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Mechanical surface treatments of electro-discharge machined (EDMed) ceramic composite for improved strength and reliability

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Abstract

To obtain size specification, ceramic composites often need to be machined, and these processes may lead to a decreased strength and reliability especially for electro-discharge machining (EDM). In this paper, two mechanical surface treatments, i.e. ultrasonic machining (USM) and abrasive blasting, have been introduced to restore and improve these properties for the electro-discharge machined (EDMed) surfaces of the toughened and electroconductive $Al_2O_3/TiC/Mo/Ni$ ceramic composite. Comparison of the flexural strength of EDMed and modified specimens revealed that the modified specimens yielded an apparent strengthening with a concurrent increase in Weibull modulus. Microstructure analysis showed that the EDMed specimens of this composite had suffered severe surface damage. Abrasive blasting and ultrasonic machining are two effective procedures to reduce this damage and to minimize the surface contribution to fracture probability. © 2002 Published by Elsevier Science Ltd.

Keywords: $Al_2O_3/TiC/Mo/Ni$; Composites; Electro-discharge machining; Machining; Surface treatment

1. Introduction

Ceramic composites have intrinsic characteristics, such as: high hardness, good chemical inertness and high wear resistance, that makes them promising candidates for high temperature structural and wear-resistance materials. The applications of advanced ceramic composites include dies, cutting tools, seal rings, valve seats, bearing parts, and a variety of engine parts etc. High dimensional accuracy and good surface integrity are frequently required of these ceramic components. So the development of machining processes to convert these materials into products is becoming a key technology in engineering applications. One reason for this is due to the volumetric shrinkage which occurs during the sintering processes, such that machining of ceramic components becomes necessary to be able to impart an accurate final shape and size to precision elements. Although advances have been made recently in near-net-shape technology, machining in the fired condition continues to be the predominant process for complex geometries and precision ceramic components such as: cutting tools, mould and dies. Among the various machining processes grinding with a diamond wheel and electro-discharge machining (EDM) are most widely applied.[1,2]

EDM is a thermal process where material is removed by a succession of electrical discharges occurring between the tool electrode and the workpiece. The mechanisms of material removal are melting, evaporation, and thermal spalling. EDM is only possible on electrically conductive ceramics and the threshold value of ceramic electrical conductivity for EDM is of 100 Ω.cm.[3,4] The thermal action used with this process acts strongly on the metallurgical properties of the ceramics. According to many studies,[4–6] EDM of ceramics may create damaged surface layers such as unfavorable residual stresses and cracks, and the machining damaged zone can extend up to 100 μm. Cracks and residual stresses in EDMed ceramic surfaces often lead to a reduction in mechanical properties and reliability. Limitations for the machined ceramics often relate to the surface sensitive properties such as fracture initiation characteristics and their effects on the properties of bulk materials. Therefore, it is necessary to modify the damaged surface before practical applications. A series of surface treatments to ceramics have been introduced recently to improve these properties and to reduce the surface contribution to

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fracture probability,[7–9] for example: changing the microstructure, or properties of the surface layer by mechanical, chemical, or thermal action and so on. However, none of them is universally effective, each kind of treatment fulfilling only certain functions.

Al_2O_3/TiC/Mo/Ni ceramic composites developed by the authors have been used for cutting tool and precision die applications for several years. However the surface sensitive properties of this machined ceramic composite often lead to a decreased performance. In this study, several mechanical surface treatments, namely ultrasonic machining and abrasive blasting, have been introduced to the wire-EDMed surfaces of Al_2O_3/TiC/Mo/Ni ceramic composite respectively. The purpose was to reduce the surface contribution to fracture probability, and to characterize the reliability modification and machining damage in terms of flexural strength, strength distribution, and the strength-controlling cracks.

2. Materials and experimental procedures

2.1. Material preparation

The starting powders were commercial Al_2O_3 (average particle size 0.5 μm) and TiC (0.8 μm). Alumina was used as the base material, additions of 55 vol.% TiC and 5 vol.% of Mo and Ni metal phases were added to Al_2O_3 matrix. The additions of metal phase to the ceramic composite were to further lower the electrical resistivity and to increase the interface bonding strength between the particles. The combined powders were prepared by wet ball milling in alcohol with cemented carbide balls. Following drying, the final densification was accomplished by hot pressing with a pressure of 35 MPa in argon atmosphere for 8 min to produce a ceramic disk. The required sintering temperature is in the range of 1600–1800°C. Details of procedures and specific processing parameters employed are described elsewhere.[5,8,10,11]

2.2. Experimental procedures

In order to study the surface modification of the wire-EDMed ceramic surfaces, test pieces of 3×4×16 mm were prepared from the sintered disks by wire-EDM. 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, the current I_p was set at 14 A and the pulse length t_i was 200 μs.

