Turning of glass fiber reinforced plastics materials with chamfered main cutting edge carbide tools

Chung-Shin Chang

Department of Mechanical Engineering, National Ilan University; No.1, Shen-Lung Road, I-Lan 26014, Taiwan, ROC

Abstract

In this paper, the machinability of high-strength glass-fiber-reinforced plastics (GFRP) materials in turning with chamfered main cutting edge of P and K type carbide tools have been investigated experimentally. Chip formation mechanisms and tool wear have been observed and the surface roughness has been measured with respect to tip's geometries and nose radii. Experimental results for cutting forces were also gotten with GFRP as the workpiece material. Force data from these tests were used to estimate the empirical constants of the mechanical model and verify its prediction capabilities. The results show a good agreement between the predicted and measured forces. A special tool holder and its geometry was designed and manufactured first, then these holders with the mounting tip’s were grinded to various tool geometries, including the width of chamfered main cutting edge, the nose radii, the side cutting edge angle, first and second side rake angle and back rake angle… etc. In this study, the nose radius R=0.3mm induce decrease of the cutting force and the smallest of the cutting force values in the case of $C_s=20^\circ$, $\alpha_{s1}(\alpha_{s2})=-10^\circ (10^\circ)$ and $R=0.3mm$. Comparing of the different P and K type of tools, K type tool is better than P type of chamfered main cutting edge tools.

1. Introduction

Fiber composites are gaining increasing importance as lightweight materials are used in vehicle and aircraft structures. The processing of the heavy-duty fibers set in different binders requires finishing by cutting for the production of finished components in virtually all processes [1]. By far the most common reinforcement for plastics in ablative and structural-composite applications was glass fibers. Although these materials have higher strength characteristics and low density, the relatively lower elastic stiffness is observed. For this reason about 40 years ago experimental work was carried out on the thermal conversion of various organic precursor materials into carbon and graphite fibers and fabrics. Glass-fiber-reinforced plastics (GFRP) has been successfully used in the aerospace, transportation, recreational, appliance, electrical equipment, tank and piping industries [2]. Sakuma et al. [3, 4] performed turning tests on both glass fiber-epoxy composite materials and carbon fiber-epoxy composite materials that contained uni-directional fibers. Several kinds of tool materials such as sintered carbides, ceramics, and cermets are used and the wear patterns and the wear land growth are analyzed. Also, the tool-wear-rates of the machining of glass-fiber-reinforced-plastics (GFRP) were studied. Ferreira etc. [5] showed that turning experiments were observed with the performance of different tool materials.
like ceramics, cemented carbide, cubic Boron Nitride (CBN), and diamond. During the tests the tool wear, the machining forces and engine motor current were measured. Experimental results showed that only diamond tools are suitable for use in finishing turning. In rough turning, the carbide tools can be used in some retractions parameters. The machining of glass fiber-epoxy composite materials is not the same as the machining of conventional metal materials. The wear of sintered-carbide tools and high-speed steel tools is very severe. Hence the cutting speed and feed rate of the machining operation should be selected carefully in the machining of carbon fiber-epoxy composite materials. Also, surface damage of the composite materials such as cracking and delimitation of the machined surface is severe and a low surface-roughness is not easy obtained [6, 7]. Kim and Ehmann [8] demonstrated the knowledge of the cutting forces is one of the most fundamental requirements. This knowledge also gives very important information for cutter design, machine tool design and detection of tool wear and breakage. Hoshi and Hoshi [9] found that the apparent strength and the life of tool were increased if a small region of negative rake angle was ground on the main cutting edge and the contact length was controlled by a chip curler. Hoshi [10] extensively studied the characteristics of the built-up edge (BUE) and developed the chamfered main cutting edge tool, which is referred to as the silver white chip (SWC) cutting method. This method involves tool geometries that produce a BUE which flows away continuously in the form of separated secondary chip. A tool of this type was reported to decrease the energy by 15% and prolong tool life by roughly 20% compared with conventional tools [11]. Chang [12] illustrated that turning of medium carbon steel with chamfered main cutting edge tools could improve cutting efficiency. However, the effects of tool on turning of the CFRP and GFRP were excluded from their discussion. Due to the time and the budget limit, some experiments had been performed to study the case of GFRP materials in turning with chamfered main cutting edge tool, i.e. turning of CFRP the results of which will be presented in future.

