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Application of Taguchi Approach in the Optimization of Cutting Parameters in Micro-Ultrasonic Drilling Process

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ABSTRACT
In the present research work, effect of several process parameters on the machining characteristics of borosilicate glass has been reported. The machining characteristics that are being investigated are material removal rate (MRR) and tool wear rate (TWR). Four different process parameters were considered for this study - power rating of the machine, static load, slurry concentration and abrasive grit size. The optimal settings of parameters were determined through experiments using Taguchi method. The significant parameters were identified and their effects on MRR and TWR were studied. The analysis reveals that, in general, the MRR is most influenced by the static load while abrasive size mainly affects the TWR.
Keywords: micro ultrasonic drilling, glass, material removal rate, tool wear rate, optimization

I. INTRODUCTION

Glass, as a substance, plays an important role in modern civilization. High hardness and near inertness of this materials makes it extremely useful in numerous scientific and industrial applications. Its chemical, physical, and in particular optical properties make it suitable for applications such as flat glass, container glass, optics and optoelectronics material, laboratory equipment, thermal insulator (glass wool), reinforcement materials and glass art. Although vast majority of microdevices are made of silicon but for many applications silicon is not an appropriate base material where glass can be a suitable replacement. Owing to superior material properties of glass like transparency, mechanical robustness and chemical resistance the usage of glass for micro mechanical, micro fluidic and micro optical microelectro mechanical system (MEMS) devices is fast emerging [1]. MEMS applications where micro-machined glass is used include: sensors, such as those incorporating pressure, accelerometer, gyroscope transducers, BioMEMS devices enabled by lab-on-chip and micro fluidics technologies and spacers for cell phone cameras.

As the desire to use glass in the MEMS industry increases, the need to develop better processing/machining methods of this material in the micro domain also increases. In addition, as the diversity of MEMS applications expands, the desired features continue to get smaller, denser and more intricate. At present, the available processing technologies for structuring glass substrate are often restricted. In general, glass is considered as one of the difficult-to-cut material. Processing brittle glass with computer numerical control (CNC) supported cutting processes like scribing or milling leads to rough surfaces. Because of the small dimensions of microstructures subsequent polishing steps cause exceeding efforts. Photo resist structures can be transferred into the underlying glass substrate with reactive ion etching (RIE). Due to low etch rate, the structure depth is limited. Laser machining creates subsurface micro-cracks and also creates a HAZ (Heat Affected Zone) which results in a kerf or damaged area at the top surface of the hole [2]. Since it is a thermal process, laser machining can crack or break thin glass pieces. It is difficult to create blind holes or remove material with a fixed depth across a large area with a laser, as it creates an uneven etching as it progresses across the part.

Ultrasonic Machining (USM) could be another alternative machining process that can be applied commercially to machining of glass. The process is known to be free from major adverse effects associated with micromachining. The micron sized holes used in MEMS can be achieved with the help of micro ultrasonic drilling (MUSD). In MUSD, removal of material is accomplished by the abrading action of grit-loaded slurry circulating between the workpiece and a tool [3]. The contributing mechanisms in MUSD can be summarized into four categories as (i) micro chipping by impact of the free moving abrasive particles (ii) mechanical abrasion by the abrasive particles against the work piece surface (iii) cavitation effects in liquid agitated by ultrasonic vibration (iv) chemical actions associated with the liquid being employed. However, a reasonable understanding of the mechanisms is yet to mature. Influence of the whole range of parameters on the process performance is also not explored exhaustively.

A well planned set of experiments in which all parameters of interest are varied over a specified range is a much better approach to obtain systematic data. Mathematically speaking such a set of experiments is complete and ought to give desired results. Taguchi has developed a method of conducting experiments based on "orthogonal array" which gives much reduced "variance" for the experiment with "optimum settings" of control parameters. Thus the marriage of 'design of experiments (DOE)' with optimisation of control parameters to obtain the best results is achieved in the Taguchi Method. Orthogonal Arrays (OA) provide a set of well balanced (minimum) experiments, while Taguchi's Signal-to-Noise ratios (S/N), as objective functions for optimisation, help in data analysis and prediction of optimum results [4].