The surfaces of the pre-machined specimen by wire-EDM were then modified by ultrasonic machining for 3 min or abrasive blasting for 1 min, respectively. Ultrasonic machining was conducted by using a J93025 machine tool (made in China) with a power of 250 W and frequency of 16–25 KHz.[5] The static load was of 10 N and the abrasive was of 80-grit B_4C powders. Abrasive blasting was conducted using IEPCO micro-blasting equipment (type Pneumatic 600S) which is equipment used for surface treatment.[8] The nozzle size was selected as 6.0 mm in diameter. Al_2O_3 abrasives with grain size of 40 μm were used.

The wire-EDMed and modified specimens were then offered for measurement of flexural strength respectively. 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 a series of related techniques based on the two-parameter Weibull distribution. For these analysis, the probability of failure, F, was calculated using the equation:

$$F = \frac{n - 0.5}{N} \tag{1}$$

where n is the rank of failure and N the total numbers of specimen tested. These results were then plotted in the usual double logarithmic form of the Weibull expression:

$$\ln\ln\left(\frac{1}{1-F}\right) = -m\ln\sigma_0 + m\ln\sigma_f \tag{2}$$

where σ_f is the measured strength, m is the Weibull modulus, and σ_0 is a scaling parameter. High-Weibull modulus denotes a good material with a high degree of homogeneity of properties and a narrow distribution of fracture stresses, whereas low-Weibull modulus shows a big scatter of strength of materials with a wide distribution of fracture strength and low reliability. The Weibull modulus, therefore, reflects the scatter of the fracture strength,[12,13] and may be used as a parameter characterizing the homogeneity of the wire-EDMed ceramic composite when subjected to different surface modifications. The microstructures of the wire-EDMed surfaces and modified surfaces of the ceramic composite were observed by scanning electron microscopy (SEM).

3. Results and discussions

3.1. Properties and microstructure of the Al_2O_3/TiC/Mo/Ni ceramic composite

Densities of the hot-pressed disk were measured by the Archimedes method with an immersion medium of deionized water plus a wetting agent.[14] Electrical resistivity was measured by the four linear probe methods.[11] Fracture toughness measurement was performed using indentation method in a hardness tester (ZWICK 3212) using the formula proposed by Cook and Lawn.[15] On the same apparatus the Vickers hardness was measured on polished surface with a load of 98 N. Data for density, hardness, fracture toughness and electrical resistivity were gathered on five specimens and are listed in Table 1.

Fig. 1 shows the microstructure of the Al_2O_3/TiC/Mo/Ni ceramic composite. Specimens were etched using a hot-solution of phosphoric acid. In this structure, the white phases with clear contrast are of TiC, and the grey phases are of Al_2O_3. It can be seen that the second phases were uniformly distributed with the matrix, and there were few second phase agglomerates or matrix-rich regions.

Typical TEM micrographs of the ceramic composite are presented in Fig. 2. It can be seen that the ceramic composite reached approximately full density. There is a large proportion of fine TiC grains heavily embedded in Al_2O_3 grains with inhomogeneous size distribution around 1–50 nm [Fig. 2(b)]. Since the Al_2O_3 grains are much larger than the fine TiC grains, nano-sized TiC grains are trapped during the later coarsening stage of sintering. This structure is very beneficial for the strength, as the existence of such fine grains may inhibit the grain growth of Al_2O_3.[16] The improved strength of this composite compared with the monolithic Al_2O_3 is attributed to a reduction in the critical crack size resulting from the suppression of grain growth by the nano-sized TiC particulate.

3.2. Strength data and statistics

Weibull plots of strength distributions of the EDMed and surface modified specimens by ultrasonic machining and abrasive blasting are shown in Fig. 3. It can be seen that all the flexural strength results of the specimens subjected to different surface modifications ascribe to the Weibull form of description. Table 2 summarizes the Weibull modulus, average strength and standard deviation measured under each condition. Referring to Table 2, it is evident from the high correlation of coefficients that the two-parameter Weibull function is a satisfactory representation of these strength results for the specimens subjected to different surface modifications measured in this study.

