AN EXPERIMENTAL STUDY ON FABRICATION OF MICRO CHANNELS IN TITANIUM NITRIDE ALUMINA COMPOSITE USING ELECTRO-DISCHARGE MILLING

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Abstract: The miniaturized device of advanced ceramics such as microreactors, micro heat exchangers are required for chemical efficiency, thermal efficiency, and effectiveness of the system. The present paper deals with the fabrication of microchannels in TiN-Al_2O_3 ceramic-composite for microreactor application using micro electro-discharge milling. TiN-Al_2O_3 ceramic-composite is a highly electro-conductive and chemically inert ceramics. The process parameters of the μ-ED Milling for TiN-Al_2O_3 composite have been analyzed. Moreover predicted values and significant parameters on MRR, EWR and overcut are also studied.

Keywords: Micro-ED Milling, Microchannel, Machining, Ceramics, Response Surface Methodology, TiN-Al_2O_3 Composite.

1. INTRODUCTION

Micro-channels have applications in Micro-Electro-Mechanical system (MEMS), Micro Chemical Reactor (MCR) and Biomedical Systems. These micro-channels could also be used in miniaturized devices such as chemical reactors, heat exchangers, [12]. Miniaturized devices of advanced ceramics are gaining importance these days for reducing weight to volume ratio and increasing thermal efficiency of the system. Miniaturized devices have the capability to enhance the thermal efficiency as they help in rapid heat transfer, [9]. Liu et al. (2008) have manufactured micro fuel-based power unit and experimentally explained that fabrication of miniaturized devices is still a challenge although micro gas turbines can offer the highest power density. Xia and Chan (2015) have studied the improvement in the effectiveness of heat exchangers using micro-channels. They have concluded that a smaller inlet area in microchannel enhances the heat transfer rate. Khan et al. (2013), [13], have fabricated micro heat exchanger and explained fluid flow behavior and temperature distribution in microchannels that are found to vary with geometric characteristics of the channels. Materials of these heat exchangers play very important roles and recently ceramics are used to build heat exchangers and reactors where high temperature and corrosion resistance are the prime criteria apart from high strength and low weight to volume ratio, [20, 21]. However, the machining of ceramics is still extremely difficult due to its high wear resistance and low fracture toughness. Moreover, high tool wear and generation of high cutting forces leads to surface damage. These problems hinder full-scale applications of advanced ceramic, [3, 14], unconventional machining process like electro-discharge machining (EDM), a non-contact type machining process in which a gap called inter-electrode gap (IEG) leads to the generation of electrical discharge plasma application of electrical field within a flowing liquid dielectric, is, therefore attempted on difficult to cut materials. Physics of EDM involves the creation of the plasma by dielectric breakdown and subsequent removal of materials and tools by melting, evaporation, and fracture. Thus, effectively the physics of erosion of electrodes in plasma is utilized in the EDM process, [4, 11, 19]. It has been observed by optical emission spectroscopy that the dielectric liquid dissociates and the electrode materials erode during the discharge, [2]. The density of plasma gradually diminishes with time, [2]. The absence of contact between tool and workpiece is a remarkable advantage which justifies the use of this process for machining very hard, brittle and fragile materials. The only force in EDM is the impulse by the flash-over, [18, 22]. Micro-EDM technology is a variant of EDM and has the ability to generate complex micro-geometry in a variety of dimensions in hard materials if the material is conductive enough electrically (Resistivity < 100 Ω.cm), [8, 10]. Moreover, it takes care of the precision in machining in very small dimension (micron level). Resistance-capacitance (RC) electrical power supply to create low spark energy for the removal of small units of material is the principal strategy behind the technology of micro EDM process, [1, 8]. The spark is produced by the dielectric breakdown of the fluid between the electrodes (tool and work-piece).

