

Development of novel tool for cutting of carbon-fiber-reinforced plastics (Positive use of abrasive wear at tool edge for reduction in cutting force)

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Abstract

This paper describes a novel design concept for a tool for cutting carbon-fiber-reinforced plastic (CFRP) composites. The cutting tool, which is termed a two-layer tool, was fabricated from two materials with a spatial distribution of hardness around the tool edge. In the two-layer tool, the rake face is made of a material with a relatively high wear resistance, i.e., polycrystalline diamond (PCD), whereas the flank face is made of a material with a relatively low wear resistance, i.e., tungsten carbide (WC-Co). The results of milling tests conducted with a unidirectional CFRP laminate and the two-layer tool showed that the existence of a hardness distribution works to reduce cutting forces, because the wear process of the two-layer tool develops with a constant roundness at the tool edge over relatively long cutting distances. A simplified model was developed to describe how friction force is reduced. Increasing the difference between the wear resistances of the PCD layer and the WC-Co substrate and increasing the clearance angle of the tool edge were found to be effective in reducing the cutting forces. The finding of this study will be helpful in the development of novel design concepts for extending the life of tools for cutting CFRP composites.

Key words: Carbon-fiber-reinforced plastics, Life of tool, Tool wear, Polycrystalline diamond, Abrasive wear, Cutting forces

1. Introduction

Carbon-fiber-reinforced plastic (CFRP) composites are widely used because of their excellent mechanical properties, such as their high-strength-to-weight ratios, high modulus-to-weight ratios, high damping capacities, and good dimensional stability. However, severe tool wear of tools during machining of CFRP composites is a serious problem (Sheikh-Ahmad, 2009; Dandekar and Shin, 2012; Che, et al., 2014) that increases the cost of machining CFRP products.

The choice of material is the most important factor in the life of the tools used in cutting CFRP composites. In the machining of CFRP composites, the abrasive wear on the flank face characterizes tool wear processes. Therefore, high-hardness materials, such as polycrystalline diamond (PCD) and chemical vapor deposition (CVD) diamond, are commonly used in CFRP cutting tools (Sakuma, et al., 1985; Ferreira, et al., 1999; Ferreira, et al., 2001; Lantrip, 2008; Chatelain and Zaghbani, 2012).

In an effort for extending the life of cutting tool that is used in CFRP machining, our group has been focusing on the positive use of the wear at the tool edge (Maegawa, et al., 2015). According to this concept, a two-layer tool with a hardness distribution around the tool edge can be used to maintain a constant roundness at the tool edge over a long cutting distance. The whole of the rake face is made of relatively high-hardness materials, i.e., PCD or CVD diamond, and a large part of the flank face is made of WC-Co. The results of some experiments have shown that the rate of increase in the cutting forces due to the progression of tool wear in a two-layer tool is smaller than that in a conventional single-material tool.

In this paper, we describe a method to enhance the cutting force reduction effect of the proposed two-layer tool. Using three types of two-layer tools, each made of a PCD layer and a WC-Co substrate, milling tests were conducted using a unidirectional CFRP laminate. Measurements of changes in the cutting forces and the edge profile during the milling tests showed that the wear resistance ratio (which is defined as the ratio of the wear resistance of the PCD layer to that of the WC-Co substrate) and the clearance angle of the tool edge are very important parameters influencing the cutting forces. Increasing the wear resistance ratio and the clearance angle can enhance the cutting force reduction effect. Based on the experimental results, a simplified model for the wear process of the two-layer tool that clarifies the method for enhancing the cutting force reduction effect was developed.

2. Cutting force reduction effect of two-layer tool in cutting of CFRP composites

Previous research results demonstrating the cutting force reduction effect (Maegawa, et al., 2015), in which time changes in cutting forces and shape of tool edge during a two dimensional milling were monitored, are shown in Fig. 1. The left side of the figure shows changes in the average value of the cutting force parallel to the feed direction, F_x , and the right side shows changes in the average value of the cutting force perpendicular to the feed direction, F_y . It should be noted that “ F_y ” in Fig. 1 corresponds to “ F_z ” in this current paper, because in this paper the Z axis is defined as the perpendicular direction (see Fig. 5). In these experiments, three types of tools were used, as illustrated in the figure; Tool I and Tool II were made of single materials, WC-Co and PCD, respectively. Tool III was made of two materials with different hardnesses, i.e., a PCD layer on the rake face and a WC-Co substrate. Tool III corresponds to the two-layer tool discussed in this paper.

As Fig. 1 shows, for all three of these cutting tools, the cutting forces F_x and F_y gradually increase with increasing cutting distance. This results from the loss of initial sharpness of the tool edge due to the progression of tool wear. The wear resistance of Tool II and Tool III (made of PCD and PCD/WC-Co, respectively) is higher than that of Tool I (made of WC-Co), and the cutting forces for Tool I increase much more rapidly than those of Tool II and Tool III. Interestingly, although most of the flank face and the bulk regions are made of a relatively low-hardness material, i.e., WC-Co, the rate of increase in the cutting forces is lower for Tool III than for Tool II. This implies that the life of Tool III is higher than that of Tool II. These results indicate that the use of a relatively low-hardness material can reduce the rate of increase of the cutting forces. In this study, this is termed as “cutting force reduction effect”.

The mechanism of the cutting force reduction effect is shown schematically in Fig. 2, which illustrates the difference between the wear processes around the tool edge of a conventional tool made of a single material and a two-layer tool made of two materials with different hardnesses. In the figure, four profiles of worn edges at cutting distances $L = L_1, L_2, L_3$, and L_4 , are illustrated, where $L_1 < L_2 < L_3 < L_4$. In both tools, the initial tool edge is gradually dulled with cutting distance due to the progression of abrasive wear on the flank face. In the single-material tool, illustrated in Fig. 2(a), a large curvature (roundness) of the flank face, which is denoted as R in the figure, is formed. The shape of the curvature is determined by the spatial distribution of the normal pressure acting on the flank face. In contrast, in the case of the two-layer tool, illustrated in Fig. 2(b), severe abrasive wear occurs locally in the region of the lower-wear-resistance material and reduces the curvature of the flank face. Consequently, the thrust cutting force

