Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Electrochemical Discharge Cross Peripheral Grinding (ECD-CPG) of borosilicate glass and its performance evaluation

V. G. Ladeesh* and R. Manu

Department of Mechanical Engineering
National Institute of Technology Calicut, Kerala - 673 601, India

Abstract

Ceramics are considered as difficult-to-machine materials due to its high hardness and brittleness. Economic and efficient machining of ceramics including glass is still a challenging task for modern industries. In this study, a new technique of combining Electrochemical Discharge Machining (ECDM) and Cross Peripheral Grinding (CPG) has been attempted to machine borosilicate glass. The new technique can be called as Electrochemical Discharge Cross Peripheral Grinding (ECD-CPG). In this process, a rotating hollow diamond core tool with its bottom portion coated with diamond grits at the lateral and end face will be maintained as a cathode in the normal ECDM setup. The electrochemical discharges beneath the rotating tool initially smoothen the glass and the grinding action of the diamond grits remove the molten glass from the machining zone. Channels of 6mm width, 15mm length and 0.7mm depth are machined using the developed technique. A systematic study has been conducted to investigate the effect of process parameters like voltage, inductance, electrolyte concentration and tool feed on average areal surface roughness using response surface methodology. Channel with low surface roughness was achieved at a low voltage of 80V, low inductance of 80mH, low electrolyte concentration of 1M and low feed rate of 1mm/min. The technique proved its potential to extend its application for machining advanced ceramics with better material removal rate and accuracy.

Keywords: Electrochemical Discharge Machining, Cross Peripheral Grinding, Hybrid Machining, Areal surface roughness, Response Surface Methodology, Analysis of variance

1. INTRODUCTION

The use of advanced ceramics and glass-ceramics are gaining more acceptance in many of the modern industries including biomedical instrumentation and aerospace industries due to its superior properties. The challenging task for these industries is the machining of these hard and brittle materials to the required shape and dimension economically and efficiently. Most of the traditional and non-traditional machining methods require high capital investment and high maintenance cost. This prevents their usage in small scale industries. Among the available non-traditional techniques, research on Electrochemical Discharge Machining (ECDM) has gained more importance in the recent years because of its high potential in machining ceramics and glass. The lack of repeatability, dimensional inaccuracy and difficulty in controlling the process restricts its application in industries. To enhance the process of ECDM, a new method of Electrochemical Discharge Cross Peripheral Grinding (ECD-CPG) has been developed. In ECD-CPG, a CNC controlled hollow diamond core grinding tool will be polarized as a cathode and a stainless steel plate acts as an anode. Both the electrodes are dipped in an electrolyte and a DC supply is applied across them. The hydrogen gas will be liberated at the tool cathode by electrochemical reactions which will eventually combine to form a gas film. This gas film intensifies the electric field due to its low electrical permittivity and thereby causes ionization and discharges. Thus several discharges emerge from the space between grits where the electric field attains its maximum value. When a workpiece is placed in the vicinity of the discharge beneath the tool, the discharges strikes its surface thereby dissipates its kinetic energy in the form of heat and converting the workpiece to a molten state. The rotating diamond core drill utilizes its grinding action to remove the molten material from the machining zone. This helps to conduct the machining of brittle ceramic material in the ductile regime.

Basak and Ghosh [1] experimentally found that the inductance of the circuit plays a predominant role in controlling material removal rate (MRR). An enhancement in MRR was observed with an extra inductance in the circuit. They developed a mathematical model to predict MRR in electrochemical discharge machining of glass. Chak and Rao [2] performed trepanning of alumina by ECDM using an abrasive tool. He observed that the use of pulsed DC reduced the cracking at high voltage and machining ability got improved with the abrasive tool. Jain et al. [3] performed electrochemical discharge machining of alumina and glass using a conventional cutting tool (CCT) and an abrasive cutting tool (ACT). The material removed for different voltages and temperatures was found to be high for ACT when compared with CCT. Ladeesh and Manu [4] performed drilling of borosilicate glass using G-ECDM and observed that thermal melting, grinding action and chemical etching are the different mechanisms contributing material removal. Liu et al. [5] used grinding aided ECDM for the machining of composites (alumina particles reinforced aluminium alloy) for the first time. In most of the studies mentioned above, researchers tried to improve the process of drilling using ECDM with the help of abrasive tools. No previous work has been reported on using abrasive tool for machining channels or slots on ceramics with the aid of ECDM
In the present study, a new technique of ECG-CPG has been attempted to develop channels on borosilicate glass. Since the process involves the electrochemical discharges to soften the work material and the grinding action happening at the periphery of the rotating diamond core grinding tool, the process is called Electrochemical Discharge Cross peripheral grinding. Response surface methodology was used to study the effect of process parameters like voltage, inductance, electrolyte concentration and tool feed on average surface roughness and channel overcut.

