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Material removal and surface damage in EDM of Ti_3SiC_2 ceramic

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Abstract

Material removal and surface damage of Ti_3SiC_2 ceramic during electrical discharge machining (EDM) were investigated. Melting and decomposition were found to be the main material removal mechanisms during the machining process. Material removal rate was enhanced acceleratively with increasing discharge current, i_e, working voltage, u_i, but increased deceleratively with pulse duration, t_e. Microcracks in the surface and loose grains in the subsurface resulted from thermal shock were confirmed, and the surface damage in Ti_3SiC_2 ceramic led to a degradation of both strength and reliability.

Keywords: B. Surfaces; C. Strength; Ti_3SiC_2; Electrical discharge machining

1. Introduction

Ti_3SiC_2 is an advanced ceramic combining the properties of ceramics and metals, including high modulus, low density, good thermal conductivity (34 W/m K) [1] and electrical conductivity ($9.6 \times 10^{-6}\ \Omega^{-1}\ m^{-1}$) [2], excellent thermal shock resistance and high-temperature oxidation resistance. Therefore, it has attracted the attention of material scientists, physicists and chemists [1–5]. It is a potential structural material for application in engineering field, such as turbine blades and stators, heavy-duty electric contacts, bearings, etc. Although conventional cutting tools can be used to machine the simple geometry shape, a part with the complex geometry shape and high precision is difficult to be machined by the cutting tools. Due to the good electrical conductivity of Ti_3SiC_2, it is usually machined by electrical discharge machining (EDM) [1,2]. EDM is a thermal process where material is removed by a succession of sparks occurring between the tool electrode and the specimen. The sparks generate heat to melt and even vaporize the sample surface. When the sparks collapse, some of the melted and vaporized material is quickly ejected and then removed by the liquid dielectric [6,7].

However, EDM of Ti_3SiC_2 is rarely reported, and some questions are remained. First, the material removal mechanisms by EDM of Ti_3SiC_2 are not yet understood. Second, how the factors of discharge current, working voltage and pulse duration affect the material removal rate? Third, how the EDM process resulted in the surface damage of bulk Ti_3SiC_2, and the influence of the damage on reliability [8–10]? It is important to investigate the effect of EDM on properties of Ti_3SiC_2 ceramic before its engineering application. In this work, the material removal mechanisms, the factors affecting material removal rate, the surface damage induced by EDM, and the reliability of EDMed Ti_3SiC_2 ceramic were systematically investigated.

2. Experimental

Monolithic polycrystalline Ti_3SiC_2 was synthesized by the in situ hot pressing/solid–liquid reaction method [5]. The specimens were electrical discharge machined using water as the dielectric. A round molybdenum wire with a diameter of 0.18 mm was used as the electrode, running with a high speed in the machining process. The parameters of discharge current, i_e, working voltage, u_i, and pulse duration, t_e, were initially selected to be 0.5 A, 105 V and 50 μs, respectively. The resolidified layer

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on the surface of Ti_3SiC_2 was examined by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) before and after etching in an acid solution consisting of 1:1:1= HF:HNO_3:H_2O (v/v/v). To analyze the phases in the machined surface layer, X-ray diffraction was used.

Subsequently, the process parameters of discharge current, working voltage and pulse duration were systematically altered to investigate their effect on material removal rate. The material removal rates were evaluated by weighing the samples (accuracy, 10^{-5} g) before and after the EDM process.

A reliability analysis was conducted by estimating the Weibull modulus of the flexural strength distribution. Eighteen EDMed specimens with dimensions of 3 mm × 4 mm × 36 mm were tested in three-point bending over a 30 mm span at a crosshead speed of 0.5 mm/min. The two-parameter Weibull distribution was calculated by the equation:

$$\ln \ln \left(\frac{1}{1 - F_i} \right) = -m \ln \sigma_0 + m \ln \sigma_i \quad (1)$$

where $F_i = i - 0.5/N$ is an estimator of the failure probability of the ith ranked specimen, i the rank of strength data and N the total numbers of samples tested, m the Weibull modulus, σ_i the measured strength and σ_0 is the proportional constant [10]. The microstructure of fractured section of spark-eroded sample was observed using SEM.

