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Comparative Study of Static and Rotary Ultrasonic Machining Process

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Abstract—*The machining of hard and brittle materials is complicated by conventional machining processes as they cannot withstand even a minimal deformation under load and fails by the brittle fracture in an irregular manner. Non-conventional machining processes are generally employed to machine such hard and brittle materials. Ultrasonic Machining (USM) process is one of the best-suited advance machining processes for machining non-conductive, hard, brittle and non-metallic materials such as glass, alumina, ceramic, ferrite, quartz, zirconium oxide, ruby, sapphire, beryllium oxide, composites etc. In present work, a setup of Rotary Ultrasonic Machining (RUM) is developed, and a comparative experimental study of rotary ultrasonic machining (RUM) and static ultrasonic machining (USM) is performed. From experimental research, it is observed that about 115% and 180% more MRR (average) is found in rotary USM at 500 rpm and 1000 rpm respectively. It is also noted that about 12% reduction in hole over cut (average) is obtained during rotary ultrasonic machining at 1000 rpm. The analysis help us to analyze the effect of various input parameters like ultrasonic power (70, 80, 90 %W), spindle speed (0,500,100 rpm), frequency (21.5, 22.5, 25.5 khz) and abrasive grit number (30, 46, 60) on MRR which help to enhance the productivity of ultrasonic drilling.*

Keywords: *Rotary Ultrasonic Machining (RUM), Ultrasonic Machining (USM), grit size, abrasive slurry, Overcut.*

1. INTRODUCTION

Nowadays a wide range of hard, brittle and non-conductive materials such as glass, ceramics, quartz, composites etc. are being utilized in automotive industries, aerospace applications, cryogenic applications, defense applications and many other general applications. Ceramic material is an inorganic, non-metallic, often crystalline oxide, nitride or carbide material. Ceramic materials are brittle, hard, strong in compression, weak in shearing and tension. They can with stand very high temperatures of the order of 1000°C to 1600°C. Glass is not considered as a ceramic material because of its amorphous (non-crystalline) character. However, glass making involves several steps of the ceramic process, and its mechanical properties are similar to ceramic materials.

1.

Ultrasonic Machining (USM) is one of the most widely used non-conventional machining processes for machining non-conductive, hard and brittle materials. In USM, a tool made of soft material such as mild steel or brass oscillating in the axial direction at ultrasonic frequency 18-20 kHz is used. During the oscillation of tool, abrasive slurry (a mixture of abrasive particle and carrier medium generally water) is continuously fed into the machining zone between tool and workpiece. The abrasive particles of the slurry are hammered on to the surface of the workpiece by means of ultrasonic vibrations causing chipping of the fine particles from it. The oscillating tool, at amplitudes ranging from 10 to 40 µm, imposes a static pressure on the abrasive grains and feeds down as the material is removed to form the required tool shape [1, 2].

USM results in overcut, conicity and out of roundness which are not desirable but these cannot be eliminated entirely. However, these can be restricted to a minimum by applying a rotation of the tool. Such a configuration of USM is generally referred to as rotary ultrasonic machining (RUM). *Azlan et al. [2017]* have investigated the improvement of surface roughness during machining of hardened steel by RUM. They have observed about 85% reduction in R_a value using RUM as compared to conventional machining under similar cutting conditions

Fernando et al. [2018] have studied rotary ultrasonic machining of basalt, marble, and travertine rocks. They have observed that RUM can produce quality holes with less cutting force and about three times faster penetration rate [4]. *Anwar et al. [2018]* have studied the effect of main process parameters on RUM. They have observed that ultrasonic power, spindle speed and feed rate are the most significant parameters during RUM of BK7 glass [5]. *Singh et al. [2018]* have investigated rotary ultrasonic machining of Macor dental ceramic. They have observed that feed rate is the most influential parameters in terms of surface roughness and smaller feed rate produces a better surface finish [6].

2. ROTARY ULTRASONIC MACHINING (RUM) SETUP

The primary requirement of RUM is the provision of tool rotation as compared to the static ultrasonic machining process. The main parts of a rotary ultrasonic machine are as follows:

Ultrasonic Transducer

Sine wave generator

Velocity transformer (horn) with a tool

RPM regulator

Ultrasonic Transducer

The transducer is a device which converts energy from one form to another. In the case of a transducer for USM, electrical energy is converted to mechanical motion.

Figure.1: Transducer

2.2. Selection of Sine wave generator

In present work, sine wave generator as per the following specification is used for USM.

