $68.145 < \text{MRR} < -44.395$ db and predicted 95% confidence interval for TW is $13.74 < \text{TW} < 29.65$ db

4.7 Confirmation Experiments

The purpose of confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiments for MRR and TW were conducted at the optimum setting of the process parameters. The average MRR and TW value its S/N ratio are shown in Table 7 and 8. MRR and TW were found to be 0.001168 mm^3/min and 0.0360 mm, respectively, which fall within the 95% confidence interval of the predicted optimum parameters.

5. Conclusion

This article has presented an investigation on the optimization of machining parameters on the MRR and TW in ultrasonic assisted micro EDM. The significance of the parameters on MRR and TW is determined by using ANOVA. Based on ANOVA, ultrasonic vibration at 60% of the peak power with capacitance of 3300 PF was found to be significant for best MRR and machining time plays a significant role in the tool wear. With the increasing machining time (deep hole drilling) the tool wear increases. The results were confirmed experimentally at 95% confidence interval. The future scope of this research work is to attempt deep hole drilling (with aspect ratio over 20) with optimized process parameters. This is a formidable task for any micromachining process available today.

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