3. Results and discussion

3.1. Material removal mechanisms

Due to the good electrical conductivity, Ti_3SiC_2 is easily machined by EDM. Fig. 1 displays the back scattered electron micrograph and EDS microanalysis of the resolidified layer on the EDMed surface of the Ti_3SiC_2 sample, machined at 0.5 A, 105 V and 50 μs. The droplets beneath the machined surface indicate the presence of a molten state (the incipient melting point of Ti_3SiC_2 is 2200 ± 20 °C [11]) during spark-erosion (Fig. 1(a)). When the spark exploded, the molten phase was ejected from the specimen and flushed by the flowing water with the high running molybdenum wire. Ti, Si and O elements were detected by EDS on the surface of resolidified layer (Fig. 1(b)), revealing that oxidation has taken place during the resolidified process. Racault et al. [12], Barsoum and El-Raghy [13] and Sun et al. [14] reported the presence of TiO_2 and SiO_2 in the oxidized surface of Ti_3SiC_2. Therefore, TiO_2 and SiO_2 may exist in the spark-eroded surface. After etching, nanosized TiC particles were observed distributing in the resolidified layer (Fig. 2(a)), and only the elements Ti and C were detected (Fig. 2(b)). It was shown that TiO_2 and SiO_2 existed on the surface of the resolidified layer but they were easily removed by etching in the acid solution [8,15]. To identify the phases, X-ray diffraction pattern of the spark-eroded surface is shown in Fig. 3. For comparison, a pattern of non-EDMed Ti_3SiC_2 is also shown. The peaks of TiC indicate that a decomposition reaction took place during the resolidified process. Because the contents of TiO_2 and SiO_2 are very few, they are not detected by X-ray diffraction. Therefore, when Ti_3SiC_2 was sharply cooled by water, Ti_3SiC_2 was firstly decomposed to TiC. And then the surface of resolidified layer exposing to the air would be oxidized under high temperature. The decomposition and oxidation process can be described as [14]:

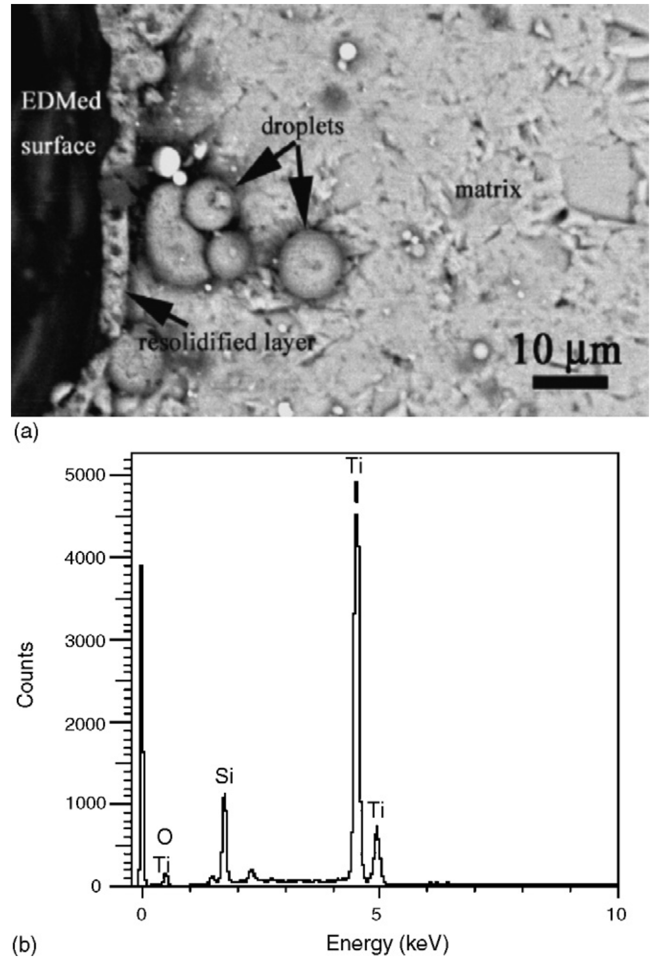

Fig. 1. (a) Back scattered electron (BSE) micrograph and (b) EDS microanalysis of the resolidified layer on the EDMed surface of the Ti_3SiC_2, machined at 0.5 A, 105 V and 50 μs.

$$Ti_3SiC_2 = 3TiC_{0.67} + Si \quad (2)$$

$$3TiC_{0.67} + 4O_2(g) = 3TiO_2 + 2CO(g) \quad (3)$$

$$Si + O_2 = SiO_2 \quad (4)$$

According to these results, the mechanisms of the removal of material from Ti_3SiC_2 by EDM are melting and decomposition with the assident oxidation.

