Int. Journal of Refractory Metals & Hard Materials 27 (2009) 892–899

Contents lists available at ScienceDirect

Int. Journal of Refractory Metals & Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

# Surface integrity and material removal mechanisms associated with the EDM of $Al_2O_3$ ceramic composite

K.M. Patel *,[1], Pulak M. Pandey, P. Venkateswara Rao

*Department of Mechanical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India*

ARTICLE INFO

*Article history:*
Received 20 March 2009
Accepted 4 May 2009

*Keywords:*
EDM
$Al_2O_3$ ceramic composite
Surface integrity
Material removal mechanism

ABSTRACT

Electric discharge machining (EDM) has been proven as an alternate process for machining complex and intricate shapes from the conductive ceramic composites. The performance and reliability of electrical discharge machined ceramic composite components are influenced by strength degradation due to EDM-induced damage. The success of electric discharge machined components in real applications relies on the understanding of material removal mechanisms and the relationship between the EDM parameters and formation of surface and subsurface damages. This paper presents a detailed investigation of machining characteristics, surface integrity and material removal mechanisms of advanced ceramic composite $Al_2O_3$–$SiC_w$–TiC with EDM. The surface and subsurface damages have also been assessed and characterized using scanning electron microscopy (SEM). The results provide valuable insight into the dependence of damage and the mechanisms of material removal on EDM conditions.



## 1. Introduction

Alumina is a popular engineering ceramic due to its high hardness, strength, wear resistance, resistance to chemical degradation and low density. The ability to retain these properties at elevated temperatures presents alumina ceramic as a potential unique solution for number of engineering applications. However, its brittle nature and low fracture toughness make machining difficult and costly by conventional grinding particularly for complex shapes generation [1]. Considerable improvement in mechanical properties of the single-phase ceramic materials has been achieved by incorporating electroconductive materials such as transition-metal-containing carbides, borides and nitrides into the ceramic matrix. The reinforcing components are often added in the form of particles and whiskers to make the composite electrically conductive so that EDM can be used [2]. Recent advances in both electrically conductive ceramic composites and computer controlled EDM have catalyzed extensive research [2–5] into developing spark erosion as the most advanced precision ceramic machining technology.

Eventhough EDM technology has proved to be very efficient in machining out complex shapes and also to machine ceramic composites, there are several problems associated with this machining method. The EDMed ceramic components are most likely to contain an uneven fusing structure, globules of debris, shallow craters, micropores, microcracks and pockmarks [5]. The major form of machining damage usually occurs as surface and subsurface damages or cracks. It greatly influences parts during their useful life, especially when such components come in contact with other elements. Numbers of investigations have been made to characterize and EDM processing of ceramic composites like $Si_3N_4$–TiN, $Si_3N_4$–TiCN, $ZrO_2$–TiN, $Al_2O_3$–$Cr_3C_2$, etc. [3,6–8]. Zhang et al. [3] used a hot pressed aluminium oxide based ceramic composite, SG4 for EDM. They found that longer pulse-on time results in higher surface roughness and generation of a thicker resolidified layer with microcracks on the subsurface. They suggested that the product of thermal conductivity and fusion temperature could be considered as an indicator of EDM machinability. Fu and Li [6] conducted experimental study, in which the pulse current, pulse duration, and electrical polarity were selected as process parameters that affect surface roughness, material removal rate and the variation of fracture strength of $Al_2O_3$–$Cr_3C_2$ composites. They observed that the fracture strength and surface roughness of the composites depend strongly on the pulse current and electrical polarity, especially at low energy input.

Liu and Huang [7] investigated the influence of EDM operation on surface integrity, machinability and strength degradation of conductive $Si_3N_4$–TiN hot pressed composites. They found that higher working voltage and current, as well as higher content of TiN particulates resulted in enhanced material removal rate. Their investigation showed that EDM at higher pulse energy caused severe microdamage, reduction in strength and increase in surface roughness. Nakamura et al. [8] reported surface damage in

* Corresponding author. Tel.: +91 11 2659 6758; fax: +91 11 2658 2053.
*E-mail address:* kaushikmpatel@gmail.com (K.M. Patel).

[1] On leave from Department of Mechanical Engineering, Institute of Technology, Nirma University of Science and Technology, Ahmedabad 382481, India.

0263-4368/$ - see front matter 
doi:10.1016/j.ijrmhm.2009.05.003

zirconium boride ($ZrB_2$) based ceramic composite induced by EDM. The effects of pulsed current, pulse duration and duty factor on the strength and the roughness were evaluated. They concluded that it would be possible to use the electric discharge machined $ZrB_2$ based ceramic composite components in structural applications without any additional finishing processes. Few attempts [9,10] were made to improve the surface integrity of the electric discharge machined ceramic composites namely $Al_2O_3$–TiC, $Si_3N_4$–TiC and $Al_2O_3$–TiC–Mo–Ni. Ultrasonic machining and abrasive blasting were used to finish EDMed ceramic components. The results indicated that the ultrasonic and abrasive blasting induced surface finishing improves both flexural strength and Weibull modulus. The findings showed that both techniques were effective in improving the surface integrity of the EDMed ceramic composites.

The two principal mechanisms of material removal which may occur during spark erosion of ceramic materials are melting, evaporation and dissociation, or fracture-related spalling, depending on the properties of material and EDM parameters. Many attempts [11–14] have been made to understand mechanisms of material removal during EDM of ceramic composites. Pitman and Huddleston [11] compared the die-sinking EDM characteristics of a zirconia based ceramic matrix composite with 30 vol.% of TiN under normal sparking and induced arcing conditions. Subsequent microscopic analysis of the arced surface and the debris collected during machining under induced arcing indicated the major mechanism of material removal and was reported as thermal spalling. Thermal spalling occurs when three distinct fractures, namely subsurface lateral cracking, vertical cracking and thermal shock induced fracture due to rapid cooling combines. Hu et al. [12] experimentally investigated material removal and surface damage of $Ti_3SiC_2$ ceramic during EDM. They concluded that melting and decomposition were found to be the main material removal mechanisms during the machining process. The surface damage led to a degradation of both strength and reliability.

