Taguchi method and Pareto ANOVA: An approach for process parameters optimization in micro-EDM drilling

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***Abstract*—** Technological advances have facilitated many developments in the MEMS, electrical, medical and aerospace industries in recent years. As the devices commonly found in these industries have become smaller, so the requirements for high-precision machining techniques have become ever more pressing. Nowadays, micro-machining processes are playing an important role in satisfying these requirements. Among the various stages of micromachining, the fabrications of holes and pins are the most basic ones. Micro-hole drilling, is becoming increasingly more prominent in various precision industries, such as the production of automotive fuel injection nozzles, watch and camera parts. Micro-drilling can generate deeper holes with better straightness, better roundness and smoother surfaces. In this work, an orthogonal array, signal to noise (S/N) ratio and Pareto analysis of variance (ANOVA) are employed to analyze the effect of the micro drilling parameters such as feed rate, capacitance and voltage. The Taguchi technique for the design of experiment and the interaction of micro-EDM drilling parameters are investigated. From the experimental result and analysis shows that low feed rate, capacitance and voltage such combination of optimized parameters gives low value of surface roughness. The experimental result shows that the most influential parameter on the surface roughness is capacitance. Also from the analysis shows that Taguchi technique is suitable to solve the above problem with minimum number of tests**.**

***Keywords*—**Micro-EDM drilling, Optimization, Pareto ANOVA Surface roughness, Taguchi method of DOE

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1. INTRODUCTION

THE demand for miniaturization of mechanical, optical and electronic parts are increasing rapidly. Recently complex shape parts of micrometer sizes are needed and the substrate materials for the small parts involve metals, ceramics, glass, plastics and so on. Micro-machining is the most basic technology for the production of such type of miniaturized parts and components. T.Masuzawa [1] summarizes the basic concepts of and applications of major methods of micro-machining. The basic characteristics of each group of methods are discussed based on the different machining phenomena. E. Kai and M. Katsumi [2] fabricate a three-dimensional and high aspect ratio of micro-shape. This is done by using micro drilling on mono-crystalline silicon using a small drilling tool. The smallest machinable hole achieved was of 6.7µm diameter. Furthermore, an aspect ratio is more than four was obtained in the drilling of a 22µm diameter and 90µm deep hole. Chris J.Morgan et al [3] provide an overview of several approaches to micro-machining by mechanical and electro-discharge means of material removal. Kuo-Yi Huang [4] proposed a novel and efficient method for sensing electrode parameters in EDM drilling process. As per his study, the proposed detection line algorithm (DLA) can detect the tool electrode length and drilling depth accurately and efficiently. The electrode wear in micro-electrical discharge milling is one of the main problems to be solved in order to improve machining accuracy. S.C. Man, et al [5] identifies the control for micro-drilling productivity enhancement. Therefore, a method for cutting force regulation was proposed to achieve continuous drilling. A proportional plus derivative (PD) and a sliding mode control algorithm are implemented and compared for controlling the spindle rotational frequency. Experimental results will show that sliding mode control reduces the nominal torque and cutting force and their variations better than PD control, resulting in a number of advantages, such as an increase in drill life, fast stabilization of the wandering motion, and precise positioning of the holes. Hyun-Ho-Kim et al [6] develop a cost effective direct monitoring system in micro drilling processes on glass, a machine vision unit with the edge detection and 3D measurement functions. U.Natarajan et al [7] conducted some experiments for the multiple response optimization in micro-end milling operation to achieve maximum metal removal rate (MRR) and minimum surface roughness (R_a). In this work, second order quadratic models were developed for MRR and surface roughness, considering the spindle speed, feed rate and depth of cut as the cutting parameters, using central composite design. The developed models were used for multiple-response optimization by desirability function approach to determine the optimum machining parameters. Azlan Abdul Rahman et al [8] investigate the effect of drilling parameter such as spindle speed, feed rate and drilling tool size on material removal rate (MRR), surface roughness, dimensional accuracy and burr. In this work, a study on optimum drilling parameter for HSS drilling tool in micro-drilling processes in order to find the best drilling parameter for brass as a workpiece material. Micro drilling experiment with 0.5 mm to 1.0 mm drill sizes were performed by changing the spindle speed and feed at three different levels. The results were analyzed using microscope and surface roughness device. H.Nakagawa et al, [9] has carried out surface roughness testing of a drilled hole wall. It was increases as drill temperature increases during drilling. Drill temperature tends to increase with the workload on the drill caused by the friction between the hole wall and the land or margin of the drill, regardless of drilling and material conditions. Therefore, a reduction in the workload caused by friction is effective for improving the quality of micro-drilled holes. K. F. Ehmann and H.C. Chyan [10] have developed a curved helical micro-drill point technology for micro-hole drilling. The drill point is the most important part of the drill which penetrates into the material of the workpiece during the machining process. The geometry of the drill tip is such that the normal rake and clearance angles and velocity of the cutting edge vary with the distance from the center of the drill. Even small variation in geometry or symmetry errors can have a very strong influence on the performance of the drill. The geometry of the point, uniquely defined by the shapes of the flute and flank surface, is the primary factor determining performance. T.Y.Tai et al [11] presents an investigation into the drilling of a deep microholes with the depth of 320 mm in tool steel SKD61 by the Micro-EDM process. The electrode with the diameter of 26 mm is machined by the method of wire electrodischarge grinding (WEDG). Optical microscopy, scanning electron microscopy, and confocal laser scanning microscopy techniques are used to determine the influence of the process parameters upon hole enlargement, electrode wear rate, material removal rate, wear ratio, and the observed surface topography. The results of the study reveal the optimum parameter settings for the Micro-EDM machining of a high aspect ratio microhole. S. T. Chen and Y. S. Liao [12] proposed a novel approach of effective production of mass micro holes. A set of micro w-EDM mechanism is designed and mounted on the developed tabletop precision machine tool. The tension of micro wire is precisely controlled by magnetic force. In addition, the micro vibrations of the wire during discharging are effectively suppressed by the developed vibration suppression system. In order to fabricate the mass micro holes, the microstructure array of the high aspect ratio 10×10 micro squared electrodes with the width and the height of 21µm and 700µm, respectively for each electrode, and the spacing between two electrodes of 24µm is fabricated first by the proposed “reverse w-EDM” machining strategy.