Input voltage – 220 V, 50 Hz Output frequency – 22 kHz +/10% Output power – 0-150 W

Figure 2: Sine wave generator

2.3. Velocity Transformer (Horn)

The velocity transformer has got several names like concentrator, horns, a mechanical focusing device, shank, horn, amplifier, tool cone, transformer stub or convergent wave-guide, etc. It amplifies and focuses the mechanical energy produced by the transducer and imparts this to work-piece in such a way that energy utilization is optimum.

Figure.3: Horn with tool

Horn may be of different shapes or configurations. Some typical shapes are exponential (circular), Exponential (wedge), Exponential (annular), Straight conical, Stepped (symmetrical), Stepped (unsymmetrical), Gaussian profile etc.

In present work, the velocity transformer (horn) used is as follows:

Type – Stepped type

Material – EN-8 (tool steel)

Threading – 3/8”

Diameter of tool – 2 mm

2.4. RPM regulator

An rpm regulator, capable of varying the rpm from 0-1500 is selected for providing different spindle speed of RUM.

Figure.4: RPM regulator

Figure.5: Setup of static & rotary ultrasonic machine

3. EXPERIMENTATION

The experiments have been performed on rotary ultrasonic machining (RUM) setup developed in-house. Soda lime glass is selected as workpiece material and silicon carbide abrasives of three different grit numbers are selected for ultrasonic machining. Chemical composition and mechanical properties of soda lime glass is shown in Table 1 and Table 2 respectively.

Table 1. Chemical composition of soda lime glass

Element	Percentage (%)
SiO_2	69-74
Na_2O	10-16
CaO	5-14
MgO	0-6
Al_2O_3	0-3
Others	0-5

Table 2. Mechanical properties of soda lime glass

Density	2500 Kg/m^3
Young's Modulus	70 MPa
Poisson's ratio	10-16
Shear Modulus	30 MPa
Knoop Hardness	6 GPa

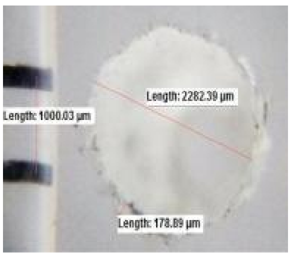
Three independent input parameters namely ultrasonic power, frequency and abrasive size are selected for experimental study whereas material removal rate (MRR) and overcut are selected as response parameters. The feasible range of input parameters is selected on the basis of preliminary experiments. For each input parameter, three level values from feasible range are selected for conducting experimental study. The input parameters and their level values are shown in Table 3.

Table 3: Machining Parameters and their levels

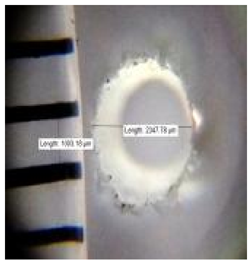
Sr. No.	Input parameter	Unit	Value		
			Level 1	Level 2	Level 3
1.	Ultrasonic Power	%	70	80	90
2.	Frequency	kHz	21.5	22.5	25.5
3.	Abrasive size	µm	30	46	60

The experiments are designed by Taguchi's orthogonal array [7]. Taguchi L9 orthogonal array for three factor-three level design is selected. The comparison between static and rotary ultrasonic machining is conducted by performing the same experiments with rotary ultrasonic machining at 500 rpm and 1000 rpm.

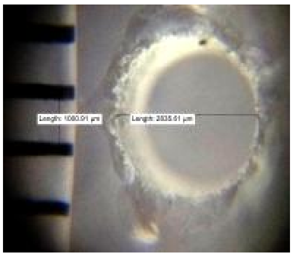
On the other hand, hole overcut is measured by optical zoom. In the present study, universal clip-type LED cell phone microscope also known as optical zoom, which is compatible with mobile software, is used for measuring actual size of machined hole. Then, overcut is calculated by subtracting tool diameter from actual size of machined hole.



(a)Overcut by static USM



(b) Overcut by rotary USM at 500 rpm



(c)Overcut by rotary USM at 1000 rpm

Figure.6: Measurement of hole diameter with optical zoom

Table 4: L9 OA experimental data for static USM

Sr. No.	Ultrasonic power (%)	Frequency (kHz)	Abrasive size (µm)	MRR (mg/min)	Overcut
1.	70	21.5	30	0.84	282.39
2.	70	22.5	46	1.15	206.61
3.	70	25.5	60	2.00	375.02
4.	80	21.5	46	1.95	1019.45
5.	80	22.5	60	1.52	373.74
6.	80	25.5	30	1.95	976.89
7.	90	21.5	60	4.46	449.15
8.	90	22.5	30	1.07	649.95
9.	90	25.5	46	7.50	243.55

