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Research Article

Investigation into the Machining Characteristics of Composites using Chemical Assisted Ultrasonic Machining Process

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Abstract

In this study, the chemical-assisted ultrasonic machining (CUSM) method is introduced in order to improve the efficiency of conventional USM method. To obtain the chemical effects, a low concentration hydrofluoric acid solution is added to the abrasive slurry with glass as workpiece. This paper investigates the effect of different input materials namely power rating, type of abrasive slurry, concentration of abrasive slurry, abrasive grit size, tool material on Material removal rate (MRR) and Surface Roughness(R_a) in Chemical assisted Ultrasonic Machining (CUSM) process. The effect of various input parameters on output responses is analyzed using statistical techniques such as ANOVA. Optimization and verification of the process parameters and the modeling of the results is done by applying Regression Analysis. Main effect plots for the significant factors and S/N ratio have been used to determine the optimal design for output response. Through various experiments and comparison with conventional results, the superiority of our novel method is verified.

Keywords: *Chemical-assisted ultrasonic machining (CUSM), Material removal rate (MRR), Surface Roughness(R_a).*

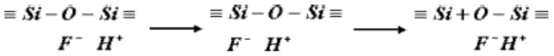
1. Introduction

Glass is known as a representative functional material for optics, electronics, thermodynamics and fluidics and so on. It has many superior qualities, such as high strength, hardness, thermal resistance, corrosion resistance and wear resistance, and is relatively light weight. However, because of its mechanical characteristics, it is one of the most difficult-to-cut materials. The conventional fabrication methods for these glass materials include diamond turning, electrochemical discharge machining, Ultrasonic machining, wet/dry etching and laser ablation Processing. Among them, the ultrasonic machining process is a process which removes materials by the impact motion of ultrasonic-vibrated abrasive particles, is non-thermal, non-chemical, and non- electrical.

Ultrasonic machining (USM) is of particular interest for the machining of non-conductive, brittle work piece materials such as engineering ceramics. Because the process is non-chemical and non-thermal, materials are not altered either chemically or metallurgically (Thoe, T.B *et al*, 1988). The process is able to effectively machine all materials harder than HRC 40, whether or not the material is an electrical conductor or an insulator (Benedict, G, *et al* 1987). Holes as small as 76_min diameter can be machined. However, despite the above benefits, ultrasonic machining has a low material removal rate and gives low surface quality. In this study, a chemical-assisted ultrasonic machining (CUSM) method is introduced to overcome former disadvantages. To get the chemical effect, a low concentration of hydrofluoric acid was added to the abrasive slurry. In order to get optimal conditions, an investigation of the machining mechanism and several experimental works was carried out and compared with conventional USM method. As a result, an increase in material removal rate and improved the surface roughness is obtained

2. Mechanism of Chemical-Assisted Ultrasonic Machining

In the process of the USM, materials are removed by micro chipping or erosion with the abrasive particles. When glasses are dipped in the hydrofluoric acid (HF) solution the total chemical reaction can be described as



$$\underset{F^-\quad H^+}{\equiv Si - O - Si \equiv} \longrightarrow \underset{F^-\quad H^+}{\equiv Si - O - Si \equiv} \longrightarrow \underset{F^-H^+}{\equiv Si + O - Si \equiv}$$

When the HF solution reacts with the glass ,the reaction between Si and the F− ions and the reaction between oxygen and the H+ ions occur simultaneously. , the bonding forces between the Si molecules on the surface area become weakened. This phenomenon improves the efficiency of ultrasonic machining and is called Chemical-assisted ultrasonic machining (CUSM) process. (Wang, H.S., *et al*, 1997).

In the conventional USM, the tip of the tool vibrates at low amplitude (2–50μm) and high frequency (20 kHz),

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*Corresponding author: **Kashish Bansal** which transmits a high velocity to the fine abrasive grains between the tool and the surface of the workpiece. The indentation of a material surface by the abrasives will cause local deformation and initiate cracks. The initiation and propagation of median and lateral cracks contribute to the material removal process the workpiece used in present study is soda glass.