Micro-hole drilling, is becoming increasingly more prominent in various precision industries, such as the production of automotive fuel injection nozzles, watch and camera parts. Micro-drilling can generate deeper holes with better straightness, better roundness and smoother surfaces. In EDM, the machining of conductive materials is performed by a sequence of electrical discharges occurring in an electrically insulated gap between a tool electrode and a workpiece. During the discharge pulses a high temperature plasma channel is formed in the gap, causing evaporation and melting of the workpiece. Debris of material is removed by the resulting explosion pressure enabling the machining of workpiece. The characteristics of the electrical discharge pulses are linked with a set of machining parameters which control the energy and frequency of discharges and thus the power in the gap. Consequently the chosen set of parameters affect the surface roughness (Ra). However in micro EDM a number of issues remain to be solved. For instance, the processing time is significantly higher. The size of electrode used and the resulting high electrode wear makes conventional die sinking methods inadequate. This has led to the development of a number of new strategies for micro-machining. One common approach is the micro-drilling. Micro drilling has been widely used in various applications. The advantages are the electrical properties of the work piece do not influence the process. Therefore metal and plastics, including their composites, can be machined easily. One typical example is the drilling of holes in laminated printed circuit board. Machining time can be controlled easily because the process is stable when an appropriate feed rate per rotation is set.

This experimental work investigates the influence of the various combinations of process parameters such as feed rate, capacitance and voltage in micro-EDM drilling process, in an attempt to optimize the surface roughness when using the Taguchi technique and Pareto ANOVA method.

2. TAGUCHI DESIGN OF EXPERIMENTS

In Taguchi method, signal to-noise (S/N) is used to represent a response or quality characteristic and the largest S/N ratio is required. There are usually three types of quality characteristics, i.e. target-the-best, larger-the-better and smaller-the better.

1. Target-the-best S/N = 10 log $\frac{\bar{y}}{y}$
2. Larger-the-better S/N = -10 log $\frac{1}{n}\left(\sum \frac{1}{y^2}\right)$
3. Smaller-the-better S/N = -10 log $\frac{1}{n}\left(\sum y^2\right)$

where *S* is the standard deviation, *yi* is the measured data, y is the average of measured data, n is the number of samples. For each type of the characteristics, with the above S/N ratio transformation, the higher the S/N ratio the better is the result.

