Int J Adv Manuf Technol (2013) 64:187–194
DOI 10.1007/s00170-012-3995-5

ORIGINAL ARTICLE

Electrical discharge machining of ceramic matrix composites with ceramic fiber reinforcements

Chenjun Wei · Li Zhao · Dejin Hu · Jun Ni

Received: 30 November 2010 / Accepted: 13 February 2012 / Published online: 3 March 2012

Abstract Ceramic matrix composites (CMC) are considered the next generation of advanced materials used in space and aviation due to their high-temperature strength, creep resistance, chemical resistance, low porosity, and low density. However, these materials are difficult to process owing to the large cutting force and high cost on tool consumption. electrical discharge machining (EDM), featured by the negligible machining force and acceptable tooling cost, is a potential nontraditional machining technique for CMC. In this paper, EDM was used to process a new class of advanced CMC, that is, those with continuous ceramic fiber reinforcements. The challenge is its low material removal rate (MRR) due to the low workpiece conductivity and debris evacuation efficiency. Electrode vibration and dielectric deep flushing were used to promote debris evacuation, and an increase of MRR and surface quality without sacrificing tool wear ratio was observed. Gap voltage, peak current, pulse duration, and duty ratio were studied using design of experiments for deeper understanding of the process. The effect of these parameters was investigated, and an analysis of variance was conducted. The optimal condition was also predicted and experimentally validated. It was found that a high gap voltage or low duty ratio leads to a high machining rate due to improved debris evacuation efficiency. The material removal mechanism was found to be cracking due to thermal expansion of the matrix and breakage of the nonconductive fibers.

C. Wei (✉) · L. Zhao
Department of Processing Technology,
Shanghai Institute of Radio Equipment,
203 Liping Rd,
Shanghai 200090, China
e-mail: vip_payton@163.com

D. Hu · J. Ni
Department of Mechanical and Power Engineering,
Shanghai Jiao Tong University,
Shanghai 200240, China

Keywords EDM · Ceramic matrix composite · Fiber reinforcement · Process optimization

1 Introduction

Ceramic matrix composites (CMC) are a new generation of advanced structural materials that are becoming increasingly popular in space and aviation field due to their extraordinary properties such as high temperature strength, creep resistance, chemical resistance, low porosity, low density, and low thermal expansion rate. These materials have been used for nozzle extensions and combustion chambers in propellers. Turbine shrouds, combustor liners, and heat exchanges have been successfully built and tested using high-performance CMC. Ceramic matrix composite is a material that contains discrete phases distributed within continuous nonmetallic, inorganic phase (e.g., Al_2O_3, SiO_2, SiC, Si_3N_4, etc.). The discrete phases can be particles, whiskers, continuous fibers, and sheets, providing additional mechanical reinforcements for the matrix through energy absorption behaviors such as debonding, crack deflection, fiber bridging, and fiber pullout [1].

Due to the superb thermo-mechanical properties against harsh working environments, CMC, particularly those with continuous ceramic fiber reinforcements, are extremely difficult to machine, as traditional cutting or grinding usually leads to low machining rate and large tool wear. Ultrasonic machining [2] attacks CMC by repetitively generating micro-cracks; however, the material removal rate (MRR) is low. Laser machining [3] may cause thermal stress and thermal-affected zones on the workpiece in addition to the high machining cost. Abrasive waterjet [4] is a fast and cost-efficient process, but it produces kerf deformation and delamination on the layered substrates.

Electrical discharge machining (EDM) [5–8], featured by the negligible machining force and low tooling cost, has been widely commercialized for fabricating difficult-to-machine geometries on difficult-to-machine materials. In EDM, the electrode and electrically conductive workpiece are close to each other, causing dielectric breakdown of dielectric media between them. Sparks occur due to the breakdown, inducing high temperature gradients on the workpiece. The workpiece is therefore thermally eroded. However, EDM generally requires the workpiece to have a maximal electrical resistivity of 100Ω cm. For example, the resistivity of SiC is in the range of 10^3 to 10^5Ω cm, making it almost impossible for direct EDM. But the resistivity can be reduced to as low as 10Ω cm by infiltrating Si to the matrix for the material to be EDMed [9].

The material removal in EDM of ceramics is attributed to micro-cracks in the surface and loose grains in the subsurface due to thermal shock [10]. Patel et al. [11] studied the surface integrity and machining mechanism in EDM of Al_2O_3 matrix composite; they showed that the machining mechanism is dissociation, melting and evaporation, oxidization and decomposition within low current range, and thermal spalling within high current range. Since EDM debris generated by cracking is always too large to be efficiently evacuated, the production rate remains low. Ghoreishi and Atkinson [12] compared vibratory, rotary, and vibro-rotary EDM and found that vibro-rotary EDM leads to high MRR, tool wear ratio (TWR), and surface roughness. Ultrasonic vibration assisted dry EDM in cemented carbides [13] has been demonstrated. Regarding process improvement and optimization, Lauwers et al. [14] developed a novel method for sinking and milling EDM of ceramics and doubled the production rate. Clijsters et al. [9] studied the effect of process parameters on MRR, TWR, and surface roughness in the manufacturing of complex features. Insulating ceramics were successfully EDMed using assisting conductive sheets [15]. The effect of conductive phase on the wire EDM performance of ZrO_2-based CMC was investigated.