3.2. Effect of energy input factors on material removal rate

In order to investigate the factors affecting material removal rate during spark machining of Ti_3SiC_2, the material removal rate as a function of discharge current, working voltage and pulse duration are presented in Fig. 4. The relationship between the material removal rate and both the discharge current and working voltage is parabolic with increasing slope with increasing intensity (Fig. 4(a and b)). This effect is ascribed

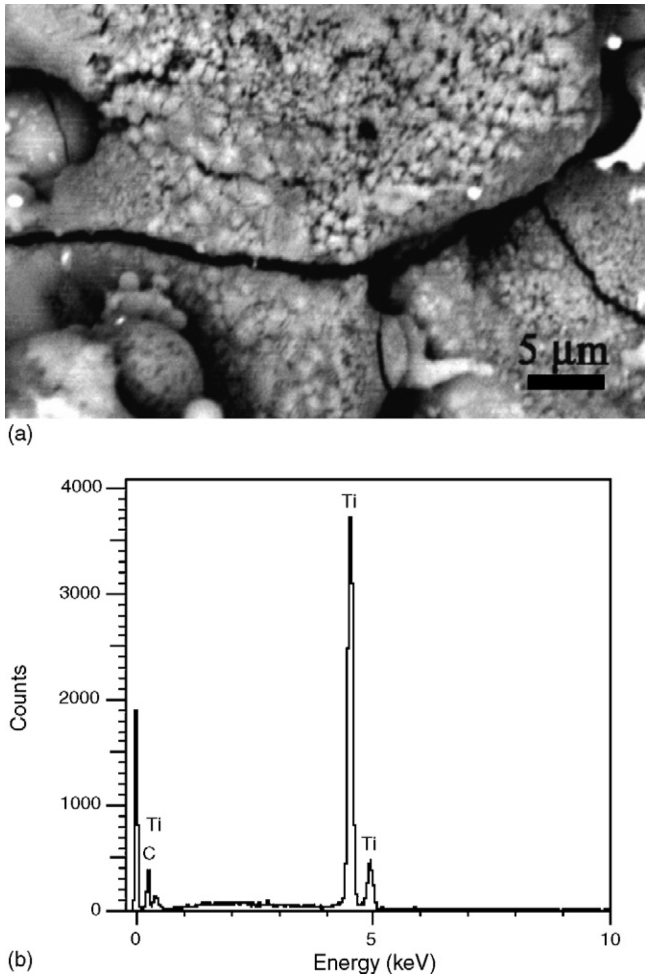

Fig. 2. (a) BSE micrograph and (b) EDS pattern of EDMed Ti_3SiC_2 surface etched in an acid solution consisting of $HF:HNO_3:H_2O$ = 1:1:1 (v/v/v).

to the enhanced spark energy that melts and ejects more amount of material of the sample surface for each single spark [9]. This result is similar to the previous report on EDM of TiN/Si_3N_4 composites [16]. However, the relationship between the material removal rate and pulse duration is parabolic with

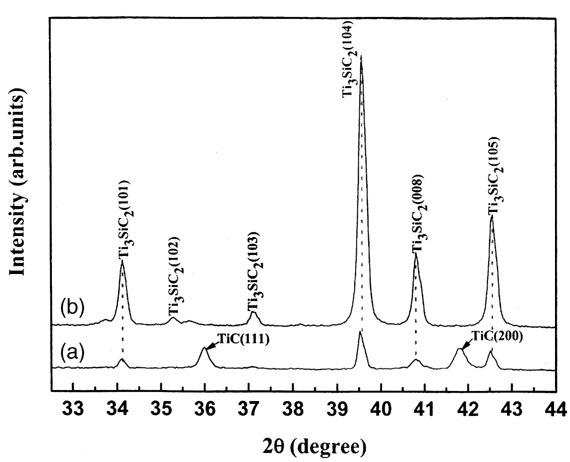

Fig. 3. X-ray diffraction patterns of (a) an electrical discharge machined (EDMed) surface and (b) a polished surface of unmachined Ti_3SiC_2.

