Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites

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This work investigated electrical discharge machining (EDM) of carbon fiber reinforced carbon composite material. The characteristics of composites machined by EDM were studied in terms of machining parameters. An empirical model of the composites was also proposed based on the experimental data. The composite material was produced by an electrical discharge sinker using a graphite electrode. The workpiece surface and resolidified layers were examined by scanning electron microscopy (SEM). Moreover, surface roughness was determined with a surface profilometer. Experimental results indicate that the extent of delamination, thickness of the recast layer, and surface roughness are proportional to the power input. The EDM process effectively produces excellent surface characteristics and high quality holes in composites under low discharge energy conditions. © *2001 Kluwer Academic Publishers*

1. Introduction

Carbon fiber reinforced carbon composites are highly promising materials for applications in the aeronautic and aerospace industry including rocket exit nozzles, nose caps, pistons for internal combustion engines, and fusion devices. These composites have advantages over other materials due to their superior strength-to-weight and stiffness-to-weight ratios and high service temperatures [1–5]. However, they are anisotropic and non-homogeneous, and their intrinsic brittleness and hardness make machining difficult, thus limiting their usefulness. Earlier investigations have discussed the peculiarities of machining composites. Hocheng *et al.* [6, 7] described the feasibility of applying conventional machining techniques to machining composites. According to their results, conventional methods damage the workpiece through chipping, cracking, delamination and high wear on the cutting tools, but several nontraditional machining methods [8, 9] are applicable. Furthermore, Hamatani *et al.* [10, 11] experimented with using abrasive water jets to produce slots and holes in metal matrix composites. Hashish [12] found that piercing holes in composite laminates with a high-pressure water jet resulted in fracture, cracking and delamination. Ramulu *et al.* [13, 14] obtained machinability data on SiCw/Al metal matrix composite and a ceramic composite TiB_2/SiC for the electrical discharge machining (EDM) processes.

Electrical discharge machining is a widely accepted process for producing complicated shapes and tiny apertures accurately. A major advantage of EDM is that the tool and the workpiece do not come into contact, thus eliminating chatter and vibration problems and allowing small or thin components to be machined without mechanical force. This method is considered suitable for machining materials that are extremely hard, strong, and wear or temperature resistant [15, 16]. Although a few studies [17, 18] have examined this research field, clear correlation among processing variables of EDM and the machinability of composite materials remain uncertain. Thus, this work investigates the characteristics of EDM machined surfaces and the effects of processing variables on delamination, recast layer, surface roughness, and material removal rate. Mechanisms for material removed are also proposed herein.

2. Experimental procedures

2.1. Preparation of the composites

Plain weave carbon fabrics were impregnated with phenolic resin using a wet dipping technique. The fabrics were then placed in a circulation air oven at 70° C for two hours to remove excess solvent. The raw materials used in this study are summarized in Table I. The prepreg hand lay-up method was used to laminate eight layers of impregnated fabrics. The stacked fabrics were then placed in a picture frame mold and compression-molded at 150° C under a pressure of 13.5 MPa for half an hour. Post-cured process was performed in an air circulation oven at 175° C for 36 hours. The post-cured carbon/phenolic composites were cut into $50 \times 10 \times 1$ mm specimens using a diamond saw under water cooling. The carbonization process was accomplished at 2200° C in a high temperature tube furnace for 1 hour under an argon atmosphere at a constant gas flow rate of 6×10^{-3} m^3 hour^{-1}, where the furnace was heated at a rate of 30° C hour^{-1}. The density of the fabricated carbon fiber reinforced carbon composites was 1470 kg m^{-3}.

2.2. Parameters in EDM

An electrical discharge sinker machine equipped with a servo-controlled head was employed to perform the machining experiments. Meanwhile, graphite was used as the tool electrode for cutting purposes. The electrode was cylindrical with a diameter of 1 mm. The tool electrode was positively polarized and the workpiece served as negative polarity during the EDM process. Kerosene was used as the dielectric fluid. The working voltage between the composite and the electrode was 35 V. The pulse current (I_p) varied from 1 to 5 A, with a duty factor of 90%. The pulse-on duration (τ_{on}) from 20 to 220 μs was employed. After each experiment, the change in volume of the workpiece, and the machining time were recorded. The value of the material removal rate was evaluated for each condition by dividing the measured amount of material removal by the machining time.