Table 5. L9 OA experimental data rotary USM (500 rpm)

Sr. No.	Ultrasonic power (%)	Frequency (kHz)	Abrasive size (µm)	MRR (mg/min)	Overcut
1.	70	21.5	30	1.81	235.75
2.	70	22.5	46	2.97	241.55
3.	70	25.5	60	5.78	864.82
4.	80	21.5	46	8.68	947.89
5.	80	22.5	60	4.86	794.72
6.	80	25.5	30	2.29	508.99
7.	90	21.5	60	5.00	63.86
8.	90	22.5	30	2.57	292.71
9.	90	25.5	46	14.21	775.81

Table 6. L9 OA experimental data rotary USM (1000 rpm)

Sr. No.	Ultrasonic power (%)	Frequency (kHz)	Abrasive size (µm)	MRR (mg/min)	Overcut
1.	70	21.5	30	2.80	344.91
2.	70	22.5	46	2.40	473.63
3.	70	25.5	60	9.04	405.63
4.	80	21.5	46	9.07	91.56
5.	80	22.5	60	5.15	791.64
6.	80	25.5	30	2.67	205.57
7.	90	21.5	60	13.31	347.14
8.	90	22.5	30	3.62	968.78
9.	90	25.5	46	14.66	379.87

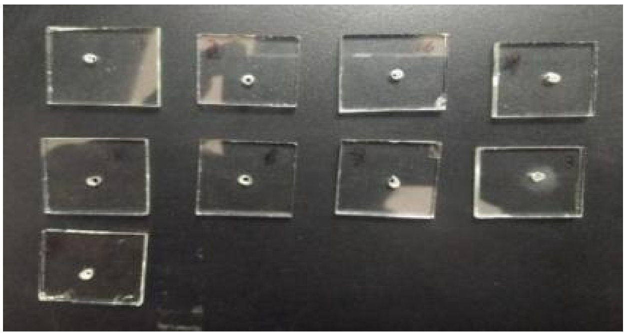


Figure.7: Holes machined by static USM

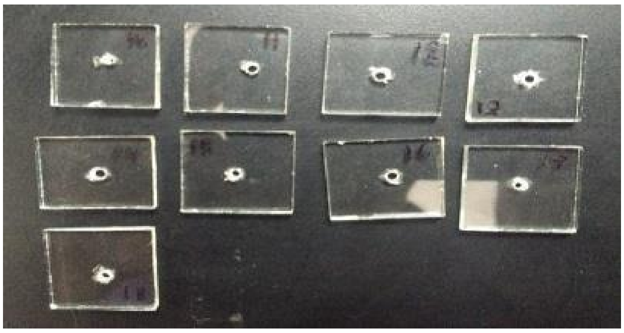


Figure.8: Holes machined by rotary USM at 500 rpm

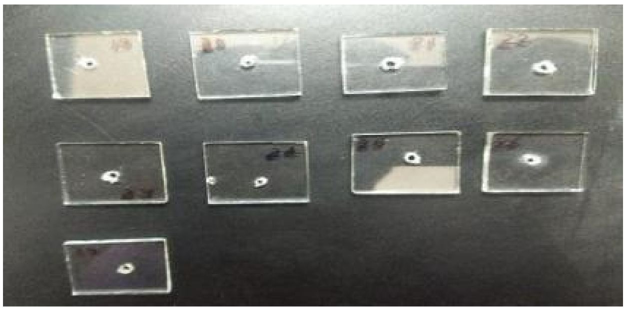


Figure.9: Holes machined by rotary USM at 1000 rpm

4. RESULTS AND DISCUSSION

Taguchi's method reduces total number of experiments to be performed without much loss of information. The experimental design using Taguchi's orthogonal array, provide mean effects of parameters on response variables. In the present study, mean effects of parameters on responses is compared for static ultrasonic machining and rotary ultrasonic machining process.

4.1. Effect of Ultrasonic Power

In ultrasonic machining process, electrical power is supplied to ultrasonic transducer which is converted into mechanical vibrations of ultrasonic range

Ultrasonic power is the main input parameter of ultrasonic machining process and it is generally expressed in percentage. The comparative effect of ultrasonic power on mean material removal rate (MRR) is shown in Fig. 11. It is observed that mean material removal increases with increase in ultrasonic power for static USM (rpm = 0) as well as rotary USM (rpm = 500 & 1000).