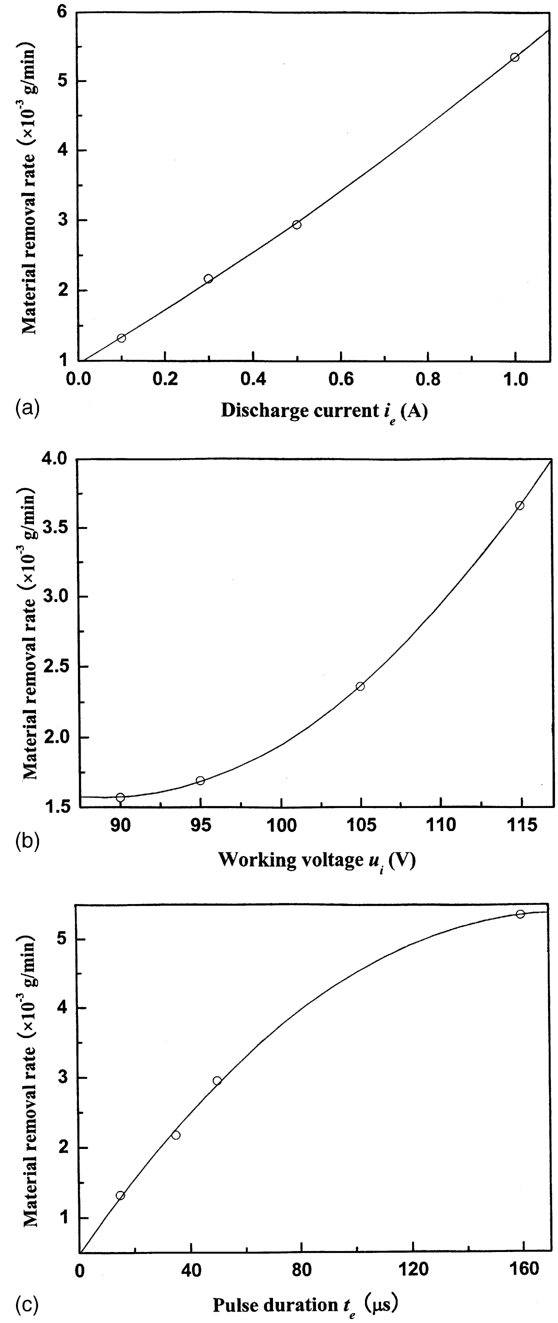

Fig. 4. The effect of (a) discharge current, i_e, (b) working voltage, u_i, and (c) pulse duration, t_e, on the EDM material removal rate of Ti_3SiC_2.

decreasing slope with increasing pulse duration (Fig. 4(c)). Increasing pulse duration maintained the energy input for a longer time, which contributed to the enhanced material removal rate [15]. But, the longer pulse duration would be disadvantageous for water removal of resolidified particles. As a result, though the value of material removal rate increases, the slope of the material removal rate tends to be decreasing.

3.3. Surface damage

Microcracks and micropores have been observed in the resolidified layer, as shown in Fig. 5. The formation of

Table 1
Weibull modulus of unmachined and EDMed Ti_3SiC_2 and typical brittle ceramics

Materials	Unmachined Ti_3SiC_2 [22]	EDMed Ti_3SiC_2	α-Al_2O_3 [23]	ZrO_2 [24]	β-SiC [25]	AlN [26]	TiN [27]	B_4C [28]
Weibull modulus	28.1	13.4	9.8	9	11	6.4	6.5	5

micropores is ascribed to the ejection of gases [8], and the development of microcracks is associated with the tensile stresses produced by the quenching effect of water [9,17]. Due to the weak intergranular strength, the grains of Ti_3SiC_2 were easily separated when the crack propagated into the inner body. Thus, the surface layer of inner body became very loose. Fig. 6 exhibits loose grains (10–15 μm depth) that resulted from thermal shock in the subsurface region of Ti_3SiC_2. Because the thermal expansion coefficient of TiC (8.3×10^{-6} K^{-1}) [18] is close to that of Ti_3SiC_2 (9.1×10^{-6} K^{-1}) [19], the resolidified layer is tightly adhered to the inner body.

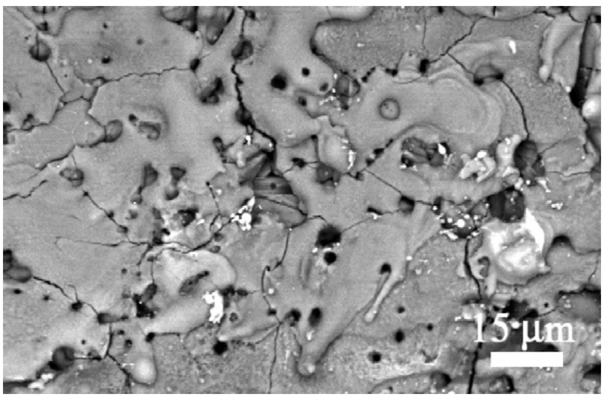

Fig. 5. BSE micrograph of an EDMed Ti_3SiC_2 surface, showing the existence of microcracks and micropores in the resolidified layer.