Trueman and Huddleston [13] reported thermal spalling as mechanism of material removal while rough machining for die-sinking EDM of sialon–TiN and SiC–$TiB_2$ composites. They established that by using high energy EDM, large scale controlled spalling can be induced to provide a rapid and efficient material removal. The material was removed in form of flake detachment due to thermal shock induced fracture. Lauwers et al. [14] investigated the EDM material removal mechanisms, surface and subsurface damage of commercially available ceramic composites based on $ZrO_2$, $Si_3N_4$ and $Al_2O_3$ by analyzing the debris and the surface and subsurface quality. They reported that besides the typical material removal mechanisms in EDM like melting/evaporation and spalling, other material removal mechanisms are likely to occur such as oxidation and dissolution of the base material. They also concluded that surface and subsurface damage was quite complex and depend not only on the generator settings (pulse parameters, etc.) but also on the material properties like melting point, thermal conductivity, fracture toughness, etc. The formation of microcracks was typical for materials, such as ceramics, having less resistance against tensile stresses.

The literature review presented above indicates that EDM of silicon nitride and zirconia based ceramic composites has been investigated in detail. In recent years, ceramic composites are of increasing interest in industrial applications with oxide matrices, particularly $Al_2O_3$ being dominant. Therefore, in this paper an attempt has been made to investigate the surface integrity and the material removal mechanisms involved during the EDM of $Al_2O_3$–$SiC_w$–TiC ceramic composite. The effects of normal and rough cutting modes on the surface and subsurface damages have been discussed. The observations of surface and subsurface damages as well as EDX analysis of EDMed surfaces have been used to predict material removal mechanisms.

## 2. Experimentation

EDM experiments were performed on an 'Electronica leader ZNC' die-sinking EDM machine. The electrically conductive $Al_2O_3$–$SiC_w$–TiC ceramic composite (CRYSTALOY 2311EDX) supplied by Industrial Ceramic Technology was selected as the workpiece. This ceramic composite was fabricated by milling the mixture of 46.1 vol.% $Al_2O_3$ powder, 30.9 vol.% SiC whiskers and 23.0 vol.% TiC powder. The powder mixture was then hot pressed in an inert atmosphere at 1700–1800 °C. The physical and mechanical properties of the $Al_2O_3$–$SiC_w$–TiC ceramic composite have been summarized in Table 1 [15]. The microstructure of the $Al_2O_3$–$SiC_w$–TiC ceramic composite has been presented in Fig. 1. Optical microscopy revealed that the $Al_2O_3$ grains and the TiC particles retained integrity during processing. The SiC whiskers were generally much shorter than when received, probably because of being fractured during milling. The $Al_2O_3$ grain size was approximately 1 μm and the TiC grain size was approximately 5 μm [15].

The composite was subjected to both normal cutting mode (low currents range) and rough cutting mode (high currents range) EDM conditions. The experimental parameters used for normal cutting mode and rough cutting mode are presented in Table 2. The electrolytic copper rod having diameter 8.0 mm was used as an electrode. In all the experiments, kerosene oil was used as dielectric

**Table 1**
Physical and mechanical properties of AlSiTi [15].

| Density ($g/cm^3$) | Hardness (Hv) | Fracture toughness ($MPa(m)^{0.5}$) | Thermal conductivity (W/m K at 400 K) | Electrical resistivity (Ω cm) |
|---|---|---|---|---|
| 3.90 | 2400 | 9.6 ± 0.6 | 63 | 0.009 |

**Table 2**
Experimental parameters.

| | | |
|---|---|---|
| Discharge current (A) | Normal cutting mode | 3, 4, 5, 6, 7 |
| | Rough cutting mode | 14, 15, 16 |
| Pulse-on time (μs) | | 10, 50, 100, 150, 200 |
| Duty cycle | | 0.72 |
| Gap voltage (V) | | 70 |
| Dielectric | | Kerosene |

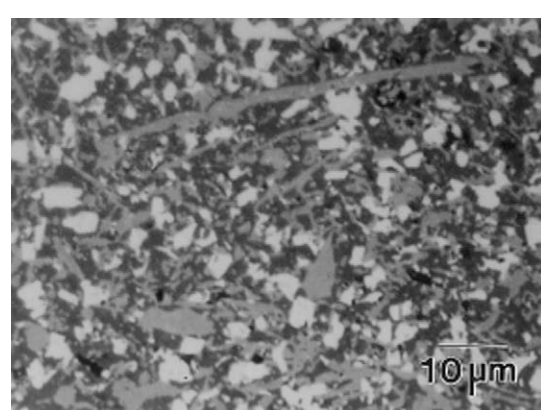


**Fig. 1.** Optical micrograph of $Al_2O_3$–$SiC_w$–TiC composite, where the bright grains are TiC particles, the light-grey filaments are the SiC whiskers, and the dark-grey background is the alumina matrix [15].