The presence of hard but electrically conducting phases like TiN and TiB_2 in a structurally important insulating ceramic matrix like Al_2O_3, Si_3N_4 etc. increases the electrical conductivity and consequent EDM machining of the composite. Subsequent studies on hybrid machining of the composite have been initiated to accelerate and improve the surface finish of the work piece, [15]. Baghel et al. (2018), [16], have observed that the surface roughness of the composite could be controlled by the parameter optimization of the diamond grinding assisted EDM. Very little information on the micro-EDM of ceramics could be available in the literature. Kumar et al. (2015) have machined conducting SiC ceramics with micro-EDM and concluded that the performance characteristics of µ-EDM are mainly governed by the plasma channel radius controlled by the discharge energy. Liu et al. (2015) have studied the machining of Si_3N_4-TiN ceramics with micro-EDM and suggested that the mechanism of material removal involves a chemical reaction that leads to the oxidation and decomposition of Si_3N_4 and TiN.

The present paper, therefore, deals with the fabrication of microchannels by ED milling on extremely hard to machine newly developed ceramics i.e. Titanium Nitride-Alumina composite (TiN-Al_2O_3). TiN-Al_2O_3 composite has outstanding physical, chemical and mechanical properties such as corrosion and abrasion resistance at high-temperature, high hardness, toughness, low friction coefficient and considerable thermal conductivity, [6, 17]. The hot hardness and good electrical conductivity suits this ceramics for the application of micro tools, micro heat exchanger. High chemical and wear resistant encourage its application as a microchemical reactor, [9]. No report is yet available on the micro EDM milling of reaction hot-pressed TiN-Al_2O_3 composite for microchannels whose physical properties are different than those of the materials studied earlier.

Response surface methodology (RSM) with three control factors such as electrode rotation speed (S), capacitance (C) and voltage (V) has been used for experiment designing. Micro-channels of 500µm depth and 5mm length are fabricated in the ceramic composite with the help of tungsten rod electrodes (diameter 500µm) by micro electro-discharge milling (µ-ED Milling).

2. MATERIALS AND METHODS

The experiments were performed on a hybrid µ-EDM (DT-110) machine (Mikrorotools, Singapore). Response surface methodology (RSM) with a series of 20 experiments was adopted with three input parameters to study the influence of each input parameters on response parameters (MRR, EWR) as shown in Table 1.

Tungsten cylindrical rods with diameter 0.5mm were used as tool electrodes. De-aromatized hydrocarbon was used as the dielectric fluid. MRR and EWR were calculated by dividing total volume removed with the total machining time for each microchannel. Geometrical measurements of the machined surfaces were taken with an optical microscope. An average gap of 25µm was maintained between the tool and the work-piece.

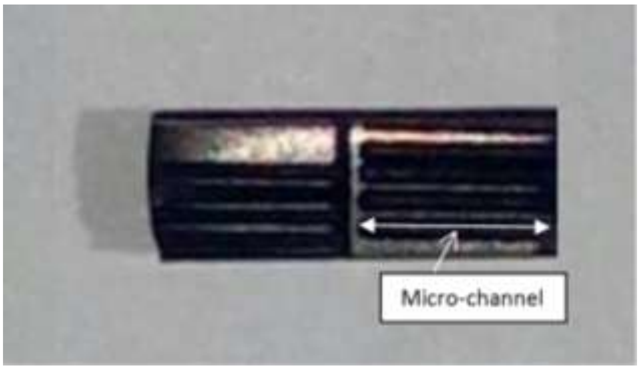


Fig.1. Microchannels of dimensions 5000 µm x 500µm x 5mm made from TiN-Al_2O_3 ceramic-composite

Table 1. ED Milling parameters

No.	Parameters (unit)	Values
1	Speed (rpm)	500,800,1100
2	Capacitance (µF)	0.01,0.1,0.4
3	Voltage (volt)	80,100,120
4	Electrode	Tungsten
5	Electrode diameter	500 micron
6	Channel length	5mm
7	EDM oil	Dearomatized Hydrocarbon Fluid

3. RESULTS AND DISCUSSION

Experimental results for MRR and EWR with predicted values of these response parameters are shown in Table 2. The predicted values are obtained with RSM results using Design Expert software®.