3. EXPERIMENTAL PROCEDURE

In this experiment with three factors at three levels each, the fractional factorial design used is a standard L_{27} (3^{13}) orthogonal array. This orthogonal array is chosen due to its capability to check the interactions among the factors. Each row of the matrix represents one trial. However, the sequence in which these trials are carried out is randomized. The three levels of each factor are represented by a ‘0’ or a ‘1’ or a ‘2’ in the matrix. The factors and levels are assigned as in Table

1. Factors *A*, *B*, and *C* are arranged in columns 2, 5 and 6, respectively, in the standard L_{27} (3^{13}) orthogonal array.

Table: 1.

INPUT MACHINING PARAMETER

Factors	Levels		
	Low (-)	Medium (0)	High (+)
A:Feed rate(µm/sec)	2	4	6
B:Capacitance (nF)	0.10	1.00	10.00
C:Voltage(V)	80	100	120

TABLE 2

EXPERIMENTAL DESIGN, MEASURED RESPONSES AND THEIR CORRESPONDING S/N RATIO

Exp .No	Factor			Design ation	Measured responses and their corresponding S/N ratio	
	A	B	C		Ra (µm)	S/N ratio for Ra(db)
1	0	0	0	$A_0B_0C_0$	0.36	0.8874
2	0	1	1	$A_0B_1C_1$	1.90	-0.5575
3	0	2	2	$A_0B_2C_2$	5.2	-1.432
4	1	0	0	$A_1B_0C_0$	0.38	0.8404
5	1	1	1	$A_1B_1C_1$	1.82	-0.5201
6	1	2	2	A1B2C2	5.9	-1.5417
7	2	0	0	$A_2B_0C_0$	0.38	0.8404
8	2	1	1	$A_2B_1C_1$	1.88	-0.5483
9	2	2	2	$A_2B_2C_2$	4.8	-1.3625
10	0	0	1	$A_0B_0C_1$	0.41	0.7744
11	0	1	2	$A_0B_1C_2$	1.9	-0.5575
12	0	2	0	$A_0B_2C_0$	3.8	-1.1596
13	1	0	1	$A_1B_0C_1$	0.45	0.6936
14	1	1	2	$A_1B_1C_2$	1.82	-0.5201
15	1	2	0	$A_1B_2C_0$	3.7	-1.1364
16	2	0	1	$A_2B_0C_1$	0.52	0.568
17	2	1	2	$A_2B_1C_2$	1.82	-0.5201
18	2	2	0	$A_2B_2C_0$	3.7	-1.1364
19	0	0	2	$A_0B_0C_2$	0.42	0.7535
20	0	1	0	$A_0B_1C_0$	1.1	-0.0828

21	0	2	1	$A_0B_2C_1$	4.2	-1.2465
22	1	0	2	$A_1B_0C_2$	0.45	0.6936
23	1	1	0	$A_1B_1C_0$	1.2	-0.1584
24	1	2	1	$A_1B_2C_1$	4.8	-1.3624
25	2	0	2	A2B0C2	0.54	0.5352
26	2	1	0	$A_2B_1C_0$	1.2	-0.1584
27	2	2	1	$A_2B_2C_1$	4.4	-1.2869

This experiment was conducted in a multipurpose micro machine tool (DT 110, MIKROTOOLS). The feed rate (A), capacitance (B) and voltage (V) are considered as input machining parameters and Ra is taken as output response. The experimental machining parameter levels are shown in Table:1. The levels of parameters that affect the performance of the micro-EDM drilling process are identified based on survey of literature and preliminary experimentation performed by authors by considering more number of variables. Through the above observation the levels of parameters, which vigorously affect the surface roughness was selected. Surface roughness is a key factor in the machining process while considering machining performance and that is why in many cases, industries are looking for machining the good surface quality of the machined parts. Surface roughness is a measure of the technological quality of a product and a factor that greatly influences manufacturing cost and quality. It describes the geometry of the machined surface and combined with the surface texture, it can play an important role on the operational characteristics of the part. Because of these, Ra is taken as output responses. In this research work, the tool electrode material, tungsten (W) was chosen because of its low wear rate. The electrode diameter was 300µm. Stainless steel shim was selected as work piece material. Also the selected spindle speed=2000rpm, Dielectric fluid = synthetic oil**,** threshold value= 30.The experimental results of the response Ra are as shown in Table: 2.