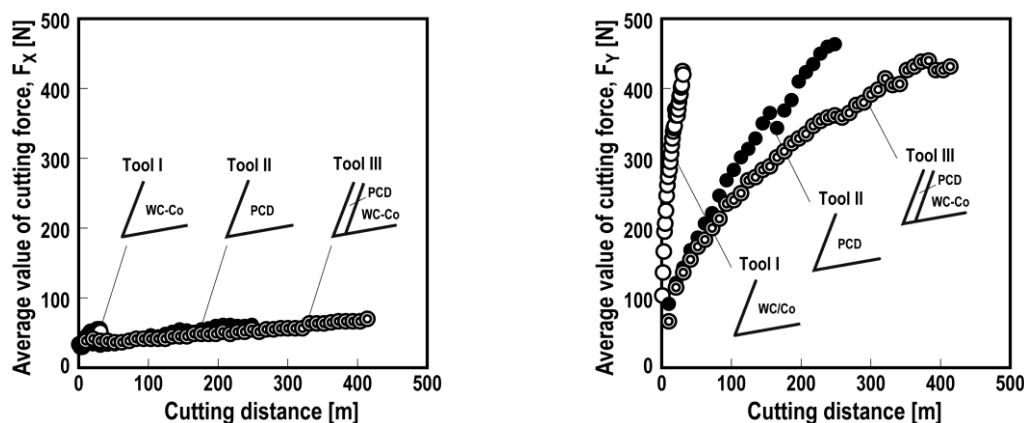


Fig. 1 Change in cutting force with cutting distance for three different cutting tools (Maegawa, et al., 2015).

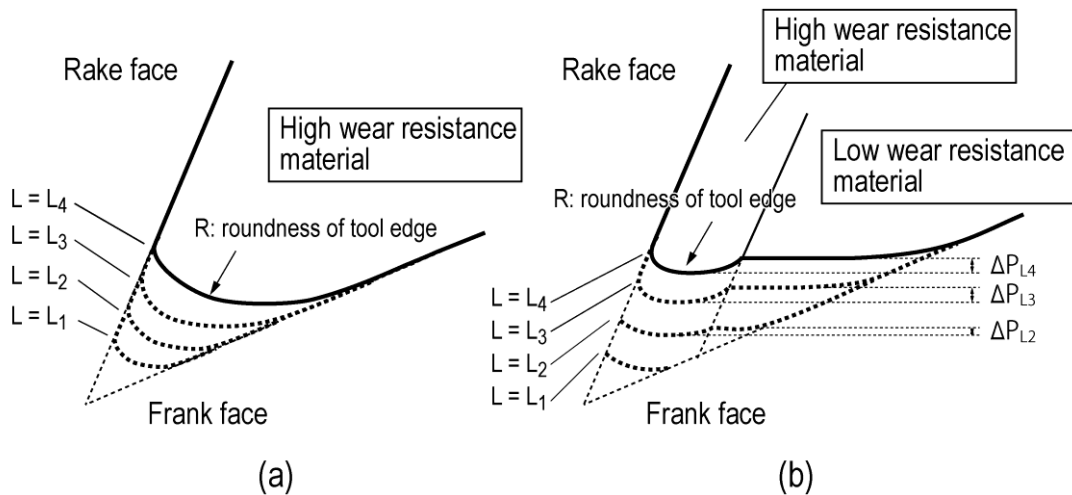


Fig. 2 Schematic of the difference in wear processes of (a) a conventional single-material tool and (b) the proposed two-layer tool made of two materials with different hardnesses.

can be reduced, because the thrust force corresponds to the force needed to press the material under the tool, i.e., the burnishing force. Small roundness decreases the pressing region, and it reduces the thrust cutting force. This is the “cutting force reduction effect” suggested in this study. The figure also denotes the difference between the position of the bottom faces at the high wear resistance layer and the low wear resistance substrate, i.e., ΔP_{L2} , ΔP_{L3} , and ΔP_{L4} . These values are important factor to determine the cutting force reduction effect, which will be discussed at later.

It should be noted that the total wear volume of the conventional single-material tool shown in Fig. 2(a) is smaller than that of the two-layer tool shown in Fig. 2(b). The reason for the difference in the total wear volumes is that the single-material tool is made entirely of a relatively high-wear-resistance material, whereas the substrate of the two-layer tool is made of a relatively low-wear-resistance material. Therefore, the wear volume at the tool edge is not the only parameter that determines the life of the tool. It should be noted that, of course, the recession of the cutting edge which rises with increasing tool wear results in a dimension error. However, the dimension error can be reduced by changing the depth of cut with changes in cutting distance using a CNC control. In this case, it is needed to estimate the relationship between the recession distance of the cutting edge and cutting distance in advance.

3. Experiment

3.1 Experimental setup

Figure 3 shows a schematic illustration of the experimental setup used in this study. A vertical machining center was used for the milling tests performed. As Fig. 3 shows, a unidirectional CFRP laminate with a thickness of 3 mm was fixed on a steel vise. The steel vise was fixed on a machining pallet via a three-directional dynamometer that was used to monitor the cutting forces during the milling tests. Each tested cutting tool was fixed on a main spindle via a tool holder. By changing the rotation and position of the main spindle of the machining center, the tool could be rotated at a constant rotation speed and moved at a constant feed rate. For all the experiments performed in this study, the cutting speed V and feed rate F were set to 30 m/min and 0.05 mm/revolution, which are in typical cutting conditions of CFRP composites. However, in many cases, the cutting is performed in higher cutting speeds. In this study, in order to avoid thermal effects on the cutting tool and the CFRP materials (Caprino, et al., 1996), experiments were performed at a comparatively low cutting speed.

3.2 Specimens

Multidirectional CFRP laminates have been used in many studies of cutting tools to ensure uniform mechanical properties in all directions. The use of unidirectional CFRP laminates simplifies the analysis; it is easy to understand the mechanical interaction between a unidirectional CFRP laminate and a cutting tool. The mechanical response and

cutting mechanism are highly dependent on the relative angle between the orientation of the carbon fibers and the traveling direction of the tool edge (Sakuma and Seto, 1983; Kaneeda, 1991; Wang, et al., 1995; Sreejith, et al., 2000). However, this study was focused on the effects of the type of material and the clearance angle of a two-layer tool on the reduction in cutting forces. In most of the tests conducted in this study, a unidirectional CFRP laminate with a thickness of 3 mm was used. The orientation direction of the carbon fibers in the CFRP laminates was set to be perpendicular to the feed direction of the tool edge. In the laminates, PAN-based carbon fibers are embedded in epoxy resin; tensile strength, tensile elasticity, and a diameter of the carbon fibers are 4,900 MPa, 240 GPa, and 7.0 μm , respectively. In order to avoid the effect of dramatic deteriorations in the base material of the CFRP laminates, the CFRP laminate was sandwiched between two plastic plates or aluminum plates with a thickness of 1 mm. The results of preliminary experiments showed that the forces required to cut these plates were much smaller than those observed in the cutting of the CFRP laminates. Therefore, the cutting forces for the plastic plates can be neglected in the analyses.