Compared with ceramics, research on CMC in terms of process augmentation and optimization is extremely lacking. In particular, EDM of CMC with continuous ceramic fiber reinforcements has not been reported so far. In fact, these reinforcing phases in CMC are almost insulating, inducing large challenge on its materials processing.

In the present work, EDM was used to process a new class of advanced CMC, i.e., those with continuous ceramic fiber reinforcements. The objective is to evaluate the machinability of the material, improve the machining performance, and understand the material removal mechanism of the process. First of all, electrode vibration and dielectric deep flushing were applied to enhance debris evacuation, making the material removal process progressive and stable. Secondly, the effect of process parameters was analyzed using design of experiments (DoE). Gap voltage, peak current, pulse duration, and duty ratio were studied for process optimization. An analysis of variance (ANOVA) was conducted; an optimal condition for high MRR was obtained and thus experimentally validated. Lastly, machined surface was examined using a scanning electron microscope (SEM) to identify the material removal mechanism.

2 Experimental details

2.1 Experimental setup

A commercial triaxial EDM die-sinker (Solution HS–150) was used for the experiments, as shown in Fig. 1a. This machine had a positioning accuracy of 2 μm in each axis. A homemade EDM head [8, 16] was mounted on the vertical axis of the machine, shown in Fig. 1b. A tool electrode was chucked on a hollow spine in the EDM head; a hose made of nylon was connected to the spine. During the machining,

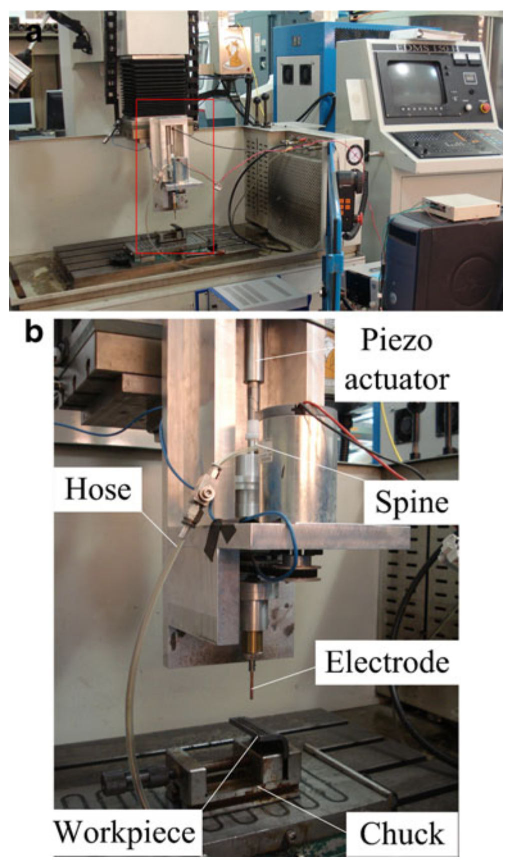

Fig. 1 The experimental setup. **a** Machine tool. **b** EDM head

dielectric fluid was pumped up to the hollow spine through the hose with a fixed flow rate of 74 ml/min. The other end of the spine was fixed on a piezoelectric actuator with a bandwidth of over 1 kHz, which was used in the EDM head to generate vibration along the axis of electrode. The piezoelectric actuator had a working range of 45 μm with an error of ±10% of the intended distance. The actuator was connected to a charge transducer, which was controlled by a function generator. Voltage signal output from the function generator was amplified and converted to charge signal to alter the length of the piezoelectric actuator at a high frequency, thus generating electrode vibration. The dielectric fluid was kerosene, which is commonly used in die-sinking EDM for high machining speed and surface quality [17]. A chuck holding the workpiece was fixed on a magnetic chuck.

The workpiece material used was continuous SiC fiber-reinforced SiC matrix composite (HiPerComp™). The composite nominally consists of 20–25 vol.% SiC fiber, 8–10 vol.% BN fiber coating, 63–70 vol.% SiC matrix melt infiltrated with Si, and <2 vol.% porosity [18]. Figure 2 shows the schematic of structure of the workpiece. As seen in the figure, the workpiece had eight laminated layers with a thickness of 0.7 mm for each layer. Fibers in neighboring layers were perpendicular to each other, and the diameter of the fibers was approximately 20 μm. Thermal properties of the composite material are listed in Table 1.