2. Theoretical analysis

Since GFRP is difficult to machine, few researches had been found in the literature concerning of GFRP materials in turning with chamfered main cutting edge carbide tools. This study presents some experimental results to clarify details of GFRP composites in turning. Sreejith et al. [13] showed the wide difference in thermal properties of the fiber and matrix material and also the relatively poor thermal conductivity of composites make it rather difficult to adopt any of the unconventional technique for machining of the polymeric composites. Moreover, the shapes obtained by traditional turning, drilling, and unconventional processes cannot obtain related processes, and therefore traditional material removed processes are the most suited for machining polymeric composites. Wang et al. [14] illustrated in chip formation, cutting forces, and the surface morphology in edge trimming of unidirectional graphite/epoxy was highly dependent on fiber orientation. The chip’s machined surface is defined as the surface in contact with the tool rake face, whereas the separated chip surface is the plane of chip discontinuity similar to the shear plane in metal cutting. Bhatnagar et al. [15] showed that on the machining of fiber reinforced plastic (FRP) composite laminates; it can be assumed that the
shear plane in the matrix will depend only on the fiber orientation and not on the tool geometry.

Generally GFRP are heat insulating and abrasive in nature; hence the cutting tools have to encounter a relatively more hazardous environment and undergo thermal associated wear processes. The available reports on cutting temperature and associated influences are mostly related to applications involving chamfered main cutting edge carbide tools. The oblique cutting parameters predicted by the tool geometry and either of maximum shear stress or minimum energy principle is in good agreement with experimental data published in the literature from Shamoto and Altintas [16]. According to Chang and Fuh [17], a basic force model of three dimensional turning process, which can accurately predict the formation of shear planes for the case of turning with a chamfered main cutting edge, must have not only nose radius \( R \), cutting depth \( d \), feed rate \( f \), cutting speed \( V \), the first side rake angle \( \alpha_{S1} \), the second side rake angle \( \alpha_{S2} \), and parallel back rake angle \( \alpha_b \) as shown in Table 1.

However, chamfered main cutting tools effects were not included in GFRP turning. The study was established in order to understand the behavior of glass-fiber-reinforced plastics during machining operations.

### Table 1 Tool geometrical specifications

<table>
<thead>
<tr>
<th>side cutting edge angle, ( C_S )</th>
<th>tool No.</th>
<th>side rake angle ( (\alpha_{S1}, \alpha_{S2}) )</th>
<th>nose radius ( R ), unit: mm</th>
<th>carbide tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td>1</td>
<td>- 10°, 10°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>20°</td>
<td>2</td>
<td>- 20°, 20°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>20°</td>
<td>3</td>
<td>- 30°, 30°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>30°</td>
<td>4</td>
<td>- 10°, 10°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>30°</td>
<td>5</td>
<td>- 20°, 20°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>30°</td>
<td>6</td>
<td>- 30°, 30°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>40°</td>
<td>7</td>
<td>- 10°, 10°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>40°</td>
<td>8</td>
<td>- 20°, 20°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
<tr>
<td>40°</td>
<td>9</td>
<td>- 30°, 30°</td>
<td>sharp ( (R=0) ), chamfered ( R=0, R=.3, R=.5, R=1.0 )</td>
<td>P10, K10</td>
</tr>
</tbody>
</table>

2.1 According to Bhatnagar et al. [15] assumed the shear force was calculated using the relations developed for metal machining, and Chang and Fuh [17] demonstrated the shear areas in the cutting medium carbon process with a chamfered main cutting sharp and nose radius \( R \) tool. The calculation of shear area \( A \) and projected area \( Q \) fall into one of the following categories depend on the relationship between nose radius, federate and the depth of cut.
1. Sharpness of the tool is such that its radius equals zero \((R=0, R<f)\), the calculations of shear area \(A\) and projected area \(Q\), is shown in Fig. 1 [17]. The areas of the shear plane \(A\) and the projected area \(Q\) of the various cases is obtained as follows:

The shear area \(A\) is equal to \(A_1 + A_2 + A_3\), as illustrated in Fig. 1(a).

\[
A_1 = \frac{t_1^3}{4 \cos^2 \alpha_s} \left( \frac{4 \cos^2 \alpha_s}{\sin^2 \varphi \cos^2 \eta} - \left[ 1 + \frac{\cos^2 \alpha_s}{\sin^2 \varphi \cos^2 \eta} \right] \frac{1}{\cos^2 \eta} \right) \left( \sin^2 \eta \cos \varphi + \cos \varphi \cos \alpha_s \right)^2
- 2 \sin \eta \sin \alpha_s \left( \sin \alpha_s + \cos \alpha_s \cot \varphi \right)]}^{1/2}
\]

(1)

\[
A_2 = \frac{t_i (2 b_i + t_i \tan \eta) / \cos \alpha_s}{2 \sin \varphi \cos \alpha_s \cos \eta} \left[ \cos^3 \alpha_s - \sin^2 \varphi \left( \sin \eta - (\sin \alpha_s + \cos \alpha_s \cot \varphi) \sin \alpha_s \right) \right]^{1/2}
\]

(2)

\[
A_3 = \frac{W_s \cos^2 \alpha_s \tan \varphi}{2 \cos \alpha_s \sin \varphi}
\]

(3)

\((A_1+A_2)\) is the area of the main chip, \(A_1\) is the area of triangle \(BCE\), \(A_2\) is the area trapezoid \(CEFD\); and \(A_3\) is the triangular area of the secondary chip. The chamfered width, \(W_s\) was constrained by the empirical formula

\[
W_s \leq f \cos C_s
\]

(4)

where \(f\) is the federate and \(C_s\) is the side cutting edge angle.