3.3 Prepared cutting tools

Figure 4 lists the geometries of the cutting tools used in this study. Tools A, C, and E were made of PCD. The rake face of Tools B, D, and F were made of PCD, and most of their flank faces and substrates were made of WC-Co (K10 grade). These three tools represent examples of two-layer tools. The size d of the synthetic diamond grains of the PCD regions of Tools A through D was 10 μm , and that of Tools E and F was 1 μm . The grain size is typically an important factor in the resistance to abrasive wear during cutting of CFRP composites. Therefore, by comparing the differences in the wear processes of these tools, the effect of the difference in the wear resistances of the PCD layer and the WC-Co substrate on the life of the tools could be investigated. The other mechanical properties of PCD (10 μm), PCD (1 μm) and WC-Co (K10) were as follows. The densities of them are 4.08, 4.37, and 14.7 g/cm^3 , respectively. The fracture toughness of them are 8.96, 13.4 and 10.50 $\text{MPa m}^{1/2}$, respectively. In this study, the thicknesses of the PCD layers were determined to avoid accidental chipping of the tool edge. From preliminary experiments, it was found that when a PCD layer with a smaller thickness is used, a large scale chipping of the PCD layer was observed. The PCD layer was integrally bonded to the WC-Co substrate (PCD was sintered on the WC-Co substrate under extreme pressures and temperatures), so that it did not peel off from the substrate during the milling tests. The clearance angle of Tools A and B was 10°, while that of the other tools was 20°. It should be noted that the performance of Tools A and B was examined in a previous study (Maegawa, et al., 2015). For Tools C through F, the radius of the tool edge was set to be approximately 2–3 μm using a pulse laser grinding technique, which creates a sharp edge without mechanical defects or cracks (Mabuchi, et al., 2015).

3.4 Experimental procedure

In the previous research by our group (Morikawa, et al., 2013), it was found that the cutting forces under a down-milling process at $\theta = 0^\circ$ is larger than other conditions, i.e., down-milling at $\theta = 90^\circ$, up-milling at $\theta = 0^\circ$, and up-milling at $\theta = 90^\circ$. Thus, the reduction of cutting forces is most needed and expected under a down-milling process

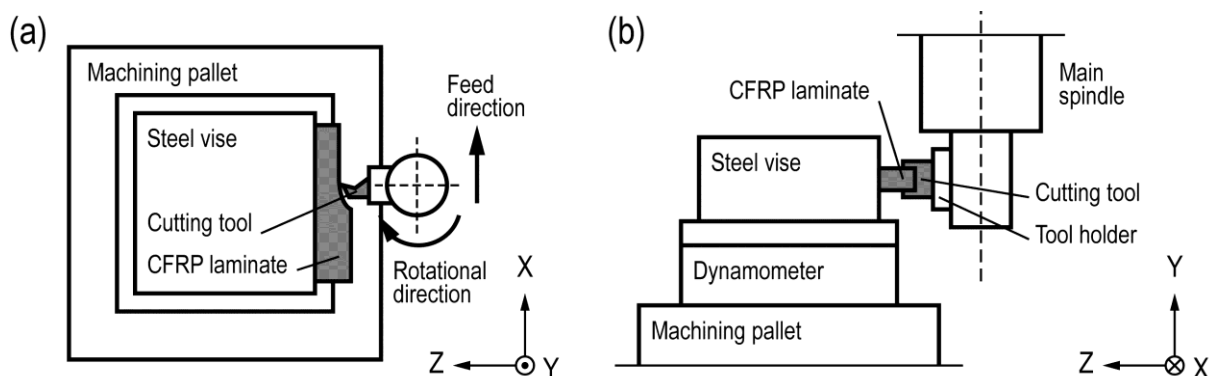


Fig. 3 Schematic of the experimental setup: (a) top view and (b) side view.