Table 1
The physics and mechanical properties of Al_2O_3/TiC/Mo/Ni ceramic composite

Density (g/cm^3)	Electrical resistivity (Ω.cm)	Hardness (GPa)	Fracture toughness ($MPa.m^{1/2}$)
4.76	$2\sim6\times10^{-3}$	20.5	5.04

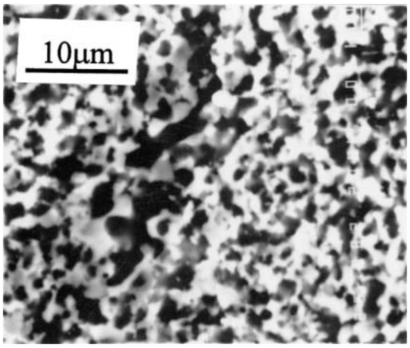


Fig. 1. Typical back scattered electron image (BEIS) of the Al_2O_3/TiC/Mo/Ni ceramic composite.

It can be seen from these results that the mechanical surface modifications for wire-EDMed ceramic composite can yield an apparent strengthening with a concurrent increase in Weibull modulus. The ceramic composite in the form of wire-EDMed test bars had an average strength of 619 MPa and a rather low Weibull modulus of 6.3. The Weibull modulus reflects the scatter of the fracture strength, the strength scatter clearly reflected the flaw variability. It appears that the EDM of the ceramic composite can introduce different flaw populations. Thus the strength scatter must be minimized to improve reliability of EDMed ceramic composites.

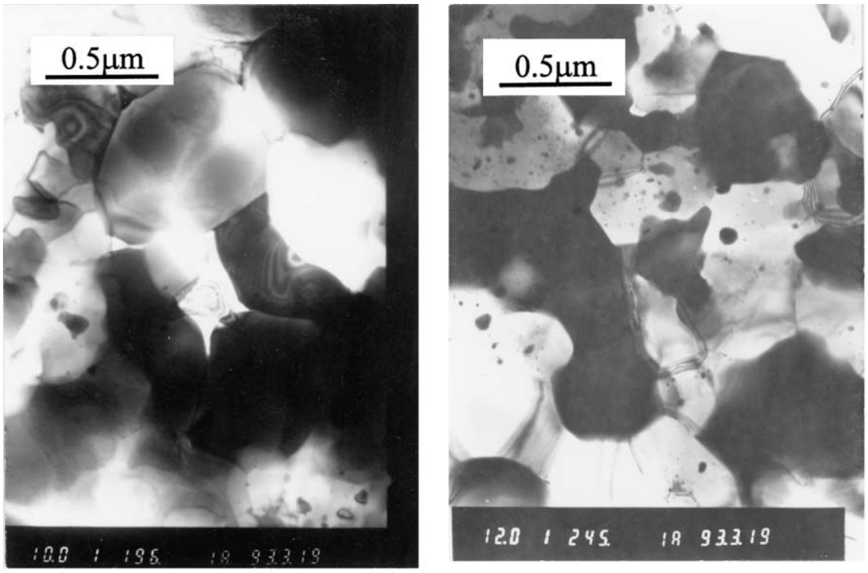
When the surfaces of wire-EDMed specimens were subjected to the surface treatment of abrasive blasting, the average strength was increased to 727 MPa and Weibull modulus to 9.4. Ultrasonic machining resulted in a further increase in strength of 781 MPa and a Weibull modulus of 14.3. At the same failure probability, flexural strength of the EDMed specimen increases about 100 MPa when subjected to abrasive-blasting surface finishing, and about 160 MPa after being modified by ultrasonic machining surface finishing.

For the purpose of comparison, the pre-machined specimens by wire-EDM were modified by grinding and polishing to remove the damaged layer. The specimens were rough machined with 180-grit diamond, finish machined with 320-grit diamond, rough polished with 40 μm diamond, and finish polished with 5 μm diamond. The Weibull plot of strength distribution of these specimens is shown in Fig. 4. It can be seen that grinding followed by polishing of the EDMed specimens resulted in a further increase in strength to 927 MPa and a Weibull modulus of 18.5. At the same failure probability, flexural strength of the EDMed specimen increases about 300 MPa when subjected to grinding and polishing.

The results suggest that an improvement in flexural strength and Weibull modulus of EDMed ceramic composite can be achieved through mechanical surface modifications such as ultrasonic machining, abrasive blasting, and grinding followed by polishing.

3.3. Surface and subsurface examinations

Ultrasonic machining and abrasive blasting are two economically feasible abrasive machining processes by



(a) (b)

Fig. 2. TEM micrographs of the Al_2O_3/TiC/Mo/Ni ceramic composite.