2.2 Experimental procedure

Process parameters were selected for EDM semi-finishing. Bronze were chosen as the electrode material, since it yields fast material removal with low tool wear [17]. The electrode was a hollow tube with an outer diameter of 3 mm and an inner diameter of 1.5 mm, allowing dielectric fluid to flush the machining area through it. The end of the electrode was flattened using a sand paper. Open voltage was set as 160 V, which is typically used in EDM. Electrode feed direction was Z down for hole drilling, as shown in Fig. 2. Machining

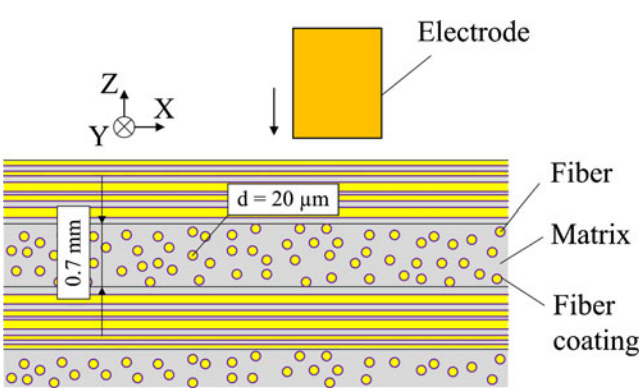

Fig. 2 Schematic of the structure of fiber-reinforced ceramic matrix composites

Table 1 Material properties of the workpiece

Material property	25°C	1,200°C
Density (g/cm^3)	2.80	2.76
Heat capacity (J/g K)	0.71	1.14
Thermal diffusivity XY (mm^2/s)	16.1	4.7
Thermal diffusivity Z (mm^2/s)	11.7	3.8
Thermal conductivity XY (W/m K)	33.8	14.7
Thermal conductivity Z (W/m K)	24.7	11.7

time for each hole was fixed at 30 min. The workpiece and electrode was cleaned using an ultrasonic cleaner and weighed using a precision scale before and after machining to calculate the MRR and TWR. The process parameters used are listed in Table 2.

This research is divided into three tests. The first one is intended to improve the machining performance by introducing electrode vibration and dielectric deep flushing. Regular EDM, EDM with electrode vibration and EDM with deep flushing were compared in terms of MRR, TWR, and surface quality. The second test focuses on parametric studies using DoE. We assumed that the correlation effect of these parameters can be ignored in this process, and a 4-factor, 3-level experiment was designed using Taguchi method [19, 20], as shown in Table 3. The last test aims at exploring the machining mechanism. The machining surface was examined using SEM.

3 Results and discussion

3.1 Tool vibration and deep flushing

Debris evacuation in the process is especially important. In our initial trials, the machining debris (mostly nonconductive phases) was not effectively cleared from the machining

Table 2 Machining condition of the experiments

Electrode	Bronze tubing
Dielectric fluid	Kerosene
Polarity	Electrode (−)
Open voltage (V)	160
Gap voltage (V)	60
Peak current (A)	5
Pulse duration (μs)	24
Duty ratio	0.25
Vibration frequency (Hz)	500
Vibration amplitude (μm)	0, 4.5
Flow rate (ml/min)	0, 74
Machining time (min)	30

Table 3 Design of the experiments

Symbol	Factor	Level 1	Level 2	Level 3
A	Gap voltage (V)	40	60	80
B	Peak current (A)	2	5	8
C	Pulse duration (μs)	8	24	40
D	Duty ratio	0.10	0.17	0.24

area, hence causing low machining efficiency. Sometimes the EDM chips generated conglomerate to large chips, which were even harder to be flushed out. Arcing occurred occasionally, and the machining reliability was seriously affected. Therefore, electrode vibration and deep dielectric flushing (i.e., flushing through the tubular electrode) were used to promote the debris evacuation. A schematic of regular EDM, EDM with tool vibration, and EDM with deep flushing is shown in Fig. 3. A comparison of the MRR is shown in Fig. 4. It is seen in the figure that both electrode vibration and dielectric deep flushing increase the MRR. This result is mainly attributed to an increased debris evacuation efficiency when tool vibration or deep flushing using tubular electrode [16] is incorporated. Tool vibration may assist debris evacuation by periodically creating larger inter-electrode gap and the pressure difference between the machining area and the outside area. Deep flushing, which seems more effective than electrode vibration regarding MRR, aids the machining in a more direct way.

The MRR increased due to the improved flushing condition, meanwhile the TWR is hardly affected, as is suggested in Fig. 5. This result indicates that tool vibration and deep flushing increase debris evacuation efficiency with little influence on the TWR.