TABLE I Resin and carbon fabrics materials

Specification	Code	Supplier
Resin Resole type phenolic resin PH = 8.0-8.5 Solid content: 62% Viscosity at 25°C: 0.10-0.25 Pa sec	PF-650	Chung-Chun Plastics Co. Ltd Taiwan
Carbon Fabrics Plain weave cloth, 2000 kg m^{-2} Fiber diameter: 7.0 μm	TR-30K	Mitsubishi Rayon Co. Ltd Japan

2.3. Surface examination

The structure of the EDM area was examined with scanning electron microscopy (SEM) to determine the nature of damage. The thickness of the recast layer was obtained by calculating the average of 25 readings measured at various locations on the cross section. A profilometer was used to measure the surface roughness of the specimens.

3. Results and discussion

3.1. Removal mechanisms

Fig. 1 shows the machining surface from the EDM process. This scanning electron micrograph reveals that the randomly distributed white layers and solid particles are resolidified and remain attached to the eroded surface. The micrograph displays that the particles formed by electrical discharge are solid spheres, and range from 3–30 μm in diameter. The solid behavior attributed to the discharge channel temperature is higher than that of molten particles ejected from the crater and nucleation generally starts internally. The perfectly spherical particles were apparently re-solidified from the gaseous state, whereas irregularly recast layers were solidified from the liquid state. Previous studies of the EDM surface morphology and debris have demonstrated that composite material was removed in both the liquid and gaseous states [19, 20].

3.2. Correlation between hole quality and machining parameters

Fig. 2a and b summarize the effects of pulse current and pulse-on duration on the hole edge damage produced by 1 mm diameter graphite electrode, and indicate the SEM photomicrographs of both the top and bottom surfaces for holes produced in composite material. Clearly, unlike with conventional machining and water jet drilling, the edges of the hole are completely free from burrs. During processing, working conditions can influence the incidence of tear-like or delamination damages. When applying the smaller pulse current 1 A and the pulse-on duration 20 μs, the hole quality was good and no machining damage was observed in composite laminate on either the top or bottom surfaces. However, as the current and pulse-on duration increased, the damage could reach 100 μm. Such

