An Experimental Investigation on Surface Roughness and Edge Chipping in Micro Ultrasonic Machining

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Abstract
Surface quality including surface roughness and edge chipping is a key process measure in micro ultrasonic machining (Micro-USM) as an efficient process for micromachining of hard and brittle materials. Process parameters such as ultrasonic vibration amplitude, static load, type of tool material, type and size of abrasive particles and slurry concentration can influence the surface quality. However, there is limited study on the parametric effects on the surface quality in micro-USM. The objective of this study is to investigate the effects of the workpiece material as well as process parameters including abrasive type, particle size and vibration amplitude on surface roughness and edge chipping in micro-USM. Silicon, alumina ceramics and soda-lime glass were selected as workpiece materials and polycrystalline diamond and alumina as abrasives. Particle size ranging from 0.3 to 3 µm and vibration amplitude ranging from 0.8 to 3 µm were selected in this study. Results indicate that workpiece material and vibration amplitude have significant effects on surface roughness. Workpiece material was found to be the most significant parameter with a percentage contribution of about 45 % in the variation of mean R_a, followed by vibration amplitude and particle size of about 28 % and 5% contributions, respectively. Results also show that alumina ceramic is a material capable of achieving better surface quality in micro-USM as compared to silicon and soda-lime glass.

Keywords
Micro Ultrasonic Machining, Surface Quality, Edge Chipping, Process Parameters, Experimental Design

1. Introduction

Ultrasonic machining (USM) is a non-chemical and non-electrical process and therefore it does not alter the properties of machined workpieces [1-3]. Thus, it is particularly suitable for micro-scale machining of delicate parts made from hard and brittle materials of which elimination of thermal distortion or stresses is essential. As such, Micro ultrasonic machining (micro-USM) is considered as a cost effective material removal process to create micro features and miniaturized products of preferably hard and brittle work materials such as silicon, glass, quartz, and ceramics [3-5]. Micro-USM meets two important requirements with regards to minimizing error generation factors, namely, minimum mechanical tool deformation and thermal workpiece distortion [6]. In this process, material is removed by fine and free abrasive particles in the machining gap; hence, there is no thermal damage and significant level of stresses on the workpiece [1].

However, micro-USM process generally produces a rather poor surface quality which is among the crucial error generation factors in tool-based micromachining, the effect of which should be minimized [6]. Low surface quality in micro-USM is caused by material removal mechanisms involved in the process including crack initiation, propagation, and chip breakage [7]. These mechanisms, are influenced by various process parameters and machining conditions. Therefore, study the effect of process parameters on surface quality in micro-USM seems necessary in order to introduce this process as a viable micromachining technique [2, 7].

Surface characteristics in micro-USM have been investigated by researchers. Yu et al. [8] studied the effect of particle size on surface roughness and reported R_a values in the range of 220-320 nm in silicon material. Zhang et al. [9] investigated the effect of vibration amplitude, type and size of the abrasive particles on the surface roughness using a micro-USM system equipped with acoustic emission monitoring system for tool contact sensing. Also, the influence of workpiece material on the characteristics of the machined surface was investigated by Hu et al. [10]. In another study, the correlation between surface/edge quality and process parameters were investigated in micro-USM with workpiece vibration method and R_a values as small as 24 nm were reported on mono crystalline silicon [11]. In the majority of the reported literature, the effect of the process parameters on surface quality has been studied using “one-factor-at-a-time” method in which the value of the input parameter (factor) under study is varied while the rest of the process parameters are kept constant [12-14].Revealing the trends of the response (R_a) with this method is somehow resources and time consuming [12]. In contrast, design-of-experiment (DOE) methods provide a systematic and efficient experimental plan to examine and optimize the response while considering the interactive effects among the process parameters [15, 16]. In particular, the Taguchi method is one of the most powerful DOE methods [15, 17].