The area of the projected cross-section \(Q\) is equal to \(Q_1 + Q_2 + Q_3\), where \(Q_1\) is the area of the trapezoid \(BCD\); \(Q_2\) is the area of the rectangle \(CC' DD'\) and \(Q_3\) is the area of triangle \(DD' Y\) (Figs. 1a and 2).

\[
Q_1 = \frac{1}{2} \frac{b_1 + b}{\cos \alpha_s} \frac{t_1}{\cos \alpha_s} \quad (5), \quad Q_2 = \frac{W b_2}{\cos \alpha_s} \quad (6), \quad Q_3 = \frac{W_s \cos \alpha_s \tan \varphi}{2 \cos \alpha_s}
\]

(7)
2. Nose radius of the tool \((R)\) is smaller than the federate \((f)\), \(R \neq 0, R < f\). The shear area \(A\) includes here both the area of (1) and the cylindrical area formed by the tool nose radius [17].

3. Nose radius of the tool \((R)\) is larger than the federate \((f)\), \(R \neq 0, R > f\), according to the depth of cutting, which can be subdivided into three parts: (a) \(d > R\), (b) \(d = R\), and \(d < R\) [17].

Although paper focuses an cases with a sharpness of the tool, such as in case (2) and (3), a further simulation is under wait to study the case of large nose radius cutting, and the results will be reported in the future.
Expressions for \( t_1 \), \( t_2 \), \( t_3 \), \( f_1 \), \( b_1 \), \( b_2 \) and \( b_4 \) are shown in Appendix; \( b \) is the width of cut. It was assumed that energy was consumed as shear energy on the shear plane and as friction energy on the tool face. The shear energy per unit time \( (U_s) \) and the friction energy unit time \( (U_f) \) [18] are:

\[
U_s = F_s V_s = F_s \frac{V \cos \alpha_e}{\cos(\varphi_e - \alpha_e)} \tag{8}, \quad \text{and} \quad U_f = F_f V_c = f_t \int_0^1 b_t db V_c = \frac{\tau_s \sin \beta \cos \alpha \cos V}{[\cos(\varphi_f + \beta - \alpha) \cos(\varphi_e - \alpha_e)]} \tag{9}
\]

where \( \int_0^1 b_t \) is the integral width of chip flow direction along the tool face \( (B_t) \) is the width measured in the direction orthogonal to the chip flow and \( db \) is an increment of integration in the direction, where

\[
F_s = \tau_s A_o \tag{10}
\]

According to Wang [14] illustrated the normal and shear forces along the fiber direction were calculated assuming that the measured resultant force equivalent to that present in the workpiece at the tool point. Transformation equations used to obtain the normal and shear forces along the fiber direction in terms of the principal and thrust components are shown in Eqs. (11) and (12) [14].

\[
N_s = F_{ht} \sin \theta + F_t \cos \theta \tag{11}, \quad \text{and} \quad F_s = F_{ht} \cos \theta - F_t \sin \theta \tag{12}
\]

where \( \theta \) denotes the angle between the fiber orientation and the trim plane. The shear force \( F_s \) was calculated using the relations developed for metal machining [14].

Bhatnagar et al. [15] showed that while the classical Merchant’s model [19] is applicable to homogeneous methods and their alloys. He applies this model in the machining of FRP in the – \( \theta \) cutting direction as a first approximation. He assumes the shear plane angle as the fiber angle where failure occurs. By substituting \( \theta \) for \( \psi \) in Merchant’s model. A basic relationship for the two components of the cutting force with the geometry of the cutting can be obtained from Eqs. (13) and (14) [15].

\[
F_c = t_o A_o \frac{\cos(\beta - r)}{\sin \theta \cos(\theta + \beta - r)} \tag{13}, \quad \text{and} \quad F_t = \tau_o A_o \frac{\cos(\beta - r)}{\sin \theta \cos(\theta + \beta - r)} \tag{14}
\]

\[
\theta_o = \theta_{\text{composite}} = \theta_{\text{fiber}} V_f \quad (V_f \text{ is fiber contains}) \tag{15}
\]

where \( A_o \) is the area of undeformed chip, \( \theta \) is the mean friction angle, \( r \) is the rake angle, \( F_c \) is the main cutting (horizontal) force and \( F_t \) is the thrust (transversal) cutting force. By knowing the shear area \( A_o \) of the undeformed chip, the shear strength \( \theta_o \) was calculated [15].

