EFFECT OF MACHINING PARAMETERS ON SURFACE ROUGHNESS AND MATERIAL REMOVAL RATE DURING ROTARY ULTRASONIC MACHINING OF SILICON CARBIDE

Cini Babuji[1], Dr. N Santhosh Kumar[2], K Vijayan [3], G NagamalleswaraRao [4], Joji J Chaman [5]

[1]Mtech student, Dept. of Mechanical Engineering, NSS college of Engineering, Kerala, India
[2]Professor, Dept. of Mechanical Engineering, NSS college of Engineering, Kerala, India
[3]Scientist/Engineer SF, ISRO Inertial Systems Unit, Vattiyoorkavu, TVM, India
[4]Scientist/Engineer SE, ISRO Inertial Systems Unit, Vattiyoorkavu, TVM, India
[5]Scientist/Engineer G, ISRO Inertial Systems Unit, Vattiyoorkavu, TVM, India

***

Abstract - *By conventional machining process, machining of brittle components with high precision and high surface finish is difficult. Also, it is costly due to long time processing. So, vibration assisted machining is introduced for this purpose. A vibration will be given to workpiece or tool which facilitates intermittent cutting rather than continuous cutting. Rotary ultrasonic machining is a type of vibration assisted machining. This helps in reducing cutting forces and temperature. By this process better surface finish, accuracy and high precision can be obtained at low cost. It also helps in machining of brittle materials without any damage. In this paper, the optimisation of parameters related to the rotary ultrasonic machining of Silicon Carbide is taken up. Silicon Carbide is a highly brittle material which is difficult for conventional machining. It is having a wide range of application in aerospace industry like space mirrors etc. Various parameters involved in rotary ultrasonic machining of silicon carbide is investigated for obtaining better surface finish and higher material removal rate. Minitab 17 is used for design of experiments and Taguchi method is used for analysis. Confirmatory test is conducted to validate the results and it is also validated through Scanning Electron Microscope (SEM) imaging.*

Key Words: Rotary Ultrasonic machining, Silicon Carbide, Minitab 17, Taguchi method, Scanning Electron Microscope

1. INTRODUCTION

Silicon Carbide is considered as an important material which can be used in harsh environments like that in aerospace, nuclear, military fields and so on. However it is a difficult to cut this material due to its low fracture toughness. Machining techniques for SiC include electrical discharge machining, electrical discharge milling, machining with diamond tools, ultrasonic machining, plasma chemical vaporization machining, laser beam machining, etc. These are time consuming and high cost methods. In this paper, Rotary Ultrasonic Machining is used for performing machining of Silicon Carbide (SiC). Rotary Ultrasonic Machining (RUM) is a hybrid of conventional grinding process combined with ultrasonic vibration which is a non-traditional machining process. RUM offers a convenient and less expensive way of machining hard and brittle materials. RUM was primarily used to drill brittle materials using core drill [1]. Then this was extended to surface machining also. Liu et al. developed a cutting force model for RUM on brittle material [2]. Prediction of subsurface damage (SSD) in Rotary Ultrasonic Face Milling (RUFM) on optical glass was also conducted [3]. It showed reduction in SSD depth and cutting forces due to RUFM. RUM on various brittle materials showed a reduced cutting forces [1, 2], better surface finish [4, 5, 7], and higher material removal rate [5, 6, 8] with various cutting parameters.

Dimensional accuracy and surface finish are the major consideration in most of the industries as quality has to be maintained in all the stages of manufacturing. To achieve this, proper selection of process parameters is very essential. Optimization helps in maximizing performance parameters within the available process variables. The study aims on the optimization of various process parameters in Rotary Ultrasonic Machining of SiC using Taguchi method of analysis.