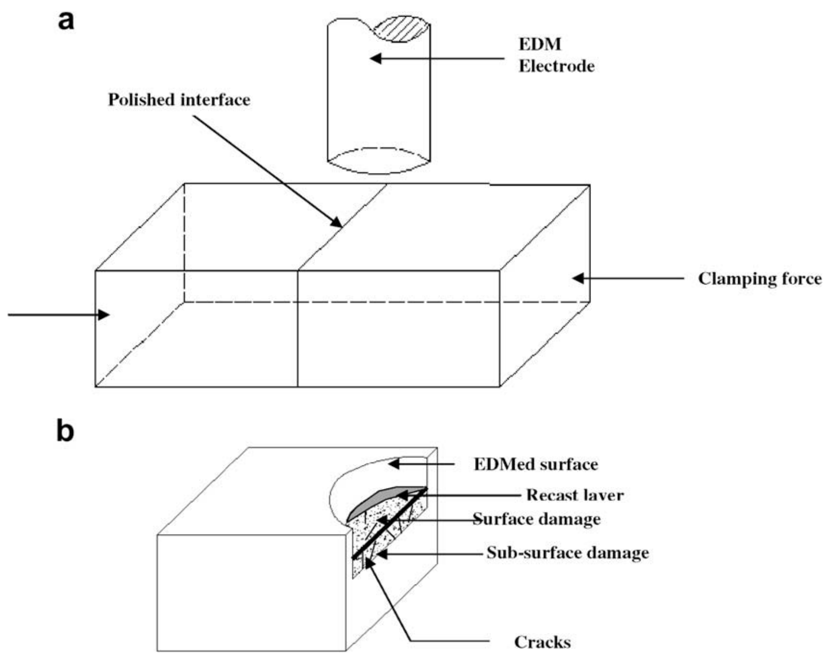


**Fig. 2.** Schematic illustration of the procedure used in preparation of SEM samples to study subsurface damage (a) clamped work pieces and (b) EDMed half-hole with recast layer and subsurface damage.

medium. The specimens of 10 × 10 mm and 5 mm thickness were used in the present study. EDM was carried out on 10 × 10 mm surface for observing surface topography, and the extent of possible surface damage and material removal mechanisms was obtained using a Scanning Electron Microscope (SEM) EVO 50. The specimens were cleaned in an acetone in an ultrasonic bath before SEM. Energy Dispersive X-ray spectroscopy (EDX) of EDMed surfaces was also performed. The roughness of the electrical discharge machined surfaces was measured using surface roughness tester (Talysurf 6, Rank Taylor Hobson, England). A traverse length of 5 mm with a cut-off evaluation length of 0.8 mm was selected.

A clamped work pieces technique was employed to examine subsurface damage and the recast layer. In this method, the two specimens were ground at same dimensions and one surface of each specimen was polished. The polished surfaces were subsequently clamped face-to-face with suitable force. All the holes were drilled at the interface of two polished surfaces of work pieces as shown in Fig. 2. The work pieces were separated after EDM and were cleaned in an ultrasonic bath. The subsurface of the EDMed half holes (on 10 × 5 mm surface) were then examined using SEM.

## 3. Results and discussion

In the EDM process, due to the bombardment of high energetic (kinetic) electrons on the electrode surface, the spot attains high temperature (about 10,000 °C) especially with materials of low thermal conductivity. At this high temperature, material at that spot melts and vaporizes leaving a crater on the surface. However, small amount of the molten material cools rapidly under the effects of the dielectric fluid. The rapid heating and cooling effect generates a highly distinctive surface morphology on electrical discharge machined surfaces.

### *3.1. Surface roughness and topography of EDMed surface*

The obtained variations of surface roughness with discharge current and pulse-on time have been shown in Figs. 3 and 4, respectively. It can be seen from Fig. 3 that surface roughness increases initially and then decreases with an increase in discharge current. The SEM micrographs of the EDM machined surfaces at pulse-on time 50 μs for various currents of normal cutting mode are given in Fig. 5. The EDM surface is characterized by an uneven fusing structure, globules of debris, shallow craters and micropores. Micrographs also show the formation of bright TiC layer on the machined surface. SEM examination of the EDM machined surface at normal cutting mode shows no surface cracks. It can be seen from surface micrographs shown in Fig. 5a and b that the surface roughness increases with an increase in discharge current. It can be explained from the fact that this increase could be due to the increase in deeper and larger discharge craters with other irregularities as the pulse current increases. An increase in discharge current forms micropores due to low facture toughness and ther-