\[
V_s = \frac{V \cos \alpha_e}{\cos(\varphi_e - \alpha_e)}, \tag{16}, \quad \text{and} \quad f_t = \frac{\tau_s \sin \beta}{\cos(\varphi_f + \beta - \alpha) \sin \varphi} \tag{17}
\]

where \( f_t \) is the friction force in orthogonal cutting for unit width of cut and \( t_o \) is the undeformed chip thickness (Fig. 1b):

\[
V_c = \frac{V \sin \varphi_e}{\cos(\varphi_e - \alpha_e)} \tag{18}, \quad \text{and} \quad \alpha_e = \sin^{-1}(\sin \alpha_{e2} \cos \alpha_e \cos \eta_e + \sin \eta_e \sin \alpha_e) \tag{19}
\]

where \( \theta_e \) is the effective rake angle; \( \theta_{2z} \) is the second normal side rake angle; \( \theta_{b2} \) is the parallel back rake angle; \( \alpha_e \) is the effective shear angle equals to fiber orientation angle, \( \theta_e \) [15]; \( \eta_e \) is the chip flow angle
which was determined that minimized the total cutting energy $U$; $\varphi$ is the mean friction angle [20], and $\tau_s$ is the shear stress [20, 21].

The cutting power is a function of at least $\varphi_b, \varphi_{S1}, \varphi_{S2}, d, W_e, C_S, C_e, f, V, \varphi_{ref}, \varphi_s, \varphi$ and $\varphi_e$. Assuming that the chip flows up the tool in a direction that minimizes the total cutting power $U$, then by changing $\eta_c$ was determined that minimized $U$, for $\varphi_b, \varphi_{S1}, \varphi_{S2}, d, W_e, C_S, C_e, f, V, \varphi_{ref}, \varphi_s, \varphi_s$ and $\varphi$ were given in the tool specifications and cutting conditions. Once $\varphi_c$ had been determined, then $\eta_c$ that describe the chip formation could be determined.

The value of $\varphi_c$ for the total minimum power $U_{min}$ to be used in equation (20) was obtained by calculating $U$ for a range of values $\varphi_c$ according to the computer flow chart (Fig. 2). Therefore, $(F_H)_{U_{min}}$ was determined by solving equation (21) in conjunction with the energy method [22].

\[ U_{min} = (F_H)_{U_{min}} \]  
\[ F_H = (F_H)_{U_{min}} = \frac{U_{min}}{V} = \frac{\tau_s \cos \alpha_s \alpha + \tau_s \sin \beta \cos \alpha_s \varphi}{\cos (\varphi + \beta - \alpha) \cos (\varphi - \alpha)} \]  
\[ F_I = \frac{\tau_s \sin \beta \cos \alpha_s \varphi}{\cos (\varphi + \beta - \alpha) \cos (\varphi - \alpha)} \]  
\[ N_I = \frac{(F_H)_{U_{min}} - (F_I)_{U_{min}} \sin \alpha_s}{\cos \alpha_s \cos \alpha_s} \]  
\[ F_s = -N_I \cos \alpha_{S2} \sin \alpha_s + F_I (\sin \eta_s \cos \alpha_s - \cos \eta_s \sin \alpha_{S2} \sin \alpha_s) \]  
\[ F_v = -N_v \sin \alpha_{S2} + F_I \cos \eta_s \cos \alpha_{S2} \]  
\[ (R_s)_H = N_I \cos \alpha_{S2} \cos \alpha_s + (F_I)_{U_{min}} \sin \alpha_s = (F_H)_{U_{min}} \]  

$(R_s)_H$ is the horizontal cutting force in the cutting force in the horizontal plane, $N_I$ is the normal force at the tip surface with minimum energy. Because of the effects of size and shape with tool edge wear, a modified cutting force is presented in this paper in order to get more precise results. Besides the $(F_H)_{U_{min}}$ force, the plowing force $F_P$ due to the effects of the tool specification and wear force $F_W$ due to the effects of flank wear [17] are considered under the prediction of the horizontal cutting force. That is

\[ F_{HH} = (F_H)_M + F_W + F_P \]  
\[ F_P = HB \cdot r \cdot L_f \]  
\[ F_W = \tau_y \cdot L_f \cdot V_b \]  

in which $r$ is the radius on the main cutting edge between the face and the flank, and $V_b$ is the length of flank wear. Based on the experimental evidence measuring the length of $V_b$, the values are between 0.05mm
and 0.1mm (cutting time equals 10 min). $L_f$ is the contact length between the cutting edge and the workpiece. $L_P$ is the projected contact length between the tool and workpiece. The contact lengths $L_f$ and $L_P$ are determined for the following conditions (Figs. 3a and 3b), as follows.

