ELSEVIER

Ceramics International 26 (2000) 825–830

CERAMICS INTERNATIONAL

Surface integrity in electro-discharge machining, ultrasonic machining, and diamond saw cutting of ceramic composites

Deng Jianxin [a,*], Lee Taichiu [b]

[a]Department of Mechanical Engineering, Shandong University of Technology, Jinan 250061, Shandong Province, PR China
[b]Department of Manufacturing Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, PR China

Received 24 October 1999; received in revised form 6 November 1999; accepted 3 February 2000

Abstract

Good surface integrity is frequently required for structural ceramic components, since the lifetime of a ceramic component is in most cases determined by its surface features. In this study, the surface integrity of electro-discharge machined, ultrasonic machined, and diamond saw cut ceramic composites has been investigated and compared. The surface roughness, hardness, and topography of the machined surface were examined. Flexural strength and its distributions were used to evaluate the effect of machining process on the surface integrity of the machined specimens. Results show that the machining process had an important effect on the surface quality of the machined ceramics. Electro-discharge machining of ceramics created a heat-affected surface layer with poor surface integrity, such as cracks and craters, and the variable surface damages on the electro-discharge machined specimens resulted in low Weibull modulus. Within most machining conditions, the ultrasonic machined and diamond saw cut specimens behaved fairly consistently, and the flexural strength and Weibull modulus were higher than that of the electro-discharge machined specimens.

Keywords: A. Finishing; B. Composites; Machining

1. Introduction

The production of ceramic composite in the fired conditions is still unable to meet the accuracy required of a finished component with complex geometry, this inevitably means that further processing has to be performed. Machining processes such as grinding, electro-discharge machining (EDM), ultrasonic machining (USM), diamond saw cutting, and laser beam machining are often used and are the major contributor to the overall cost of a ceramic component [1,2]. The relatively low fracture toughness of ceramics makes them very sensitive to the damage, which is introduced into the ceramic surface during machining. The type of produced damage includes surface and sub-surface cracks and unfavorable residual stresses. The combination of surface cracks and residual stresses can greatly affect the characteristics of ceramics and play an important role in the final strength of a ceramic component.

The strength of ceramic materials depends on both its inherent resistance to fracture and the stochastically distributed defects such as grain boundaries, pores and cracks, which can lead to immense variations in strength. Fracture analysis have shown that the mechanisms responsible for the failure of ceramics are in most cases surface defects, which are often originated during mechanical treatment in the final machining. These machining damages on the surface limit the strength and determine the strength distribution since they influence crack growth under stress [3–5]. It is quite common to observe that fracture strength varies significantly among different specimens of the same material. This is partly due to the randomly distributed surface damages. For this reason, a statistical measure is required to account for its variability. Several studies [6–8] have shown that the Weibull modulus of flexural strength can be used to characterize the surface integrity of the machined ceramics. As the Weibull modulus describes the distribution of individual values of the flexural strength within a population. A high value of Weibull modulus implies a narrow distribution of strength, and denotes a good material with a high

* Corresponding author. Tel.: +86-531-294-0972; fax: +86-531-295-5999.
E-mail address: dengjx@jn-public.sd.cninfo.net (D. Jianxin).

0272-8842/00/$20.00
PII: S0272-8842(00)00024-9

degree of homogeneity of properties. Whereas low Weibull modulus indicates that the size distribution of the strength-controlling cracks is broader, which may be resulted from surface damages during the final machining.

In this study, the surface integrity of electro-discharge machined (EDMed), ultrasonic machined (USMed), and diamond saw cut Al_2O_3/TiC/Mo/Ni ceramic composite have been investigated. The surface roughness, hardness, and topography of the machined surfaces were examined. Flexural strength and its distribution were used to evaluate the effect of machining process on the surface integrity of the machined specimens. The purpose was to compare the surface integrity, and to characterize the effect of machining process on the strength and its distribution.