Table 2. Process parameters and predicted responses

Run	Spindle Speed [rpm]	Voltage [volt]	Capacitance [μF]	MRR [mm^3/min]	Predicted MRR [mm^3/min]	EWR [mm^3/min]	Predicted EWR [mm^3/min]
1	800	100	0.1	0.036585	0.048000	0.002356	0.0053955
2	1100	80	0.4	0.054022	0.048785	0.00453	0.0068326
3	1100	120	0.4	0.060274	0.085355	0.006710	0.0068326
4	500	120	0.01	0.016152	0.055895	0.003850	4.1E-05
5	1100	80	0.01	0.007009	0.013435	0.005950	0.0011378
6	800	100	0.1	0.035658	0.048000	0.000249	0.0053955
7	500	80	0.4	0.035767	0.032950	0.002389	0.0068326
8	500	80	0.01	0.013783	0.000590	0.00155	0.002214
9	800	100	0.01	0.038760	0.045690	0.00217	0.0016334
10	800	100	0.1	0.040179	0.048000	0.000259	0.0053948
11	1100	100	0.1	0.013377	0.004400	0.00437	0.0062302
12	800	100	0.1	0.056890	0.048000	0.00266	0.0053955
13	500	120	0.4	0.106383	0.105845	0.00339	0.0068326
14	500	100	0.1	0.022796	0.008220	0.00294	0.0062302
15	800	100	0.1	0.035629	0.048000	0.002204	0.0053955
16	800	100	0.4	0.113136	0.102650	0.00326	0.0062302
17	1100	120	0.01	0.015085	0.003795	0.004270	0.0068326
18	800	100	0.1	0.035942	0.048000	0.002978	0.0053955
19	800	120	0.1	0.089463	0.071090	0.003093	0.0062302
20	800	80	0.1	0.044643	0.039460	0.003030	0.0062302

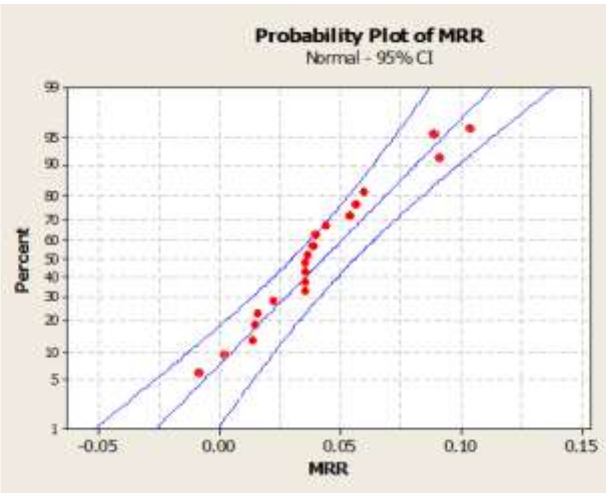


Fig. 2 Probability plot for MRR

The normal probability plots of residuals for MRR and EWR (Figure 2 and Figure 3) show that most of the residuals are falls within the six sigma limit and forming almost a straight line representing that the errors are normally distributed.

The empirical relation between the response parameters and control factors are can be expressed by the second-order polynomial equation (1) and (2). The equations are:

$$MRR=0.0463+(0.00081xS)-(0.00621xV)-(0.21139xC)-(4.15x10^{-7}xS^2)+(2.887x10^{-5}xV^2)+(0.0204xC^2)+(0.00041xVxC) \quad (1)$$

$$EWR=0.0316178-(1.33264x10^{-5}xS)-(3.28437x10^{-4}xV)-(0.00438857xC)+(0.000282318xS^2) \quad (2)$$

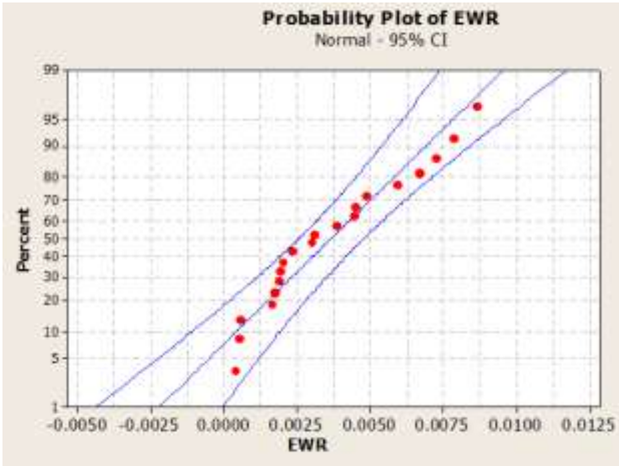


Fig. 3. Probability plot for EWR

The influence of control factor could be understood by the main effects plot. It is a plot of the means at each level of factors. The magnitude of various main effects and relative strength can be compared with these plots. Since MMR is desired to be maximized, the S/N ratio is calculated by “larger is better” equation (3):