\[
L_f = \frac{d}{\cos C_s} + f_1 \cos C_s / \left[ \cos (C_s - C_s) \cos \alpha_{s2} \right] \tag{30}
\]

\[
L_P = \left( \frac{d}{\cos C_s} \cdot \sin C_s \right) + \left( f_1 \cos C_s \cos C_s \right) / \left[ \cos (C_s - C_s) \cos \alpha_{s2} \right] \tag{31}
\]

\[
(F_T)_M = F_T \quad \tag{32}, \quad (F_P)_M = F_P + L_P \cdot Vb \cdot \tau_y \tag{33}
\]

Fig. 3  Contact length (a) $L_f$ and (b) $L_P$ between cutting edge and workpiece at $f>R$, $R=0$

If HB is the Brinell hardness of the workpiece, the expressions of $\tau_y$ and $\sigma_y$ are given by [23]

\[
\tau_y = \sigma_y / 2 \quad \tag{34}, \quad \sigma_y = HB / \pi
\]

Based on Fig. 4a, the final modified cutting force components are rewritten for $C_s \neq \theta$, as,

\[
F_{iy} = (F_{iy})_u \cos C_s + (F_{iy})_u \sin C_s \quad \tag{36}, \quad F_{yy} = (F_{yy})_u \cos C_s - (F_{yy})_u \sin C_s \quad \tag{37}
\]

3. Experimental method and procedure

Experimental set up is shown in Figs. 4(b,c). Workpiece is observed in Fig 4b, to be held in the chuck of a lathe, and the cutters that which were mounted with a dynamometer were employed for measuring the three axes compound of forces ($F_H$, $F_V$ and $F_T$). Dry cutting tests were carried out on a 5 HP high-speed lathe (SJ 600*700, 2000rpm, brand name). In measuring the cutting forces, a Kistler type 9257B three-component piezoelectric dynamometer was used with a data acquisition system that consisted of Kistler type 5807A charge amplifiers. An infrared detector (Thermo Hunter) was used to monitor the temperature at the cutting tip and the computer recorded the temperature. All measured data were recorded by a data acquisition system (Keithley Metro byte-DAS1600) and analyzed by the control software (Easiest). The reliability of the measurement techniques was checked constantly by repeating the experiments. At the end of each cutting test, the tool flank wear ($V_b$) was measured using a toolmaker's microscope.
3.1 Workpiece

The work material used was 0°, unidirectional filament wound fiber of E-glass-fiber-reinforced plastics (GFRP) with Vinylester resin composite materials in the form of bars having a diameter of 40 mm and 500 mm length [21]. Table 2 shows some of the physical and mechanical properties of GFRP prior to carry out the cutting experiments.

<table>
<thead>
<tr>
<th>nominal form</th>
<th>density gm/cm³</th>
<th>thermal conductivity kCal/hr ℃</th>
<th>fiber contain</th>
<th>coefficient of thermal expansion (10^-6/℃)</th>
<th>thermo-setting resins</th>
<th>hardness (Shore, Hs)</th>
<th>tensile strength (kg/mm²)</th>
<th>compressive strength (kg/mm²)</th>
<th>modulus tensile (kg/mm²)</th>
<th>shear strength (kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>roving</td>
<td>1.8~2.1</td>
<td>0.21~0.28</td>
<td>75%</td>
<td>2~9</td>
<td>vinylester</td>
<td>55~60</td>
<td>45~65</td>
<td>45~60</td>
<td>2000~4000</td>
<td>20</td>
</tr>
<tr>
<td>continuous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Cutting tools

Two kind tool materials [24] (Sandvik P10-S1P and K10-H1P) and various tool geometries were employed in the study. Tool composition, S1P (P type): WC 56%, TiC 19%, Ta(Nb)C 16% and Co 9.5%; H1P (K type): WC 85.5%, TiC 7.5%, Ta(Nb)C 1% and Co 6%. Oblique turning tests were carried out for each tool. However, for the purpose of comparing tool wear, all cutting test had a fixed time and the same cutting conditions. During the cutting process, the tool temperature was measured using a thermo hunter onto the tool rake face from the cutting edge.

3.3 Experimental conditions

During the cutting test, the following conditions are assigned:

(1) dry cutting, and cutting velocity is 252m/min (N=2000 rpm),
(2) cutting depth: d=1.5, 2.0 and 2.5mm, and feedrate: f=0.24mm/rev,
(3) the tool holder was vertical to the feeding direction, and extension of the tool from the dynamometer is 30mm.