2. DUCTILE REGIME BRITTLE MACHINING

In conventional machining of brittle materials, brittle fracture is the phenomenon of material removal but in the case of RUM, ductile regime brittle fracture is the phenomenon occurring. Because of the intermittent cutting, fracture in Brittle – Ductile Transition occurs in RUM. When the depth of cut is maintained in a very low value, it is possible to cut brittle material as they are ductile one [9]. When the depth of cut is small, conventional machining process becomes uneconomical. By rotary ultrasonic machining it is possible to achieve the same process at higher depth of cut. This in turn increases the material removal rate and reduces machining time.

Liu et al. [10, 13] found that there was a transition from ductile mode to brittle mode in both the conventional cutting and Ultrasonic Vibration Assisted Cutting (UVA cutting), but the critical depth of cut in UVA cutting was several times larger. In addition, the material removal ratio (the volume of material removal to the volume of the machined groove) in UVA grooving is close to 1, indicating a reduction on ploughing effect by the ultrasonic vibration. Moriwaki et al. [11] machined soda-lime glass with 1D Vibration Assisted Machining (VAM) and maintained ductile cutting to a depth of 1.4μm, an improvement of almost seven times over the critical depth of cut in conventional cutting. Negishi [12] performed groove cutting experiments on silicon carbide with 2D VAM and maintained ductile cutting to 3.5 μm depth.

3. EXPERIMENTAL CONDITIONS AND PROCEDURE

Experiment was conducted on DMG Mori Ultrasonic 60 eVo Rotary Ultrasonic Machining centre. The work material used for experiment is sintered silicon carbide. Milling tool (with metal bonded diamond abrasives) of diameter 3mm (MT Do3-06-8-9-D91H) was used. The coolant used was soluble oil (1:20). Experimental setup is shown in fig 1.

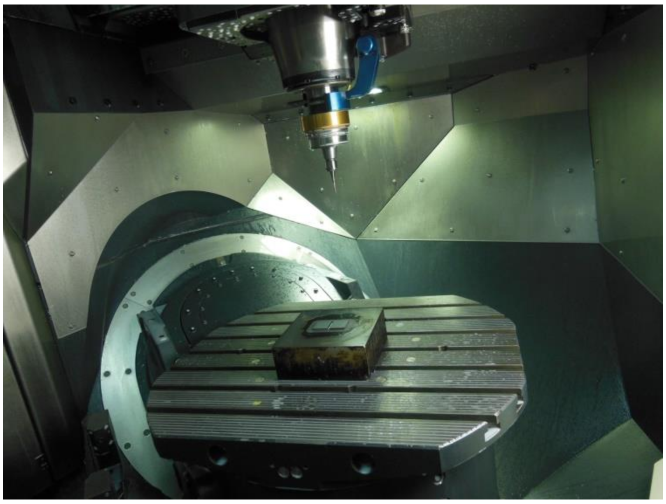

Figure 1: Experimental Setup

The workpiece is bonded on a fixture as shown in fig 2 and this fixture is used for clamping the workpiece on the machine table. The surface roughness was measured across feed direction using Taylor/Hobson form talysurf (fig 3). Microhite was used for measuring actual depth of cut for calculating material removal rate. Taguchi's L18 OA was chosen for work.