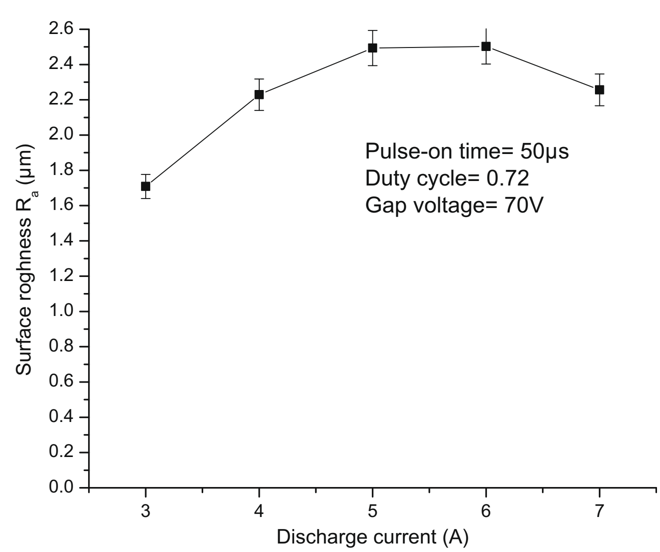


**Fig. 3.** Effect of discharge current on the surface roughness.

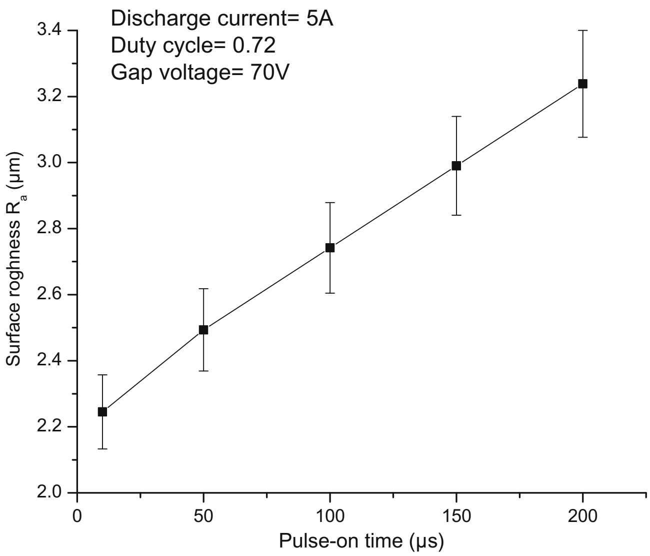


**Fig. 4.** Effect of pulse-on time on the surface roughness.

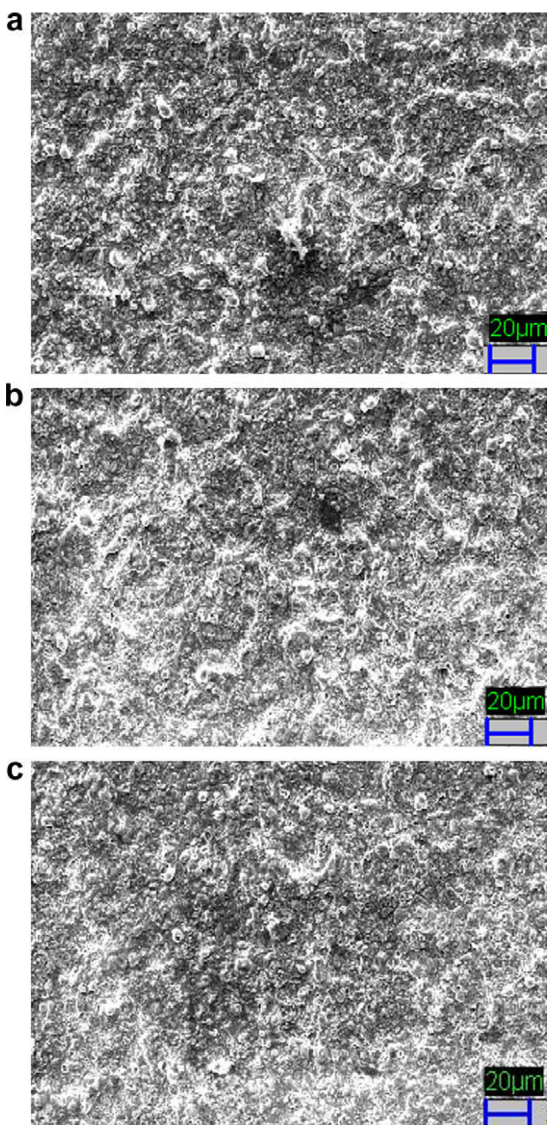


**Fig. 5.** EDMed surface characteristics of $Al_2O_3$–$SiC_w$–TiC ceramic composite under a duty cycle of 0.72, a gap voltage of 70 V and a pulse-on time of 50 μs: (a) discharge current 3 A, (b) discharge current 5 A and (c) discharge current 7 A.

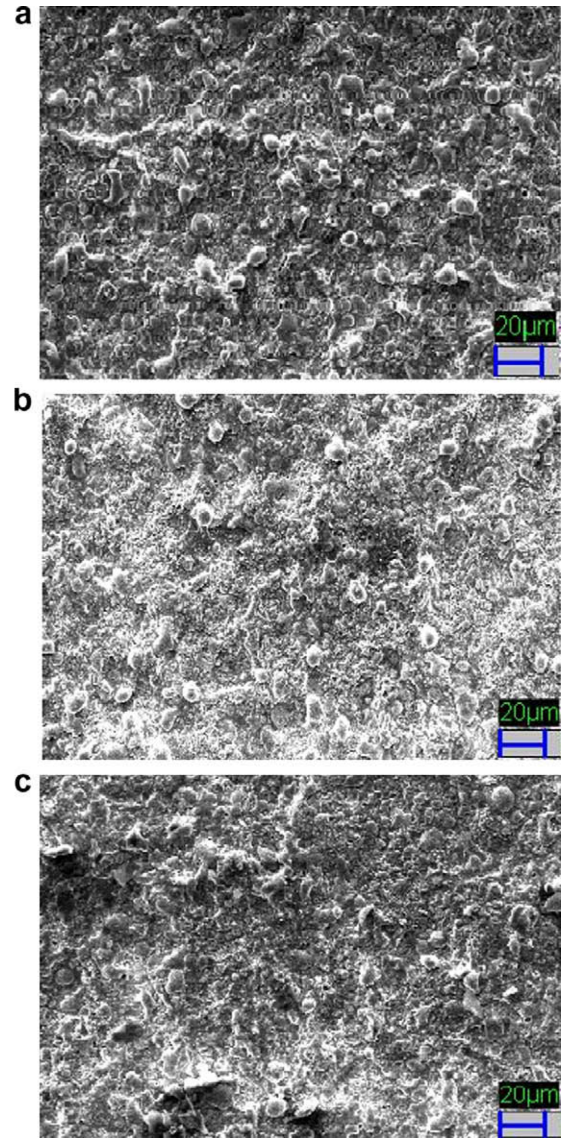


**Fig. 6.** EDMed surface characteristics of $Al_2O_3$–$SiC_w$–TiC ceramic composite under a duty cycle of 0.72, a gap voltage of 70 V and a pulse-on time of 200 μs: (a) discharge current 3 A, (b) discharge current 5 A and (c) discharge current 7 A.

mal shock resistance of $Al_2O_3$–$SiC_w$–TiC ceramic composite. Improvement in surface roughness was observed at discharge current at 7 A for 50 μm pulse-on time (micrograph of Fig. 5c). The decrease in surface roughness may be due to the enhanced TiC deposition and could also due to the uniform sparking in presence of Al and Si particles in form of debris.

It can also be seen from Fig. 4 that surface roughness increases with an increase in the pulse-on time. This may be due to the plasma channel expansion with the increase in pulse-on time. It widens the contact zone of discharge and subsequently reduces both energy density and the impulsive force. The melted debris might not be removed completely due to reduction in impulsive force and forms an apparent globule-like recasted layer to degrade the surface roughness. These effects become more pronounced as the pulse-on duration increases. Besides, reduction in the removal of debris and the carbon accumulation on machined surface [16], micropores and fine pock mark formation also attribute to further increase in surface roughness with an increase in pulse-on time. The SEM micrographs of the EDM machined surfaces at pulse-on time 200 μs for various currents of normal cutting mode are shown in Fig. 6. On comparison of the micrographs shown in Figs. 5 and 6, it can be seen that the surface roughness increases with an increase in pulse-on time. The increase in surface roughness is more predominant with an increase in pulse-on time in comparison to an increase in discharge current. These results are in agreement with the surface variation with pulse-on time as shown in Fig. 4.