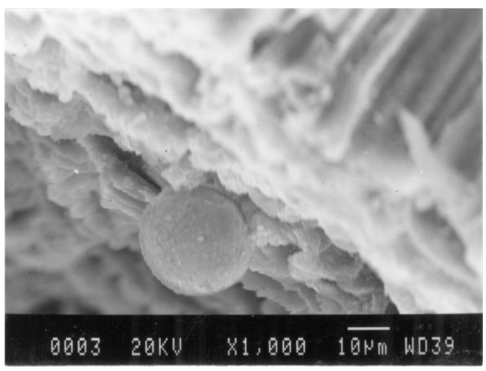
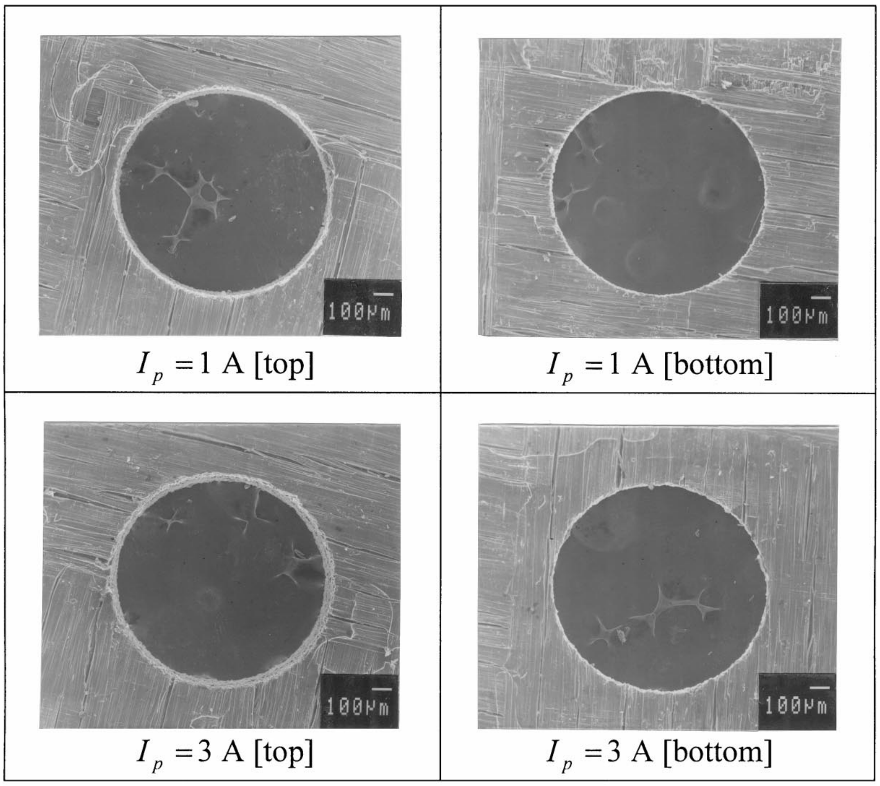
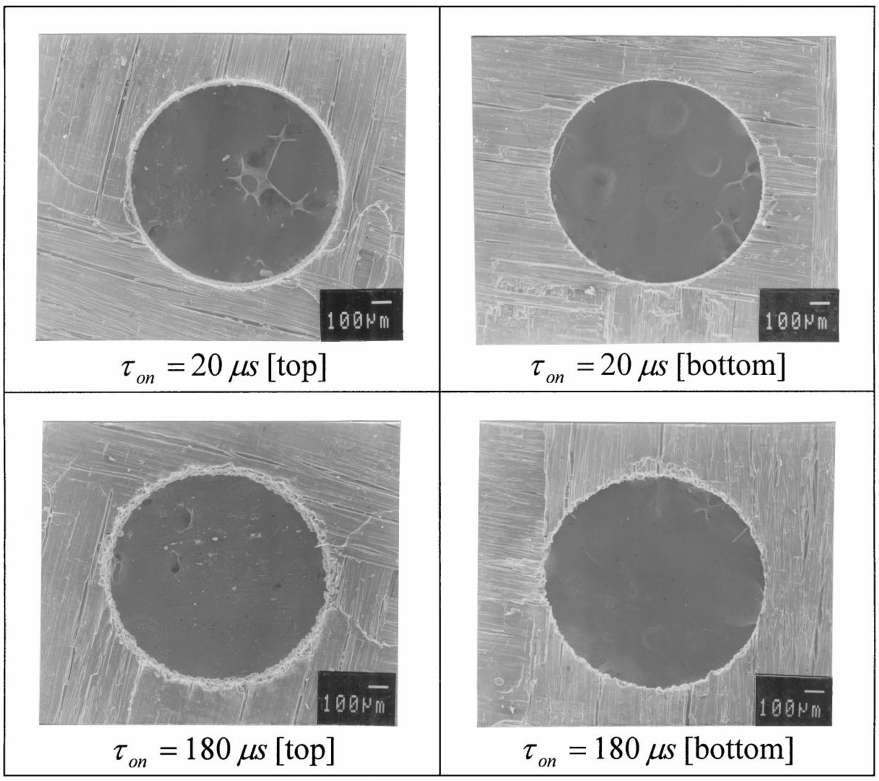


Figure 1 Scanning electron micrograph of the EDM surface (pulse current 3 A, pulse-on duration 20 μs).



(a)



(b)

Figure 2 (a) SEM photomicrographs of the top/bottom surfaces ($\tau_{on} = 20\ \mu$s, electrode diameter 1 mm). (b) SEM photomicrographs of the top/bottom surfaces ($I_p = 1$ A, electrode diameter 1 mm).

damage extends far beyond the thermally influenced area and into the base material, causing stress concentration along the holes, and eventually decreasing the service strength. These results also demonstrate that the machining quality on the bottom surface is superior to that on the top surface.