2. Materials and experimental procedures

2.1. Material preparation

The material used in the present investigation was an alumina-based ceramic composite fabricated by the authors. Monolithic Al_2O_3 (average particle size 0.5 μm) was used as the baseline material. Additions of TiC particles (average particle size 0.8 μm) were added to Al_2O_3 matrix according to the combinations listed in Table 1. The final densification was accomplished by hot pressing with a pressure of 36 MPa in argon atmosphere for 8 min to produce a ceramic disk. The required sintering temperature was in the range of 1600–1800°C. Small amount Mo and Ni metal phases were added to lower the electrical resistivity and to increase the interface bonding strength between the particles. Table 1 lists the mechanical properties of this ceramic composite.

2.2. Machining methods and experimental procedures

EDM is a thermal process where material is removed by a succession of electrical discharges occurring between the tool electrode and the workpiece. EDM provides a mean of machining of ceramic materials, irrespective of their hardness and strength, provided that their electrical conductivity is of the order of 100 Ωcm. The wire-EDM machine used in this study was a Mitsubishi Wire System Model DWC 90G with a transistor pulse circuit having a maximum machining current of 30 A. The wire electrode used was a brass wire of 0.25 mm diameter. The average machining voltage was set at 55 V and the current $\mathbf{I}_p$ was set at 5, 10, and 14 A, respectively.

Table 1
Mechanical properties of Al_2O_3/TiC/Mo/Ni ceramic composite

Composition (vol %)	Flexural strength (MPa)	Fracture toughness ($MPa{\cdot}m^{1/2}$)	Hardness (GPa)
Al_2O_3/50%TiC/5% Mo/Ni	900	5.04	20.5

USM is an abrasive machining process by which hard and brittle materials can be machined whether conducting or not, and the workpiece experiences no thermal damage. In the ultrasonic machining, the abrasive particles in slurry with water are under a tool, which is excited of an ultrasonic frequency with small amplitude (normally less than 75 μm), and the material is removed primarily by impact of the abrasive particles on the ceramic surface. In this study, USM was conducted by using a J93025 machine tool (made in China) with a power of 250 W and frequency of 16–25 kHz. The static load was of 10 N and the abrasives used were of 80, 120, and 240-grit B_4C powders, respectively.

Diamond saw cutting was carried out using a Struers Accutom-2 machine tool with a diamond blade. The feedrate was of 0.5 mm/min and the speed of the diamond blade was of 6 m/s.

A minimum of 10 specimens (3×4×16 mm) from each machining condition were prepared for the measurement of flexural strength. Three-point-bending mode was used to measure the flexural strength over a 10 mm span at a crosshead speed of 0.5 mm/min. The strengths were then analyzed by two-parameter Weibull distribution. The surface roughness measurements for the machined specimens were carried out on a Talysurf 10 system. Vickers hardness was tested on Zwick3212 hardness tester. The microstructures of the machined surfaces were observed by scanning electron microscopy (SEM).