The machining performance of ultrasonic machining has been investigated by a few researchers using DOE techniques. In [5], authors investigated the tool wear rate in ultrasonic drilling of engineering ceramics. The effect of five important process variables - workpiece material, tool material, grit size of the abrasive, power rating and slurry concentration on oversize, out-of-roundness and conicity of hole was computed using Taguchi's L-27 OA. It was concluded that all of these input variables significantly affect the quality characteristics except slurry concentration in case of out-of-roundness and conicity. In [6], authors modelled the material removal rate during ultrasonic machining of titanium and its alloys using Taguchi approach. Relationships between material removal rate and other controllable machining parameters (power rating; tool type; slurry concentration; slurry type; slurry temperature and slurry size) was deduced using Taguchi technique. The results suggested that ultrasonic power rating significantly improves the material removal rate with contribution of 28%, followed by type of tool with contribution of 24.6%. The third significant factor was type of slurry with contribution of 13.3%. The remaining three input parameters, namely slurry concentration, slurry grit size and temperature were in-significant. Same approach was used using different orthogonal arrays by other authors [7] [8] [9] [10] and results were discussed while machining with macro or rotary ultrasonic machining. With micro USM, the influence of machining load on machining rate and tool wear has been reported [11]. Machining rate as well as tool wears increases with the increase in machining load. This is because of debris accumulation at the bottom of the hole. Some studies on possible effect of tool geometries on machining rate and tool life were also carried out with micro USM [12]. The observed higher tool wear ratio in case of hollow tool is attributed to reduced contact area.

It has been observed from the published works that the Taguchi/DOE approach was used on macro USM and no effort has been made to investigate the machining performance on micro ultrasonic drilling process. The present work is an attempt to explore the machining characteristics of micro USD using Taguchi's L9 orthogonal array. Relationships between MRR, TWR and other controllable machining parameters (power rating; static load; slurry concentration and abrasive size) are deduced using Taguchi technique.

II. MACRO VS MICRO USD

Although micro USD germinated from macro USD, but the downsizing for micromachining requires exhaustive efforts and some changes in the process. This requires a micro sized tool (or tool feature), smaller amplitude, and micro sized abrasive particles. The static load should be in grams and vibration frequency must be more than 20 kHz. The major problem encountered with micro USD is the fabrication of micro tool and fixing it to the machine. Ultrasonic vibration of the machining head makes accurate tool holding difficult. Because of the size of the tool, the tool stiffness must be taken into consideration. 'Unit Removal' of sub-micrometer order is required when the object size is very small or when high precision of the product is required. Higher precision of the micromachining equipment is desired to reduce the dimensional error in proportion to the size of product [13]. A micro USD set up as shown in Figure 1 has been developed to investigate the feasibility of drilling on glass in micron domain. The micro tools are fabricated with the help of wire electric discharge grinding (WEDG) as shown in Figure 2. In WEDG the electrically conductive wire is travelling continuously and the cylindrical tool (workpiece) is rotating. Both the tool and workpiece are separated with a spark gap. Solid cylindrical tools having a circular cross section of 300 µm diameter made up of austenitic stainless steel were fabricated by this method.

III. EXPERIMENTAL PROCESS AND CONDITIONS

Ultrasonic machining is a non conventional process in which removal of material takes place mainly because of the impact forces generated by the vibrating tool on to the abrasive particles. The abrasives further hit the workpiece with high momentum energy and erode the surface. The frequency of the impacting tool head is above 20 kHz and amplitude is set in the range of 10 to 15µm. The process is ideally suited for hard and brittle materials which are otherwise difficult to machine such as glass, ceramics etc.

Commercial borosilicate glass micro slides with 2 mm thickness were employed as workpiece material for the USD trials. Table 1 shows the experimental conditions and mechanical properties of the workpiece material. The experiments were carried out in an upgraded version of stationary Sonic- Mill machine (Model: AP-500) with a power output of 500 W and attached three axis motion controller unit. The power supply is equipped with an automatic frequency control and automatic load compensation unit that provides constant output amplitude at desired settings to meet the different energy requirement encountered during the operation cycles [14].