3.3. Correlation between delamination factor and machining parameters

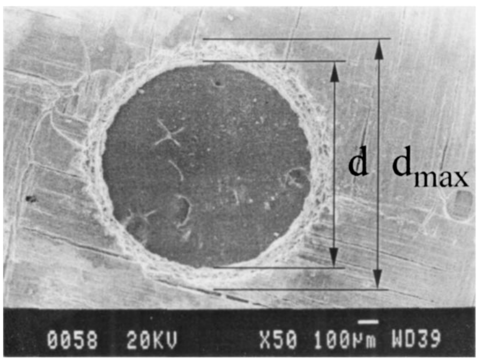
During the EDM process, the extremely high temperature produced by electrical discharge sparks rapidly vaporizes the dielectric fluid and creates pressure impulses around the tool electrode. The impact pressure and high thermal stresses generated by the discharge produces the delamination in the machining surface. The extent of delamination can be determined according to the maximum hole diameter in the damage zone (Fig. 3). Herein, the delamination factor is proposed to facilitate analysis of the delamination degree and comparison with different machining conditions. The delamination factor is defined as

$$D_f = d_{max}/d \tag{1}$$

where D_f denotes the delamination factor, d_{max} represents the maximum diameter of the damage zone, and d is the hole diameter. Fig. 4 shows the correlation between the delamination factor and machining parameters for the drilling of the composites. The delamination factor clearly increases with the energy supply. This increase occurs because the impulse force increases with increasing discharge energy, thus increasing the delamination degree. The variation in the maximum diameter of the damage zone under coarse conditions was higher than under fine cutting conditions. Therefore, properly choosing operating parameters can eliminate the damage to the workpiece. Regression analysis of the experimental data produces the empirical formula

$$D_f = 0.815 I_p^{0.0681} \tau_{on}^{0.0579} \tag{2}$$

where I_p denotes the pulse current and τ_{on} represents the pulse-on duration. Equation 2 gives average error of 6.3% with respect to the experimental results.



$$\text{Delamination factor} = \frac{d_{max}}{d}$$

Figure 3 Estimation of the delamination factor ($I_p = 3$ A, $\tau_{on} = 100\ \mu$s, $d = 1$ mm).

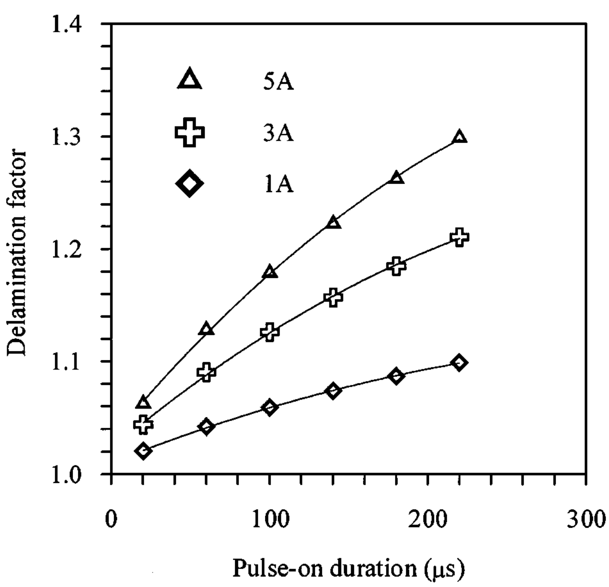


Figure 4 The correlation between delamination factor and machining conditions.

3.4. Correlation between recast layer and machining parameters

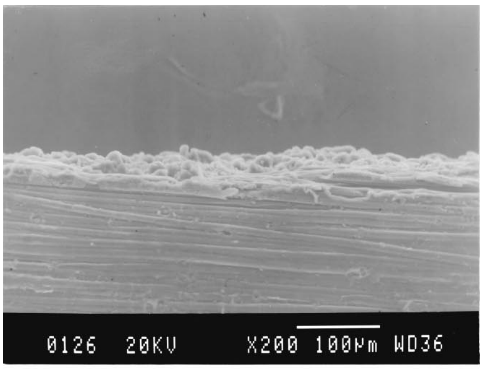
The surface of the workpiece closest to the electrode in EDM is subjected to a temperature rise of up to 40000 K [21]. The upper material in the extremely high temperature region will vaporize, while the lower material will melt. The present investigation attempted to evaluate the effect of process parameters on the recast layer of the composite material by examining a cross section of the specimen. Fig. 5 depicts scanning electron microscopy observation of the composites. Obviously, two regions are present in the composites: one is the original material and the other is the recast layer (which has a white color). A smaller thermal gradient occurs at the lower pulse current, thus forming a thinner recast layer. The recast layers appear thicker as pulse current increases, since at a higher pulse current, a steeper thermal gradient builds up in the composites, possibly causing a thermal effect beneath the melting zone. This phenomenon leads to a greater residual melted layer that is not flushed out by the dielectric fluid, and that then resolidifies and remains attached to the machined surface. Fig. 6 shows the thickness of the recast layer on the machined surface under various machined conditions. The figure shows that the pulse current has a greater effect on the surface roughness than the pulse-on duration. The correlation between the thickness of the recast layer (d_t) and machining conditions using regression analysis yields

