Effect of Carbon Fiber Orientation on Machining Phenomena in Electrical Discharge Machining of Carbon Fiber Reinforced Plastics

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Abstract

This paper discusses the effect of the carbon fiber orientation on machining phenomena such as short-circuiting in the electrical discharge machining (EDM) of carbon fiber reinforced plastics (CFRP). Sinking EDM was carried out for a CFRP, where the carbon fiber orientation in each prepreg was even but different among the prepreps, in a configuration in which many prepreps were concurrently machined, and top and cross-section views of the machined surfaces were observed. It was found that the relative frequency of short-circuiting due to the fraying of carbon fibers decreases when the gap width is narrower. It was also found that the machined surface became uneven because of the different local material removal rates and electrode wear ratios among the prepreps.

Key words: electrical discharge machining, carbon fiber reinforced plastics, fiber orientation, short-circuiting, material removal rate

1. INTRODUCTION

Carbon fiber reinforced plastics (CFRP) has excellent characteristics such as high strength and a light weight but is difficult-to-machine material. In the cutting of CFRP, significant tool wear, as well as delamination and the formation of burrs, has been the main problem. Recently, the electrical discharge machining (EDM) of CFRP has been attempted by the authors^{1) 2)} and by Wang et al.³⁾, Ichii et al.⁴⁾ and Marui et al.⁵⁾. One of the features of CFRP affecting on the EDM properties is that CFRP has anisotropy due to the carbon fiber orientation. Ichii et al.⁴⁾ pointed out that when the machining direction is perpendicular to the carbon fiber orientation, the CFRP is removed not only by melting and boiling but also by fiber breakage, whereas it is removed only by melting and boiling when the machining direction is parallel to the carbon fiber orientation. Marui et al.⁵⁾ reported that the range of the matrix resin removal is larger in the direction parallel to the carbon fiber orientation than in the perpendicular direction because heat conduction in CFRP is also anisotropic. The authors^{1) 2)} observed short-circuiting caused by the fraying of carbon fibers, which is also related to the anisotropy of CFRP. In the EDM of CFRP, carbon fibers on the machining surface of the CFRP are attracted to the tool electrode by an electrostatic attractive force, which leads to short-circuiting^{1) 2)}. Although short-circuiting does not contribute to material removal in the EDM of metals, it can contribute to material removal in the EDM of CFRP because the matrix resin of the CFRP is removed by

the Joule heating of carbon fibers^{1) 2)}. The authors^{1) 2)} also reported that very long carbon fibers of more than 500 μ m in length, namely, much longer than the gap width, are often found among the debris, and these carbon fibers can also cause short-circuiting. Most CFRP is formed by laminating prepreps, where the carbon fiber orientation in each prepreg is even but different among the prepreps. Since short-circuiting due to the fraying of carbon fibers will frequently occur at prepreps whose carbon fiber orientation is parallel to the machining surface, and the machining properties such as material removal rate and tool electrode wear ratio depend on the frequency of short-circuiting, the local material removal rate is expected to vary among the prepreps. In this paper, the surface of EDMed CFRP is observed to discuss the effect of the carbon fiber orientation on machining phenomena.

2. SHORT-CIRCUITING DUE TO FRAYING OF CARBON FIBERS

In this section, short-circuiting in the EDM of CFRP previously reported by the authors^{1) 2)} is presented as a background. Figure 1 shows the typical situations observed during the sinking EDM of CFRP. In the case shown in Fig. 1(a), mild light is emitted and machining sound is generated from the gap space, similar to the phenomena observed in the conventional EDM of metals. On the other hand, in the case shown in Fig. 1(b), intense light and high-frequency sound are generated intermittently from the machining domain. Figures 2(a) and (b) show the waveforms of the gap voltage

Fig. 1 Typical machining situations

Fig. 2 Waveforms of gap voltage and current

and current observed in the cases shown in Figs. 1(a) and (b), respectively. In Fig. 2(b), the decrease in gap voltage and increase in current are steeper than those in Fig. 2(a). The obtained gap voltage during the discharge duration and the peak current are approximately 30V and 20A in Fig. 2(b), whereas those are 50V and 12A in Fig. 2(a). In addition, when several carbon fibers, prepared by fiberizing a carbon fiber cloth, were connected to the power supply of the sinking EDM machine and electrical current was applied through them, the intense emission of light similar that shown in Fig. 1(b) was observed. From these results, the situation shown in Fig. 1(b) is considered to be short-circuiting due to the fraying of carbon fibers, whereas that in Fig. 1(a) is considered to be normal discharge.