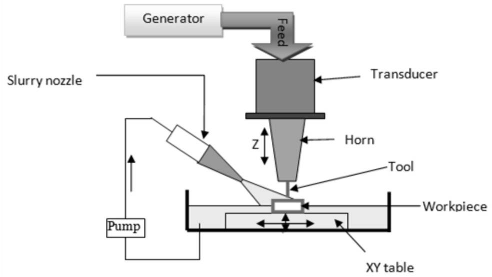

Fig 1: Schematic of A Micro USD Process

Figure 2: The Wedg Set-Up Used For Making Microtools

An electrostrictive PZT transducer converts the electric oscillations into mechanical vibrations in the frequency range of 20 kHz. Power rating in the range of 10% to 30% was used during the experiments. The static load applied on the horn was taken in the range of 100 g to 300 g throughout the experiments. A solid tool made up of austenitic steel having a circular cross section of 300 µm was used as cutting tool a schematic of which is shown in Figure 3. The material removal rate was determined by measuring reduction in weight of work piece and divided by time of drilling and respective densities of work piece. The tool wear rate was considered as the reduction in the length of tool in drilling the given depth of the hole to the time taken in drilling.

The tool wear length was calculated by the "Reference Point" method [15] and can be defined as the position difference in the Z axis when the reference point at the workpiece surface was touched by the tool tip before and after machining. Scanning electron microscopy was employed to characterize the micro mechanisms related to material removal under micro ultrasonic abrasion condition.

Table 1 Experimental Conditions

Work conditions		Description
Work material		Borosilicate glass micro slides 25 mm ⍰ 75 mm ⍰ 2 mm
Workpiece properties	Density (g/cm^3)	2.5
	E (GPa)	69
	H (GPa)	6.865
	K_{IC} ($MPam^{1/2}$)	0.7-0.8
Tool material		Austenitic steel, diameter 300 µm; length 7 mm
Abrasive used		Silicon carbide (SiC)
Frequency of vibration		20 - 30 kHz
Amplitude of vibration		10- 15 µm
Drilling Depth		2 mm
Tool Geometry		Conical with Straight cylindrical edge
Slurry Temperature		28° C (ambient room temperature)
Slurry Media		Water

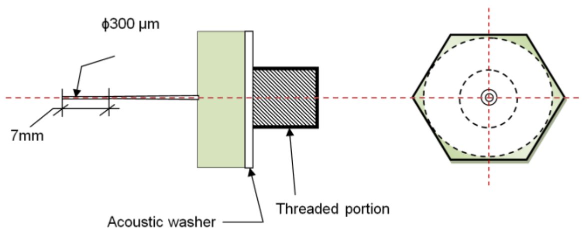

Figure 3: Schematic Of A Typical Micro Tool

IV. DESIGN OF EXPERIMENTS AND DATA ANALYSIS

The experimental layout for the machining parameters using Taguchi's L9 orthogonal array was used in this study. This array consists of four control parameters coded as A, B, C and D with three levels A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3 and D_1, D_2, D_3 as shown in Table 2. In the method, most of the observed values were calculated based on 'higher the better' and 'smaller the better' criteria. Thus in this study, the observed values of responses MRR and TWR were set to maximum and minimum respectively. All the experiments were replicated twice; hence three trials were conducted at each experimental run. The output variables were recorded for each trial and then the results for each experimental run were averaged out to obtain the mean value of response variables (MRR, TWR) for that particular experiment. The experimental results are summarized in Table 3.

Optimisation of the observed values was carried out by comparing the standard analysis and analysis of variance (ANOVA) which was based on the Taguchi's method. In order to establish the relative significance of the individual factors, ANOVA was performed, both on raw data and on S/N data. Because of the ability of S/N data to reflect both the average effects and the variation in the results, ANOVA results based on S/N data are depicted here in Tables 4 and 5.