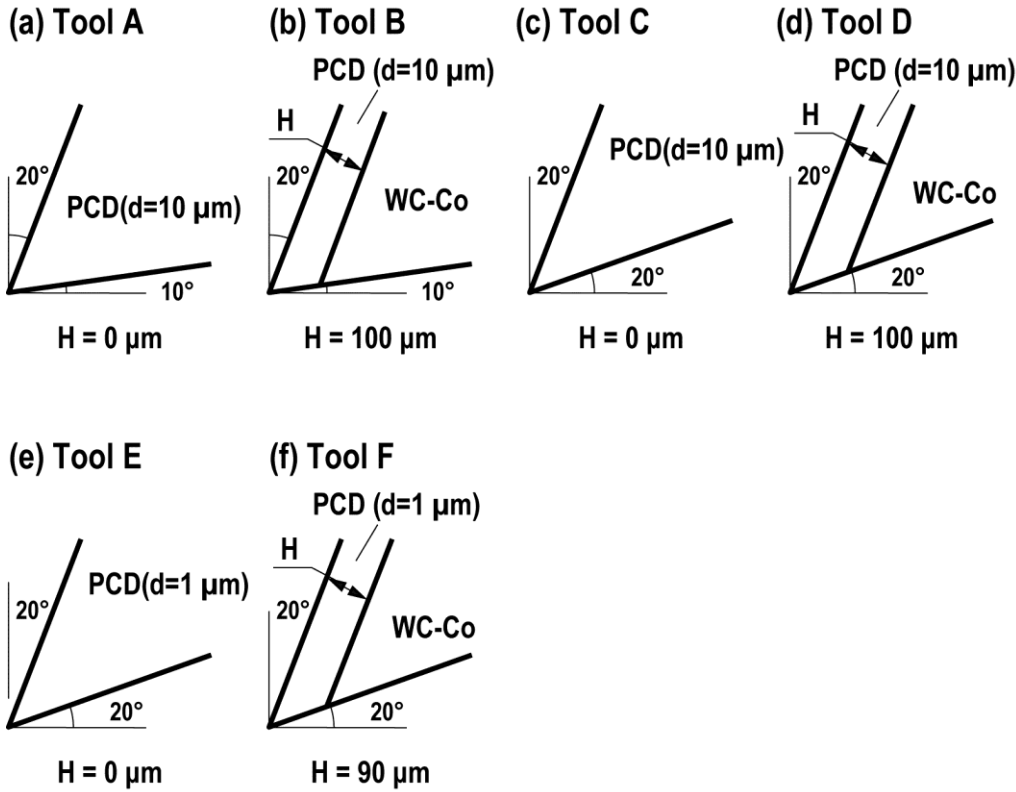


Fig. 4 Geometries of prepared cutting tools; H : thickness of PCD layer, d : grain size of diamond in PCD.

at $\theta = 0^\circ$. From this reason, in the most of experiments in this study, the plane down- milling process was investigated.

Figure 5 shows the configuration of the plane down-milling process used in this study. The edge of the tool rotates at a constant speed V , and it travels forward in the direction shown in the left of the figure at a constant feed rate of F . The undeformed chip thickness h varies continuously with the change in the engagement angle φ . The tilted thick black lines in the figure indicate the orientation direction of the carbon fibers in the CFRP laminates. As described in the previous section, most of our experiments were performed with $\theta = 0^\circ$.

During the milling tests, the cutting forces in the X and Z directions, F_X and F_Z , were measured at a sampling rate of 10 kHz using the dynamometer. At predetermined values of the cutting distance L , the edge profile of the tool edge was measured with a surface roughness meter. In addition, the width of flank wear was measured from microscope images.

To better understand the relationship between the cutting forces and the position of the tool edge, F_X and F_Z were transformed into principle and thrust forces, F_P and F_T , as shown in Fig. 5, using the following equations:

$$\begin{aligned} F_P &= F_X \cos \varphi + F_Z \sin \varphi \\ F_T &= -F_X \sin \varphi + F_Z \cos \varphi \end{aligned} \quad (1)$$

where φ is the engagement angle.

The relative angle θ_{rel} between the orientation of the carbon fibers and the tool traveling direction during a single milling pass is described using the engagement angle φ as follows:

$$\theta_{\text{rel}} = \varphi - \theta \quad (2)$$

The engagement angle φ changes during a single pass from $\varphi = \varphi_{\text{max}} = 24.62^\circ$ (at the start position of the single pass) to $\varphi = \varphi_{\text{min}} = 0^\circ$ (at the end position of the single pass). Similarly, the undeformed chip thickness h varies continuously with the changing φ as follows (Shaw, 1984);

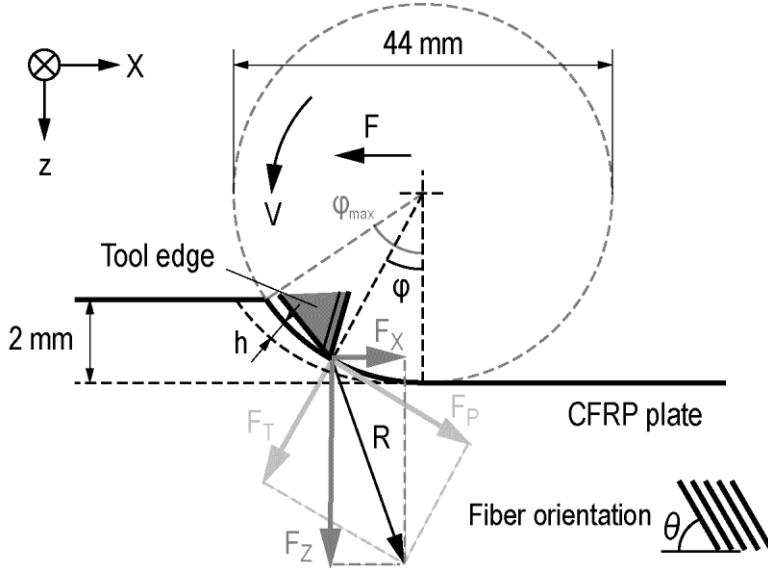


Fig. 5 Configuration of down-milling process for CFRP composites.

$$h = f \sin \phi \quad (3)$$

where f is the feed per tooth, which was set to 50 μm .

4. Experimental results

4.1 Changes in cutting forces during a single pass

Figure 6 shows typical results for the changes in the cutting forces F_p and F_T during single milling passes at cutting distances $L = 10, 50, 100, 150$, and 200 m for Tool A. At the onset of cutting, i.e., at $\phi = \phi_{\max} = 24.62^\circ$, the cutting forces F_p and F_T suddenly increase, and then they gradually decrease over time. This tendency is consistent with the changes in the undeformed chip thickness h during the down-milling process. As described by Eq. (3), h gradually decreases with decreasing ϕ . The increases in the cutting forces F_p and F_T indicate that the initial sharpness of the tool edge is gradually dulled due to the progression of tool wear.

At all cutting distances, the values of F_p were found to be much smaller than those of F_T . As noted by Koplev (1983), the principal force corresponds to the sum of the forces needed to make a cutting chip and the friction force acting on the flank face of the tool. The former, i.e., the chip formation force, typically does not depend on the progression of tool wear. Therefore, small changes in F_p result from changes in the friction force, which can be expressed as the product of the normal load and the friction coefficient. In contrast, the thrust force represents the deformation resistance of the CFRP substrate. The value of the thrust force corresponds to the force needed to press the material under the tool, i.e., the burnishing force. Therefore, as described in Fig. 2, F_T increases with increasing penetration volume, which is determined by the roundness of the flank face of the cutting tool.

4.2 Changes in average cutting forces

To describe the dependence of the cutting forces on the cutting distance, we calculated the averaged cutting forces over single passes, $F_{p\text{ave}}$ and $F_{T\text{ave}}$, as follows:

$$F_{p\text{ave}} = \frac{\int F_p dt}{T} \quad F_{T\text{ave}} = \frac{\int F_T dt}{T}, \quad (4)$$

where T is the time period of a single pass.