Figure 6 compares the surface integrity in different flushing conditions. It is evident in the figure that machining with deep flushing has the best integrity while regular EDM has the worst. It is also suggested in Fig. 6a, b that the area with the worst flush condition (i.e., the central area of the hole) was most seriously damaged while the other area had better

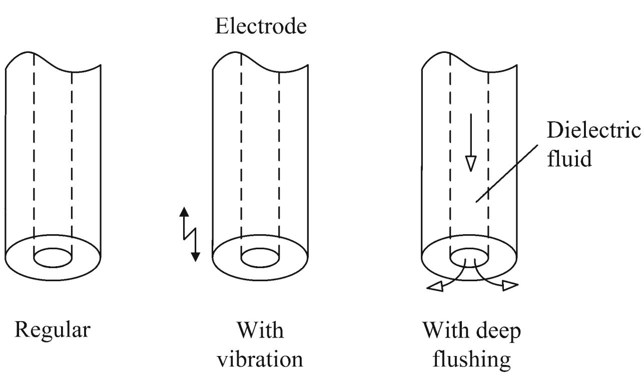

Fig. 3 Schematic of regular EDM, EDM with tool vibration and with dielectric deep flushing

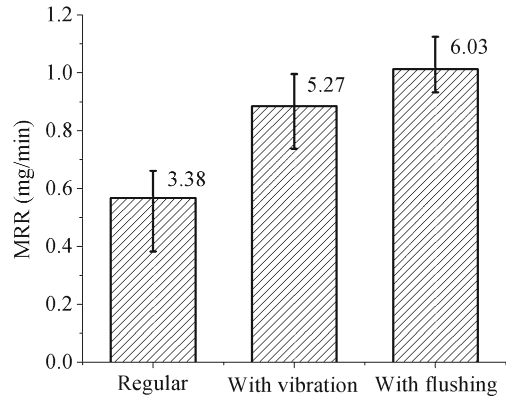

Fig. 4 The effect of electrode vibration and deep flushing on material removal rate

surface integrity. This phenomenon may be due to the difference in debris evacuation condition at different locations, i.e., debris in the side area is much easier to be taken out than that in the central area of the hole. When the floating debris is trapped in the machining area, it tends to induce arcing to damage the workpiece surface. It is also seen in Fig. 6 that electrode vibration or deep flushing does not change the entrance diameter of hole.

Since electrode vibration and deep flushing lead to high MRR and surface finish without sacrificing TWR, both of them were used simultaneously for the following process optimization.

3.2 Process optimization

3.2.1 The effect of process parameters

Table 4 shows the experimental design and the results of MRR based on Taguchi method. It is seen in the table that the fifth run produced the highest MRR, while the lowest was observed in the first fun. With the data shown in Table 4, we were able to investigate the effect of process parameters. Figure 7 shows the effect of gap voltage, peak current, pulse

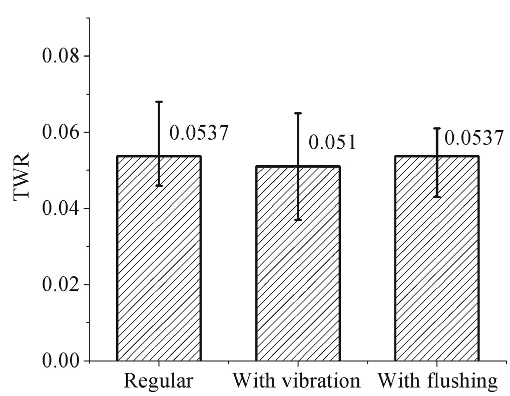

Fig. 5 The effect of electrode vibration and deep flushing on tool wear ratio

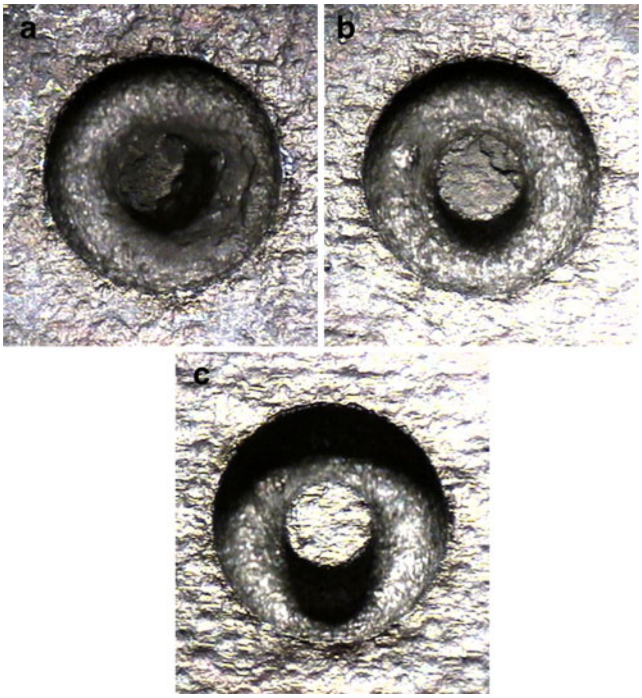

Fig. 6 The effect of electrode vibration and dielectric deep flushing on surface quality. **a** Regular EDM, **b** with tool vibration, and **c** with deep flushing