Table 2: Machining Parameters And Their Levels

Parameters	Factor	Level 1	Level 2	Level 3
Power rating (%)	A	10	20	30
Static load (g)	B	100	200	300
Slurry concentration (%)	C	30	35	40
Abrasive size (micron)	D	10	15	20

Table 3 Experimental Result/Matrix

S.NO.	MRR (mm^3/min)			S/N RATIO (dB)	TWR (mm/min)			S/N RATIO (dB)
	R1	R2	R3		R1	R2	R3	
1.	0.886	0.854	1.335	-0.29	0.191	0.193	0.198	14.25
2.	1.128	1.034	0.857	-0.12	0.305	0.302	0.302	10.38
3.	0.954	1.034	0.745	-1.07	0.328	0.285	0.265	10.64
4.	0.623	0.548	0.563	-4.80	0.267	0.267	0.269	11.45
5.	1.367	1.284	1.323	2.43	0.256	0.268	0.262	11.63
6.	0.879	0.895	0.979	-0.77	0.218	0.243	0.273	12.19
7.	0.942	0.989	0.953	-0.35	0.240	0.241	0.260	12.14
8.	1.756	1.241	1.412	3.08	0.331	0.288	0.301	10.24
9.	1.654	1.552	1.819	4.42	0.243	0.244	0.246	12.25

V. RESULTS AND DISCUSSION

5.1 Material removal rate

As S/N response takes into account both the magnitude as well as the variation in a response, the factor levels that correspond to the highest S/N ratio are termed as optimum. The main effects of four machining parameters (Power Rating, Static load, Slurry Concentration and Abrasive size) on MRR are shown in Figure 4. The variation of MRR with ultrasonic power rating is not uniform or linear; the MRR decreases with increase in power rating but after crossing certain level of power rating, MRR rises (corresponding to A_3=30%). This might be attributed to the relative low frequency of vibration at the starting which is insufficient to drag out the work material. Increased power causes high stresses in the impact zone and more material removal results.

The MRR increases with the increase in static load upto a value and then starts decreasing. This is in contrary with macro USM as in case of micro USM after a certain depth the cutting energy of abrasives diminishes because of insufficient recycling abrasive particles at the machining interface owing to accumulation of the debris (due to small size of the feature).

The use of high concentration of slurry and increase in abrasive size promotes the overall decrease in MRR. The reason lies in the puddle of slurry. The high concentration squeezes the movement of the tool and abrasive particles collide with each other causing loss of cutting energy and thus results in reduced MRR. The most important characteristic of the abrasive that highly influence the material removal rate is the grit size or grain size of the abrasive. Increase in abrasive size reduces the total number of abrasives in the cutting zone and thus reduces the MRR.

5.2 Tool wear rate

The machining characteristic TWR in micro ultrasonic drilling of glass have been found to be correlated and dependent upon the input parameters such as slurry concentration and grit size used. It can be observed (Figure 5) that TWR tends to increase sharply with a corresponding increase in the size of the grits. Coarser grits apply stronger impact on the surface of the tool and hence the rate of fracture increases. Use of high concentration of slurry results in high tool wear rate. Because of the choking of the tool movement at high concentration, the amputation of tool material starts instead of work piece material removal.

When tools of very small dimensions are used, the static load needs to be small to avoid breakage of the tool. The high static load imparts high pressure over the tool material and suppresses it.

As the load is increasing for a constant area, the stress produced will be more which results in easy and quick work hardening of the tool tip. This leads to an induced brittleness on the tool tip causing a favourable condition to be eroded by the deflected abrasives.

The tool wear rate (TWR) has been found to be nearly constant with a corresponding increase in power rating of the ultrasonic machine from 10% to 20%, the rate of increase being sluggish while the power rating is increased from 20% to 30%.

5.3 ANOVA Analysis

The ANOVA test summary for MRR and TWR has been recorded for S/N response Table 4 & Table 5. The percent contribution of each factor has been shown in Figure 6 & Figure 7.