$$d_t = 13.696 I_p^{0.534} \tau_{on}^{0.204} \tag{3}$$

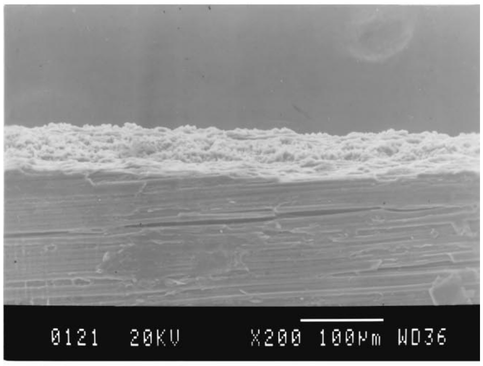
where the constants depend on electrode materials, the type of dielectric, and the flushing conditions. Equation 3 gives average error of 6.3% with respect to the experimental results.

3.5. Correlation between material removal rate and machining parameters

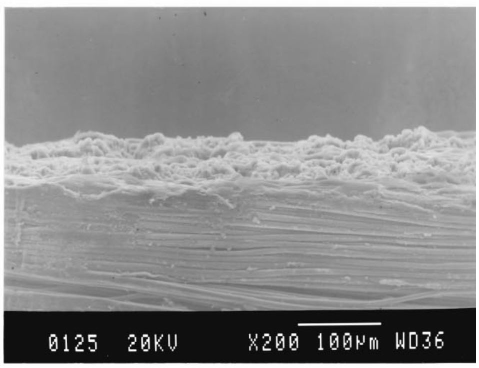
Fig. 7 presents the material removal rate (*MRR*) during the EDM process as a function of pulse-on duration and pulse current. Clearly, the value of *MRR* initially increases with pulse-on duration owing to the greater energy input rate. At a small pulse-on duration, the discharge energy is insufficient and the *MRR* is unable to rise. A pulse-on duration of 100 μs removes material more effectively than other times, but beyond this level the high energy input becomes inefficient and the *MRR* decreases. Additionally, the surface temperature increases with the pulse-on duration and consequently the melting boundary deepens and



(a) 1 A



(b) 3 A



(c) 5 A

Figure 5 SEM photomicrographs of the recast layer of the composites after EDM at (a) 1 A, (b) 3 A, and (c) 5 A. The pulse-on duration is 100 μs.

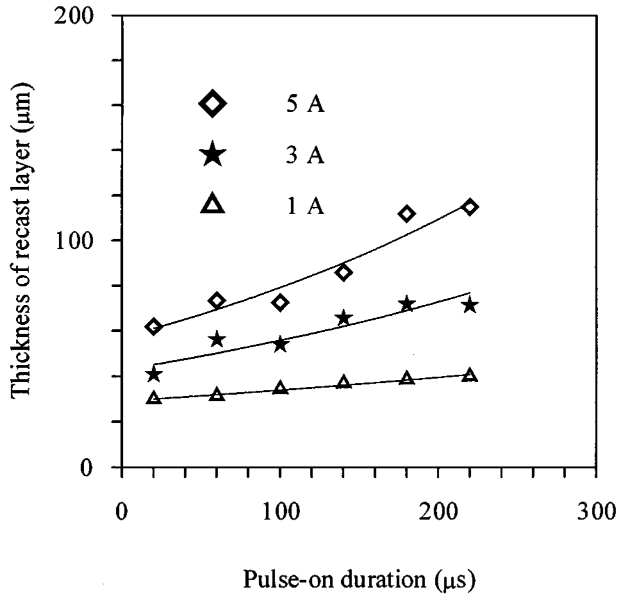


Figure 6 Thickness of the recast layer under various machined conditions.