$$\left(\frac{S}{N}\right)ratio_{MRR} = 10\log_{10}\frac{\sum_{i=1}^{n}\frac{1}{Yi^2}}{n} \quad (3)$$

$$\left(\frac{S}{N}\right) ratio_{EWR} = \log_{10} \frac{\sum_{i=1}^{n} Yi^2}{n} \quad (4)$$

where n is the number of replications.

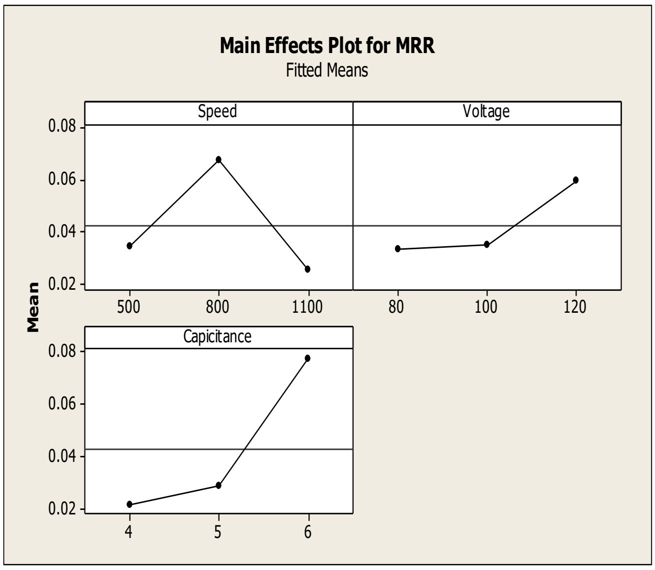


Fig. 4. Main effects plot for MRR

MRR is low at low electrode rotation speed, increases with an increase in the speed and reaches an optimal value; then decreases. MRR also increases with the increase in the value voltage and capacitance. Capacitance has the highest S/N ratio and, therefore, holds rank one followed by speed and voltage for MRR as shown in Figure 4. The value of EWR is desired to minimize, The S/N ratio for EWR is calculated by "smaller is better" equation (4). The main effect plot (Figure 5) for electrode wear shows that capacitance holds rank one followed by speed and voltage. Higher capacitance and higher speed lead to more EWR. Here capacitance is the most influencing parameter followed by electrode rotation speed that indicates at higher speed and higher capacitance, discharge energy is high enough to wear out the electrode.