duration and duty ratio on the MRR. It is observable in Fig. 7a that the MRR increases with the gap voltage. This is due to the fact that a high gap voltage leads to a larger inter-electrode gap, thus making it easier for the debris to be flushed out of the machining area. It is seen from Fig. 7b that the MRR increases dramatically with the peak current. An obvious reason for this is a high peak current implies a high energy input, which is desirable for faster material removal [17]. Figure 7c suggests that an optimal value of pulse duration is around 24 μs. Pulse duration of 10 μs is probably too low for sufficient power input by each discharge. On the other side, 40 μs is too long compared with the pulse interval, thereby causing insufficient recovery of dielectric strength [17] and inefficiently evacuation of the EDM chips. Figure 7d indicates that an optimal duty ratio is around 0.17. This optimal value is much lower than that of other metal workpieces, which implies that machining of CMC with ceramic fiber reinforcements is highly difficult. When the duty ratio is set higher (e.g., 0.3), arcing will occur, and the machining speed will be down.

Table 4 Experimental results of material removal rate

Run	A	B	C	D	MRR (mg/min)
1	1	1	1	1	0.393
2	2	1	2	3	0.744
3	1	3	3	3	0.914
4	1	2	2	2	0.951
5	3	3	2	1	1.137
6	2	2	3	1	0.680
7	2	3	1	2	0.912
8	3	1	3	2	0.739
9	3	2	1	3	0.818

3.2.2 Analysis of variance

To deeper understand the influence of process parameters on the MRR, an ANOVA was carried out using the data listed in Table 4. The ANOVA results are illustrated in Fig. 8; each area stands for the contribution of each parameter of power generator to the MRR. It is evident in this figure that the peak current makes more than 55% of the contribution to the MRR. This implies that one may first consider increasing the peak current in order to maximize the production rate. The result is also consistent with the findings shown in Fig. 7b, in which the MRR almost rises linearly with the peak current. The contributor second to peak current is the pulse duration, which makes approximately a quarter of the total contribution. Gap voltage and duty ratio account for 10.3% and 7.6%, respectively. An exceptional case is, when pulse duration reaches 0.30, machining will become extremely unstable due to arcing, dramatically lowering the MRR. Hence, we suggest that the upper limit for duty ratio should be 0.24 in EDM of CMC with ceramic fiber reinforcements.

3.2.3 Optimal condition and validation

With the data listed in Table 4, the process was optimized for the highest MRR. The optimal result predicted using Taguchi method is 1.27 mg/min at a gap voltage of 80 V, peak current of 8 A, pulse duration of 24 μs, and duty ratio of 0.17. Subsequently, an experiment was run with this set of parameters to validate the optimization result. A comparison between the highest MRR measured, highest MRR predicted and MRR measured at the optimal condition is plotted in Fig. 9. It is seen that this set of parameters does result in the highest MRR, which exceeds all the data measured in Table 4. However, the experimental result is reasonably higher than the prediction. This difference may indicate the existence of correlation effect between the parameters (e.g., the correlation between pulse duration and duty ratio), which causes prediction error in the use of Taguchi model.

With the guidance of the above parametric analysis, a through hole was made with minimal machining time. The machining condition selected was a gap voltage of 80 V, peak current of 20 A, pulse duration of 72 μs and duty ratio of 0.17. It took 25 min to make the through hole with a depth of 5.6 mm that is equal to an average MRR of