### 3.2. Material removal mechanisms and recast layer formation at normal cutting mode

Due to good electrical conductivity, $Al_2O_3$–$SiC_w$–TiC ceramic composite is easily machinable by EDM. During electric discharge machining, the material can be transferred between the electrodes in solid, molten or gaseous state simultaneously [17,18].

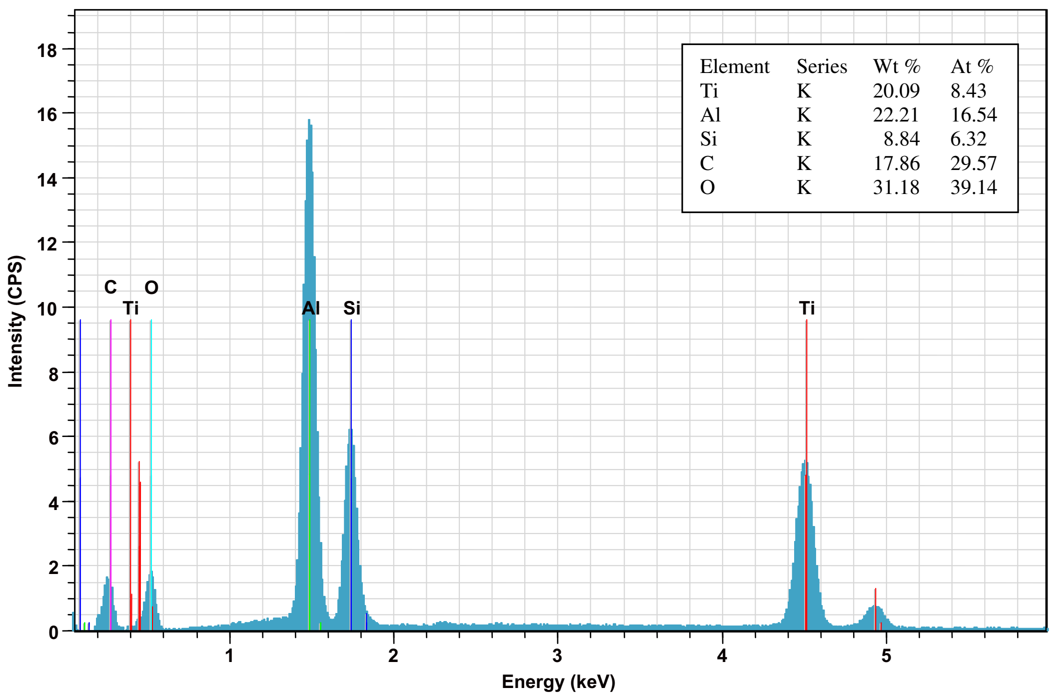


**Fig. 7.** EDX showing the relative intensities of various elements on the EDM surface, discharge current 7 A, pulse-on time 200 µs, duty cycle 0.72 and gap voltage 70 V.