In this study, the effect of various process parameters on surface roughness is investigated using Taguchi method. The advantages of this method are that more factors can be optimized simultaneously and significant information can be obtained by minimal experimental runs. The analysis of signal-to-noise (S/N) ratio and analysis of variance (ANOVA) are performed to determine the significance and contribution of various process parameters with regards to surface roughness. Also, the effect of workpiece materials on edge chipping at entrance and exit of the through micro holes were studied as a quality measure in micro-USM process.

2. Experimental Design and Methodology

2.1 Process Parameters

A cause-and-effect diagram (Figure 1) is applied to identify the process parameters of the micro-USM that may affect the surface roughness of the machined workpieces. Among the process parameters presented in Figure 1, four parameters including abrasive type, workpiece material, particle size, and vibration amplitude were selected for this study. The parameters levels were decided based on the existing literature, the results of preliminary experiments and workable range of the parameters in the micro-USM system. The selected controllable parameters and their respective levels are as listed in Table 1. In order to determine the non-linear behavior of the parameters of a process, more than two levels must be used. Therefore, it is decided that one of the four selected parameters are studied at four levels and another two are studied at three levels.

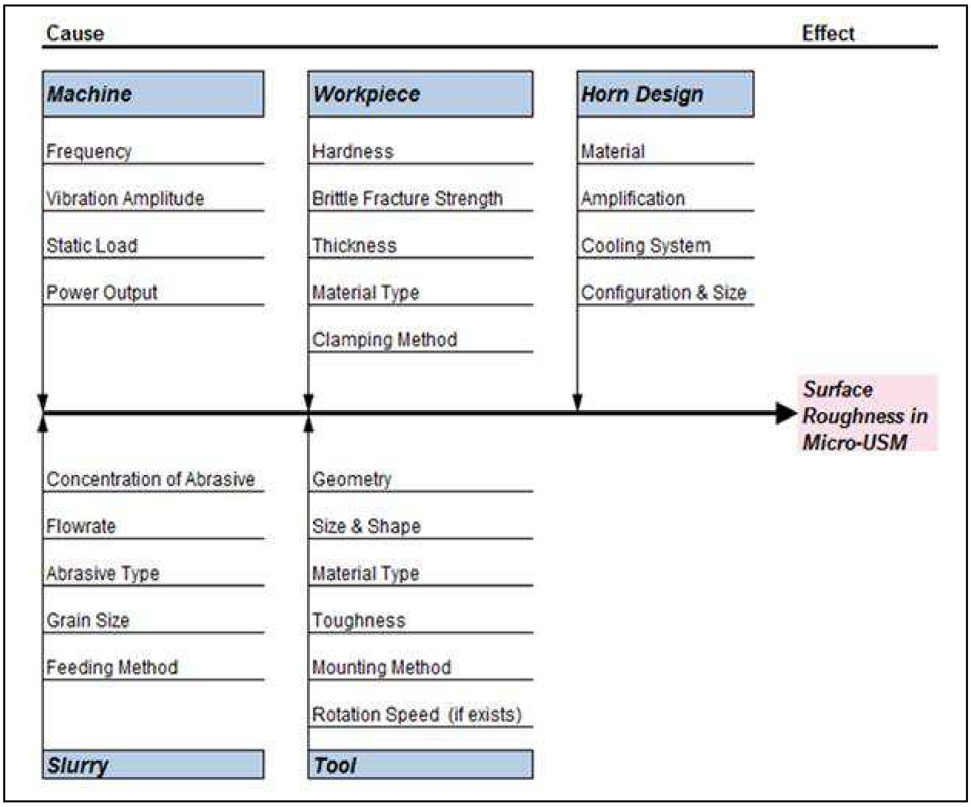

Figure1. Cause-and-effect diagram for surface roughness in micro-USM

Table1. Control parameters and their levels

Parameter symbol	Process parameter	Level 1	Level 2	Level 3	Level 4
A	Abrasive type	Alumina	PCD	*	*
B	Workpiece material	Alumina	Silicon	SL glass	*
C	Particle size	3 µm	1 µm	0.3 µm	*
D	Vibration amplitude	0.8 µm	2 µm	3 µm	1.4 µm

2.2 Methods

To conduct the DOE and analysis, first an appropriate orthogonal array (OA) is selected and the process parameters are assigned to the OA. Then, the experiments are conducted according to OA runs and each experimental run is repeated three times. Subsequently, the raw data and signal-to-noise (S/N) ratio analyses are performed and plots of the main effects are presented to investigate the effects of the selected process parameters on surface roughness. Finally, the analysis of variance (ANOVA) is conducted to determine the percent contribution of each parameter at a specified confidence level.