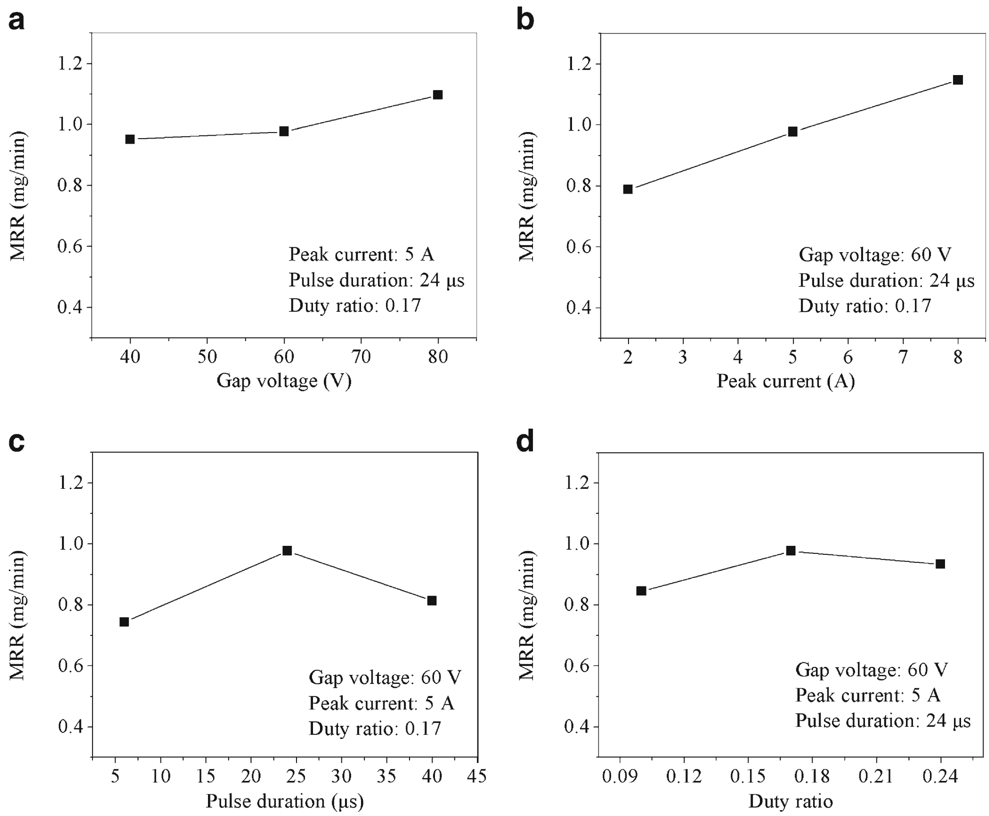

Fig. 7 The effect of process parameters on the MRR. **a** Gap voltage, **b** peak current, **c** pulse duration, and **d** duty ratio

4.56 mg/min. Figure 10 demonstrates the machined surface of the hole with Fig. 10a, b showing the top view and the bottom view, respectively. The dotted circles are the profile of the electrode. The overcut of the hole is 0.1 mm at the entrance and down to 0.04 mm at the exit. The overcut is due to the inter-electrode gap and excessive sparks during EDM [17].

3.3 Material removal mechanism

The machined surface was examined using a scanning electron microscopic system to identify the material removal mechanism. The evolution of material removal in EDM of the fiber-reinforced CMC is shown in Fig. 11. Figure 11a shows the original surface of the workpiece without machining. This surface is mainly ceramic matrix with no fibers exposure. In EDM, discharges occur between the electrode and the conductive phase of the workpiece. Micro-cracks gradually emerge due to thermal shock by the sparks, as shown in Fig. 11b. Micro-craters can hardly be observed on the surface, which indicates that little material removal is caused by thermal melting. Also, the micro-cracks do not have a consistent direction. This effect indicates that thermal stress is equally distributed on the surface, and the energy is released in a random direction in the form of micro-cracks. As