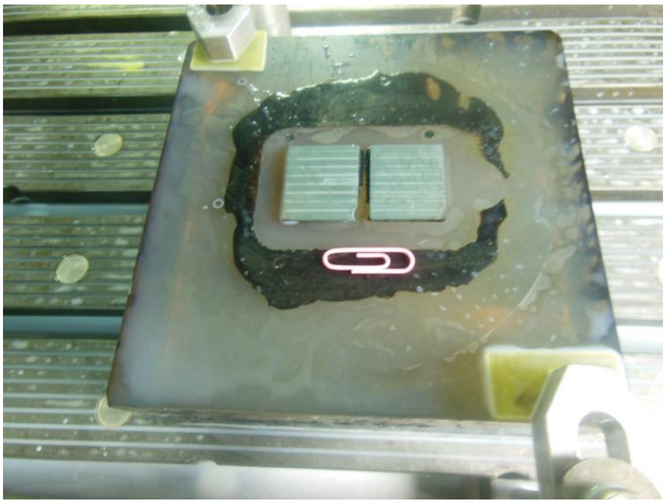

Figure 2: Workpiece Bonded on Fixture

Figure 3: Experimental setup for measurement of surface roughness

3.1 Parameters and Levels

The input parameters selected for machining are frequency (Hz) of spindle vibration, spindle speed (rpm), feed rate (mm/min), and depth of cut (μm). The cutting parameter level selected is shown in table 1. The Taguchi's L18 OA is shown in table 2

Table 1: Cutting parameter levels

Levels	Frequency of vibration (Hz)	Spindle Speed (rpm)	Feed Rate (mm/min)	Depth of cut (µm)
Level 1	0	1500	100	30
Level 2	41430	2000	150	40
Level 3	-	2500	200	50

Table -2: Design of Experiments

Exp no	Frequency of vibration (Hz)	Spindle Speed (rpm)	Feed Rate (mm/min)	Depth of cut (µm)
1	0	1500	100	30
2	0	1500	150	40
3	0	1500	200	50
4	0	2000	100	30
5	0	2000	150	40
6	0	2000	200	50
7	0	2500	100	40
8	0	2500	150	50
9	0	2500	200	30
10	41430	1500	100	50
11	41430	1500	150	30
12	41430	1500	200	40
13	41430	2000	100	40
14	41430	2000	150	50
15	41430	2000	200	30
16	41430	2500	100	50
17	41430	2500	150	30
18	41430	2500	200	40

3.2 Experiment

Rectangular workpiece of silicon carbide having dimension 25mm×30mm was used. It is bonded on a fixture using glue (pitch) for clamping it on the machine table. Machining was carried out and various output parameters like surface roughness and actual depth of cut (for material removal rate) were measured.

3.3 Data Analysis

Surface roughness was measured after every machining experiment. Material Removal Rate (MRR) has been calculated from the difference in height before and after machining. Taguchi method of analysis was used for the study. S/N ratio was calculated for each of the responses. For all surface roughness parameters, criterion selected was "Lower the better" and for MRR it was "Higher the better". The S/N ratio for each parameter level is calculated by averaging the S/N ratios obtained when the parameter is maintained at that level.

Table 3: Experimental Results

Exp no	Actual Depth of cut (µm)	Surface roughness, Ra (µm)	MRR (mm^3/min)
1	21.5	0.4063	6.4500
2	20.0	0.2807	8.9982
3	15.2	0.2597	9.1200
4	22.0	0.4598	6.6000
5	27.5	0.2666	12.3725
6	13.5	0.2043	8.1000
7	28.8	0.1564	8.6400
8	11.8	0.1559	5.3089
9	18.0	0.3901	10.8000
10	42.3	0.9052	12.6900
11	14.0.	0.2666	6.2987
12	21.3	0.2798	12.7800
13	25.6	0.0893	7.6800
14	20.8	0.3367	9.3581
15	12.0	0.2920	7.2000
16	21.2	0.1144	6.3600
17	11.0	0.1759	4.9490
18	26.3	0.1460	15.7800

S/N ratio was calculated using the equations given below. Equation (1) is for lower the better condition and equation (2) is for higher the better condition.

$$S/N_s = -10log\,\frac{1}{n}\Sigma_i^n\,y_i^2 \qquad (1)$$

$$S/N_s = -10log\,\frac{1}{n}\Sigma_i^n\,1/y_i^2 \qquad (2)$$

Table 4: S/N ratio of parameters

Exp no	S/N Ratio for surface roughness	S/N Ratio for Material Removal Rate
1	7.8231	16.1912
2	11.0352	19.0831
3	11.7106	19.1999
4	6.7486	16.3909
5	11.4828	21.8491
6	13.7946	18.1697
7	16.1152	18.7302
8	16.1431	14.5001
9	8.1765	20.6685
10	0.8651	22.0692
11	11.4827	15.9850
12	11.0630	22.1306
13	20.9829	17.7072
14	9.4551	19.4238
15	10.6923	17.1466
16	18.8314	16.0691
17	15.0946	13.8903
18	16.7129	23.9621

Table 5 and figure 4 shows the optimum levels of parameters to achieve high surface finish. The optimal combination of levels of parameters to get low value of surface roughness (R_a) is Level 2- Level 3 – Level 2 – Level 2 within tested range.