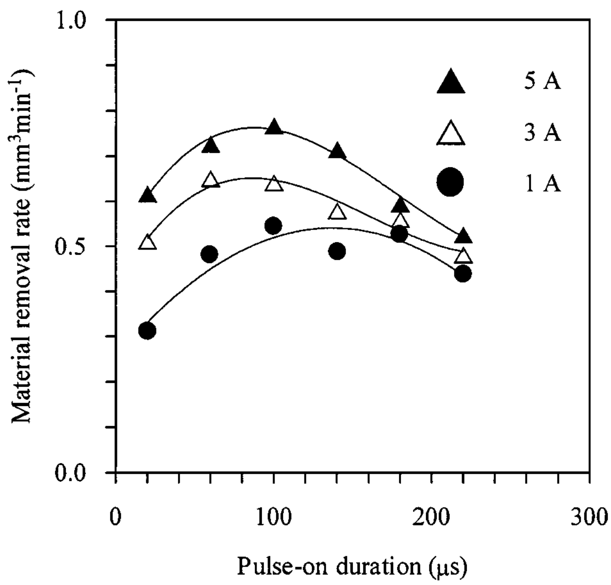


Figure 7 Variation of the material removal rates of the composites during EDM process as functions of pulse current and on duration.

widens. This phenomenon prevents the melted material from being completely flushed out by the dielectric fluid and disturbs the gap condition for the next discharge due to the eroded chips filling the gap. The *MRR* for a larger pulse current with a higher energy input rate also exceeds that for a smaller pulse current. A pulse current of 5 A and duration of 100 μs produces the highest removal rate, of 0.768 mm^3 min^{-1}.

Using regression analysis to reveal correlation between the material removal rate and machining parameters produces:

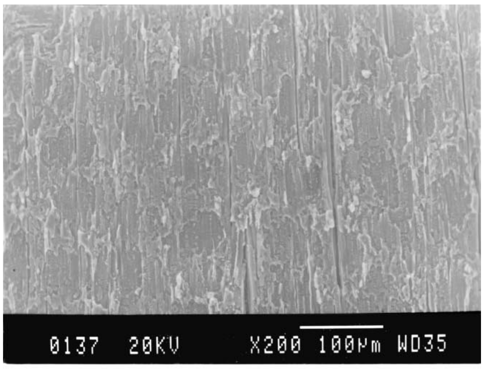
$$MRR = 0.378 I_p^{0.216}\ \tau_{on}^{0.041} \quad \text{as } \tau_{on} \leq 100\ \mu\text{s} \quad (4)$$

$$MRR = 4.400 I_p^{0.134}\ \tau_{on}^{-0.428} \quad \text{as } \tau_{on} > 100\ \mu\text{s} \quad (5)$$

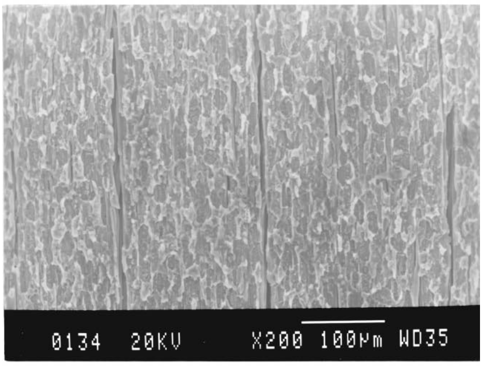
Equations 4 and 5 give average errors of 6.2% and 4.8% respectively correspond to the experimental results.