2. EXPERIMENTAL SETUP AND METHODS

A CNC router was used to control the tool movement in X, Y and Z direction which is shown in Fig. 1. The tool used is a diamond core grinding tool of 6mm diameter. The tool has diamond grits electroplated at its lateral and end face of the bottom portion. The workpiece used was a borosilicate glass of dimension 200mm x 50mm x 5mm. The electrolyte used was potassium hydroxide (KOH). A circuit has been developed (Fig. 2.) to study the effect of parameters like voltage and inductance on the ECD-CPG performance. An autotransformer helps to regulate the voltage and a bridge rectifier converts the AC to DC. Another autotransformer connected in series serves as a variable inductor whose inductance values at different positions of the selector nobe was determined using an LCR meter.

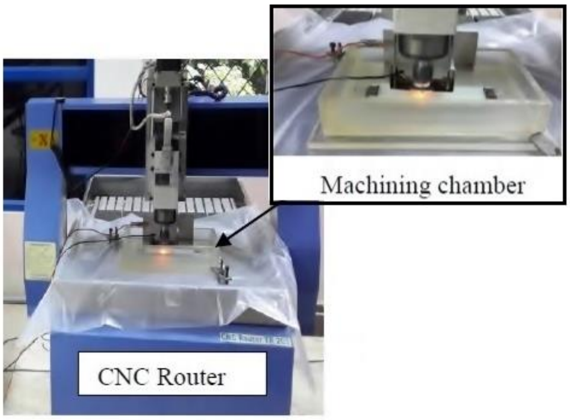

Fig. 1. Experimental Setup

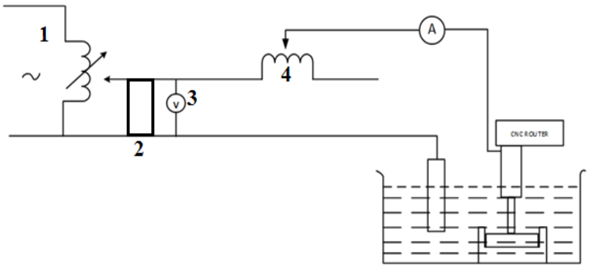

Fig. 2. Schematic diagram of circuit 1)Autotransformer1 2) Bridge rectifier 3) Voltmeter 4) Variable inductor

The surface roughness is measured using surface roughness tester (SURFTEST SJ-410, Mitutoyo, India) with cut-off length 0.8mm. Channel overcut was determined by taking the difference of the machined channel width and the tool diameter. Machined channel width was measured using a vision measuring system (Make: Insize, model – ISD A100 P). Initially, experiments are conducted using the approach of single factor at a time in which each factor is varied keeping the others constant. This helps to study the main effects of factors. To study the interaction effects, another experiment was conducted using Response Surface Methodology.

3. RESULTS AND DISCUSSIONS

3.1 Effect of machining parameters

Variation of surface roughness with process parameters is shown in Fig. 3. to Fig. 6. Here roughness value rapidly increases with increase in circuit inductance value till reaching a point and then shows a gradual increase with further increase in inductance (Fig. 3). Inductance is the property of the circuit by which an electro motive force will be induced in the circuit due to a change in the current flow. An inductor is a passive component in the circuit which stores energy in the form of a magnetic field. An increase in the inductance value produces discharges with higher energy which removes material in the form of micro craters with higher depth. These craters with higher depths when overlap creates a surface with higher surface roughness value. This explanation is applicable in the case of voltage also, where an increase in voltage increases the Ra value (Fig. 4). The use of higher voltages supplies more energy for the discharges, thereby increasing the crater dimension and surface roughness values. An increase in electrolyte concentration increases the specific conductivity of the electrolyte, this helps to draw more current and accelerates the electrochemical reaction thereby increasing the hydrogen bubble liberation rate. Thus a major portion of the supplied energy per unit time will be utilized by the discharges producing craters of higher depth thereby increasing the Ra value initially. Further increase in concentration reduces the ionic mobility and cause a degradation in specific conductivity which produces discharges with lesser energy. Moreover, the effect of high temperature chemical etching is prominent at higher concentrations. These combined effects reduce the surface roughness value at higher concentrations (Fig. 5). Feed rate is another important factor that controls the surface roughness. When tool feed increases, the surface roughness increases (Fig. 6). As the feed increases, the number of discharges striking a particular location decreases and thus the interaction time of the discharge energy with the workpiece also reduces which eventually reduces the thermal melting action. This cause the grinding action of the grits to predominate in the material removal action and the deep grooves or grinding marks increases the Ra value of the machined surface