Figure 7 summarizes the changes in the average cutting forces, F_{Pave} and F_{Tave} over the cutting distance. The open circles indicate the changes in the cutting forces for Tools A, C, and E (single-material tools), while the solid circles

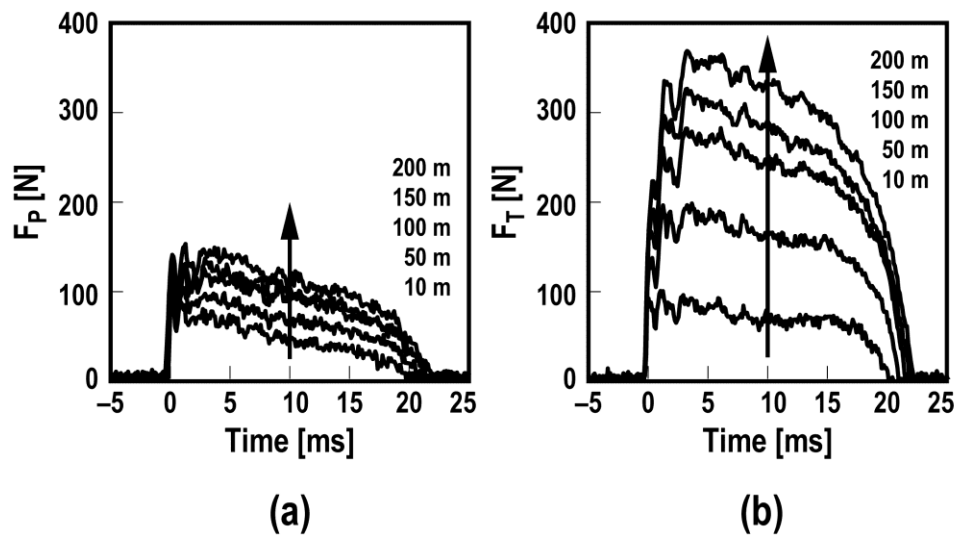


Fig. 6 Typical results for changes in cutting forces during single passes at $L = 10, 50, 100, 150$, and 200 m with Tool A.

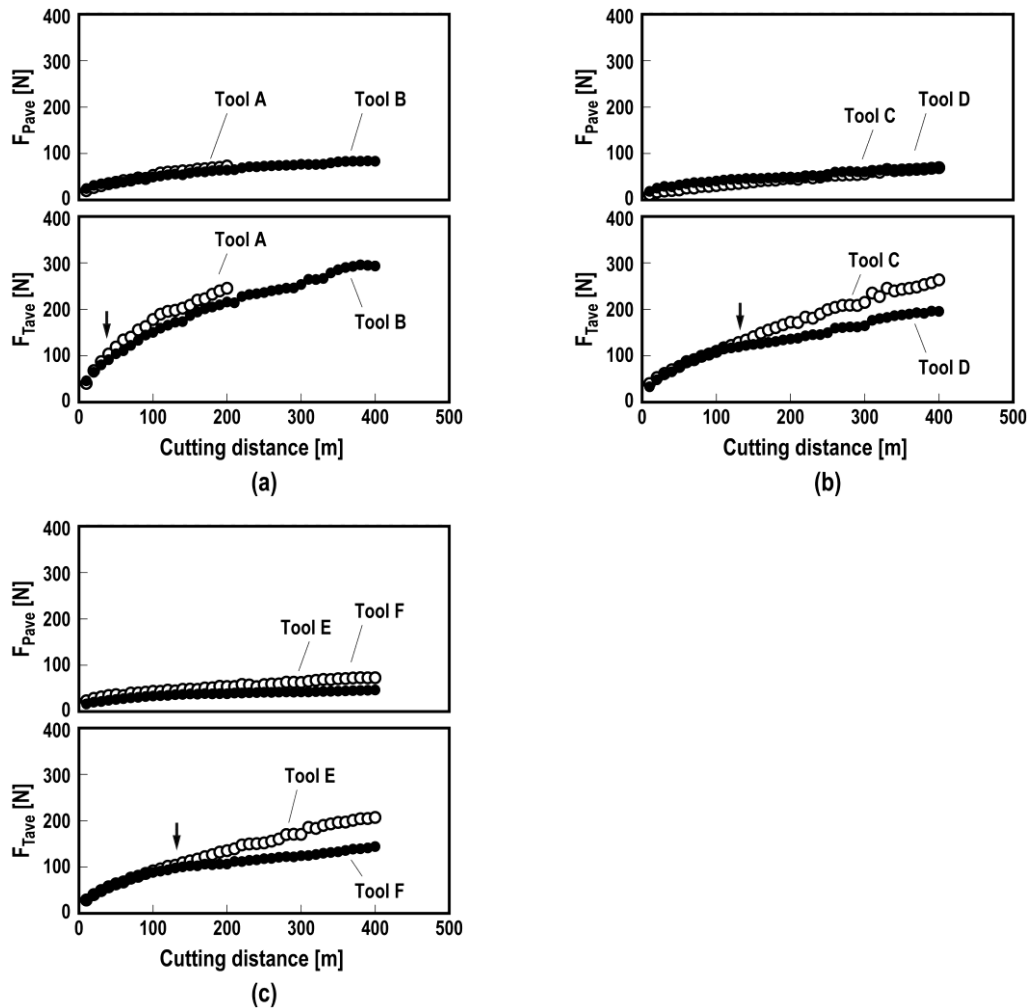


Fig. 7 Changes in averaged cutting forces with increasing cutting distance; (a) open circles: Tool A, solid circles: Tool B, (b) open circles: Tool C, solid circles: Tool D, and (c) open circles: Tool E, solid circles: Tool F.

indicate the changes in the cutting forces for Tools B, D, and F (two-layer tools). It should be noted that only for Tool A was the cutting test terminated at a cutting distance L of 200 m.

In general, the cutting forces of the single-material tools, i.e., Tools A, C, and E, were larger than these of the two-layer tools, i.e., Tools B, D, and F. Thus, the reduction in the cutting forces of the two-layer tools, i.e., cutting force reduction effect, occurred for all two-layer tools, despite the differences in the composition of the PCD layer and the clearance angle. In addition, a comparison of Figs. 7(a) and (b) or Figs. 7(b) and (c) shows that an increase in the clearance angle and a decrease in the diamond grain size of the PCD are both effective in enhancing the reduction effect of cutting forces. In addition, it was found that differences in the cutting forces between single-material tools and two-layer tools occur after a certain cutting distance, as indicated by the down-pointing arrows in Fig. 7.