2.3 Formation of the Orthogonal Array

The OA derived for the experimentation is a modified L_{18} OA with 18 trial runs. The corresponding OA with assigned parameter levels is given in Table 2.

Table2. Modified L18 array with assigned parameter levels

Exp. No.	Process Parameters			
	Abrasive type (A)	Workpiece material (B)	Particle size (μm) (C)	Vibration amplitude (μm)(D)
1	Alumina	Alumina	3m	0.8
2	PCD	Alumina	1	0.8
3	Alumina	Silicon	0.3	0.8
4	Alumina	SL lass	0.3	0.8
5	PCD	SL lass	0.3	2
6	PCD	Alumina	3	2
7	Alumina	Alumina	1	2
8	PCD	Silicon	0.3	2
9	PCD	SL lass	3	3
10	Alumina	SL lass	1	3
11	PCD	Alumina	0.3	3
12	PCD	Silicon	3	3
13	Alumina	Silicon	1	3
14	Alumina	Alumina	0.3	1.4
15	Alumina	Silicon	3	1.4
16	PCD	Silicon	1	1.4
17	Alumina	SL glass	3	1.4
18	PCD	SL glass	1	1.4

3. Experimental Procedure and Data Collection

3.1 Materials and Tools Preparation

Different types of workpiece materials, listed in Table 1, were cut into squares with size of 9.5mm by dicing of the wafers. Rods made of pure tungsten with diameter and length of 300 μm and 80 mm, respectively were used as micro tools. The tool tip was ground and then inspected before machining process by using a v-shape fixture equipped with objective lenses. This helps to maintain a uniform gap between micro tool face and workpiece surface and hence providing more stable machining conditions at the beginning of the process.

Abrasive particles mixed in deionized water were used as slurry medium. The slurry concentrations were 0.04 wt% and 0.5 % wt in study of surface roughness and edge chipping, respectively.The slurry was agitated using an ultrasonic bath for about 15 min in order to completely wet the particles before use. Then, the slurry container was placed on the magnetic stirrer before feeding the slurry to the micro-USM system.

3.2 Micro-USM System and Machining Experiments

Figure 2 shows the schematic diagram of employed micro-USM system. The ultrasonic vibration with frequency of 50 kHz is generated through a power generator and ultrasonic transducer. Then, the mechanical vibration is transmitted to the workpiece through booster and horn. The workpiece is held on the face of ultrasonic horn using a vacuum clamping system which consists of vacuum pump, liquid separator and flexible tubes.A force sensor is mounted on the tooling system and connected to the computer to measure the machining force i.e. the contact load between micro-tool and abrasive slurry. The machining force is maintained within a specified range by controlling the infeed motion of the micro-tool via computer interface.