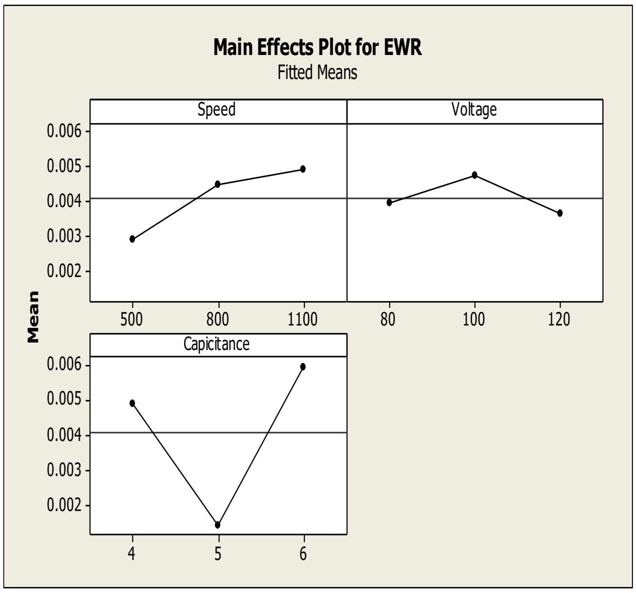


Fig. 5. Main effects plot for EWR

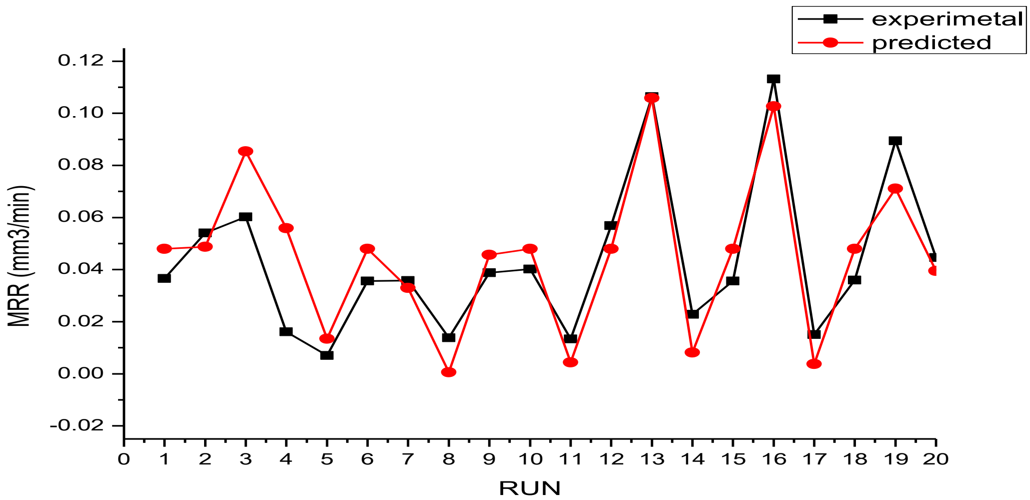


Fig. 6. Experimental and predicted values of MRR

The response and predicted values graphs are shown in Figure 6 and Figure 7. The predicted values of MRR and EWR are showing the same pattern as experimental values that indicates adequacy of the predicted model for MRR as well as for EWR. In EDM, the electric spark occurs between the two nearest points on the positive and negative electrode in the presence of dielectric. Thus machining may occur on the side surface that leading to overcut.

Overcut cannot be prevented as it is inherent to the EDM process, it could only be controlled by a suitable parameter setting. The effects of various control parameters on overcut are shown in Figure 9.

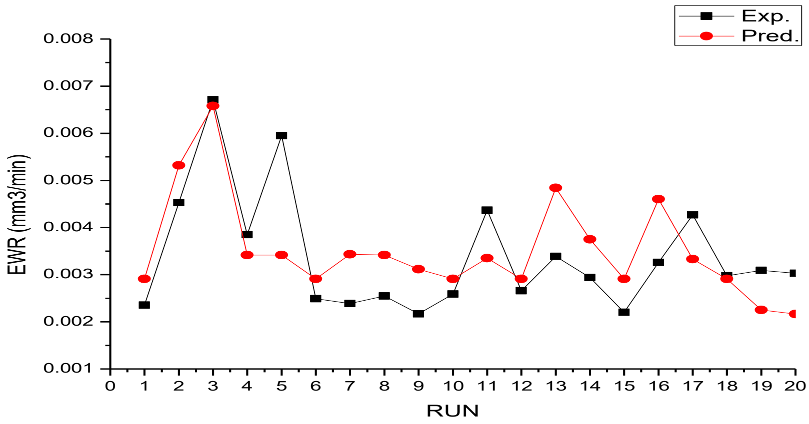
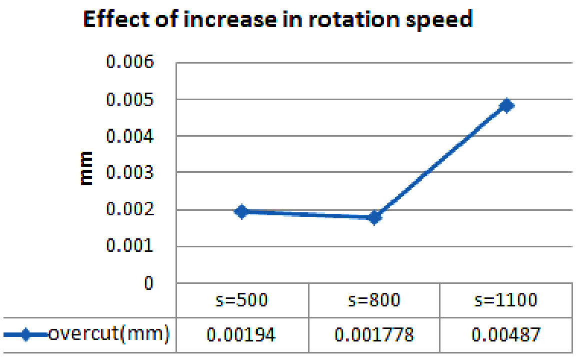
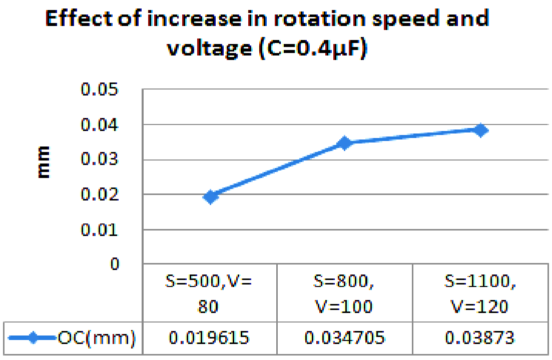