Fig. 1 shows the difference in the machining mechanisms between the USM and the CUSM. (Choi J.P., *et al* 2007). However, in chemical-assisted ultrasonic machining, the propagation of impact energy in the lateral direction is limited because the linking forces between the molecules are weakened. Alternatively, in the median direction, the transmitted energy increases and results in deep median cracks. Therefore, the crater size of a single impulse of an abrasive is reduced and the removal rate can be increased.

3. Materials and Methods

Soda Glass has been used as the work material in the present investigation. The chemical composition and other mechanical properties of the material are shown in table 1. Two type of tools made of High Carbon Steel, High Speed Steel, with straight cylindrical geometry (diameter 8 mm) were used in this investigation. All the tools were made as one piece unit and attached to the horn by tightening the threaded portion of the tool with the horn.

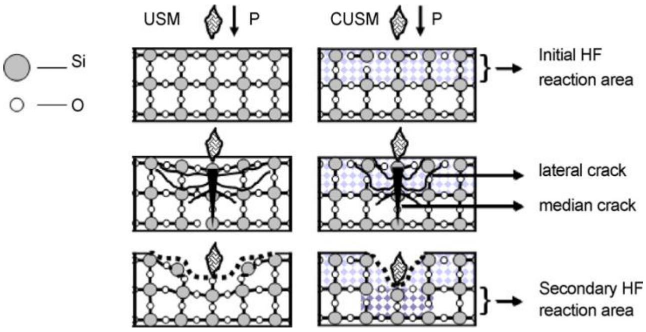

Figure 1: Mechanisms of USM and CUSM

Table 1: Typical Composition of Workpiece Material (%)

SiO_2	Na_2O	CaO	MgO	Al_2O_3	Fe_2O_3	K_2O
71.86	13.13	9.23	5.64	0.08	0.04	0.02

Three types of abrasive materials were used: silicon carbide, aluminium oxide and mix (silicon carbide+ aluminium oxide). Three different grit sizes were selected for each abrasive material: 280, 400 and 600. Slurry concentrations used were 20%, 25% and 30%. Power rating of the ultrasonic machine was selected as another process parameter for this investigation. Three levels of power rating were finalized from the pilot experimentation: 100 W, 200 W and 300 W. The process parameters and their levels selected for the final experimentation has been depicted in Table 2. The Orthogonal Array (OA) which was for this experimentation is L_{18}, which has 17 DOF assigned to its various columns. The additional four DOF were used to measure the random error. Table 3 shows fixed Input Process parameters.

The experiments were conducted on an 'AP-500 model Sonic-Mill' ultrasonic machine. The complete setup is divided into the four sub systems; power supply, Mill module unit, slurry re-circulating system and Workpiece.

Table 2: Process parameters and their levels

Factors	Level 1	Level 2	Level 3
Tool Material(A)	HSS	SS	
Power Rating(%)(B)	20	40	60
Slurry Concentration (%)(C)	20	25	30
Abrasive Slurry(D)	Al_2O_3	50% SiC +50% Al_2O_3	SiC
Abrasive Grit Size(E)	280	400	600

Table 3: Fixed Input Process Parameters

S.No.	Parameters	Constant Value
1	Frequency of vibration	20 KHz
2	Static load	1.63 Kg
3	Amplitude of vibration	25.3-25.6 µm
4	Depth of cut	2mm

4. Experimentation

Before finalizing a particular orthogonal array for the purpose of designing the experiments, the following two things must be established:
1. The number of parameters and interactions of interest
2. The number of levels for the parameters of interest

In the present investigation, five different process Parameters have been selected as already discussed. The tool material factor has two levels whereas all other parameters such as abrasive type, grit size, slurry concentration and power rating of the machine have three levels each. Hence, L-18 array (in modified form) was selected for the present investigation. L-18 array has a special property that the two way interactions between the various parameters are partially confounded with various columns and hence their effect on the assessment of the main effects of the various parameters is minimized.