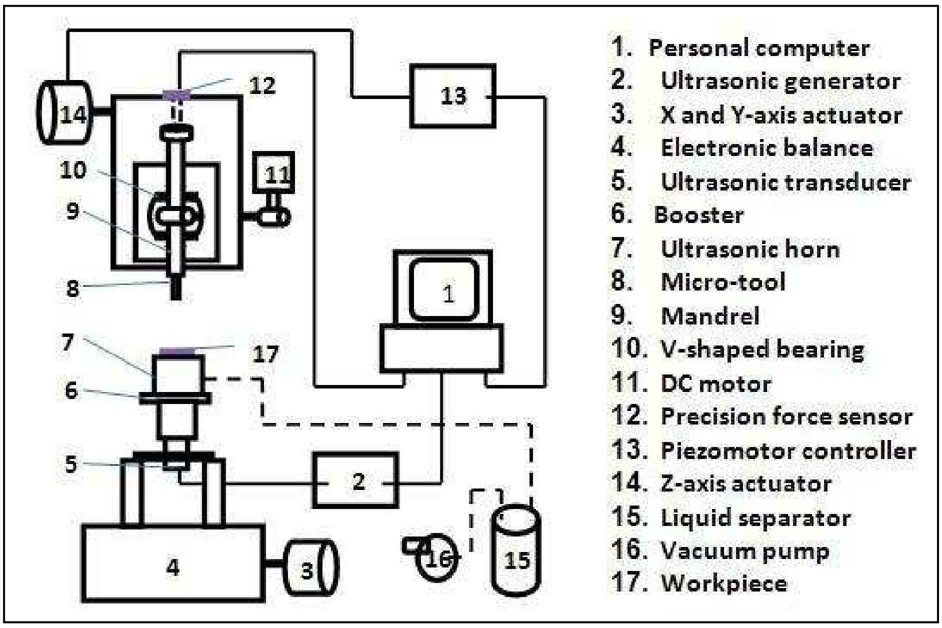

Figure2. Schematic diagram of in-house developed micro-USM system

Machining experiments were conducted using the developed micro-USM system. The amplitude of vibration is adjusted by setting the output voltage of the ultrasonic generator. Fresh abrasive slurry is delivered continuously into the machining zone throughout the process. The 18 experimental runs were conducted on trial conditions given in Table 2. Each experimental runs was replicated three times resulting in a total of 54 machining experiments.

3.3 Data Measurements

The mean surface roughness (R_a) of the micro holes bottom was measured using Nikon Eclipse L150 con focal image profiler. The R_a value for each micro hole is obtained by averaging the values of five different spots on the surface. The R_a values for each experimental run are given in Table 3.

Table3. Experimental results for surface roughness (Ra)

Exp. no.	Surface Roughness, R_a (nm)			
	R1	R2	R3	S/N*
1	354.2	341.0	274.6	-50.24
2	386.0	334.0	406.0	-51.52
3	523.2	478.0	475.0	-53.85
4	449.8	437.6	514.0	-53.41
5	652.6	585.8	541.0	-55.49
6	375.4	385.6	350.6	-51.38
7	195.6	184.8	256.2	-46.63
8	235.4	373.2	314.8	-49.91
9	961.8	971.8	1013.2	-59.85
10	906.6	815.8	851.0	-58.68
11	285.2	260.8	306.2	-49.09
12	300.4	292.6	377.2	-50.25
13	581.4	476.4	473.6	-54.20
14	196.6	183.8	219.6	-46.04
15	234.2	225.0	286.2	-47.96
16	245.0	200.6	230.2	-47.08
17	753.0	657.2	711.8	-57.01
18	197.6	302.8	195.0	-47.50

4. Analysis of Data

4.1 Evaluation of S/N Ratios

Taguchi method uses the signal-to-noise (S/N) ratio as a measure to determine the robustness of a process. Therefore, it can be applied as a measure of the amount of variation present in the parameter under study which is R_a in this paper. The 'smaller-the-better' type S/N which is used for the analysis as desirable objective is lower values of R_a. The signal-to-noise ratio can be computed as:

$$S/N = -10 \log \left[\frac{1}{R}\sum_{i=1}^{R} y_i^2\right] \quad (1)$$

Where R is the number of repetitions in a trial and y_i is the value of the i^{th} data point. The S/N ratios were calculated for the 18 trial conditions and corresponding values are given in Table 3.

4.2 Assessment of Main Effects

The main effects of the process parameter on surface roughness can be studied by averaging the R_a values of raw data or that of S/N data at each parameter level in different experimental runs. This average value is also named as 'mean R_a'. The plots of mean values based on the S/N ratio data help in optimizing the respective parameter. The pick points of these plots correspond to the optimum condition. The main effects of raw data and those of the S/N ratio are shown in Figure 3 and 4 respectively.