4. EXPERIMENTAL RESULT AND ANALYSIS

Usually performance of various types of cutting operator is judged by different measures. In case of rough cutting operation, the metal removal rate and surface roughness are the primary importance whereas in finishing operation the surface roughness is primary importance. In order to assess the effect of each machining parameter on the micro-EDM drilling process, the Taguchi technique was used. This technique is type of statistical technique called Design of Experiments (DOE) that makes it possible to analyses the effect of more than one factor at the same time while reducing the number of experiments. Thus using the Taguchi approach, the design of experiments and analysis of results can be done with less effort and expenses. Hence this technique considerably reduces the number of experiments. One important step in the Taguchi technique is the identification of the control factors and of their values considered for investigation. These factor levels should be placed very carefully, since the Taguchi technique defines the significant and optimal parameters only within the selected range. The main objective of this experimental work is to optimize the micro-EDM drilling parameters to achieve the low value of surface roughness, the smaller the better characteristics is used. The table 2 shows the actual value for surface roughness along with their computed S/N ratio. The table 3 shows the response table for average S/N ratio for surface roughness factors and significant interaction. The graphical representations of these data are as shown in figure 2. Taguchi recommends analyzing the mean and S/N ratio using conceptual approach that involves graphing the effects and visually identifying the factors that appear to be significant, without using ANOVA, because of these the analysis is simple. From the graphical representation of the factors and their interaction results shows that the capacitance and interaction between feed rate and voltage are more significant. Also from the graphs, we conclude that the feed rate and voltage is insignificant. The low value of surface finish was obtained when the capacitance is low. The feed rate and voltage are insignificant on the average S/N response. But the interaction AXC is significant, the two ways table AXC is used [13]-[15] to select their levels as calculated and the values are as shown in Table 5. Based on the results of two way table AXC, it is concluded that the optimum combination of factor A and factor C gives good result. The optimum combination of that factor is B_0C_0. Therefore the optimal combination to get the low value of surface roughness is $A_0B_0C_0$ within the tested range of experiment.

TABLE 3

RESPONSE TABLE FOR AVERAGE S/N RATIO FOR AVERAGE SURFACE ROUGHNESS AND SIGNIFICANT INTERACTION.

Symbol	Cutting parameters	Mean S/N ratio			
		Level 0	Level 1	Level 2	Max.-Min.
A	Feed rate	-0.2912	-0.3346	-0.341	0.04498
B	Capacitance	0.7318	-0.4026	-1.296	2.0278
C	Voltage	-0.1404	-0.3873	-0.4391	0.2987
AXC	Interaction AXC	-0.2855	-0.3661	-0.3153	0.0806

TABLE 4

THE CALCULATED AC TWO WAY TABLE FOR Ra

Factor	A_0	A_1	A_2	Total
C_0	0.8874-1.1596-0.0828=-0.355	0.8404-1.1364-0.1584=-0.4544	0.8404-1.1364-0.1584=-0.4544	-1.2638
C1	-0.5575-0.7744-1.2465=-1.0296	-0.5201+0.6936-1.3624=-1.1889	-0.5483-0.5201+0.5352=-1.2672	-3.4857
C_2	-1.432-0.5575+0.7535=-0.7343	-1.5417-0.5201+0.6936=-1.3682	-1.3625-0.5201+0.5352=-1.3474	-3.4499
Total	-2.1189	-3.0115	-3.069	-8.1994

TABLE 5.

PARETO ANOVA ANALYSIS FOR Ra

	Factor and interaction								
Sum at factor level	**B XA C**		**B**	**C**	**B XA C**	**XA X CA B**	**XA X C**	**B**	
0	-3.3939	-2.6206	6.5856	-1.2638	-2.9253	-2.852	-2.9904	-2.5691	-2.8913
1	-2.9941	-3.0115	-3.6232	-3.4857	-3.076	-2.756	-2.8314	-3.2947	-2.8522

2	-2.3131	-3.069	-11.6644	-3.9516	-2.6998	-3.0911	-2.8793	-2.8373	-2.9576
Sum of squares of difference (S)	1.7917	0.3572	501.994	12.3782	0.2151	0.1787	0.04	0.0808	0.017
Contribution ratio (%)	0.34 %	0.07 %	96.95%	2.39%	0.04 %	0.03 %	0.007 %	0.16 %	0.003 %

Check on Significant interaction: AC two way table (Table: 5)

Optimum combination of significant factor level: $A_0B_0C_0$

Pareto ANOVA is one of the techniques to analyze the data for the optimization. It is a simplified ANOVA method which uses Pareto principles. It is a quick and easy method to analyze the results of parameter design. The Pareto ANOVA technique of analysis has been performed, which requires least knowledge about ANOVA method and suitable for engineers. The table 6 shows the Pareto ANOVA analysis for Ra. From the Pareto ANOVA method, the results of shows that the capacitance (factorB) and interaction AXC have strong influence on the surface roughness. Based on the result it is concluded that, good surface finish was obtained at low value of capacitance, feed rate and voltage. That is the optimal combination to get the low value of surface roughness is $A_0B_0C_0$ within the tested range of experiment.