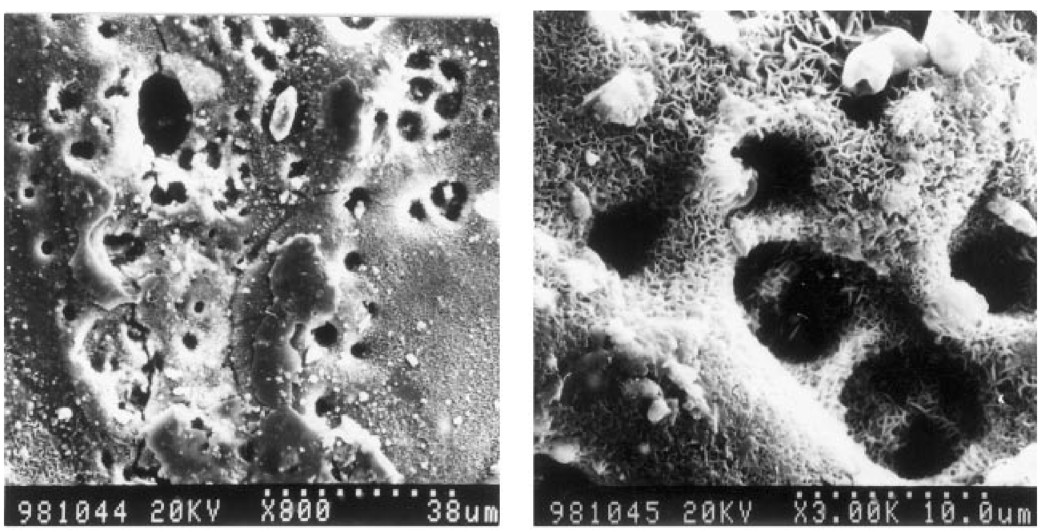
3. Results and discussion

3.1. Surface topography of the machined Al_2O_3/TiC/Mo/Ni ceramic composite

Fig. 1(a) shows the typical SEM micrograph of the EDMed surface of the Al_2O_3/TiC/Mo/Ni composite, which reveals quite a number of spark-induced craters. The overall surface appears pitted with molten-looking bumps of varying diameter and morphology, significant surface damage with micro-cracks and small droplets can also be seen. The probability of finding such features on the EDMed surface was significantly greater. It can be concluded that Al_2O_3/TiC/Mo/Ni ceramic composite are EDMed by either melt formation for low melting phases or thermal spalling for refractory phases, the effect of micro-cracking is more pronounced for the material removal and surface formation. The possible mechanism for the formation of the craters in EDMed surfaces is that sparks are formed at the conductive phase such as Mo and Ni, which melts and may evaporate. The high thermal conductivity of these metal phases allows deeper melting, which may further increase the machined surface roughness. Fig. 1(b) shows clearly at higher magnification the craters and re-solidified layer of the surface. It can be seen that the surface damage caused by EDM leads to severe Mo and Ni erosion and exposure of Al_2O_3 and TiC grains. The possibility and extent of subsurface damage were explored by preparing cross section view through the eroded crater, perpendicular to the specimen surface. Fig. 2 is a SEM micrograph, taken near the center of the crater base, showing the subsurface damage. It reveals that there is a distinct heat-affected surface layer. This surface layer exhibits a darker color than the inside core, and the depth is about 8 μm in thickness. The combination of surface cracks and craters can greatly effect the characteristics of ceramics and play an important role in the strength of the ceramic as can be seen later.

The USMed ceramic surface was quite different from those of the EDMed. Fig. 3 shows the typical SEM micrograph of the USMed surface of Al_2O_3/TiC/Mo/Ni ceramic composite. It reveals that the material is removed primarily by brittle fracture. The fracture mode is obviously mixed transgranular and intergranular. The machined surface is characterized by numerous small chipped region zones. In comparison with Fig. 1, it exhibited a relative smooth surface, and there is no distinct crack on the USMed surface.

Typical SEM micrograph of the diamond saw cut surface of Al_2O_3/TiC/Mo/Ni ceramic composite is shown in Fig. 4. It can be seen that the machined surface contains



(a) (b)

Fig. 1. SEM micrographs of the EDMed surface of Al_2O_3/TiC/Mo/Ni ceramic composite.

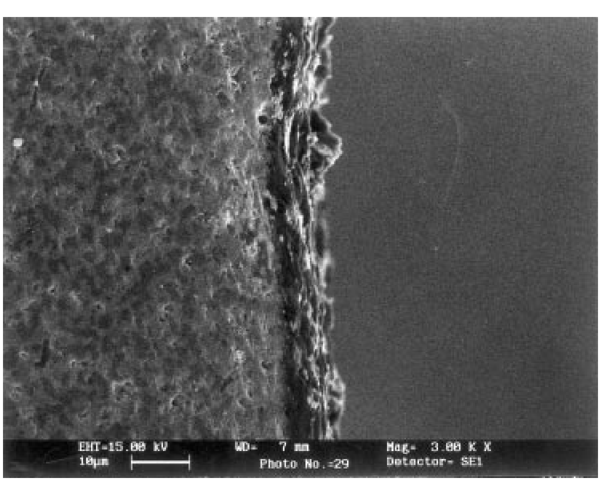


Fig. 2. Cross-sectional SEM micrograph of the EDMed surface of Al_2O_3/TiC/Mo/Ni ceramic composite.