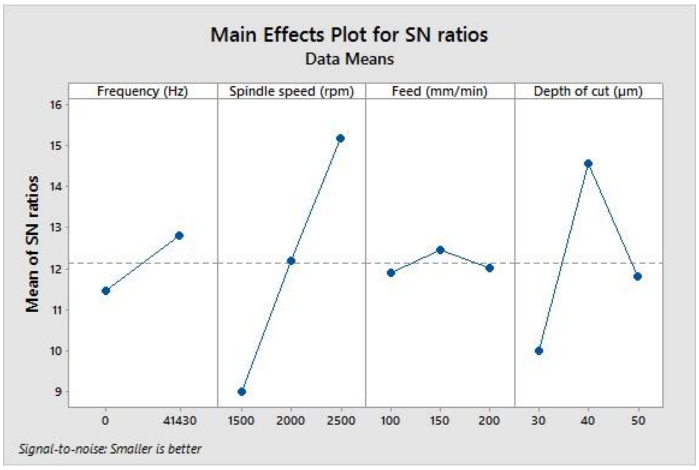

Figure 4: Main effect plot for S/N Ratios of Surface Roughness vs. performance measures

Table 5: Data mean of S/N Ratio of Surface Roughness

Levels	**Factors**			
	Frequency	Spindle Speed	Feed	Depth of cut
1	11.448	8.997	11.894	10.003
2	12.798	12.193	12.449	14.565
3	-	15.179	12.025	11.800
Optimum level	**2**	**3**	**2**	**2**
Variation	1.350	6.182	0.555	4.562
Rank	3	1	4	2

Table 6 and figure 5 shows the optimum levels of parameters to achieve high MRR. The optimal combination of levels of parameters to get low value of MRR is Level 2- Level 1 – Level 3 – Level 2 within tested range.

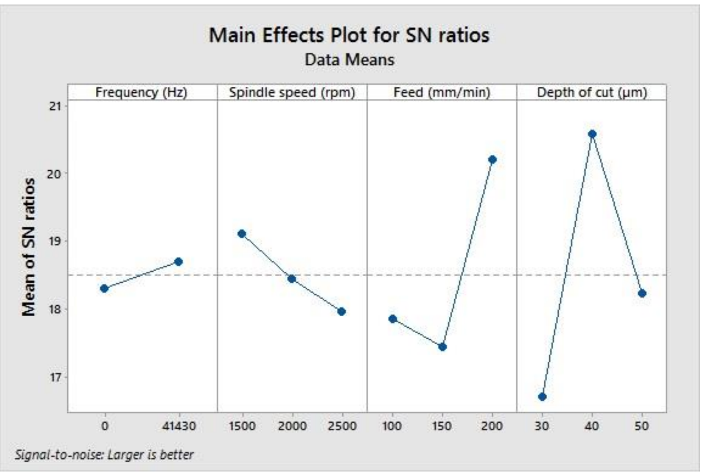

Figure 5: Main effect plot for S/N Ratios of MRR vs. performance measures

Table 6: Data mean of S/N Ratio of Material Removal Rate

Levels	**Factors**			
	Frequency	Spindle Speed	Feed	Depth of cut
1	18.310	19.110	17.860	16.710
2	18.710	18.450	17.460	20.580
3	-	17.970	20.210	18.240
Optimum level	**2**	**1**	**3**	**2**
Variation	0.400	1.140	2.760	3.860
Rank	4	3	2	1

A confirmatory test is also conducted for these optimal levels alone for minimum surface finish and maximum material removal rate.