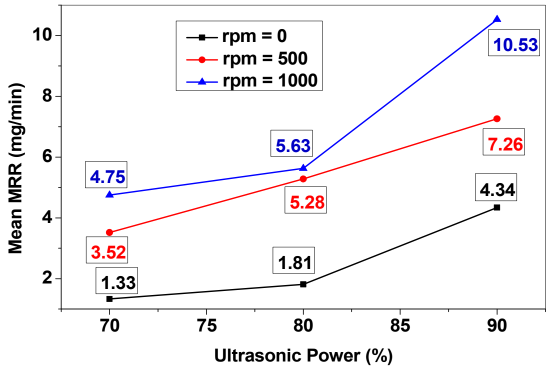


Figure.10: Mean effect of ultrasonic power on MRR

This is due to the fact that the amplitude of ultrasonic vibrations directly related to ultrasonic power. Higher ultrasonic power produces ultrasonic vibrations of relatively large amplitude which results in greater impact of abrasive grains onto the surface of workpiece as well as deeper penetration of abrasive grains. As a result of which higher MRR is obtained

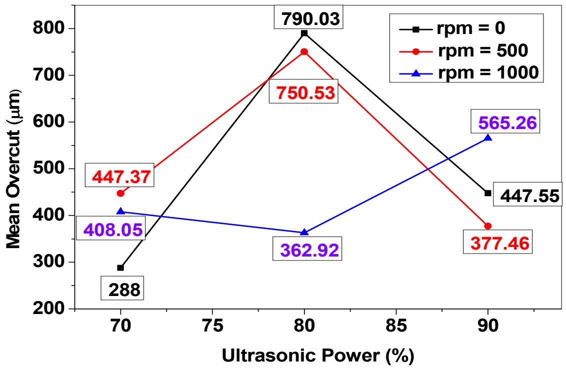


Figure.11: Mean effect of ultrasonic power on Overcut

Further, from Fig. 11, it can be seen that relatively much higher mean MRR is obtained in rotary USM in comparison to static USM. As compared to static USM, about 115% and 180% more MRR (average) is observed in rotary USM at 500 rpm and 1000 rpm respectively. The effect of ultrasonic power on hole overcut is shown in Fig.

12. The trends of overcut are very random due to brittle fracture taking place during machining. It is observed from Fig. 12 that at 80% ultrasonic power, smaller hole overcut is observed during rotary USM relative to static USM. On an average, about 12% reduction in hole overcut is observed during rotary USM at 1000 rpm as compared to static USM process. During rotary USM at 500 rpm, nearly same overcut (average) is observed.

4.2. Effect of Ultrasonic Frequency

The frequency of vibrations beyond 20 kHz falls in ultrasonic range i.e. beyond human hearing capacity. The effect of ultrasonic frequency on mean MRR is shown in Fig. 13. It is observed that with increase in ultrasonic frequency, MRR is increasing. This is due to the reason of increased hammering and abrasion action caused by increased frequency.

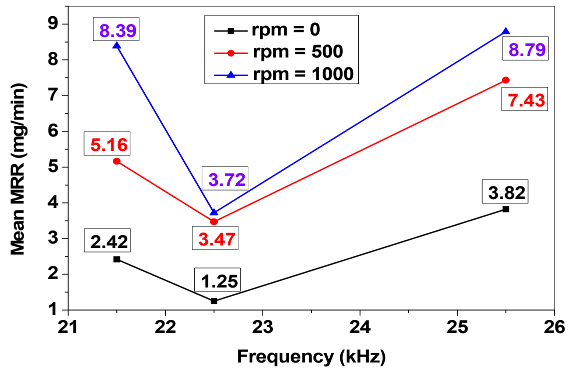


Figure.12: Mean effect of ultrasonic frequency on MRR

It also helps in extraction of used abrasive slurry and flow of fresh abrasive slurry in machining zone to ensure proper machining. It can be observed from Fig. 13 that mean MRR obtained in rotary USM process is much higher than that in static USM process

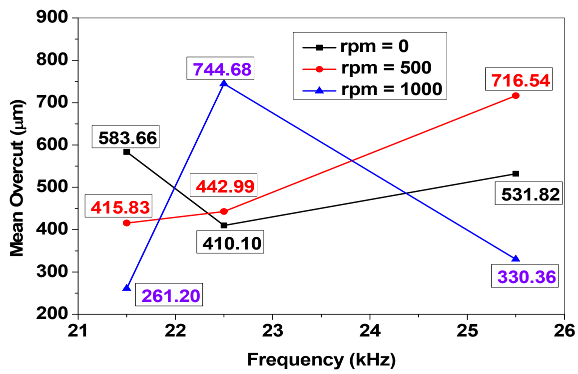


Figure.13: Mean effect of ultrasonic frequency on Overcut

It is also observed that greater MRR is obtained at 25.5 kHz frequency in both static and rotary USM. This is due to deep penetration of abrasive particles in workpiece surface at high frequency of ultrasonic vibration. Another observation is smaller MRR at 22.5 kHz frequency. The reason may be improper ultrasonic vibration as well as the machining system is unable to produce resonance at 22.5 kHz. About 115% and 180% more MRR (average) is obtained with 500rpm and 1000rpm respectively as compared to static USM.