Each trial was replicated twice. The slurry was maintained constant at a value of 36.4 x 10^3 mm3/min. To avoid any possibility of dullness of the edges of the abrasive grains, a large volume of slurry was prepared.

Evaluation of S/N Ratios

The S/N ratio is obtained using Taguchi's methodology. Here, the term 'signal' represents the desirable value (mean) and the 'noise' represents the undesirable value (standard deviation). Thus, the S/N ratio represents the amount of variation present in the performance characteristic.

Table 4: Control Log for Experimentation Based On L-18 OA

Trial No	Tool	Power Rating (%)	Slurry Concentration (%)	Type of Slurry	Grit size
1	HSS	20	20	SiC	280
2	HSS	20	25	Al_2O_3	400
3	HSS	20	30	Mix	600
4	HSS	40	20	SiC	400
5	HSS	40	25	Al_2O_3	600
6	HSS	40	30	Mix	280
7	HSS	60	20	Al_2O_3	280
8	HSS	60	25	Mix	400
9	HSS	60	30	SiC	600
10	SS	20	20	Mix	600
11	SS	20	25	SiC	280
12	SS	20	30	Al_2O_3	400
13	SS	40	20	Al_2O_3	600
14	SS	40	25	Mix	280
15	SS	40	30	SiC	400
16	SS	60	20	Mix	400
17	SS	60	25	SiC	600
18	SS	60	30	Al_2O_3	280

Main Effects due to Parameters

The main effects can be studied by the level average response analysis of raw data or of S/N data. The analysis is done by averaging the raw and/or S/N data at each level of each parameter and plotting the values in graphical form. The level average responses from the raw data help in analyzing the trend of the performance characteristic with respect to the variation of the factor under study. The level average response plots based on the S/N data help in optimizing the objective function under consideration. The peak points of these plots correspond to the optimum condition

Analysis of Variance (ANOVA)

The percentage contribution of various process parameters on the selected performance characteristic can be estimated by performing ANOVA. Thus, information about how significant the effect of each controlled parameter is on the quality characteristic of interest can be obtained

5. Results and Discussion

5.1 Material Removal Rate

The effects of parameters i.e. dielectric, workpiece, angle, concentration, current, pulse on time, pulse off time, powder were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trials was completed to measure the Signal to Noise ratio (S/N Ratio). MRR is calculated from the loss of weight of the workpiece during performance trial.

$$\mathrm{MRR} = \frac{W_i - W_f}{\rho t} \times 1000 \ \mathrm{mm^3/min}$$

Where Wi= Initial weight of workpiece (gm)
W_f = Final weight of workpiece (gm)
t= time period of trial (minutes)
ρ = density of the workpiece material (gm/cc)

The variance data for each factor and their interactions were F-tested to find significance of each factor. ANOVA table shows that the Power Rating (F value 279.14), Slurry Type (F value 202.62), Tool (F value 194.83), Slurry Concentration (F value 19.950), Grit Size (F value 8.660) and interaction AxD (F value 8.850) are the factors that are significant and affects MRR. The interactions AxB is found to be insignificant. It is observed that pulse on time is the most significant factor which contributes to MRR followed by current, concentration and type of powder used. Fig 2 shows Main Effects for Means.

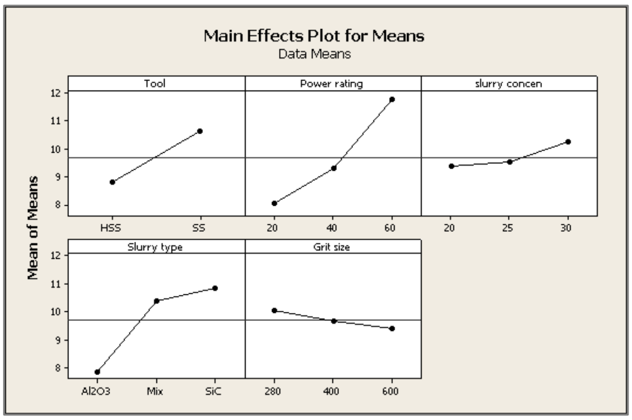

Figure 2: Main Effects of MRR for means

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the MRR. MRR is Higher is better type response which is given by:

HB: $S/N\,ratio = -10\log 10[\frac{1}{n}\sum_{i=1}^{n} y_i^{-2}]$

ANOVA for S/N ratio for MRR at 95% confidence interval shows that Power rating (F value 76.29) is the most significant factor in affecting MRR according to F-test. Fig 3 shows Main Effects for S/N Ratio.