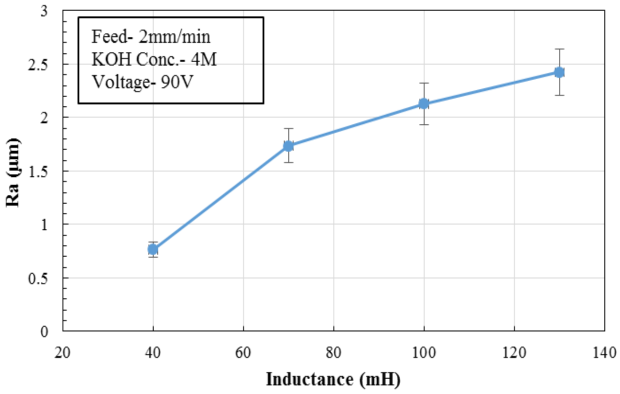

Fig. 3. Effect of inductance on Ra

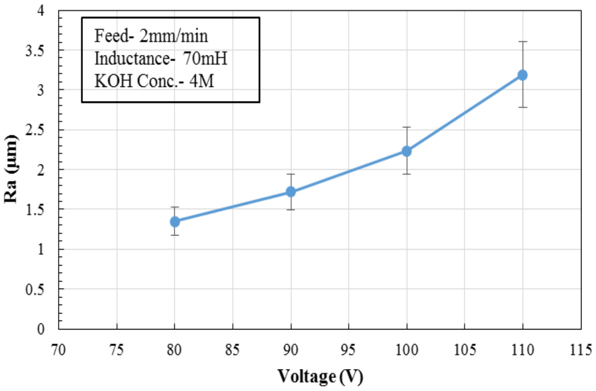

Fig. 4. Effect of voltage on Ra

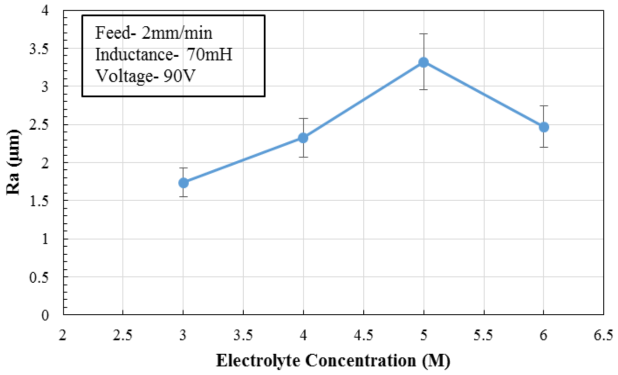

Fig. 5. Effect of electrolyte concentration on Ra

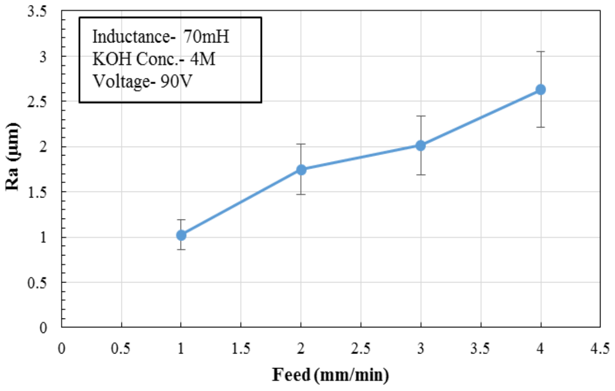

Fig. 6. Effect of feed rate on Ra

3.2 Design of Experiment

The interaction effects of the factors can only be analyzed systematically with the aid of the principles of Design of Experiment. The main effects and interaction effects of factors are studied with the help of Response Surface Methodology (RSM). Box- Behnken Design is a widely used three level response surface design which helps to perform the experiments in a more economical manner as it reduces the experimental runs without compensating the efficiency. The effect of parameters like voltage, inductance, electrolyte concentration and feed rate on the surface roughness of machined channels and channel overcut are studied using RSM. The areal surface roughness of the machined channels are measured with the help of an optical profilometer (make: alicona, model: Infinite Focus G5). In the case of contact surface roughness measurement, the probability that the probe makes contact with the true highest or lowest points of peaks and valleys of the surface is infinitesimally small. This can be overcome with the help of non-contact measuring technique using optical profilometer. The average areal surface roughness value will be always higher than that measured using contact type techniques since it measures the true peak and valley points. The selected factor and their levels are shown in Table 1.

Table 1 Selected factors and their levels

Factors & Notations	Unit	Levels		
		Low	Medium	High
Feed (A)	mm/min	1	2	3
Voltage (B)	V	80	90	100
Inductance (C)	mH	40	80	120
Concentration (D)	M	2	4	6

The main effects plot for average areal surface roughness (Sa) is shown in Fig. 7. The trend of the graphs is similar to that shown in section 4.1. The areal surface roughness value increases with an increase in feed, voltage and concentration. In the case of inductance, the mean surface roughness value initially decreases and reaches its minimum value for a medium inductance value of 80mH. A further increase in inductance shows an increase in roughness value.