3.6. Correlation between surface roughness and machining parameters

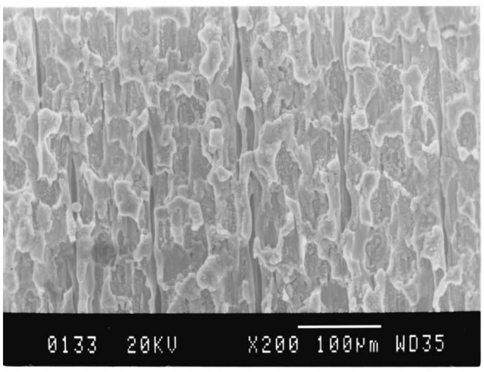
Fig. 8 displays the SEM micrographs of the machined surfaces formed at a normal discharge. With a 1 A pulse current, the surface characteristics are relatively smooth. However, when the discharge energy increases to 5 A, the machined surface shows irregular valleys, and deeper and longer grooves craters are formed by the electrical discharge channel. Carbon fiber reinforced carbon composites are anisotropic, and thus the strength and thermal conductivity of the composite material depends on the fiber direction. Therefore, crater shape relates strongly to fiber direction and the discharge channel position. If the axial direction of the adjacent fibers runs at a tangent to the region of the discharge crater, the crater is narrow. The narrow crater is a result of less heat conduction along the transverse direction of the fiber. When the fibers are positioned at the crater margin,



(a) 1 A



(b) 3 A



(c) 5 A

Figure 8 Surface morphology of the faces after EDM with (a) 1 A, (b) 3 A, and (c) 5 A pulse current, observed by SEM. The pulse-on duration is 100 μs.

the delamination propagation occurs more easily along the longitudinal direction than the transverse direction. This phenomenon causes the crater to extend along the fiber direction. Therefore, material surface formation by the EDM process in this composite material differs from that of metals. Notably, the increase of crater depth with the applied pulse current appears minimal under a small input energy.

EDM erodes surfaces randomly. To determine the effect of the EDM on the surface roughness of composites, this study measured the surface profiles of the topography of the EDM surfaces. Fig. 9 shows the measurement results. Clearly, a poorer surface finish is obtained with higher pulse current, since a higher pulse current causes more frequent cracking of the dielectric fluid, hence more frequent melt expulsion, and a poorer surface finish. An excellent machined finish can

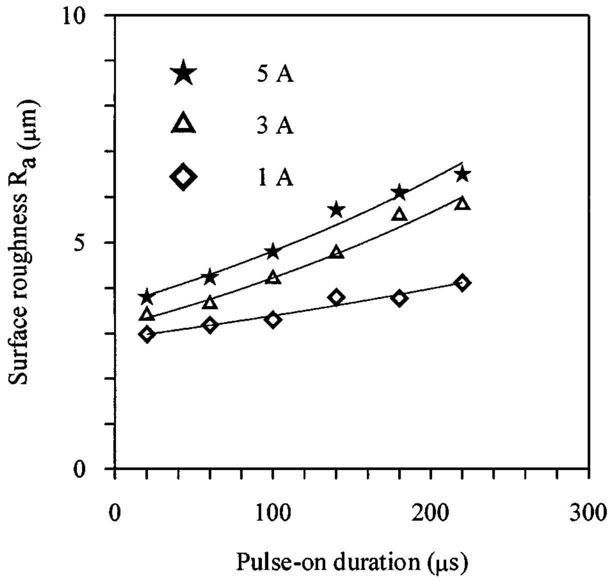


Figure 9 Surface roughness of the EDM surface under various machined conditions.

be obtained by setting the machine parameters at low pulse currents and a small pulse-on duration, but this approach is more time consuming. The surface roughness (R_a) is affected by the process parameters of pulse current and pulse-on duration. Regression analysis of the experimental data produces the empirical model

$$R_a = 1.326 I_p^{0.224} \tau_{on}^{0.216} \quad (6)$$

Equation 6 gives average error of 6.1% with respect to the experimental results.

4. Conclusions

The experimental investigation of the carbon fiber reinforced carbon composite material has led to empirical formulae at various machining conditions and obtained the following conclusions. Smaller pulse energy can prevent delamination defects around holes in composites on both the top and the bottom surfaces. Moreover, increasing the discharge energy causes high temperatures. This phenomenon increases surface roughness, creates a much larger recast layer and more delamination on the cutting edge. The optimum material removal rate for the composites is at a pulse current of 5 A and a pulse-on duration of 100 μs. Meanwhile, composites are removed by melting and vaporization. Based on the experimental results obtained herein, EDM can be successfully applied to machine carbon fiber reinforced carbon composite material.

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