4. CONFIRMATORY TEST

A confirmatory test was conducted to validate the results obtained for the Taguchi method of analysis. Two methods where used for confirmatory tests – experimental method and SEM analysis

4.1 Experimental Analysis

In experimental analysis, the optimum combination of parameters obtained from Taguchi method was again used for confirmatory test. In the confirmatory test, machining was done with and without vibration. The table 7 shows the experimental results.

Table 7: Confirmatory Test Results

Optimum parameter	Frequency (Hz)	Spindle speed (rpm)	Feed Rate (mm/ min)	Depth of Cut (µm)	Surface Roughness, R_a	Material Removal Rate, (mm/ min)
For Surface Roughness	41430	2500	150	40	**0.1391**	10.348
	0	2500	150	40	0.2981	9.448
For Material Removal Rate	41430	1500	200	40	0.3143	**15.720**
	0	1500	200	40	0.4053	15.000

From the table it is clear that better surface finish and higher material removal rates are obtained in the optimum levels obtained by Taguchi method of analysis.

4.2 Scanning Electron Microscope (SEM) Image Analysis

Second method used for confirmatory test was by SEM image analysis. In this method, the SEM images of the machined area were used to determine the surface undulations. Fig 6 and fig 7 shows the SEM images.

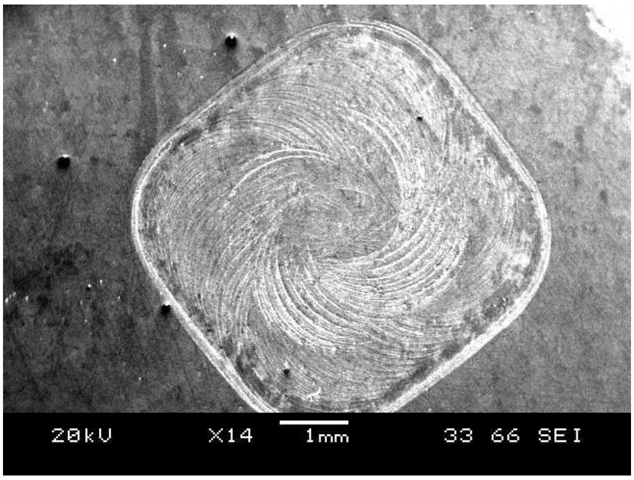

Figure 6: SEM image of area machined without vibration

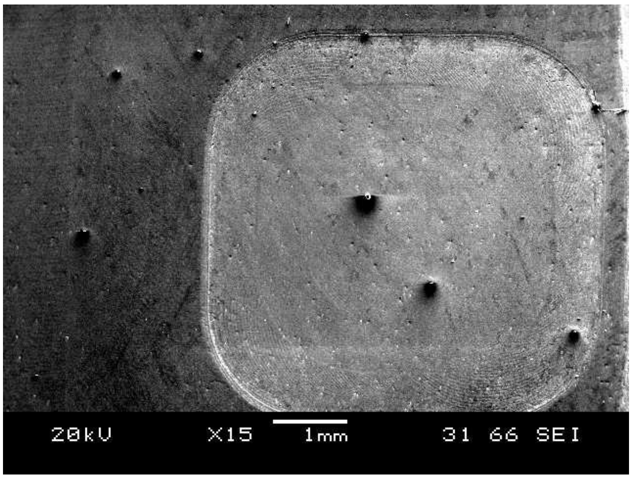

Figure 7: SEM image of area machined with vibration

The parameters used for machining were the optimum parameters derived to achieve high surface roughness obtained by S/N ratio analysis. Machining was done with vibration and without vibration to identify the effect of vibration on the machined area. From the figures it is clear that a smoother surface is obtained when the machining is done with vibration.
The major aim of this confirmatory test was to justify the results obtained by S/N ratio analysis.