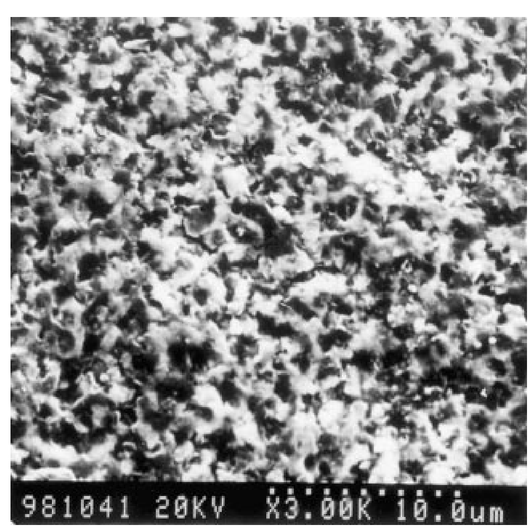


Fig. 3. SEM micrograph of the USMed surface of Al_2O_3/TiC/Mo/Ni ceramic composite.

grooves produced by micro cutting and pits produced by microfracture. On the flanks of the grooves small spalling occurs. This spalling may indicate the presence of brittle fracture during chipping. There was very little evidence of pullout of individual grains on the diamond saw cut surface.

3.2. Surface roughness and hardness of the machined Al_2O_3/TiC/Mo/Ni ceramic composite

The results of the surface roughness and hardness of the EDMed, USMed, and diamond saw cut surfaces are listed in Table 2. It can be seen that the EDMed surfaces showed the highest surface roughness and the lowest hardness. The highest surface roughness of the EDMed specimens attributed to the existence of surface cracks, craters and droplets as can be seen in Fig. 1. While the low surface hardness of the EDMed ceramic may be resulted from its heat-affected layer as shown in Fig. 2. A decrease of surface roughness in EDM can be reached by using smaller current, because of a decreasing amount of discharge energy density. The surface hardness shows no noticeable differences among these two abrasive machining processes.

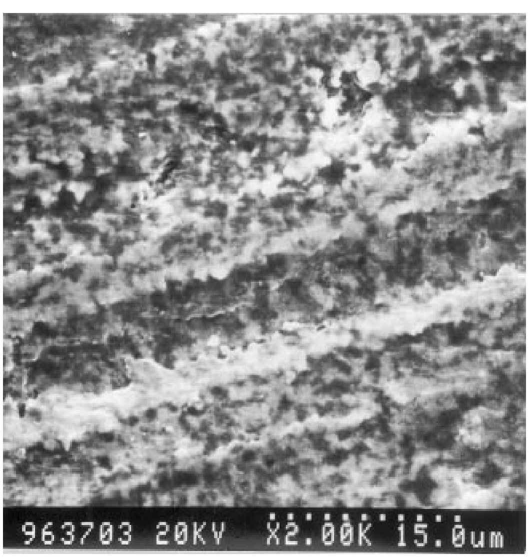


Fig. 4. SEM micrograph of the diamond saw cut surface of Al_2O_3/TiC/Mo/Ni ceramic composite.

Table 2
Surface roughness and hardness of the machined Al_2O_3/TiC/Mo/Ni ceramic composite

Specimen	Conditions	Ra (μm)	H_v (GPa)
EDMed	$U = 55$ V, $\mathbf{I}_p = 5$–14 (A)	1.64–2.55	14.7–16.5
USMed	B_4C abrasive, grit size 80–240	0.15–0.85	18.2–19.8
Diamond saw cut	Saw speed $V = 6$ m/s	0.65–1.42	18.5–20.2