In experiment for each tool geometrical configurations, the workpiece were turned 240mm in the feed
direction. Data were recorded three times in different section and the results were averaged with each other. The cutting force, the shapes of chips and tips wear were observed and discussion in sections 4.

4. Results and Discussion

A series of preliminary tests were conducted to assess the effect of tool material on the tool wear, cutting forces, surface roughness and cutting temperature during the turning of GFRP.

4.1 The cutting forces

According to Chang [17], in Fig. 5, showed in turning of plain carbon steels with chamfered main cutting edge tools decreases about 15% of resultant cutting force, \( F_R \), than unchamfered main cutting edge tool. The increase of the side rake angle \( \alpha_{S1} \) and \( \alpha_{S2} \), the decrease the total cutting force \( F_R \) in case of the constant of \( C_S \).

The increase of the side cutting edge angle, \( C_S \), from 20° to 30° is indicated to induce the decrease of cutting force. However, the cutting force would increase if the angle is increased from 30° to 40°.

![Fig. 5 Resultant experimental cutting forces \( F_r \) (N), vs. \( C_S \) (°) for different values of \( \alpha_{S1} \) and \( \alpha_{S2} \) at \( d=2.5 \), \( f=33\text{mm/rev} \) and \( V=145\text{m/min} \) (medium carbon steel) respectively](image-url)
Figs. 6 and 7 indicate the experimental horizontal ($F_H$), and vertical ($F_V$) cutting forces respectively are obtained with the sharp tool (unchamfered and chamfered) versus nose radius tool $R$ at $CS=20°$ of chamfered geometrical configurations. Fig. 8 shows that the experimental horizontal ($F_H$) cutting forces is obtained with the sharp tool (unchamfered and chamfered) versus $CS$, $\theta_{S1}$ and $\theta_{S2}$ at $R=0.3$ of chamfered main cutting edge tools.

The observed results shown in the figures imply that:

4.1.1 Comparing with turning of carbon steel and GFRP workpiece:

(1) A turning of GFRP materials with chamfered main cutting edge tools decrease the cutting forces $F_H$, $F_V$ and $F_T$ than unchamfered tool. In Figs. 6 and 7, the results show good agreement with Chang and Fuh in turning medium carbon steel [17].

(2) In the case of the constant of $\theta_{S1}$ and $\theta_{S2}$, $R=0.3$mm, Fig. 8, the increase of the side cutting edge angle $CS$, from $20°$ to $30°$, the cutting forces $F_H$ is increased, but $CS$ from $30°$ to $40°$, the cutting forces $F_H$ is decreased, this is different from Fig. 8. Chang [12] studied of turning medium carbon steel, the increase of $CS$ from $20°$ to $30°$, and the decrease of cutting force. However, the cutting force would increase if the angle is increased from $30°$ to $40°$. This would probably the difference materials, the shear zone is different and during cutting GFRP, the chip is both powder and fiber and the chip was fractured by the compressive tool load to fiber. The large $CS$, the more fiber chip and the larger the contact between the cutting edge and workpiece will be, and the resistant force $F_H$ and $F_V$ are produced as show in Fig. 4(c). But the $CS$ more than $30°$, the fiber easier to be cut and the cutting forces $F_H$ and $F_V$ are decreased as shown in Fig 8. During machining, the cutting zone experiences both thermal and mechanical stresses. This also leads to unstable cutting forces.

4.1.2 Comparing with different tool geometries in turning of GFRP materials

(1) In the case of the constant of $CS$, the increase of the nose radius $R$, from 0 to 0.3mm is indicated from Figs. 6 and 7, to induce the decrease of cutting force. This event would be occurring since the chip flows more flexible and it is produced more obviously. However, the cutting force would increase if the radius $R$ is increased from 0.3 ~1.0mm. This would probably occur as a result of the chatter leading unstable cutting forces.

(2) The cutting force values are observed in Figs. 6 to 8, to be the smallest in the case of $CS=20°$, $\theta_{S1}$ ($\theta_{S2}$)=$\theta$ 10° ($10°$), $R=0.3$mm. The reason is due to decrease the fiber chip, and more obvious and smooth formation and flow of the powder chip. Especially, smaller the $CS$, the shorter contact length between the chip and tool, which caused the cutting GFRP efficiency to increase and decrease the difficulty of chip formation, as shown in section 4.2, Figs. 10-11 (a, b and c).

4.1.3 Comparing with different P and K type of chamfered main cutting edge carbide tools

(1) Due to severe edge chipping, the cutting forces for the chamfered main cutting edge of P type carbide tools
were much higher than experience by chamfered main cutting edge of K type carbide tools.