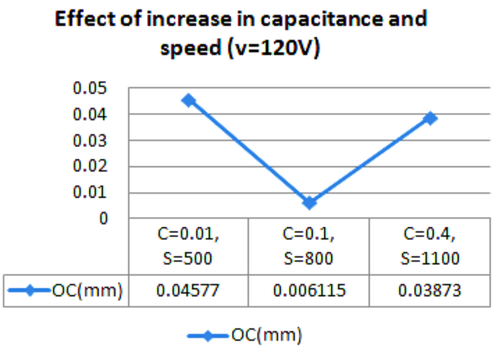
Fig. 7. Experimental and predicted values of EWR

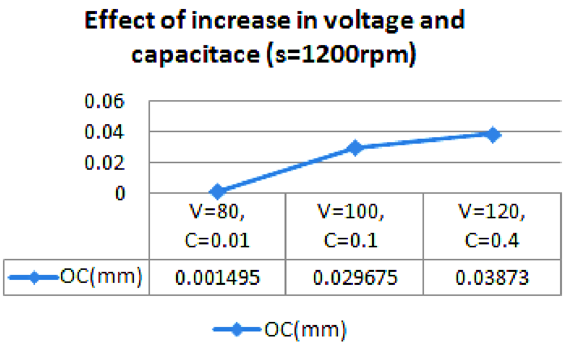


(a) Effect of increase in rotation speed



(b) Effect of increase in rotation speed and voltage





(c) Effect of increase in capacitance and speed at high voltage, (d) Effect of increase in voltage and capacitance at high speed

Fig. 8. Influence of control factors on overcut

As shown in Fig. 8a, the overcut tends to increase with the increase in the value of electrode rotation speed. This is due to the fact that the centrifugal force increases by increasing the rotational speed that leads to removal of debris from the interelectrode gap (IEG) and places them in side-gap thus lead to side spark. This phenomenon increases with the increase in speed and leads to more overcut. Figure 8b is showing the effect of voltage with electrode rotation speed. The graph is showing, the increase in overcutting with combined increased in speed and voltage. The first reason for the increase of overcutting is an increase in centrifugal force on debris and another reason which leads to increasing overcut is an increase in discharge energy. More discharge energy tends to remove more material from the channel wall.

As higher voltage leads to more overcut thus at a high voltage setting the overcut is studied. Figure 8 (c) is showing the effect increase in capacitance and speed at high voltage. High capacitance and high speed leads to an increase in discharge energy thus more active pulse in the wall gap that results in increasing the size of crater on the sidewalls of tool electrode and workpiece and lead to generating discharge between them, and, as a result, OC is highest at up to capacitance value 0.4 µF and minimum at 0.1µF. Figure 8d is showing the effect of an increase in voltage and capacitance at high speed. The combination of high discharge energy and high speed leads to more removal of sidewall surface thus more overcut. These iterations suggest that for at high capacitance and voltage value, the MRR and overcut both are high then these parameters should be optimized based on application.

4. CONCLUSIONS

The present study has shown that fabrication of microchannels on $TiN-Al_2O_3$ ceramic-composite considering its potential application in a micro heat exchanger and micro-chemical reactors could be accomplished by the µ-ED Milling process. Material removal rate (MRR) mainly depends on high electrical discharge energy created by capacitance and applied voltage while the electrode wear rate (EWR) depends on the rotation speed of the tool. High speed with high capacitance leads to more EWR. The overcut is high at high discharge energy value i.e. $0.5\ CV^2$.

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