4.3 Measurement of changes in edge profile

Figure 8 shows changes in the profile of the tool edge. It should be noted that in Fig. 8(a), i.e., for Tool A, the edge profiles were drawn only at cutting distances of $L = 50, 100, 200$ m, because the cutting test was stopped before $L = 300$ m. In contrast, in Figs. 8(b) to (f), i.e., for Tools B to F, the profiles on the flank face were drawn at $L = 50, 100, 200, 300$, and 400 m.

The edge profiles shown in Fig. 8 conform to the shape shown in Fig. 2. In single-material tools, as shown in Figs. 8(a), (c), and (e), the tool edge has a large curvature, which corresponds to R in Fig. 2. In contrast, in two-layer tools, as shown in Figs. 8(b), (d), and (f), the position of the bottom face of the WC-Co substrate is located at a relatively high position compared to the bottom faces of the PCD layer. This is the result of the difference between the abrasive wear resistance of the PCD and that of the WC-Co region. For two-layer tools, abrasive wear occurs locally in the WC-Co region. These results are consistent with those shown in Fig. 7: for the two-layer tools the thrust forces are smaller than

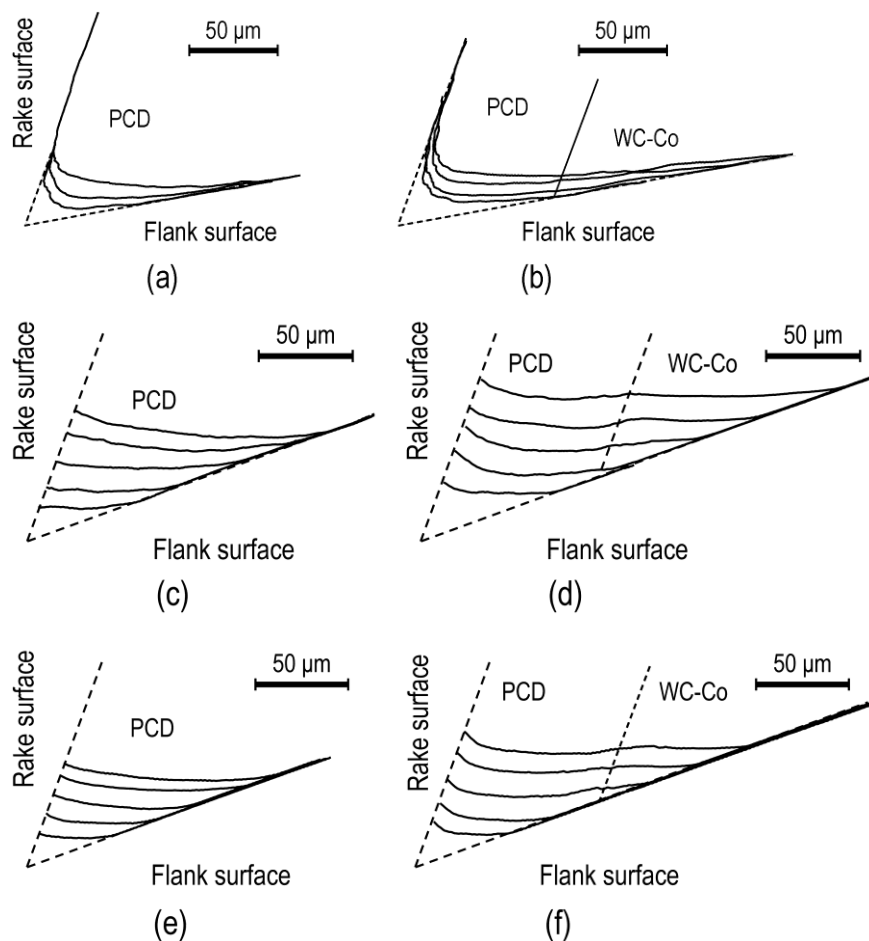


Fig. 8 Changes in profile of tool edge; (a) Tool A, (b) Tool B, (c) Tool C, (d) Tool D, (e) Tool E, and (f) Tool F.

for the single-material tools. Thus, as Fig. 2 shows, for two-layer tools, a small roundness at the tool edge is maintained for a relatively long cutting distance, leading to slow the increase in cutting forces.

Figures 8(c) and (e) show that the wear volume of Tool E, which was fabricated of PCD with a grain size d of 1 μm , was smaller than that of Tool C, which was fabricated of PCD with a grain size d of 10 μm . These results show that the abrasive wear resistance of PCD at a grain size of $d = 1 \mu\text{m}$ is higher than that of PCD at a grain size of $d = 10 \mu\text{m}$. Thus, the wear ratio of the wear resistances of the PCD and WC-Co regions in Tool F is larger than that in Tool D.

5. Discussion

Figure 9 shows the changes in the wear width at the flank face of Tools A and B. There is a large difference between the wear widths of Tools A and B beyond a cutting distance L of 50 m. This means that at $L = 50 \text{ m}$, the wear width due to abrasive wear on the flank face extends to the WC-Co region in Tool B. Beyond that point, in Tool B, severe abrasive wear occurs in the WC-Co region, and the rate of increase of the wear width of Tool B is larger than that of Tool A. Thus, the local abrasive wear occurs beyond $L = 50 \text{ m}$. These findings are consistent with the results shown in Fig. 7, i.e., the differences in the cutting forces for Tools A and B are evident beyond $L = 50 \text{ m}$. The reduction in the cutting forces was found to be attributable to the changes in the edge profile due to severe local abrasive wear on the flank face of Tool B.