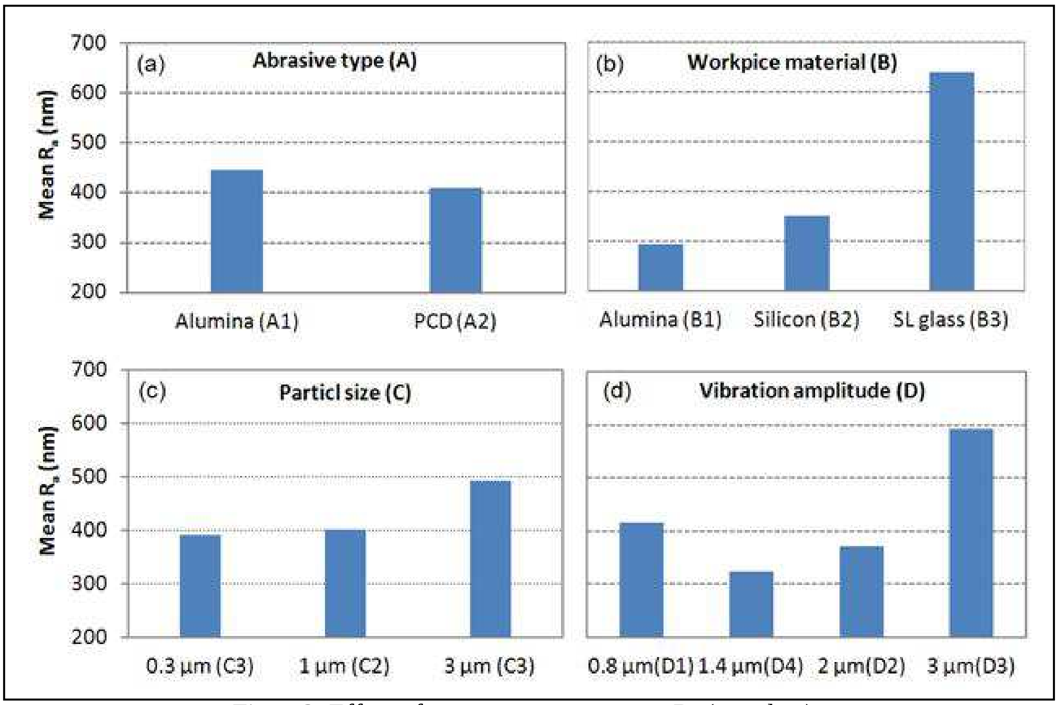

Figure3. Effect of process parameters on R_a (raw data)