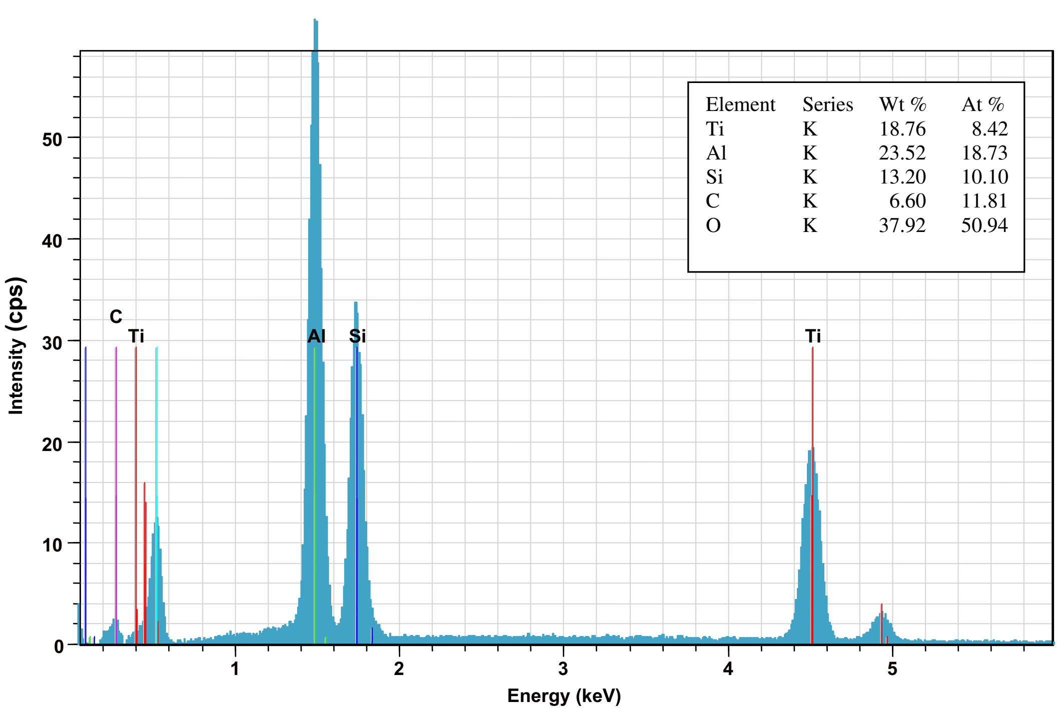


**Fig. 8.** EDX showing the relative intensities of various elements on the non-EDM surface.

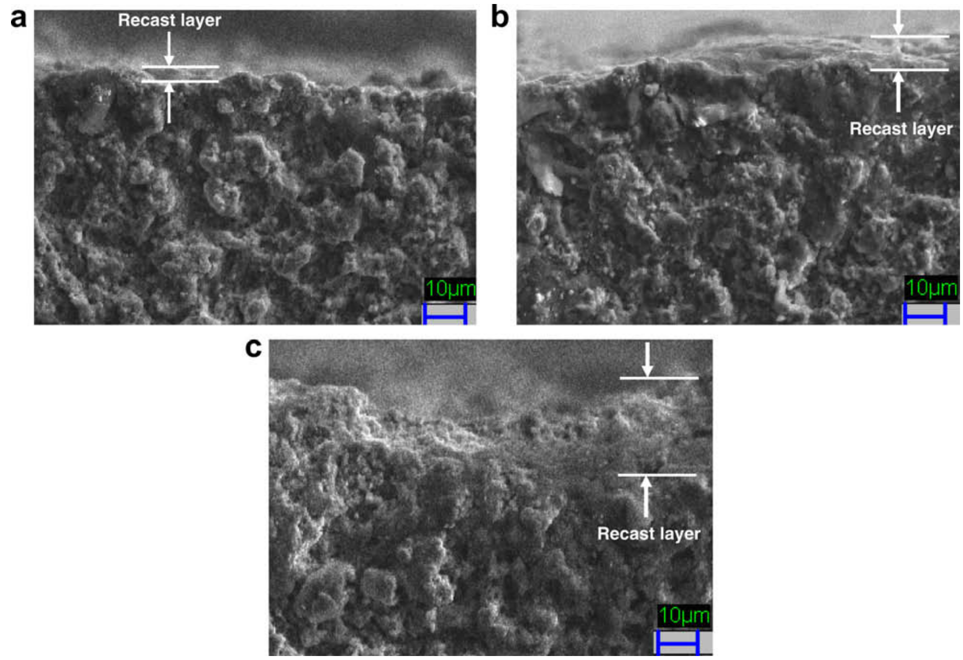


**Fig. 9.** SEM micrographs at a duty cycle of 0.72 and a gap voltage of: 70 V (a) 3 A/50 μs, (b) 7 A/50 μs and (c) 7 A/200 μs, where the micrographs (b) and (c) qualitatively show variation in the thickness of the recast layer for different values of pulse-on time.

Fig. 7 shows the qualitative Energy Dispersive X-ray spectroscopy (EDX) patterns of the EDMed surface layer for the $Al_2O_3$–$SiC_w$–TiC ceramic composite. The elements of the specimen were indicated by the peaks corresponding to their energy levels. It is evident that Ti, Al, Si, C and $O_2$ are the main contents in the resolidified layer. The presence of Cu is not observed in the resolidified layer as indicated by EDX analysis. This implies that there is absence of any visible tool electrode material transfer to the workpiece surface during the electrical discharge process. For comparison, the EDX analysis was also conducted on a non-EDM surface, as shown in Fig. 8. It is evident that there is a reduction of Si content on the machined surface whereas there is no evidence of the change in the contents of Al and Ti. The drastic increase of carbon over the machined surface was due to the deposition of carbon separated from the consumed kerosene dielectric medium. The rich presence of the Ti and C indicated the presence of TiC in the resolidified droplets formed on the machined surface. The substantial amount of reduction in $O_2$ may be due to formation of carbon monoxide gas which is also evident by decrease in Si content. This indicates that material removal may be predominantly due to melting and evaporation and to some extent also due to oxidization and decomposition.

The micrographs of surface during normal cutting conditions have been shown in Figs. 5 and 6. No surface damage and has been observed in this case. Subsurface damage and recast layer of the EDMed specimens were also investigated and is presented in Fig. 9. When the spark eroded area was observed for subsurface damage, melt flow of the recast layer was observed. The extremely fine cracks have been filled by the recast layer. It can be seen from the micrographs shown in Fig. 9b and c that the thickness of the recast layer varies for different values of pulse-on time. The recast layer thickness is influenced by the pulse-on time, and increases as the pulse-on time increases. This can be explained by the fact that the amount of material which can be flushed away by the dielectric is constant while EDM occurs. Therefore, as more heat is transferred into the sample as the pulse-on time increases, the dielectric is increasingly unable to clear away the material debris, and so it builds up upon the surface of the sample. During the subsequent cooling, this material resolidifies to form the recast layer, the depth of which depends upon the volume of debris which is left on the sample surface during machining. Similar experimental results were reported by previous investigators [19,20].

### 3.3. Cracks formation and thermal spalling at rough cutting mode

The SEM micrographs of the surface machined at rough cutting mode in the current range of 14–16 A are shown in Fig. 10. Extensive material damage including large microcracks occurred during EDM when rough cutting mode was used. It can be seen from this figure that an increase in both discharge current and pulse-on time resulted in an increase in surface cracking. Among these two parameters pulse-on time significantly affected crack formation. The observations are consistent with the experimental results reported by previous investigators [19]. The rapid heating and cooling effect in EDM induces a high-temperature gradient within the heat affected area and therefore generates a significant stress within the machined surface. It has been found that crack formation is caused by the stress induced while EDM. When the degree of induced stress exceeds the maximum tensile strength of the material, cracking occurs on the machined surface [21–23]. Two types of cracks namely radial and circumferential cracks, induced by EDM can be clearly observed in Fig. 10a and b. This cracking is due to rapid cooling of the material after intensive sparking at rough cutting mode. Low facture toughness and thermal shock resistance of $Al_2O_3$–$SiC_w$–TiC ceramic composite are also responsible for cracking while EDM. It can also be seen from an enlarged view of one of the EDMed workpiece surface (Fig. 10e).