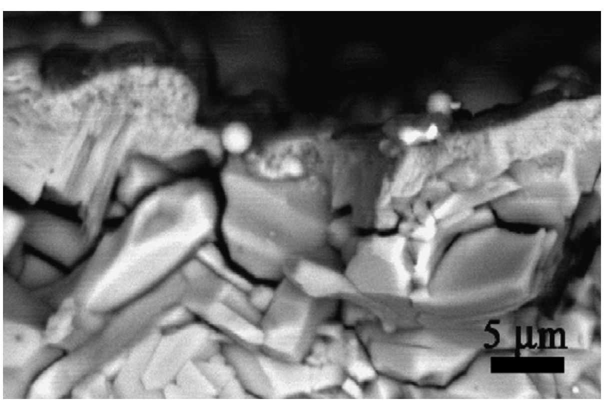

Fig. 6. BSE fractograph of an EDMed Ti_3SiC_2 specimen after flexure testing showing loose grains in the subsurface region.

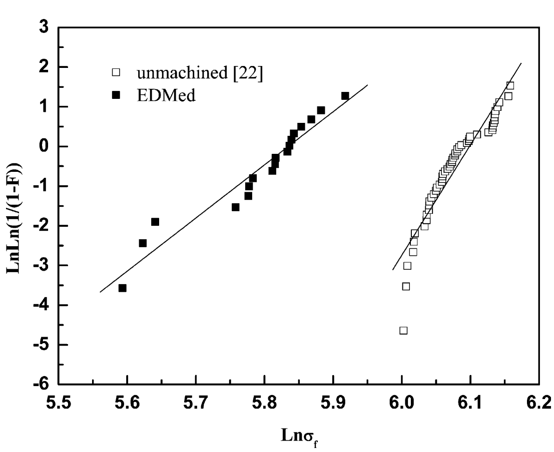

Fig. 7. Weibull plot of the flexural strength distribution of unmachined and EDMed Ti_3SiC_2 samples.

Whereas, different from Al_2O_3–SiC_w–TiC [8] and SiC–TiB_2 [17] ceramic composites, the spalling was not observed in the EDMed surface of Ti_3SiC_2. It may be due to the high fracture toughness [1,5] and the local energy dispersion characteristic of Ti_3SiC_2 [20,21].

3.4. Reliability

A low Weibull modulus exhibits a wide distribution of fracture strengths and low reliability [10]. Fig. 7 is a Weibull plot of the flexural strength distribution of unmachined and EDMed Ti_3SiC_2 samples. It is shown that the flexural strengths of EDMed samples distribute in a wider range. The average flexural strength decreases from 437 MPa to 329 MPa, nearly 25% degradation of the initial strength. And the Weibull modulus decreases from 28.1 [22] to 13.4. It means that the spark-erosion process degrades the strength and reliability of Ti_3SiC_2 ceramic. However, as listed in Table 1, the Weibull modulus of EDMed Ti_3SiC_2 is still higher in comparison with that of typical brittle ceramics [23–28]. This result exhibits a high damage tolerance in Ti_3SiC_2, i.e., though the machining process results in the surface damage, Ti_3SiC_2 ceramic still possesses the higher reliability than other brittle ceramics.

Generally, brittle ceramics are very sensitive to surface damage. The big cracks usually initiate from the microdefects, such as micropores, microcracks, weak interfaces and impurities, rapidly extending with high cracking rate. But for Ti_3SiC_2, the local energy dissipation due to the multiple intragrain slips and intergrain sliding [20,29] would disperse the stresses as plentiful microcracks. Big cracks do not easily initiate from the microdefects and rapidly propagate. Therefore, the EDMed Ti_3SiC_2 ceramic would not abruptly fracture, showing a quasi-plastic fracture mode [16].

4. Conclusions

The material removal and thermal shock induced damage during electrical discharge machining (EDM) on Ti_3SiC_2 were investigated using water as the dielectric. The main results are summarized as follows:

(1) Easy material removal and nice machinability of Ti_3SiC_2 by the electrical discharge machining mainly attribute to the excellent electrical conductivity and thermal conductivity.

Melting and decomposing are confirmed as the main material removal mechanisms.

(2) The acceleration of the material removal rate increases with the discharge current and working voltage, but decreases with increasing pulse duration.

(3) The damage caused by cooling water shows typical thermal shock cracks and loose grains in subsurface, which result in about 25% of strength degradation and scatter in strength data. The depth of the surface damage is found around 10–15 μm, so that the EDMed specimens should be ground and polished to remove at least the thickness of the damage layer for obtaining reliable strength.

(4) Owing to the nanolayered microstructure, Ti_3SiC_2 has excellent damage tolerance. Despite the formation of microcracks in the resolidified layer and the loose grains in the subsurface, the EDMed Ti_3SiC_2 ceramic still possesses the higher Weibull modulus than brittle ceramics.

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