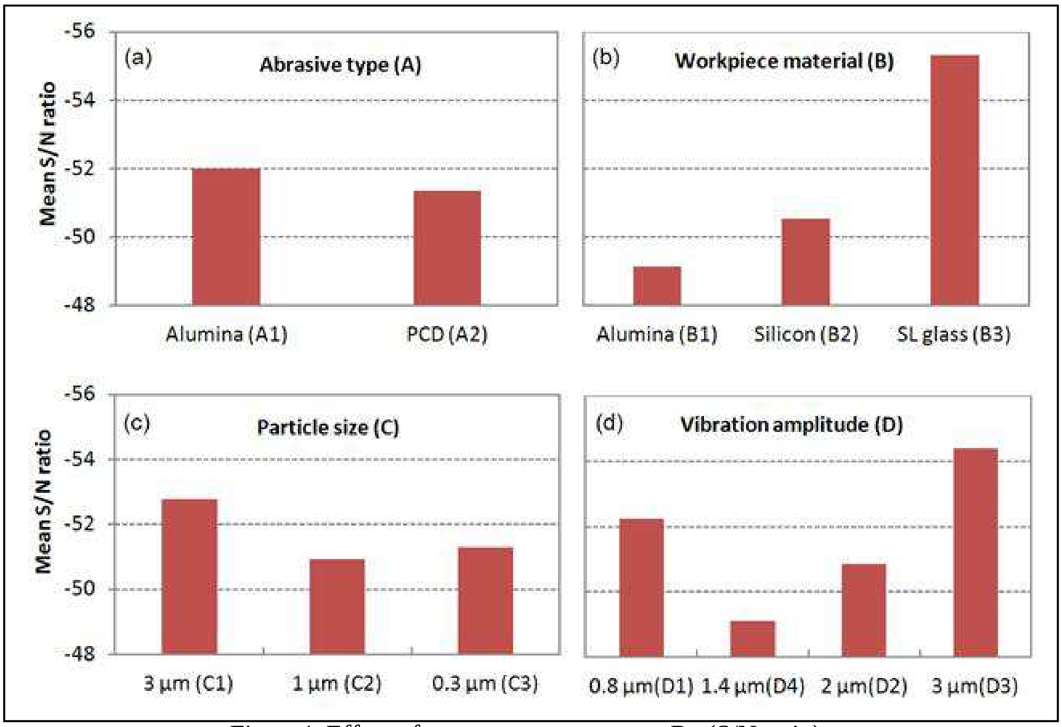

Figure4. Effect of process parameters on Ra (S/N ratio)

4.3 Analysis of Variance

The percentage contribution of different process parameters on the surface roughness can be estimated by performing the analysis of variance (ANOVA). Therefore, the ANOVA for raw data and S/N data can be used to determine significance of each parameter and to quantify its effect on surface roughness. ANOVA for raw data identifies the parameters that considerably affect the mean R_a rather than reducing the variation in the response. In contrast, ANOVA for S/N data considers both of these aspects and thus it is performed in this study. The results of ANOVA for R_a based on S/N data are presented in Table 4. Also, the percentage contribution (P) of the process parameters to surface roughness for S/N data are given in Table 4 and plotted in Figure 5.

Table4. ANOVA results for R_a (S/N data)

Source	DOF	SS	F-value	P (%)
Abrasive type (A)	1	4.567	0.56	1.54
Workpiece material (B)	2	132.419	8.05	44.65
Particle size (C)	2	13.889	0.84	4.68
Vibration amplitude (D)	3	83.260	3.37	28.07
Error	9	74.049		24.97
Total	17	296.583		100.00

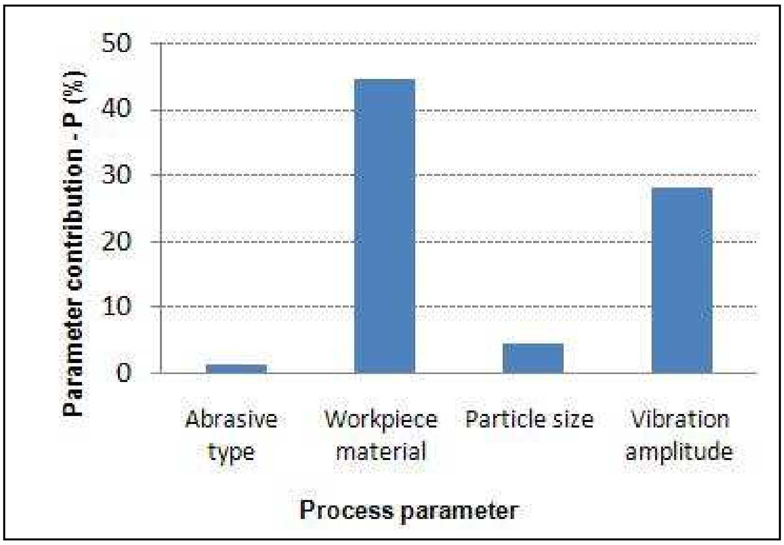

Figure5. Percentage contribution of various parameters to surface roughness

5. Results and Discussions on Surface Roughness

It is clear from Figure 3(a) that applying PCD abrasive particles leads to a slightly lower surface roughness as compared to that of alumina particles. The abrasive material should be harder than the workpiece to give optimum material removal condition [18, 19]. In this case, PCD being a harder abrasive is able to indent the workpiece easier and gives a cleaner cut of workpiece during the material removal process. This could lead to a lower surface roughness in case of using PCD particles.