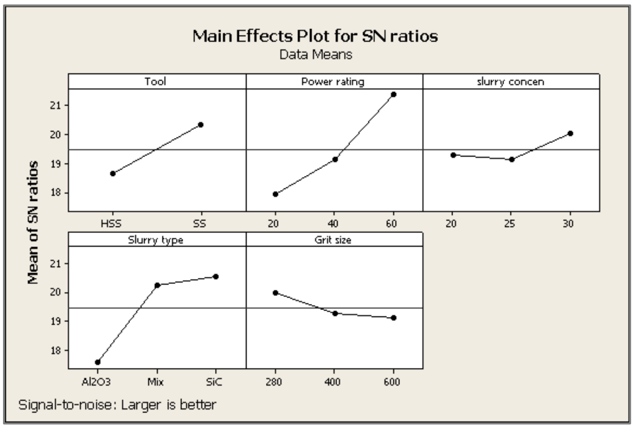

Figure 3: Main Effects of MRR for S/N ratio

It was observed that Power Rating was found to be the most significant factor with contribution of 44.76 % followed by Slurry type, type of Tool, Slurry Concentration, Interaction between Tool and Type of slurry and Grit Size with a contribution of 32.33 %, 15.53% ,2.1% ,0.86% and 0.82 % respectively. The interaction between Tool and Power Rating was found insignificant.

Confidence Interval around the Estimated Mean

$$CI = \sqrt{\frac{F_{\alpha,v1,v2}V_e}{\eta_{eff}}}$$

Where $F_{\alpha,v1,v2}$ = F ratio

α= risk (0.05) confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

CI around the MRR is given by 14.69 ± 1.13 mm^3/min.

5.2 Surface Roughness (SR)

The effects of parameters i.e. effects of parameters i.e. tool, power rating, slurry concentration, type of slurry, grit size and interaction between Tool and Type of slurry, Tool and Power Rating were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trials was completed to measure the Signal to Noise ratio (S/N Ratio). Surface Roughness (R_a) is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement. It is a 'Lower is Better' phenomena. Surface Roughness was measured using the Perthometer.

The variance data for each factor and their interactions were F-tested to find significance of each. ANOVA table shows that the Power Rating (F value 63.6), Slurry Type (F value 13.06) and Slurry concentration (F value 9.85) are the significant factors that are affecting SR. The type of tool, grit size and the interactions BxC are found to be insignificant.

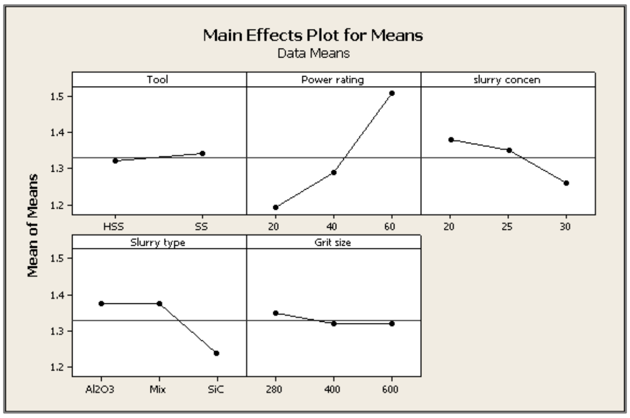

Figure 4: Main Effects of SR for means

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the SR. SR is Lower is better type response which is given by:

LB: S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}Y_i^2\right]$

ANOVA for S/N ratio for SR at 95% confidence interval shows that Power rating (F value 59.23) is the most significant factor in affecting MRR according to F-test.