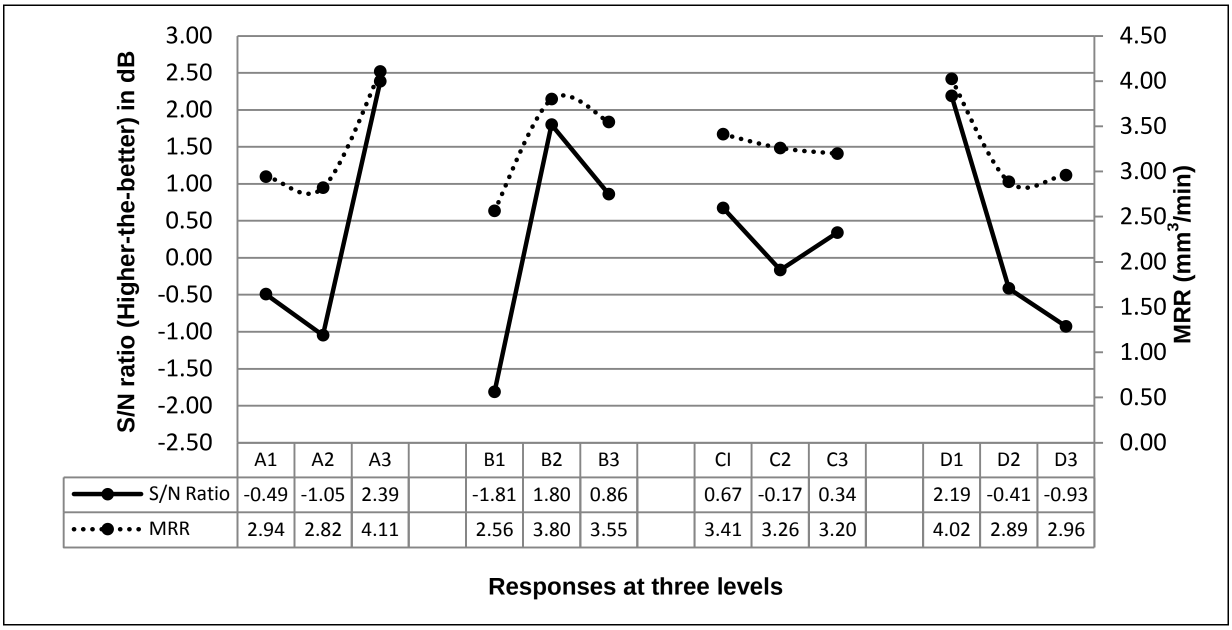

Figure 4 Effect Of Process Parameters On Mrr Raw Data And S/N

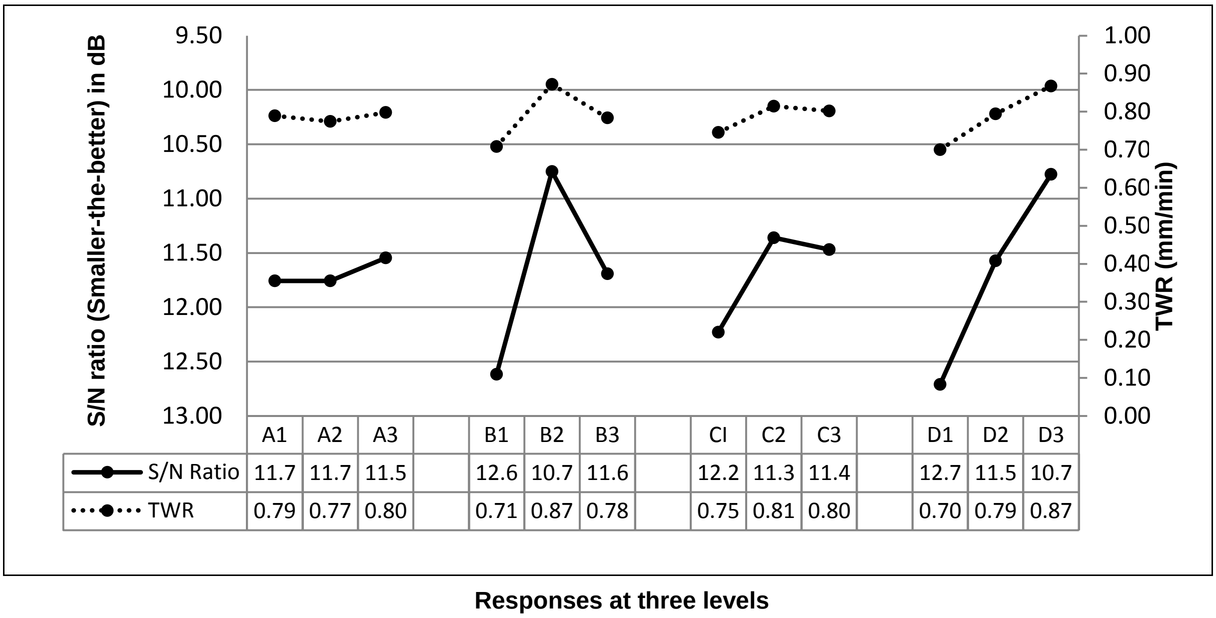

Figure 5 Effect Of Process Parameters on TWR Raw Data And S/N

Table 4: MRR POOLED ANOVA RESULTS

Source	SS	DOF	V	Var ratio	SS'	P
Power rating	20.368	2	10.184	19.037	19.298	32.565
Static load	21.073	2	10.537	19.696	20.003	33.755
Slurry conc	1.070	2	**Pooled**	-	-	-
Abrasive size	16.749	2	8.375	15.655	15.679	26.459
Error	1.070	2	0.535	1.000	4.280	7.222

Table 5: TWR POOLED ANOVA RESULTS

Source	SS	DOF	V	Var ratio	SS'	P
Power rating	0.089	2	**Pooled**	-	-	-
Static load	5.220	2	2.610	58.513	5.131	41.653
Slurry conc	1.344	2	0.672	15.069	1.255	10.189
Abrasive size	5.665	2	2.832	63.494	5.575	45.261
Error	0.089	2	0.045	1.000	0.357	2.897

Static load emerges as the most significant factor at 95% confidence level with a percent contribution of 33.75. Power rating emerges as another highly significant factor, with a percent contribution of 32.56 in the variation of MRR, followed by Grit size with contribution of 26.49 percent. The relative influences are presented in Figure 6.