It can be seen from Figure 3(b) and 4 (b) that workpiece material has a significant effect on surface roughness. Also, different workpiece materials can be ranked with regards to increase of mean R_a as aluminum, silicon and soda-lime glass. Generally, workpiece materials with brittle removal behavior exhibit higher material removal rates which are generally associated with higher surface roughness of the machined part [20]. From Table 5, alumina is the least brittle material followed by soda-lime glass and silicon. However, silicon exhibits a better surface roughness despite being more brittle than soda-lime glass. This could be ascribed to the difference in the structure of silicon and soda-lime glass. The mechanism of the crack formation could be different in brittle materials depending on their type and structure. For instance, in silicon which is a mono crystalline material, fracture failure usually occurs along certain crystalline directions. In contract, in the case of soda-lime glass which is an amorphous (non-crystalline) material, the plastic deformation and fracture take place along slip lines of the glass. Hence, it leads to a higher surface roughness as the fracture mechanism which is in non-uniform directions. This could be the cause of the higher R_a value in soda-lime glass as compared to that of silicon as seen in Figure 3.

Table5. Properties of Workpiece Material

Material	Hardness *H* *(GPa)*	Fracture Toughness K_{IC} $(MPa.m^{1/2})$	Index of Brittleness (H/K_{IC})	Structure
Alumina	14.1	4.0	3.5	Polycrystalline
Silicon	12.6	0.74	17.0	Monocrystalline
SL glass	5.7	0.74	7.7	Amorphous

As shown in Figure 3(c), the value of mean R_a increases with rise in the particle size. Using particles with larger size leads to increased indentation depth [21, 22]. As a result, the volume of the material removed per particle indentation increases, resulting in craters with larger size and thus higher surface roughness [20]. However, based on the trend observed in Figure 3(C), the effect of the particle size on mean R_a can be considered insignificant especially in lower range of the particle size. In this case, the increase of the particle size from 0.3 µm to 1 µm leads to an increase of R_a value only by 2.8 %.This might be attributed to low kinetic energy of the smaller particles and hence, their inability to generate larger fracture zones which could increase the surface roughness.

As depicted in Figure 4(D), surface roughness decreases with a decrease in vibration amplitude from 3 µm to 1.4 µm up to an optimum point. Further decrease of vibration amplitude to 0.8 µm leads to rise in mean R_a. By reducing the vibration amplitude, the velocity of the impacting particle and consequently the kinetic energy of the particles decrease. Therefore, the penetration depth and thus the resulted crater size become smaller resulting in a lower surface roughness.

The plots of mean values based on the S/N ratio analysis (Figure 4) suggests for minimum average surface roughness, the optimum process parameters are alumina (B_1) for workpiece material and 1.4 µm (D_4) for vibration amplitude. In addition, abrasive type and particle size are insignificant as process parameters with respect to the effect on variation in the surface roughness.

To study the relative significance of the individual parameters, ANOVA was performed on the S/N data. The respective results (Table 4) indicate that workpiece material and vibration amplitude have a significant effect on surface roughness. Workpiece material (B) was found to be the most significant parameter with a percentage contribution of 44.65 % in the variation of mean R_a, followed by vibration amplitude (C) with 28.07 % contribution. Moreover, the abrasive type (A) has the least contribution (1.54 %) in the variation of surface roughness.

6. Edge Chipping in Micro-USM of Different Materials

In second part of this study, the effect of workpiece materials on edge chipping was investigated. Unlike surface roughness study, the workpiece material is the only variable parameter. The remaining constant parameters are abrasive type (PCD), particle size (1 µm), and vibration amplitude (1.4 µm). The workpiece materials used are alumina, silicon and soda-lime glass. The slurry concentration is maintained at 0.5% wt.

Through micro holes were machined on different materials and OMIS II machine was used to observe the edge of the machined micro holes for chipping both at the entrance and exit sides. As shown in Figure 6, it is obvious that edge chipping is the least in alumina and the most in silicon. It can be explained based on the brittleness of the material (Table 5). Alumina is the least brittle material, thus having the least edge chipping effect. Silicon which has the highest index of brittleness was found to have most edge chipping at the micro hole machined onto it.