3.3. Flexural strength and its distribution of the machined Al_2O_3/TiC/Mo/Ni ceramic composite

Weibull plot of strength distributions of the EDMed specimens is shown in Fig. 5. The slopes of the lines are the Weibull modulus for each distribution. A higher slope indicates less variability in the strength data. Table 3 summarizes the Weibull modulus and average strength measured under each condition. Referring to Tables 1 and 3, it is evident that the average strength values of the EDMed specimens are considerably low, only 68–80% of the original value of the material. The value of Weibull modulus is in the range of 6.3–8.7. This indicates that the EDM process has a detrimental effect on the flexural strength of the machined specimens. The plot for the high current condition shows more scatter. The composite EDMed with a current of 5 A had an average strength of 716 MPa and a Weibull modulus of 8.7. When the current was of 10 A, the average strength was decreased to 665 MPa and Weibull modulus to 7.1. Current of 15 A resulted in further decrease in strength of 619 MPa and Weibull modulus of 6.3. As higher discharge current leads to a higher discharge energy density, thus increasing the material removal rate and the surface roughness. Surface flaws are introduced that can lead to catastrophic failure of the specimen.

One of the most serious problems in ceramic machining is the initiation of cracks on the workpiece surface.

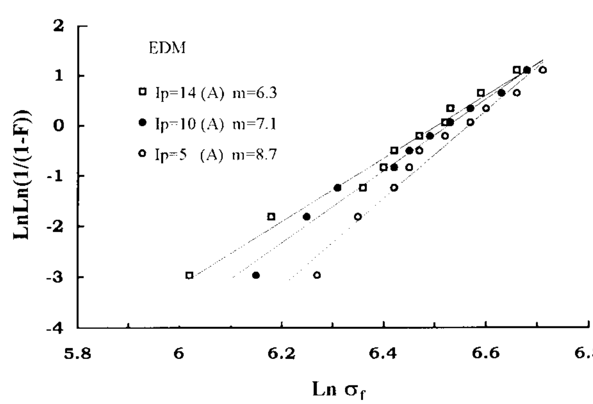


Fig. 5. Weibull plot of the strength distribution of the EDMed Al_2O_3/TiC/Mo/Ni ceramic composite.

Table 3
Weibull parameters for the strength distribution of the EDMed ceramic composite

Specimen	Current $\mathbf{I}_p$ (A)	Weibull modulus	Average flexural strength (MPa)
EDMed	14	6.3	619
	10	7.1	665
	5	8.7	716

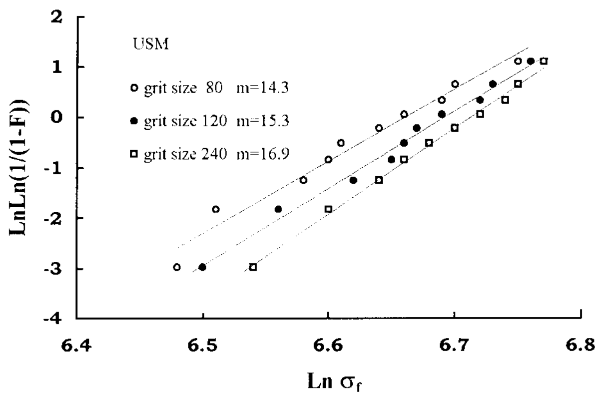


Fig. 6. Weibull plot of the strength distribution of the ultrasonic machined Al_2O_3/TiC/Mo/Ni ceramic composite.

This is due to the fact that the crack initiation results in the considerable reduction of the strength of the machined components, and the strength is inversely related to the size and distribution of existing flaws — predominantly surface flaws. The basic factors that control the strength of brittle materials will determine the flaw size generated during machining. The spark-induced cracks and craters on the EDMed surfaces may serve as fracture origins and cause degradation of strength, and the variable surface damages on the EDMed specimens resulted in low Weibull modulus.