Although short-circuiting does not contribute to material removal in the EDM of metals, it can contribute to material removal in the EDM of CFRP because the matrix resin of the CFRP is removed by the Joule heating of carbon fibers.

3. RELATIONSHIP BETWEEN GAP WIDTH AND OCCURRENCE OF SHORT-CIRCUITING

3.1 Gap Width and Relative Frequency of Short-Circuiting

In order to discuss the relationship between gap width and the occurrence of short-circuiting, the gap width during an actual EDM process and the relative frequency of short-circuiting were measured. In this experiment, a flat plate CFRP of 11mm thickness made by laminating prepreps was used, where the carbon fiber orientation in each prepreg was even but different among the prepreps. Sinking EDM of the CFRP using deionized water was carried out in a configuration in which many prepreps were concurrently machined, as shown in Fig. 3. The machining conditions are listed in Table 1. The average gap voltage was varied from 11 to 17V to change the gap width. Machining time was chosen twenty minutes in this experiment. The waveforms of the gap voltage and current were observed and each pulse was classified into normal discharge or short-circuiting. The gap width was

Fig. 3 Experimental configuration

Fig. 4 Relationship between average gap voltage and gap width

obtained as the difference between the z-axis position measured during the machining process and that measured when the tool electrode was moved so that it come in contact with the workpiece after stopping the machining process. The z-axis position was measured using an electric micrometer.

Figure 4 shows the relationship between the measured average gap voltage and the measured gap width. It can be seen that the gap width increases with increasing the average gap voltage. However, in the case of a high average gap voltage, the dispersion of the measured gap width is very large, whereas it is small in the case of a low average gap voltage.

Figure 5 shows the effect of the average gap voltage on the relative frequency of short-circuiting. In this experiment, the total pulse frequency was almost the same at all four voltages. It was found from Figs. 4 and 5 that the total pulse frequency is almost independent of the gap width, and the relative frequency of short-circuiting decreases with decreasing gap width, which are the opposite results from those expected. However, if the degree of carbon fiber fraying is smaller with decreasing gap

Table 1 Machining conditions

Tool electrode	Copper ($\phi 10\text{mm}$)
Dielectric liquid	Deionized water
Open voltage	85V
Polarity	Tool electrode (+)
Discharge current	22A
Discharge duration	32 μs
Pulse interval	130 μs
Average gap voltage	11, 12, 13, 17V
Machining time	10, 20, 40min

Fig. 5 Relationship between average gap voltage and relative frequency of short-circuiting

width, the results are reasonable. Therefore, to investigate the reason for the results, the machined surface of the CFRP was observed as discussed in the following section.

3.2 Discussion

Figures 6 and 7 respectively show top-view and cross-section scanning electron microscope (SEM) images of the EDMed surface of the CFRP obtained in the experiment discussed in the previous section. The cross-section was prepared by cutting using a diamond cutter. In these figures, the prepreps whose carbon fiber orientations are parallel, oblique and perpendicular to the machined surface are indicated by 'A', 'B' and 'C', respectively. White dashed lines in Fig. 7 indicate the boundary of the matrix resin removal.

First, focusing on the case of a lower average gap voltage, shown in Figs. 6(a) and 7(a), the depth of matrix resin removal is approximately 100-200 μm . However, matrix resin can be seen in places on the machined surface, and therefore the binding effect on carbon fibers on the machined surface is thought to be strong. In addition, the prepreg with carbon fiber orientation parallel to the

Fig. 6 Top-view of machined surface of CFRP

Fig. 7 Cross-section of machined surface of CFRP

machining surface has sunk. Therefore, it is thought that short-circuiting due to the fraying of carbon fibers cannot easily occur.

On the other hand, in the case of a higher average gap voltage, shown in Figs. 6(c) and 7(c), the depth of matrix resin removal is significant compared with that in the other cases, and the depth reached several hundred micrometers. Since little resin can be seen on the machined surface, as shown in Fig. 6(c), the binding effect on carbon fibers on the machined surface is thought to be weak. Therefore, the carbon fibers with orientation parallel to the machining surface are easily attracted to the tool electrode by the electrostatic force caused by the applied voltage, which leads to short-circuiting.

For an average gap voltage of 17V, although the relative frequency of short-circuiting is as large as that for an average gap voltage of 13V, the depth of matrix resin removal is much smaller. Since the fluctuation of the z-axis during the EDM process was relatively wider in this case than the other cases and the measured gap width varied more widely, short-circuiting not only due to the fraying of carbon fibers but also due to the tool electrode coming in contact with the workpiece (CFRP) is thought to frequently occur in this case.