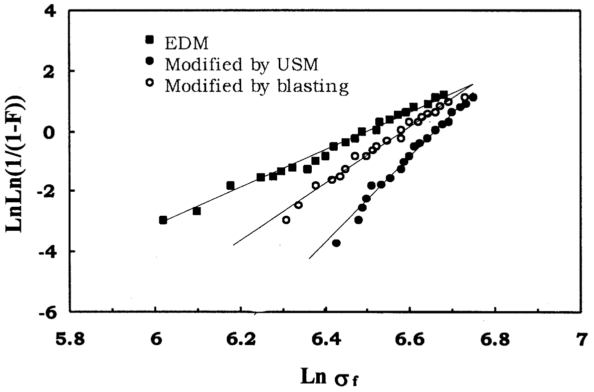


Fig. 3. Weibull plot of the strength distribution of the wire-EDMed and modified ceramic specimens.

Table 2

Weibull parameters for the strength distribution of the wire-EDMed and surface modified ceramic specimens

	Specimen number N	Weibull modulus m	Average strength (MPa)	Standard deviation R^2
EDM	20	6.3	619	0.98
EDM→abrasive blasting	20	9.4	727	0.97
EDM→USM	20	14.3	781	0.97
EDM→grinding→polishing	30	18.5	927	0.97

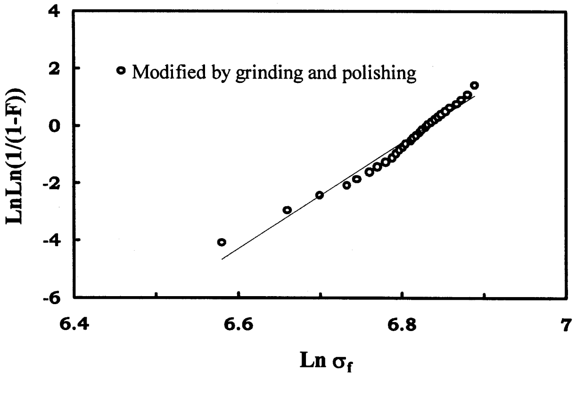


Fig. 4. Weibull plot of the strength distribution of the wire-EDMed ceramic composite subjected to grinding and polishing.

which hard and brittle materials can be machined whether electrically conductive or not, and the workpiece experiences no thermal damage in both cases. In ultrasonic machining, abrasive particles in slurry with water are under a tool which is excited using an ultrasonic frequency of small amplitude (normally less than 75 μm), and the material is removed primarily by impact of the abrasive particles on the ceramic surface. Because the impact occurs only when the tool is in close proximity to the workpiece, and no pressure is applied between the tool and the abrasive, there is very little strength-limiting damage to the machined ceramic surfaces through the control of the abrasive dimensions.[17] While in the process of abrasive blasting, abrasive particles are accelerated by compressed air and are directed through a nozzle against the workpiece. The high velocity abrasive can cause material removal when it strikes a hard and brittle material. With less air pressure and smaller abrasive size, the impact of a single abrasive is very small, and the resulting erosion can be used for polishing.[18]

Machining damage often limits the strength and determines the strength distribution of ceramic composites since it influences crack growth under stress. Surface cracks resulting from machining are a common source of failure in ceramic composites.[19,20] The morphological and structural characteristics of the machined surfaces are directly related to the material removal mechanisms. The surface roughness of the wire-EDMed and the modified surfaces are listed in Table 3. It can be seen that the EDMed surfaces show the highest surface roughness, while surfaces subjected to grinding and polishing show the lowest surface roughness. The higher surface roughness of the EDMed surface can be attributed to the existence of surface cracks, craters and droplets[5] as can be seen in Fig. 5. Several studies[19,20] have shown that a decrease in surface roughness alone is not sufficient to improve the strength. The damage caused in machined ceramic surfaces may not be removed simply by further burnishing of the surface to achieve better surface finish. The reason for this is that the strength controlling factors are predominantly crack generation and propagation through brittle fracture.

Fig. 5 shows the SEM micrographs of the wire-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 holes of varying diameter and morphology. Significant surface damage with micro-cracking and small droplets can also be seen. It can be concluded that the Al_2O_3/TiC/Mo/Ni ceramic composite is EDMed by either melt formation for low melting phases or thermal spalling for refractory phases. The effect of micro-cracking was found to be the dominant mechanism for 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 the metal phase allows deeper melting, which may further increase the machined surface roughness. Therefore, the micro-cracks and the craters on the machined surfaces may serve as fracture origins and cause degradation of strength and Weibull modulus of the EDMed specimens.

Table 3
Surface roughness and hardness of the EDMed and surface modified ceramic specimens

Specimen	Surface roughness Ra (μm)	Hardness (GPa)
EDMed	2.26	15.5
EDM→abrasive blasting	0.85	19.7
EDM→USM	0.15	18.7
EDM→grinding→polishing	0.08	20.5

Fig. 5. SEM micrograph of the wire-EDMed surface of the Al_2O_3/TiC/Mo/Ni ceramic composite.