In order to investigate the effect of the grain size of PCD on the cutting force reduction effect, the thrust force ratio λ , which is defined as the ratio of F_{Tave} for a two-layer tool (Tool D or F) to F_{Tave} for a corresponding single-material tool (Tool C or E), was derived as shown in Fig. 10. The open circles indicate the changes in $\lambda = F_{\text{Tave}}$ for Tool D / F_{Tave} for Tool C over the cutting distance L , and the solid circles indicate the changes in $\lambda = F_{\text{Tave}}$ for Tool F / F_{Tave} for Tool E. Before $L = 100 \text{ m}$, λ has a value of one for both conditions. This means that the effect of reducing the cutting forces of the two-layer tools does not occur in the early stage of cutting. After $L = 100 \text{ m}$, the value of λ gradually decreases with cutting distance. It means that the reduction effect of cutting forces appears after $L = 100 \text{ m}$; it is consistent with the results in Figs. 7(b) and (c). A visible large difference in cutting forces between single materials and two-layer tools were observed after $L = 150 \text{ m}$, which are denoted as black arrows in the figure. Focusing on values under large L , it is found that they approach to different values. Thus, we can clearly see the difference, denoted by $\Delta\lambda$, at large L values. The reducing effect between Tools E and F was found to be larger than that between Tools C and D. Thus, a decrease in the diamond grain size enhances the cutting force reduction effect. Furthermore, it was found that the difference between the two layer tools with different grain size were observed after a certain cutting distance, i.e., approximately 250 m. The reason is not clear. However, after $L = 300 \text{ m}$, the value of $\Delta\lambda$, keeps a constant value. It implies that the difference of the cutting forces is observed under a certain equilibrium condition.

Figure 11 illustrates a simplified model of the wear process for the two-layer tools, i.e., Tools B, D, and F. The edge

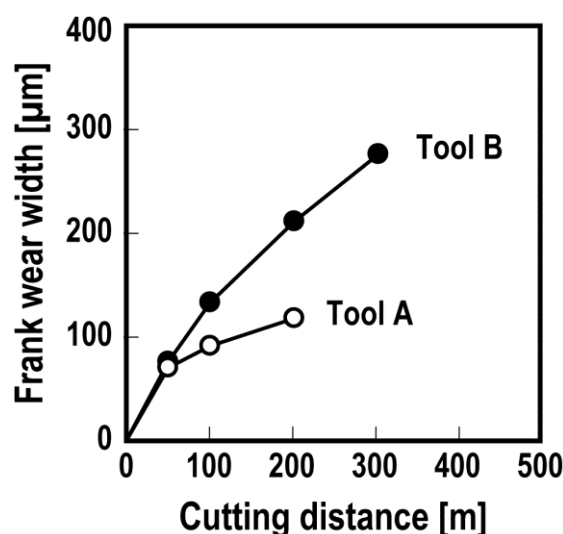


Fig. 9 Changes in flank wear width for Tool A and Tool B.

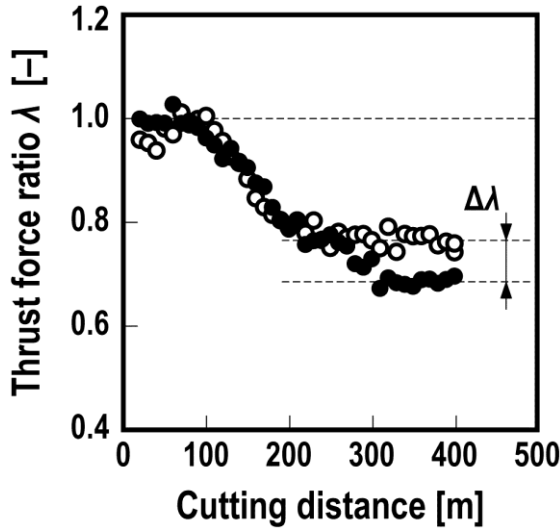


Fig. 10 Changes in thrust force ratio λ with cutting distance; open circles: ratio of F_{Tave} for Tool D to F_{Tave} for Tool C, and solid circles: ratio of F_{Tave} for Tool F to F_{Tave} for Tool E.

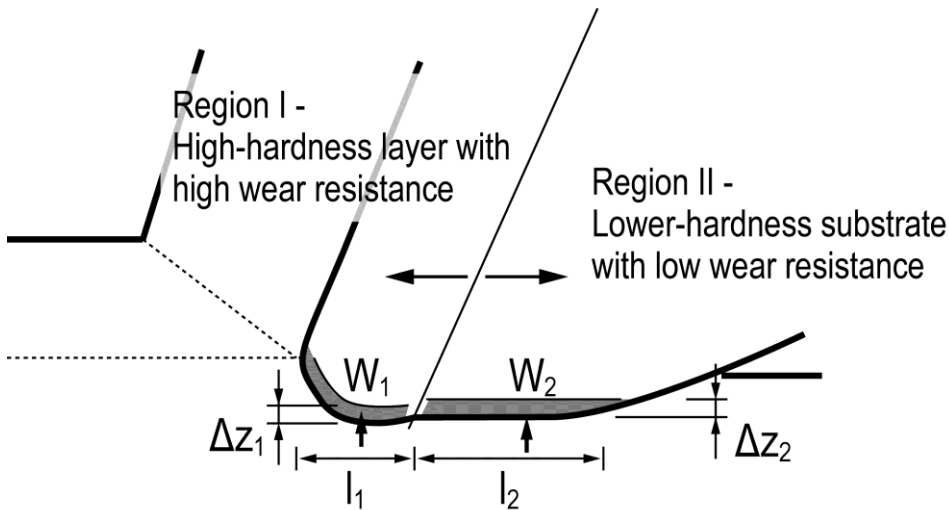


Fig. 11 Schematic of simplified model of wear process for proposed two-layer tool.

of the tool consists of two different regions: region I, which is a high-hardness layer with high wear resistance, and region II, which is a lower-hardness substrate with low wear resistance. The contact lengths of regions I and II are l_1 and l_2 , respectively. In regions I and II, the normal loads W_1 and W_2 act on the contact interface between the rake face of the tool and the CFRP substrate. These forces correspond to the restriction forces of the CFRP substrate. The gray areas indicate the wear volumes ΔV over the sliding distance ΔS . It should be noted that the model is simplified; the wear widths of the two regions in the vertical direction are treated as equal. It is difficult to base a quantitative analysis on a simplified model because the simplified model cannot be used to simulate the wear process realistically. However, the use of a simplified model is sufficient for the purposes of qualitative determination of the factors that influence the cutting force reduction effect.