It was also observed that there was very minimal edge chipping in the machined workpiece during the experiments for surface roughness test. This could be due to the lower slurry concentration used in the surface roughness study (0.04%) as compared to that in edge chipping (0.5%).

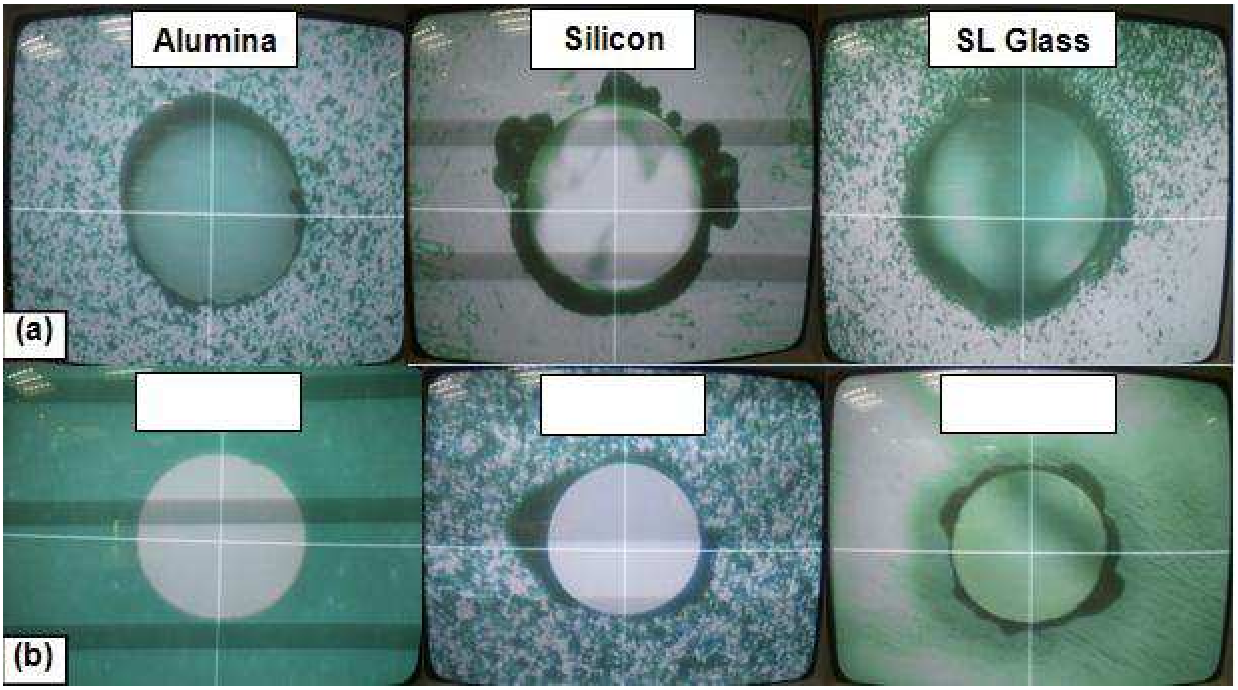

Figure6. Edge chipping in the machined micro hole: (a) entrance, (b) exit

7. Conclusions

In this study, the influence of micro-USM process parameters on surface roughness was investigated and parameters with significant effect on surface roughness were determined using Taguchi method of experimental design. Also, the effect of workpiece materials on edge chipping in micro-USM was studied. The following conclusions could be made from this study:

1- The type of workpiece material was identified as the most significant factor for surface roughness with contribution of 44.65 %, followed by vibration amplitude with 28.07 % contribution in the variation of mean R_a. Furthermore, abrasive type and particle size appeared to have insignificant effect on mean R_a.

2- To achieve minimum surface roughness, the optimum process parameters are identified as alumina for workpiece material and 1.4 µm for vibration amplitude.

3- The effect of workpiece material on edge chipping in micro-USM process was investigated by machining through micro holes on different types of material. It was observed that edge chipping increases as brittleness of the material increases. Also, edge chipping increases at higher slurry concentrations.

8. References

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