Fig. 6 Experimental horizontal cutting forces $F_H (N)$ vs. $R$, $\gamma_{S1}$ and $\gamma_{S2}$ (°) of chamfered and unchamfered tools at $C_s = 20^\circ$, $d=2.5$, $f=0.25mm/rev$ and $V=252m/min$ (GFRP) respectively.
Fig 7 Experimental vertical cutting forces $F_v \,(N)$ vs. $R$, $\theta_{S1}$ and $\theta_{S2}$ ($^\circ$) of chamfered and unchamfered tools at $C_s = 20^\circ$, $d=2.5$, $f=0.25\,mm/rev$ and $V=252\,m/min$ (GFRP) respectively
4.2 The shape of chips

Chang and Fuh [17] showed, when turning of medium carbon steel with chamfered main cutting edge tools, the secondary chip is formed more obviously and has flowed more easily under the situation of $C_S=30^\circ$, $\alpha_{S1} = 30^\circ$ and $\alpha_{S2} = 30^\circ$. Producing a secondary chip in the case of $C_S=20^\circ$, $\alpha_{S1} = 10^\circ$ and $\alpha_{S2} = 10^\circ$ is rather difficult, as shown in Figs. 9 (a, b, c).

---

**Fig. 8** Experimental horizontal cutting forces $F_H(N)$ vs. $C_S$, $\alpha_{S1}$ and $\alpha_{S2}$ of chamfered cutting edge tools at $R=0.3$, $d=2.5$, $f=0.25\,\text{mm/rev}$ and $V=252\,\text{m/min}$ (GFRP) respectively.

<table>
<thead>
<tr>
<th>Graph</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="chart.png" alt="" /></td>
<td>Fh: experimental values vs Cs of P type tool at side rake angle -30 &amp; 30</td>
</tr>
<tr>
<td></td>
<td>Fh: experimental values vs Cs of K type tool at side rake angle -30 &amp; 30</td>
</tr>
<tr>
<td></td>
<td>Fh: experimental values vs Cs of P type tool at side rake angle -20 &amp; 20</td>
</tr>
<tr>
<td></td>
<td>Fh: experimental values vs Cs of K type tool at side rake angle -20 &amp; 20</td>
</tr>
<tr>
<td></td>
<td>Fh: experimental values vs Cs of P type tool at side rake angle -10 &amp; 10</td>
</tr>
<tr>
<td></td>
<td>Fh: experimental values vs Cs of K type tool at side rake angle -10 &amp; 10</td>
</tr>
</tbody>
</table>

---
Knowing the relation between the main chips and secondary chips, the different tool geometrical configurations on various side rake angles and cutting edge angles is first attempted to be understood. Nine kinds of tools were used in turning the GFRP workpiece in the same cutting condition. The different chip shapes with K type tool and P type tool are provided in Figs. 10(a, b, c)-11(a, b, c) respectively.

(1) producing a secondary chip in these nine kinds of chamfered main cutting edge tools is rather difficult and it is formed unobvious.

(2) in Fig. (10a), the powder chip is formed more obviously and has flowed more easily under the situation of $C_S=20^\circ$, $\alpha_{S1}=\alpha_{S2}=10^\circ$.

(3) for producing the fiber chips, in Fig. 11, the fiber chip is more obviously when we used the chamfered main cutting edge of P type tool, and the $C_S$ from $20^\circ$ to $40^\circ$, $\alpha_{S1}=30^\circ$ and $\alpha_{S2}=30^\circ$.

(4) in turning of GFRP with chamfered main cutting edge tools, no secondary chips are observed for all kind of the tools, in Figs. 10-11, because the turning of GFRP, the chips are a powder and fiber, it is difficult to obvious the shear zone, and the secondary flows unobserved.
4.3 The temperature of tip’s surface

Cutting tools usually have higher temperature over the three distinct zones. Namely the cutting nose, the secondary grooving zone and the depth of cut region or primary cutting edge.

Knowing the temperature of cutting tools and how this chamfered main cutting edge tools decrease the temperature of the tool tip surface, Chang [17] demonstrated that in turning medium carbon steel, the temperature of main chip rises to nearly 300 °C, but the tips surface temperature is not over 200 °C.

(1) in Fig. 12, shows the tip’s surface temperature as a function of various side cutting edge angle $\alpha_S$ and nose radius $R$ for different $\alpha_{S1}$ and $\alpha_{S2}$, and P or K type of chamfered main cutting edge carbide tools respectively. In which, it can be seen that the temperature in the case of tool unchamfered is larger than that chamfered, and the nose radius $R=0.3$, the tip’s surface temperature is the lowest, the cutting forces also smallest.