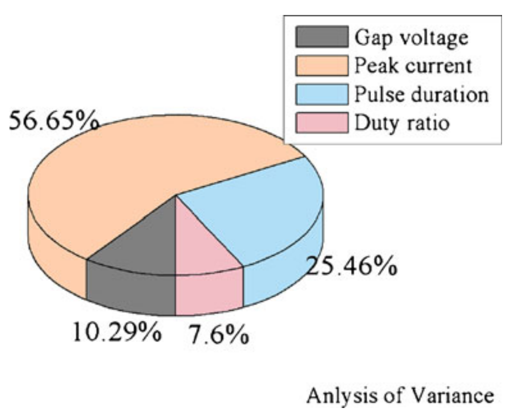

Fig. 8 Result of the analysis of variance for the MRR

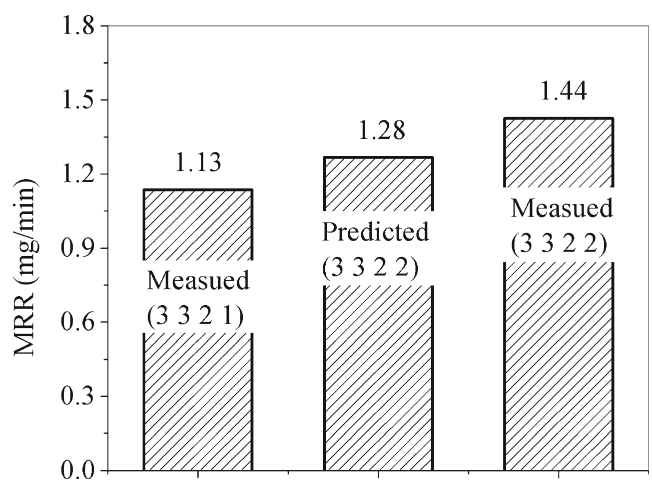

Fig. 9 Process optimization and experimental validation for the MRR

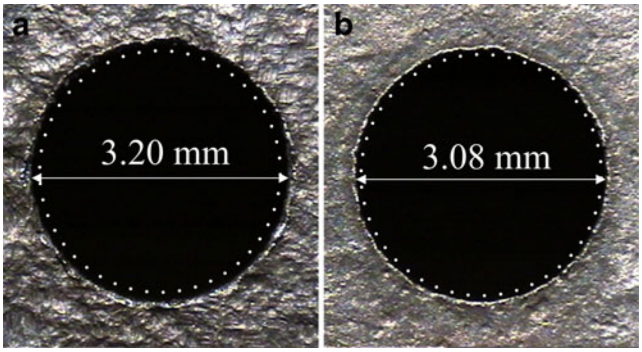

Fig. 10 Geometry of the machined hole. **a** Top view. **b** bottom view

the workpiece is continuously bombarded by the sparks, these cracks expand, as shown in Fig. 11c. The cracks become increasingly longer and wider, and the surface is loosened. In Fig. 11d, it is seen that the cracks are stripped off; ceramic fibers are exposed. Then, the remaining ceramic matrix seems to crack along the fiber direction, which is considered the most convenient way for energy release. A few ball-shaped particles are observed in Fig. 11d. These particles may be EDM chips, and they tend to rebond on the workpiece during EDM. Another possibility is that they are those phases with very low conductivity, making them hard to be removed in the first place. It is important to clearly identify these particles in the future for further improving surface quality and machining rate. In Fig. 11e, the ceramic fibers are completely exposed. It is visible that the fibers are broken in a brittle manner. The section is perpendicular to the fiber axis, suggesting that the breakage is due to an axial expansion/compression. The expansion/compression has to be result from the thermal shock by the sparks. Since these broken ceramic fibers are almost insulating, they are difficult to be evacuated.

4 Conclusions

In the present study, a new set of advanced materials, ceramic matrix composites with ceramic fiber reinforcements, was processed using EDM with electrode vibration and deep flushing. The purpose is to improve the machining performance, especially the material removal rate, and

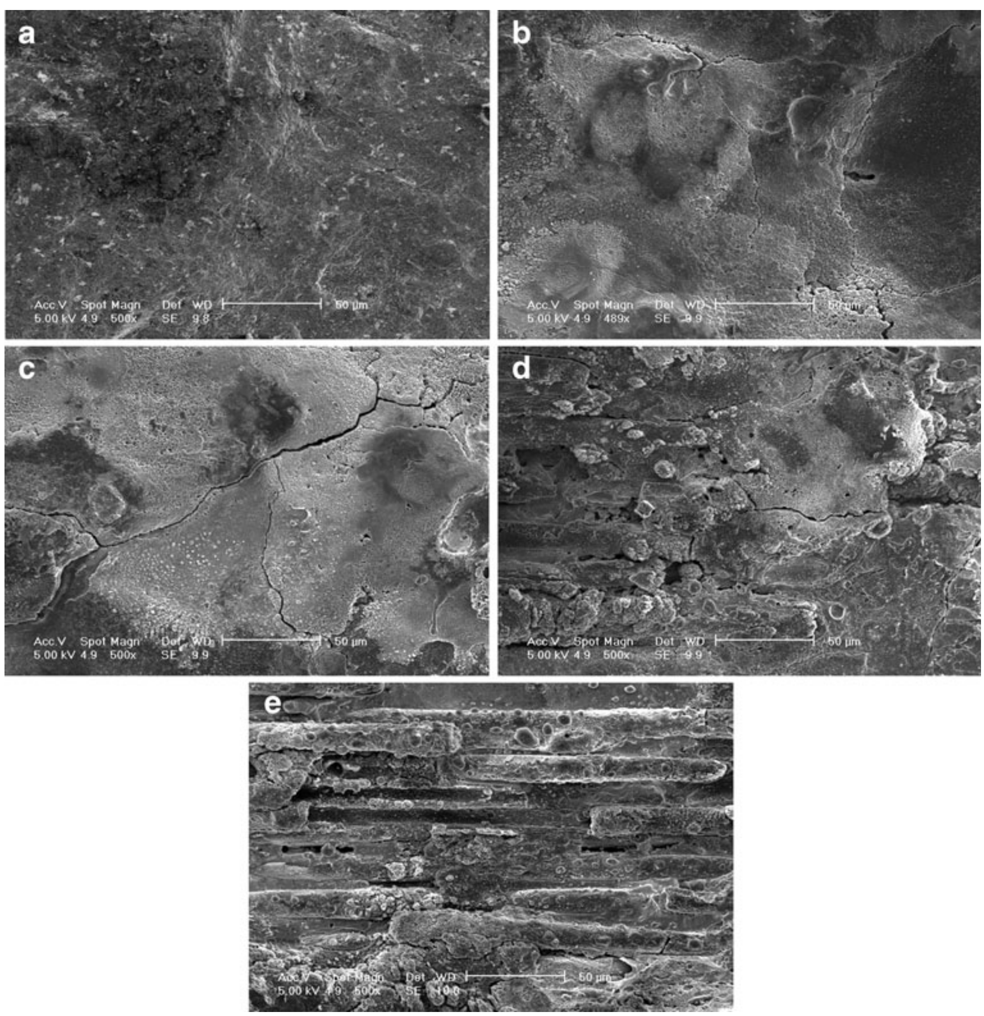

Fig. 11 The evolution of material removal in EDM of ceramic matrix composites with ceramic fiber reinforcements. **a** Original surface, **b** occurrence of thermal cracks, **c** expansion of thermal cracks, **d** chipping, and **e** fiber exposure and fiber breakage

advance the understanding of process. Conclusions can be made as follows:

1. Both tool vibration and dielectric deep flushing increases the MRR and surface integrity without sacrificing the TWR by promoting debris evacuation.
2. The material removal rate increases with the gap voltage and peak current; 24-μs pulse duration and 0.17 duty ratio are found optimal in this range.
3. Peak current and pulse duration are the dominant factors for MRR contribution. Arcing should be avoided by setting the duty ratio less than 0.3. A high gap voltage and relatively small duty ratio is desirable for efficient debris evacuation. Debris evacuation efficiency is key in EDM of CMC with ceramic fibers.
4. The highest MRR is 1.27 mg/min at an optimal condition of a gap voltage of 80 V, peak current of 8 A, pulse duration of 24 μs, and duty ratio of 0.17, which has been validated by experiments.
5. The material removal procedure of the ceramic matrix is through cracking, crack expansion, and stripping-off. The insulating fibers are broken due to thermal expansion/compression by the sparks. However, thermal melting hardly contributes to direct material removal.

Acknowledgments This work is sponsored by the Natural Science Foundation of PR China (grant no. 50775143) and Education Ministry of PR China (grant no. 20060248031). We would like to thank GE Aviation for providing the workpiece sample. The corresponding author gratefully acknowledges the financial support from China Scholarship Council.

References

1. Chawla KK (2003) Ceramic matrix composites, 2nd edn. Kluwer, Boston
2. Kumar J, Khamba JS, Mohapatra SK (2009) Investigating and modeling tool-wear rate in the ultrasonic machining of titanium. Int J Adv Manuf Tech 41(11–12):1107–1117
3. Tsai CH, Lin BC (2007) Laser cutting with controlled fracture and pre-bending applied to LCD glass separation. Int J Adv Manuf Tech 32(11–12):1155–1162
4. Liu HT, Schubert E (2009) Piercing in delicate materials with abrasive-waterjets. Int J Adv Manuf Tech 42(3–4):263–279
5. Kunieda M, Lauwers B, Rajurkar KP, Schumacher BM (2005) Advancing EDM through fundamental insight into the process. Cirp Ann-Manuf Techn 54(2):599–622
6. Rajurkar KP, Yu ZY (2000) 3D micro-EDM using CAD/CAM. Cirp Ann-Manuf Techn 49:127–130
7. Zhao WS, Meng QG, Wang ZL (2002) The application of research on powder mixed EDM in rough machining. J Mater Process Tech 129(1–3):30–33
8. Wei CJ, Xu KZ, Ni J, Brzezinski AJ, Hu DJ (2011) A finite element based model for electrochemical discharge machining in discharge regime. Int J Adv Manuf Tech 54(9–12):987–995
9. Clijsters S, Liu K, Reynaerts D, Lauwers B (2010) EDM technology and strategy development for the manufacturing of complex parts in SiSiC. J Mater Process Tech 210(4):631–641
10. Chiang K (2008) Modeling and analysis of the effects of machining parameters on the performance characteristics in the EDM process of Al_2O_3+TiC mixed ceramics. Int J Adv Manuf Tech 37(5–6):523–533
11. Patel KM, Pandey PM, Rao PV (2010) Optimisation of process parameters for multi-performance characteristics in EDM of Al_2O_3 ceramic composite. Int J Adv Manuf Tech 47(9–12):1137–1147
12. Ghoreishi M, Atkinson J (2002) A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electro-discharge machining. J Mater Process Tech 120(1–3):374–384
13. Xu MG, Zhang JH, Li Y, Zhang QH, Ren SF (2009) Material removal mechanisms of cemented carbides machined by ultrasonic vibration assisted EDM in gas medium. J Mater Process Tech 209(4):1742–1746
14. Lauwers B, Kruth JP, Brans K (2007) Development of technology and strategies for the machining of ceramic components by sinking and milling EDM. Cirp Ann-Manuf Techn 56(1):225–228
15. Liu YH, Ji RJ, Li XP, Yu LL, Zhang HF, Li QY (2008) Effect of machining fluid on the process performance of electric discharge milling of insulating Al_2O_3 ceramic. Int J Mach Tool Manu 48(9):1030–1035
16. Fujiki M, Ni J, Shih AJ (2009) Investigation of the effects of electrode orientation and fluid flow rate in near-dry EDM milling. Int J Mach Tool Manu 49(10):749–758
17. Jameson EC (2001) Electrical discharge machining. Society of Manufacturing Engineers, Dearborn, MI
18. Bansal NP, Knovel (Firm) (2005) Handbook of ceramic composites. Kluwer, Boston
19. Khan AA (2008) Electrode wear and material removal rate during EDM of aluminum and mild steel using copper and brass electrodes. Int J Adv Manuf Tech 39(5–6):482–487
20. Yan BH, Wang CC, Liu WD, Huang FY (2006) Machining characteristics of Al_2O_3/6061Al composite using rotary EDM with a disklike electrode. Int J Adv Manuf Tech 16(5):322–333