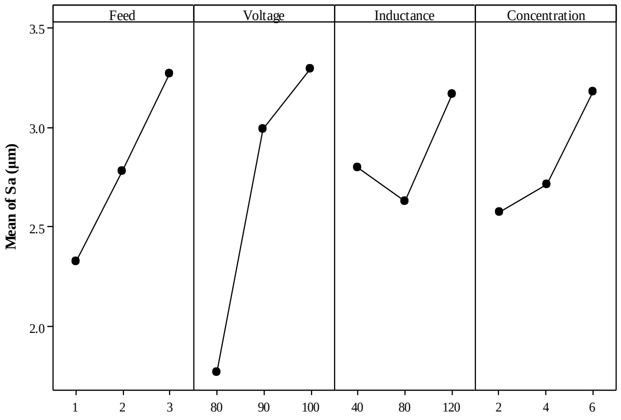

Fig. 7. Main effects plot of average areal surface roughness (Sa)

Analysis of variance was conducted to study the significance of machining parameters on average areal surface roughness. Backward elimination regression was performed to remove the insignificant terms. From the F-value, Voltage is identified as the most significant factor and concentration is identified as the least significant factor. The square effects of voltage and inductance as well as the interaction effects of Feed-Voltage, Feed-Concentration are also identified as significant in controlling the surface roughness. A second order regression model is developed to correlate the Sa value with the machining parameters which is given by (1). The R^2 value and R^2 (adj) values for the model are 83.3% and 75.88% respectively which are in good agreement with each other and is an indication that the model can predict the Sa value well. The scanned images of the machined channels using the optical profilometer are shown in Fig. 8.

$$Sa = -41.4 + 3.30*A + 0.854*B - 0.0228*C - 0.228*D - 0.00383\, B*B + 0.000206\, C*C - 0.0460\, A*B + 0.1770\, A*D \qquad (1)$$

Table 2 Results of ANOVA for surface roughness

Source	* DoF	Sum of Squares	Mean Squares	F-Value	P-Value
A	1	0.7641	0.76407	5.38	0.032
B	1	6.4211	6.42111	45.19	0.000
C	1	1.9797	1.97966	13.93	0.002
D	1	0.20856	0.20856	1.47	0.241
B*B	1	0.9382	0.93820	6.60	0.019
C*C	1	0.6954	0.69538	4.89	0.040
A*B	1	0.8473	0.84732	5.96	0.025
A*D	1	0.5013	0.50126	3.53	0.077
Error	18	2.5577	0.14210		
Lack-of Fit	16	2.4949	0.15593	4.97	0.180
Pure Error	2	0.0628	0.03139		
Total	26	15.3179			

*DoF- *Degrees of Freedom*

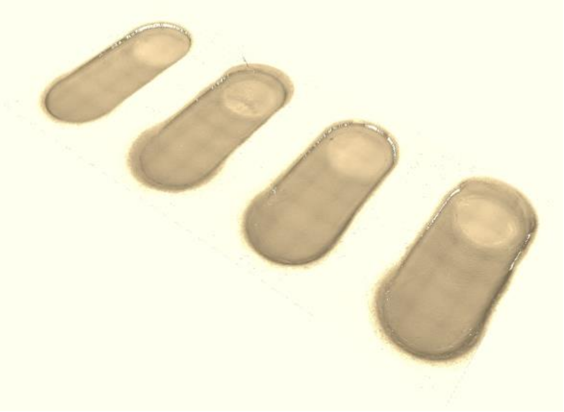

Fig. 8. Scanned image of the machined channels

4. CONCLUSIONS

In the present study, a new technique of Electrochemical Discharge Cross Peripheral Grinding (ECD-CPG) has been successfully performed on borosilicate glass to develop channels. The process of ECD-CPG is identified as a thermal-assisted machining technique in which the electrochemical discharges initially soften the workpiece and the grinding action of the abrasive tool completes the material removal from the machining zone. The effect of machining parameters like voltage, inductance, electrolyte concentration and feed rate on average profile surface roughness (Ra) and average areal surface roughness values (Sa). Both Ra and Sa values increase with an increase in voltage, inductance, electrolyte concentration and tool feed rate. From the analysis of variance, voltage and inductance ate identified as the major factors controlling the Sa value. A second order regression model has been developed to correlate the Sa value with the machining parameters. The process of ECD-CGP proved its potential in machining glass in a more efficient and economic manner. The usage of ECD-CGP can be further extended for the machining of advanced ceramics.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support provided by Kerala State Council for Science Technology and Environment (grant no. 935/2015/KSCSTE) to carry out this study. The authors would like to thank as well Department of Science and Technology (DST), India for providing me the facility of Optical Profiler available at Dept. of Mechanical Engineering, NIT Calicut which is purchased under the scheme FIST:2015-2020.

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