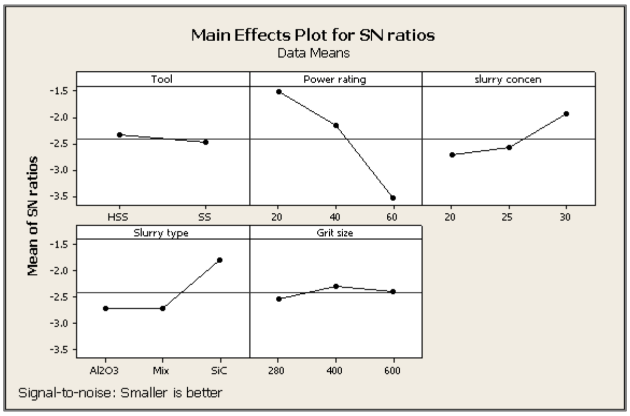

Figure 5: Main Effects of SR for S/N ratio

It was observed that Power Rating was found to be the most significant factor with contribution of 66.03 % followed by Slurry type and Slurry Concentration with a contribution of 15.77% and 9.71% respectively. Type of tool, Grit Size and Interaction between Power Rating and slurry Concentration was found insignificant.

Confidence Interval around the Estimated Mean

$$CI = \sqrt{\frac{F_{\alpha,v1,v2}V_e}{\eta_{eff}}}$$

Where $F_{\alpha,v1,v2}$ = F rati

α= risk (0.05) confidence= 1-α

v_1= dof for mean which is always = 1
v_2= dof for error = v_e
CI around the MRR is given by 1.02 $\pm$ 0.65 µm.

5.3 Comparison between USM and CUSM

As in MRR a higher average response characteristic is better has been seen that the MRR in USM is much less that of CUSM. So in order to compare the MRR results, the mean value of MRR is found for both the cases. Fig. 5 and Fig. 6 represent the comparison in values of MRR and SR respectively for both the processes graphically.

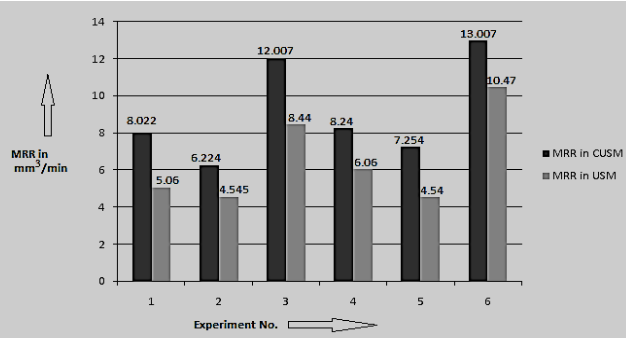

Figure 5 Graphical representation of MRR in CUSM and USM

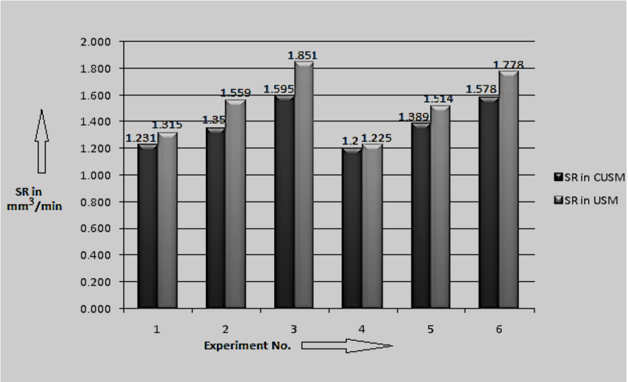

Figure 6 Graphical representation of SR in CUSM and USM

It was found that a poorer performance was obtained in USM as compared to CUSM in terms of MRR and a better surface finish is obtained in CUSM. It was found that in CUSM the MRR was increased by 40%.

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