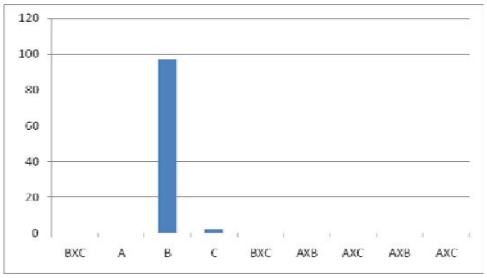
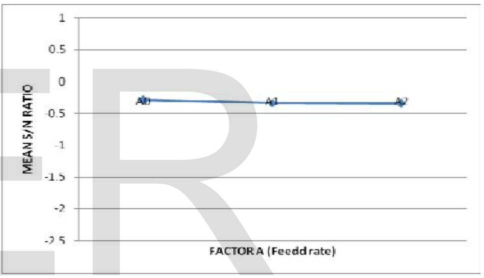
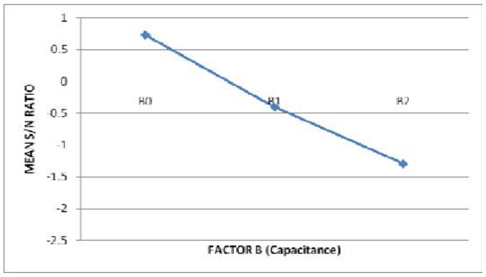


Fig1: Pareto Diagram



(a)



(b)

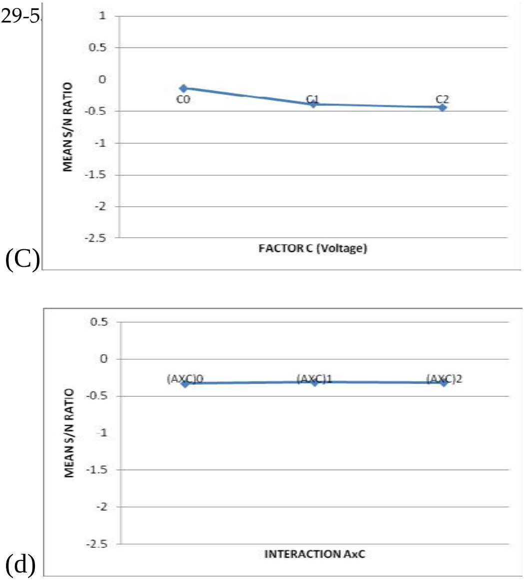


Fig.2. The Smaller the better S/N graph(a-d) for surface roughness

TABLE: 6
CONFIRMATION EXPERIMENT

Optimized parameter for the micro-EDM drilling process	Using Taguchi technique	Using Pareto ANOVA	Measured value of Response
1.Feed rate µm/sec (Factor A)	A_0= 2	A_0= 2	Surface roughness=0.36 µm
2.Capacitance in nF(Factor B)	B_0= 0.10	B_0= 0.10	
3.Volatge in V (Factor C)	C_0= 80	C_0= 80	

5. CONCLUSIONS

In this study, the effects of the process parameters on the surface roughness in the micro-WEDG were investigated. Taguchi's robust design of experiment technique is suitable to analyze the micro-EDM drilling problems. From this experimental work shows the optimal parameters for micro-EDM drilling process using Taguchi approach and Pareto ANOVA for data analysis draw same conclusion. From the statistical analysis, it was concluded that capacitance is more significant factor for surface roughness. Based on the Taguchi analysis and Pareto ANOVA analysis shows that surface roughness increase with increase of capacitance. At the same time the result shows that the feed rate and voltage are less contribution on surface roughness. It is concluded that use of low feed rate, capacitance and voltage are recommended to obtain the good surface finish in micro-EDM drilling process. The optimum micro-EDM drilling process parameters for good surface finish are determines as feed rate =2µm/sec, capacitance = 0.1nF and Voltage = 80 V within the tested range of experiment. The optimized machining parameters were used for the confirmation of experiments (Table 6) for validation; the measured value for the surface roughness is 0.36 µm.

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