Figs. 6 and 7 show the SEM micrographs of the modified surface by ultrasonic machining and abrasive blasting respectively. In comparison with Fig. 5, they exhibited a relative fine structure and smooth surface, irregularities produced by fracture damage can not be clearly observed, and there is no distinct crack on the machined surface. Therefore, EDMed ceramic specimens had severe surface damage, mechanical surface modifications with ultrasonic machining and abrasive blasting can greatly minimize surface contribution to fracture probability, and are the main cause for increase of strength and Weibull modulus. For ceramic components of complex gemetry such as moulds and dies, EDM is one of the most widely used shaping methods. To further improve the surface integrity and reliability of

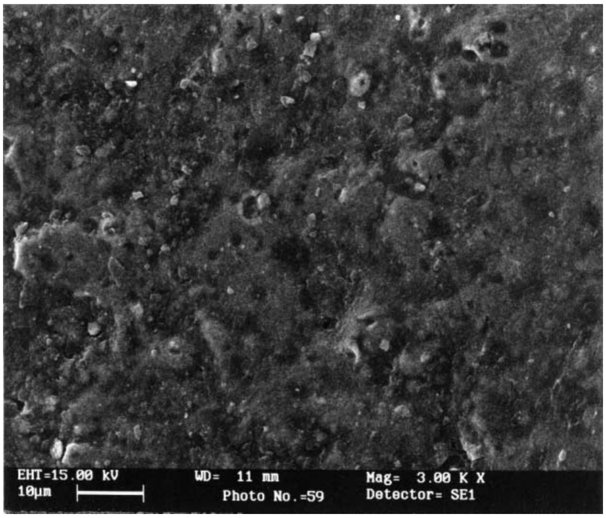


Fig. 6. SEM micrograph of the EDMed surface of the Al_2O_3/TiC/Mo/Ni ceramic composite when subjected to surface modification by ultrasonic machining.

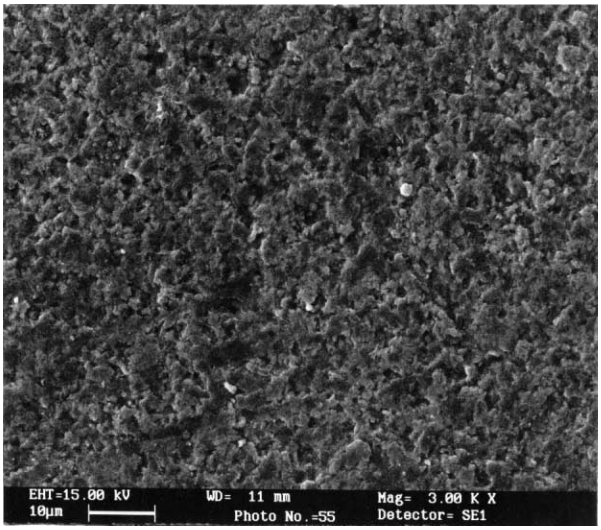


Fig. 7. SEM micrograph of the EDMed surface of Al_2O_3/TiC/Mo/Ni ceramic composite when subjected to surface modification by abrasive blasting.

these ceramic components, surface finishing with ultrasonic machining and abrasive blasting using finer and more uniform abrasives are two feasible and effective procedures to reduce the surface damage and to minimize the surface contribution to fracture probability.

4. Conclusions

Electroconductive and toughened Al_2O_3/TiC/Mo/Ni ceramic composites were produced using hot pressing. Several mechanical surface modifications, i.e. ultrasonic machining and abrasive blasting, have been introduced respectively to the wire-EDMed surfaces of this ceramic composite. The following conclusions were obtained.

1. The two mechanical surface modifications for wire-EDMed Al_2O_3/TiC/Mo/Ni ceramic composite can yield an apparent strengthening with a concurrent increase in Weibull modulus.

2. The ceramic composite in the form of EDMed test bars had an average strength of 619 MPa and a Weibull modulus of 6.3. When subjected to abrasive blasting, the average strength was increased to 727 MPa and Weibull modulus to 9.4. Ultrasonic machining resulted in a further increase in strength to 781 MPa and a Weibull modulus of 14.3.

3. Microstructure analysis showed that the EDMed specimens of this composite had suffered severe surface damage. Abrasive blasting and ultrasonic machining are two effective procedures to reduce this damage and to minimize the surface contribution to fracture probability.

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