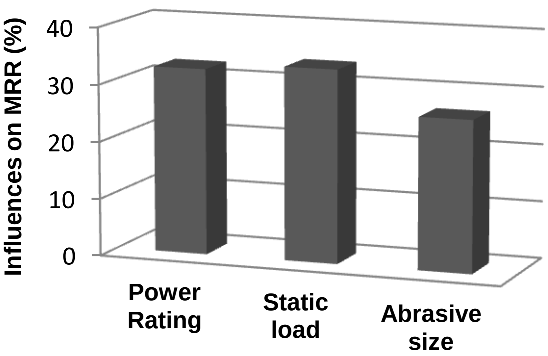

Figure 6 Percent Contributions For Mrr (S/N Data)

With regarding to the S/N response of TWR, grit size factor has emerged as the most significant factor with a percent contribution of 45.26% (Table 5) followed by the static load (41.65%). Slurry concentration factor can be termed as the least significant factor for TWR with a percent contribution of 10.18% (Figure 7).

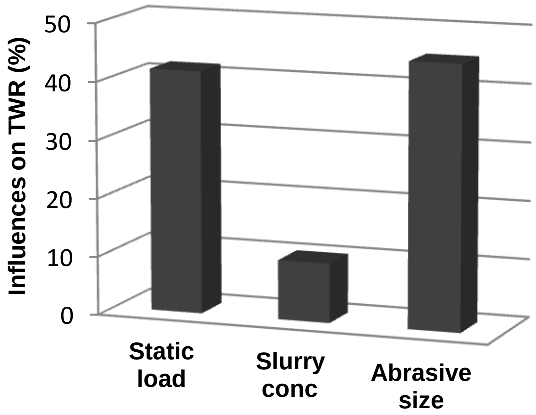

Figure 7 Percent Contributions For Twr (S/N Data)

VI. CONCLUSION

This paper has discussed the feasibility of drilling borosilicate glass by micro USM. Taguchi method has been used to determine the main effects, significant factors and optimum machining condition for both performance of micro USM. Some results found in case of MRR are differing with the nominal trend in macro USM. Based on the results presented herein, it can be concluded that, the MRR is most influenced by static load while abrasive size mainly affects the TWR.

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