4. EFFECT OF FIBER ORIENTATION ON LOCAL MATERIAL REMOVAL RATE

4.1 Uneven Shape of Machined Surface

When EDM of a CFRP was carried out in a configuration in which many preregs were concurrently machined, the machined surface of the CFRP workpiece became uneven, as shown in Fig. 7(a). This result indicates that the local material removal rate is different among the preregs. Therefore, in order to discuss the effect of the carbon fiber orientation on the local material removal rate, time variation of the unevenness of the machined surface was observed. The experimental setup, the CFRP workpiece material and the machining conditions were the same as those in Section 3. In this experiment, the average gap voltage was chosen 11V, and, therefore, the relative frequency of short-circuiting was approximately 15%, as shown in Fig. 5.

Figure 8 shows the cross-section of the machined surface in the cases of machining time of ten minutes and forty minutes, respectively. It is found that the machined surface is uneven and the removal depth of the prepreg whose carbon fiber orientation is parallel to the machined surface (indicated 'A1' to 'A8' in Fig. 8) is larger than that of

Fig. 8 Cross-section of machined surface of CFRP

Fig. 9 Profile curve of discharging surface of tool electrode

the other preregs. It is also found that the difference in the removal depth increases with machining time.

4.2 Cause of Uneven Shape of Machined Surface

4.2.1 Difference in Material Removal Mechanism

In the case of the prepreg whose carbon fiber orientation is perpendicular to the machining surface, short-circuiting due to the fraying of carbon fibers does not occur. Therefore, most of the carbon fiber and matrix resin will be removed by discharge.

On the other hand, in the case of the prepreg whose carbon fiber orientation is parallel to the machining surface, short-circuiting due to the

fraying of carbon fibers can occur. Thus, the matrix resin of the CFRP will be removed not only by discharge but also by the Joule heating generated by the short-circuit current, whereas the carbon fibers are thought to be removed only by discharge. However, the carbon fibers in this prepreg can also be removed as chopped fibers divided by the discharge, as pointed out by Ichii et al.⁴⁾. In this case, a large volume of carbon fibers, as well as the surrounding matrix resin, can be removed in addition to the volume removed by sublimation. If matrix resin near the machining surface has been removed by short-circuiting, the removal volume of

the chopped fibers will further be larger. Therefore, the local material removal rate of this prepreg is considered to be larger than that of the other prepregs.

It can be concluded that one of the reasons for the difference in the removal depth among the prepregs, as shown in Fig. 8, is the difference in the material removal mechanism.

4.2.2 Shape of Discharging Surface of Tool Electrode

An uneven shape is also formed on the discharging surface of the tool electrode because the region facing to the prepreg whose carbon fiber orientation is parallel to the machining surface need lower discharge frequency than the region facing to the other prepregs. Thus, the tool electrode wear volume at the region is smaller and, therefore, the convexity of the tool electrode is synchronized with the concavity of the CFRP workpiece. This further increase the unevenness of the machining surface of the CFRP workpiece.

Figure 9 shows the profile curve of the discharging surface of the tool electrode measured using a surface roughness and profile measurement instrument. It is found that large convexities are formed at the position facing to the concavities of the CFRP workpiece (indicated 'A2' to 'A7' in Fig. 9), and the height of the convexities are comparable to the depth of the facing concavities.

It can be concluded that formation of unevenness on the discharging surface of the tool electrode also affect the difference in the removal depth among the prepregs

5. CONCLUSIONS

In this paper, the surface of EDMed CFRP is observed in order to discuss the effect of the carbon fiber orientation on machining phenomena. The following conclusions were obtained.

- (1) In the EDM of a CFRP, short-circuiting due to the fraying of carbon fibers frequently occurs, which can contribute to material removal.
- (2) When the average gap voltage is reduced so that the gap width is narrower, the relative frequency of short-circuiting decreases.

- (3) When the carbon fiber orientation is parallel to the machining surface, short-circuiting due to the fraying of carbon fibers easily occurs. In this case, the local material removal rate is high and the local tool electrode wear is small. Therefore, when a CFRP formed by laminating prepregs, where the carbon fiber orientation in each prepreg is even but different among the prepregs, is machined by EDM in a configuration in which many prepregs are concurrently machined, the machined surface becomes uneven.

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