Assuming that the wear volume can be characterized by Archard's wear law (Archard, 1953; Rabinowicz, 1965), the wear widths in the regions Δz_1 and Δz_2 at a sliding distance ΔS can be expressed as follows:

$$\Delta z_1 = \frac{W_1 \Delta S}{K_1 l_1} \quad (5)$$

$$\Delta Z_2 = \frac{W_2 \Delta S}{K_2 l_2} \quad (6)$$

where K_1 and K_2 are wear constants determined by the wear resistance, depending on the types of materials, and l_1 and l_2 are the contact lengths of regions I and II, respectively. The model assumes that the wear widths are directly proportional to the normal loads W_1 and W_2 and that the sliding distance ΔS and inversely proportional to the constants K_1 and K_2 .

When L is a small value, the tool wear develops under a transient condition; here, ΔZ_1 and ΔZ_2 does not have a same value. The transient wear process was already illustrated in Fig. 2, where the difference between two positions, i.e., ΔP_{L1} , changes with varying cutting distance, i.e., $\Delta P_{L2} \neq \Delta P_{L3}$. This is also shown in Fig. 8. In order to develop the cutting force reduction effect, therefore, it is required to increase ΔP ; $\Delta Z_2 > \Delta Z_1$. The result is consistent with the discussion in Fig. 2 that $K_1 > K_2$ is effective to avoid for decreasing the roundness of tool edge. After that, the wear process reaches to an equilibrium condition, because the valance of the normal loads changes with developing tool wear. When the position of the bottom face at region I is much higher than that at region II, W_1 will be much larger than W_2 . During the equilibrium condition (i.e., large L condition), the values of Δz_1 and Δz_2 should be identical, i.e., $\Delta z_1 = \Delta z_2$. Thus, using Eqs. (5) and (6), we can obtain following relationship:

$$\frac{W_1}{K_1 l_1} = \frac{W_2}{K_2 l_2} \quad (7)$$

The total thrust force F_T can be expressed as follows:

$$F_T = W_1 + W_2 \quad (8)$$

Using Eqs. (5) and (6), Eq. (8) can be written as follows:

$$F_T = W_1 \left(1 + \frac{K_2 l_2}{K_1 l_1} \right) \quad (9)$$

As Eq. (9) shows, the dimensionless ratio K_2/K_1 , which corresponds to the ratio of the wear resistance in region I to the wear resistance in region II, is an important factor in characterizing the thrust force F_T under the equilibrium condition. In general, the used of a high-wear-resistance material reduces the volume of tool wear and slows the rate of increase in the cutting forces. However, in the case of two-layer tools, the use of a low-wear-resistance material decreases the thrust force. For example, it is expected that the combination of diamond layer and the high-speed steel is more effective for enhancing the cutting force reduction effect. In addition, an increase in the clearance angle corresponds to a decrease in the contact length l_2 . Thus, the simplified model developed in this study can explain the results shown in Fig. 7.

In a typical case of CFRP cutting, the orientation direction of the carbon fibers is an important factor in determining the wear process during the cutting process (Sakuma and Seto, 1983; Kaneeda, 1991; Wang, et al., 1995; Sreejith, et al., 2000). In addition, the cutting configuration (i.e., up or down cut) is also an important parameter. Figure 12 summarizes the tool edge profiles after a cutting distance of 8 m (Morikawa, et al., 2013). The orientation direction of the carbon fibers (θ) and the cutting configuration were varied. In the images, the edge profiles are expressed using the shape of the mold. After the cutting tests, the worn tools were molded by a thermosetting plastic. After the mold was hardened, the tool was removed, and the cross section of the mold without the tool was examined using a microscope. It should be noted that the entire tool was made of high-speed steel for the purpose of performing acceleration tests.

Of cause, the wear processes of the high-speed steel material and other high hardness materials, e.g., PCD or WC-Co, are not same. However, it is easily expected that the wear process of these materials will also strongly depend on the cutting configuration (up cut or down cut) and orientation direction, if not exactly the same as the wear process in high-speed steel tools. Thus, this implies that the magnitude of the cutting force reduction effect also depends on the orientation direction and cutting configuration. Therefore, additional experiments and analyses are required to develop a more realistic design guide for two-layer cutting tools. However, these experiments and analyses were beyond the scope of this study, which was focused on the basic design of a two-layer tool.

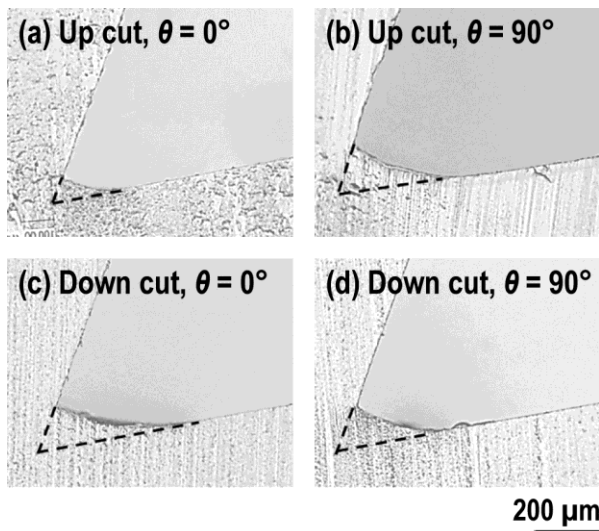


Fig. 12 Profiles of tool edge depending on cutting configuration (up or down cut) and orientation direction of carbon fibers θ ; material of tool: high-speed steel, cutting distance L : 8 m.

6. Conclusion

This study examined the cutting force reduction effect in two-layer tools used to cut carbon-fiber-reinforced plastic (CFRP) composites. The rake face and a portion of each of the two-layer tools used in this study were made of a material with a relatively high wear resistance, i.e., polycrystalline diamond (PCD). In contrast, the other region of the flank face of each tool was made of a material with relatively low wear resistance, i.e., tungsten carbide (WC-Co). The results of milling tests performed using unidirectional CFRP laminates and two-layer tools showed that the use of a two-layer tool can reduce the thrust cutting force by taking advantage of abrasive wear on the flank face of the tool. The wear resistance ratio, defined as the ratio of the wear resistance of the PCD layer to the wear resistance of the WC-Co substrate, and the clearance angle of the tool were found to be important factors in the reduction of cutting forces. A simplified model for the wear process of a two-layer tool was developed to describe how to enhance the cutting force reduction effect of a two-layer tool. The findings of this study indicate that it is possible to take advantage of the abrasive wear on the flank face of a cutting tool to reduce the cutting force without improvement of the tool material.

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