Subsurface damage of the EDMed specimens prepared using the clamped work pieces technique was examined using SEM. Two types of subsurface cracks, near vertical and angular cracks can be seen from micrographs shown in Fig. 11a and b. The $Al_2O_3$–$SiC_w$–TiC ceramic composite also has thermal mismatch between dispersoid and matrix, due to large coefficient of thermal expansion ratio of 0.65:1.2:1 for the SiC whisker and TiC particles in the $Al_2O_3$ ceramic composite [24]. This may be responsible for the generation of subsurface cracks. Quenching induced large

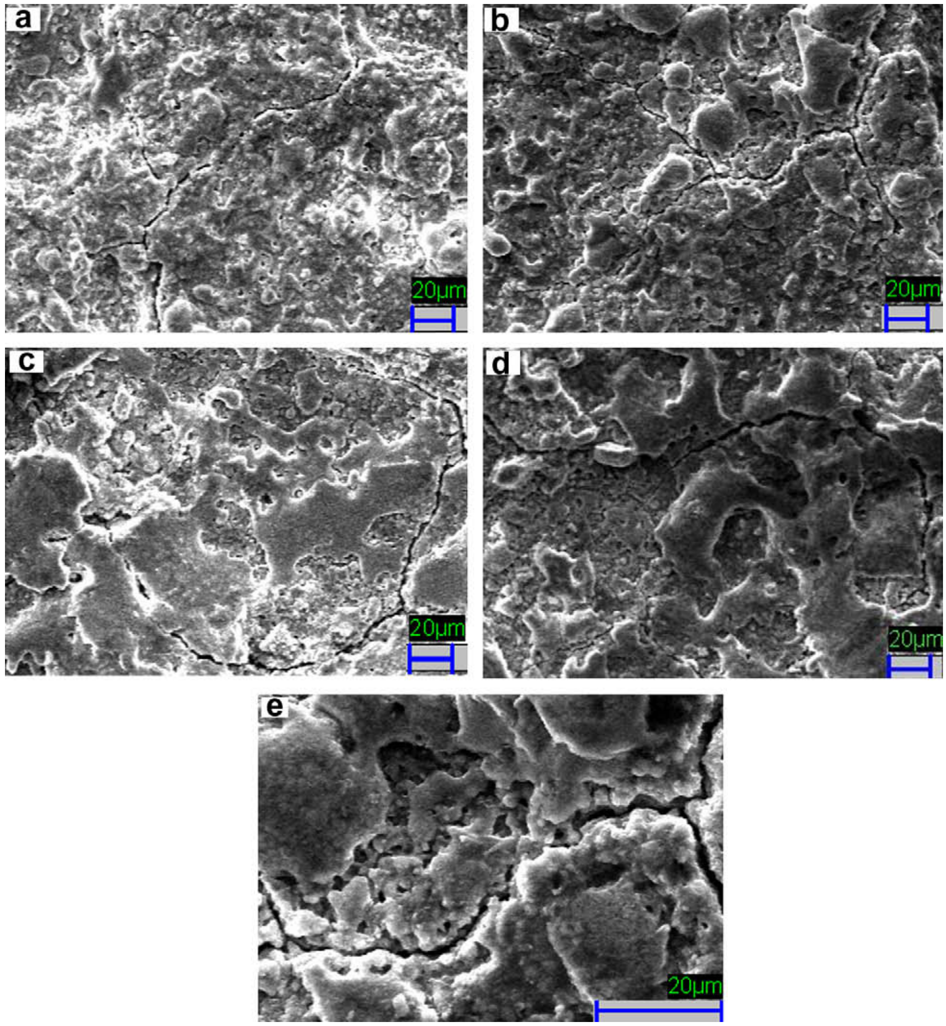


**Fig. 10.** EDMed surface characteristics of $Al_2O_3$–$SiC_w$–TiC ceramic composite under a duty cycle of 0.72 and a gap voltage of 70 V: pulse-on time of 50 µs (a) discharge current 14 A (shows radial cracks clearly), (b) discharge current 16 A (shows circumferential cracks clearly), pulse-on time of 200 µs, (c) discharge current 14 A, (d) discharge current 16 A and (e) discharge current 15 A (at 1500× magnification).

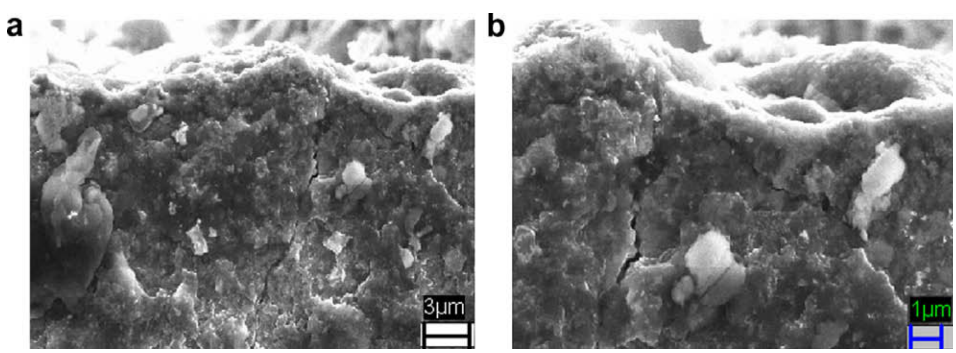


**Fig. 11.** (a) Subsurface cracking of $Al_2O_3$–$SiC_w$–TiC ceramic composite at 16 A/200 µs/70 V/0.72 duty cycle (b) an enlarged view of (a).

microcracks and subsurface cracks may together be responsible for the separation of small volumes of material in form of flake detachment from the base material. Therefore, the material removal mechanism may be called thermal spalling which is another material removal mechanism for the $Al_2O_3$–$SiC_w$–TiC ceramic composite at rough cutting mode. This mechanism of material removal (thermal spalling) has been further confirmed by the increase in material removal efficiency at rough cutting mode in comparison to normal cutting mode. In the current investigation, it could be concluded that thermal spalling effect is related to the formation of cracks and observed at high energy EDM.