5. CONCLUSIONS

This paper presents a research work on various cutting parameters affecting the surface roughness and material removal rate in rotary ultrasonic machining on Silicon carbide material. The study indicates that

1. For maximum surface finish the optimum combination of parameters are frequency – 41430 Hz, Spindle speed – 2500 rpm, Feed – 150 mm/min, Depth of cut - 40µm.

2. For maximum material removal rate the optimum combination of parameters are frequency – 41430 Hz, Spindle speed – 1500 rpm, Feed – 200 mm/min, Depth of cut - 40µm.

An orthogonal array with Taguchi analysis was used to optimize performance characteristics in the RUM of SiC. The results show the effect of frequency, spindle speed, feed and depth of cut on the output parameters. The results obtained were validated using experimental method and SEM analysis.

ACKNOWLEDGEMENT

The authors are thankful to ISRO Inertial Systems Unit, Thiruvananthapuram and NSS College of Engineering, Palakkad for providing facilities for research and conducting experiments.

REFERENCES

[1] N. Qin, Z.J. Pei, C. Treadwell, D.M. Guo: "Physics-based predictive cutting force model in ultrasonic-vibration-assisted grinding for titanium drilling",Journal of Manufacturing Science and Engineering, Vol. 131 (2009), pp.041011-9.

[2] D.Liu, W. L. Cong, Z. J .Pei, andY. J. Tang, "A cutting force model for rotary ultrasonic machining of brittle materials", International Journal of Machine Tools and Manufacturevol.52, 2011,pp.77–84.

[3] J.J Wang, C. Zhang, P Feng, and J Zhang, "A model for prediction of subsurface damage in rotary ultrasonic face milling of optical K9 glass",International Journal of Advanced Manufacturing Technology, 2015.

[4] C Zhang, P. Feng, S. Zheng, Z. Wu, and D. Yu, "Experimental investigation of rotary ultrasonic face milling of K9 glass",Advanced Materials Research Vols. 230-232 (2011) pp. 644-648.

[5] S. Zheng and X. Xu, "Experimental investigation on ultrasonic face machining of glass with free abrasives",Key Engineering Materials Vols. 375-376 (2008) pp. 268-273.

[6] Z. J. Pei and P. M. Ferreira, "An experimental investigation of rotary ultrasonic face milling", International Journal of Machine Tools and Manufacture Vol. 39, 1999, pp. 1327-1344.

[7] M. R Razfar, P Sarvi, and M. M. A. Zarchi, "Experimental investigation of surface roughness in ultrasonic-assisted milling", Journal of Engineering Manufacture,Vol. 225,2011, pp. 1615-1620.

[8] Z. J. Pei and P. M. Ferreira, "Modeling of ductile-mode material removal in rotary ultrasonic machining", International Journal of Machine Tools and Manufacture, vol 38 (1998), pp. 1399–1418

[9] J. B. Chen, Q. H. Fang, C.C. Wang, J. K. Du, and F. Liu, "Theoretical study on brittle-ductile transition behaviour inelliptical ultrasonic assisted grinding of hard brittle materials", Precision Engineering, 2016.

[10] Liu K, Li XP, Rahman M (2008) "Characteristics of ultrasonic vibration-assisted ductile mode cutting of tungsten carbide". International Journal of Advanced Manufacturing Technology 35:833–841

[11] Moriwaki T, Shamoto E, Inoue K. Ultraprecision ductile cutting of glass by applying ultrasonic vibration. CIRP Ann 1992:41.

[12] Negishi N. "Elliptical vibration-assisted machining with single crystal diamond tools". MS thesis. North Carolina State University; 2003.

[13] Liu K, Li XP, Rahman M et al (2004) "Study of ductile mode cutting in grooving of tungsten carbide with and without ultrasonic vibration assistance". International Journal of Advanced Manufacturing Technology 24:389–394

[14]