Table 4
Weibull parameters for the strength distribution of the USMed ceramic composite

Specimen	Grit size	Weibull modulus	Average flexural strength (MPa)
USMed	80	14.3	781
	120	15.3	808
	240	16.9	828

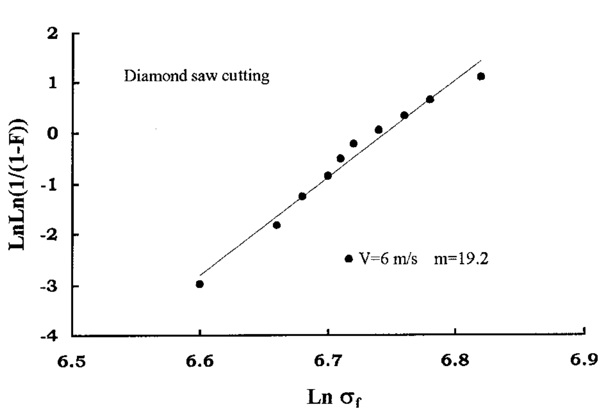


Fig. 7. Weibull plot of the strength distribution of the diamond saw cut Al_2O_3/TiC/Mo/Ni ceramic composite.

Table 5
Weibull parameters for the strength distribution of the diamond saw cut ceramic composite

Specimen	Weibull modulus	Average flexural strength (MPa)
Diamond saw cut	19.2	846

Weibull plot of strength distributions of the USMed specimens is shown in Fig. 6. Table 4 summarizes the Weibull modulus and average strength measured under each condition. It is evident that the average strength values of the USMed specimens are higher than that of the EDMed specimens. The value of Weibull modulus is increased, in the range of 14.3–16.9. This indicates that the USM process has little strength limiting damages to the machined ceramic surfaces compared with the EDM process. The smaller the abrasive grit-size, the higher the strength and Weibull modulus. Weibull plots of strength distributions of the diamond saw cut specimens are shown in Fig. 7. Table 5 summarizes the Weibull modulus and average strength. The diamond saw cut specimens with saw speed of 6 m/s had an average strength of 846 MPa and a Weibull modulus of 19.2. It can be seen that within the most machining conditions, the USMed and diamond saw cut specimens behaved fairly consistently, and the flexural strength and Weibull modulus were higher than that of the EDMed specimens.

4. Conclusions

The surface integrity of EDMed, USMed, and diamond saw cut Al_2O_3/TiC/Mo/Ni ceramic composites have been investigated. The following conclusions were obtained:

1. EDM of Al_2O_3/TiC/Mo/Ni ceramic composite created a heat-affected surface layer with poor surface integrity such as spark-induced cracks and craters. The surface integrity and residual strength of the EDMed specimens decreased with increasing current, and the variable surface damages on the EDMed specimens resulted in low Weibull modulus.
2. USMed and diamond saw cut surfaces are of better quality than the EDMed surfaces within the most machining conditions. The strength and Weibull modulus of these two abrasive machined specimens were much higher than that of the EDMed specimens. An improvement in both flexural strength and Weibull modulus can be achieved with decreasing abrasive grit size in the USM process.

References

[1] S. Jahanmir, M. Ramulu, P. Koshy (Eds.), Machining of Ceramics and Composites, New York: Marcel Dekker, Inc., 1998.
[2] P.K. Mishra, Non-conventional Machining, Narosa Publishing House, London, 1997.
[3] D.A. Lucca, E. Brinksmeier, Progress in assessing surface and subsurface integrity, Annals of the CIRP 47 (2) (1998) 669–693.
[4] L Kun, T. Warren Liao, Surface/subsurface damage and the fracture strength of ground ceramics, Journal of Materials Processing Technology 57 (1996) 207–220.
[5] H.K. Tönshoff, H. Trumpold, Evaluation of surface layers of machined ceramics, Annals of the CIRP 38 (2) (1989) 699–708.
[6] E. Schubert, H.W. Bergmann, Surface modification of ceramic materials using excimer lasers, Surface Engineering 9 (1) (1993) 77–81.
[7] T.C. Lee, J.H. Zhang, Surface treatment of wire electro-discharge machined engineering ceramics by abrasive blasting, Journal of Adhesion Science and Technology 12 (6) (1998) 585–592.
[8] T.C. Lee, T.C. Zhang, C.Y. Tang, Strengthening of wire electro-discharge machined sialon ceramic by quenching, Key Engineering Materials 145–149 (1998) 1773–1778.