## 4. Conclusions

In the present study, the machining characteristics and surface integrity of EDMed TiC particle and SiC whisker reinforced $Al_2O_3$ ceramic composite has been studied for exploring the material removal mechanisms involved in EDM. It is concluded that surface roughness increases with discharge current and pulse-on time. The thickness of the recast layer increases with the pulse-on time at normal cutting mode. This study provided an important insight for selecting EDM parameters using the ceramic composite $Al_2O_3$–$SiC_w$–TiC and showed it could be efficiently machined without causing a significant loss to the surface integrity.

The surface and subsurface damage have been investigated as they could provide key information on the mechanisms of material removal. The mechanisms by which material is removed are being predominately dissociation, melting and evaporation, and to some extent, oxidization and decomposition at lower current range, and thermal spalling at higher current range. Therefore, the material removal rate could be considerably increased due to thermal spalling induced flake detachment at higher current range. Therefore, rough EDM machining leading to thermal spalling and poor surface roughness followed by gentle material removal at lower current range with almost no surface or subsurface cracks and good surface quality could be advantageously used to obtain better quality $Al_2O_3$–$SiC_w$–TiC ceramic composite components.

## Acknowledgements

The authors would like to express their sincere thanks to Mr. John J. Schuldies, President, Industrial Ceramic Technology Inc., Ann Arbor Michigan, USA, for supplying the work material. The authors are also thankful to Dr. Rajesh Prasad, Applied Mechanics Department, Indian Institute of Technology Delhi for the fruitful discussion and suggestions on the material science aspects.

## References

[1] Agarwal S, Rao PV. Experimental investigation of surface/subsurface damage formation and material removal mechanisms in SiC grinding. Int J Mach Tools Manuf 2008;48:698–710.
[2] Fu C-T, Wu J-M, Liu D-M. The effect of electrodischarge machining on the fracture strength and surface microstructure of an $A1_2O_3$–$Cr_3C_2$ composite. Mater Sci Eng A 1994;188:91–6.
[3] Zhang JH, Lee TC, Lau WS. Study on the electro-discharge machining of hot pressed aluminium oxide based ceramics. J Mater Proc Tech 1997;63:908–12.
[4] Put S, Vleugels J, Biest OV, Trueman C, Huddleston J. Die sink electrodischarge machining of zirconia based composites. Brit Ceram Trans 2001;100:207–13.
[5] Liu C-C. Microstructure and tool electrode erosion in EDMed of $TiN/Si_3N_4$ composites. Mater Sci Eng A 2003;363:221–7.
[6] Fu C-T, Li A-K. The dependence of surface damage induced by electrical discharge machining on the fracture strength of $Al_2O_3$–$Cr_3C_2$ composites. Mater Chem Phys 1994;39:129–35.
[7] Liu C-C, Huang J-L. Effect of the electrical discharge machining on strength and reliability of TiN–$Si_3N_4$ composites. Ceram Int 2003;29:679–87.
[8] Nakamura M, Shigematsu I, Kanayama K, Hirai Y. Surface damage in $ZrB_2$-based composite ceramics induced by electro-discharge machining. J Mater Sci 1991;6:6078–82.
[9] Zhang JH, Lee TC, Lu CL, Tang CY. Surface integrity and modification of electro-discharge machined alumina-based ceramic composite. J Mater Proc Tech 2002;123:75–9.
[10] Lee T, Deng J. Mechanical surface treatment of electro-discharge machined (EDMed) ceramic composite for improved strength and reliability. J Eur Ceram Soc 2002;22:545–50.
[11] Pitman A, Huddleston J. Electrical discharge machining of $ZrO_2$/TiN particulate composite. J Brit Ceram Trans 2000;99:77–84.
[12] Hu CF, Zhou YC, Bao YW. Material removal and surface damage in EDM of $Ti_3SiC_2$ ceramic. Ceram Int 2008;34:537–41.
[13] Trueman CS, Huddleston J. Material removal by spalling during EDM of ceramics. J Eur Ceram Soc 2000;20:1629–35.
[14] Lauwers B, Kruth JP, Liu W, Eeraerts W, Schacht B, Bleys P. Investigation of material removal mechanism in EDM of composite ceramic materials. J Mater Proc Tech 2004;49:347–52.
[15] Smirnov BI, Nikolaev VI, Orlova TS, Shpeizman VV, Arellano-Lopez ARD, Goretta KC, et al. Mechanical properties and microstructure of an $Al_2O_3$–SiC–TiC composite. Mater Sci Eng A 1998;242:292–5.
[16] Wu KL, Yan BH, Huang FY, Chen SC. Improvement of surface finish on SKD steel using electro-discharge machining with aluminum and surfactant added dielectric. Int J Mach Tools Manuf 2005;45:1195–201.
[17] Roethel F, Kosec L, Garbajs V, Peklenik J. Contribution to the micro-analysis of the spark eroded surfaces. Ann CIRP 1976;25:135–40.
[18] Guu YH, Hou MT-K. Effect of machining parameters on surface textures in EDM of Fe–Mn–Al alloy. Mater Sci Eng A 2007;466:61–7.
[19] Lee HT, Tai TY. Relationship between EDM parameters and surface crack formation. J Mater Proc Tech 2003;142:676–83.
[20] Lee SH, Li XP. Study of the surface integrity of the machined workpiece in the EDM of tungsten carbide. J Mater Proc Tech 2003;139:315–21.
[21] Tai TY, Lu SJ. Improving the fatigue life of electro-discharge-machined SDK11 tool steel via the suppression of surface cracks. Int J Fatigue 2009;31:433–8.
[22] Lee LC, Lim LC, Wong YS, Fong HS. Crack susceptibility of electro-discharge machined surfaces. J Mater Proc Tech 1992;29:213–21.
[23] Manoj Kumar BV, Ramkumar J, Basu B, Kang S. Electro-discharge machining performance of TiCN-based cermets. Int J Refract Met 2007;25:293–9.
[24] <www.lucasmilhaupt.com>.