The effect of ultrasonic frequency on a hole overcut is shown in Fig. 14. The trends of overcut are random, similar to that obtained during analysis of ultrasonic power. It can be observed from Fig. 14 that with increase in frequency mean overcut for rotary USM (rpm = 500 & 1000) increases whereas it remains almost constant during static USM process. This is due to the reason that high frequency ultrasonic vibration and spindle rotation cause random movement of abrasive particles in machining zone which results in uneven removal of material and therefore increased overcut. However, from experimental results, it is concluded that about 12% reduction in hole overcut (average) is obtained at 1000rpm in comparison of static USM.

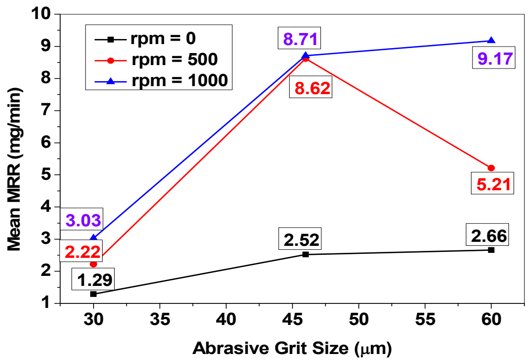


Figure.14: Mean effect of abrasive grit size on MRR

4.3. Effect of Abrasive Grit Size

The abrasive powders are generally specified by grit number. The grit number refers to number of holes per square inch in a sieve of sieve shaker machine through which it does not pass. Higher the grit number smaller will be abrasive particle size. The effect of abrasive grit size on mean MRR during machining of glass is shown in Fig.

In Fig. 14 it is observed that mean MRR is increasing with increase in abrasive grit size. This is due to the fact that smaller size abrasive particles result in easy flow of slurry in machining zone with large number of abrasive particle and thus large number of cutting edges. They create deep penetration into workpiece and results in more number of cavities due to removal of material as a result of which high MRR is obtained. But there is always a limiting size of abrasive grains beyond which abrasive slurry will become ineffective. It is observed from Fig. 15 that higher material removal rate is obtained with rotary ultrasonic machining process as compared to static ultrasonic machining process.

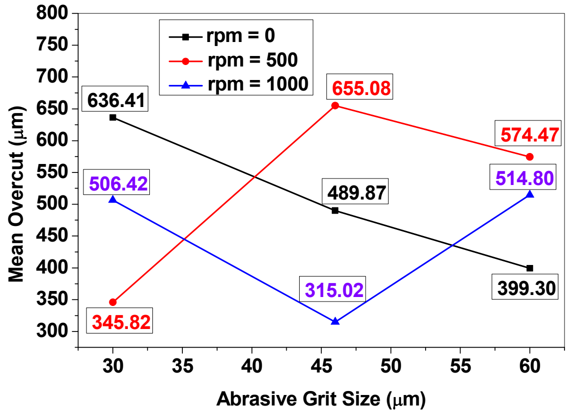


Figure.15: Mean effect of abrasive grit size on Overcut

The abrasive grit size directly affect overcut. The effect of abrasive grit size on a hole overcut is shown in Fig. 16. It can be seen that for static USM hole overcut is decreasing with increase in grit number. Further, during rotary USM at 1000 rpm relatively reduced the hole overcut is observed.

5. CONCLUSIONS

An experimental setup of rotary ultrasonic machining process is developed in-house. Further, experiments have been conducted for comparative study of static ultrasonic machining process and rotary ultrasonic machining process. From above experimental study, following conclusions are drawn:

1. Ultrasonic machining process is one of the best suitable machining processes for soda lime glass. But as far as machining quality is concerned, it is subjected to low material removal rate and overcut.
2. It is observed that rotary ultrasonic machining process can be used for machining relatively good quality holes in brittle materials as compared to static ultrasonic machining process.
3. About 115% and 180% more MRR (average) is observed in rotary USM at 500 rpm and 1000 rpm respectively.
4. It is also observed that about 12% reduction in hole overcut (average) is obtained at 1000 rpm in comparison of static USM.
5. Rotary ultrasonic machining process effectively reduces the hole taper by means of tool rotation during deep hole drilling in materials that exhibits brittle nature.

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