(2) using the chamfered main cutting tools in turning GFRP materials, the tip’s surface temperature are not over 160 °C.

![Fig. 12 Experimental cutting temperature $T_e$ (°C) vs. $R$, $\alpha_{S1}$ and $\alpha_{S2}$ of chamfered and unchamfered P and K type](image-url)
tools at $C_S = 20^\circ$, $d=2.5$, $f=0.25\text{mm/rev}$ and $V=252\text{m/min}$ respectively

4.4 The wear of tips

(1) The chamfered main cutting edge P and K type of turning tool have been ground according to various designed specifications, but the unchamfered main cutting edge with sharpness turning tool ($R=0$) has the more crater and flank wear than the above tool after face turning time about 10 min, as shown in Figs. 13 to 14. The design of chamfered main cutting edge tools are better and more resistance than that of the unchamfered main cutting edge tools.

(2) The chamfered main cutting edge tool with the nose radius ($R \neq 0$) has the least wear among various tools as observed in Figs. 13 and 14(a,b,c) from a comparison of the wear of the tips. Additionally, the chamfered main cutting edge with sharpness tool ($R=0$) has a medium level of wear, and unchamfered tool ($R=0$) has the largest. The reason are that the formal tools possess a lower oxidation wear associated with low temperature at chamfered main cutting edge and the chip produces more easily and these tools have the smaller cutting forces among the other tools.

(3) K type of chamfered main cutting edge carbide tools sustained to the least tool wear compared to P type of chamfered main cutting edge carbide tools. This undoubtedly due to K type of tools superior hardness and wear resistance, as well as low coefficient of friction together with high thermal conductivity. On the other hand the P type of tools suffered from excessive crater wear and chipping.

![Worn of K type tool view](image)

Fig. 13  Worn of K type tool view (a), (b), (c) and (d) with $C_S=20^\circ$, and $D_{s1}(D_{s2})=\square 20^\circ$ $(20^\circ)$, at cutting time 10 min, $d=2$, $f=0.24\text{mm/rev}$ and $V=252\text{m/min}$ respectively
5. Conclusions

A series of preliminary tests were conducted to assess the effect of tool geometries of P and K type of chamfered main cutting edge carbide tool on the tool wear, cutting forces, workpiece surface roughness and cutting temperature during the turning of GFRP. Due to the K type tools superior hardness and wear resistance, as well as low coefficient of friction together with high thermal conductivity, it was shown that chamfered main cutting edge K type carbide tools sustained the least tool wear, compared to unchamfered K and P type of tool. The cutting forces, cutting temperature and workpiece surface roughness for the chamfered main cutting edge of P type carbide tools in turning were much higher than experience by chamfered main cutting of K type carbide tools. On the other hand, the K type of chamfered main cutting carbide tools suffered from lower crater wear and chipping. K type of chamfered main cutting edge tools with $C_S=20^\circ$, the conditions $f=0.24\text{mm/rev}$, $a_{s1}=10^\circ$, $a_{s2}=10^\circ$ and nose radius $R=0.3\text{mm}$, produce the lower cutting forces, lower cutting temperature and tip wear. Further work will extend to the analysis of CFRP materials turning with chamfered main cutting edge tools. Another important about GFRP machining is workshop environment; the powder and fiber chip generated irritates the skin and is dangerous for the health. The use of a vacuum cleaner and safety protections for the operators is highly recommended.

In all experiments, turning of GFRP, the cutting forces presented small values compared to turning of carbon steel, the small forces values observed could be explained by fact the chip generated during the cutting is a powder and fiber, set it does not present tool cutting edge strength. A new tool model is presented which
proposes a new concept for calculating the variation of shear areas using the energy approach to predict 3-dimension turning forces with a chamfered main cutting edge tools. A force model has been built to predict the cutting force of a chamfered main cutting shape tool. The results show a good agreement between the predicted and measured forces.

6. References

Acknowledgement

This work was supported by National Science Council, Taiwan, R.O.C. under grant number NSC 2002-2622-E-197-001-CC3

Appendix

Coefficients of the tool having a sharp corner \((R=0)\) without tool wear

\[
t_1 = f \cos C_x \quad (A1), \quad t_2 = W_s \cos \alpha_{s1} \quad (A2), \quad t_3 = t_1 - t_2 \quad (A3) \quad \text{and} \quad f_r = f - W_s \cos \alpha_{s1} \quad (A4)
\]

\[
b = d / \cos C_x \quad (A5), \quad b_1 = t_2 \tan C_y \quad (A6) \quad \text{and} \quad b_2 = b - b_1 \quad (A7)
\]
Dear Manager Salem,

Thank you very much for your e-mail of May 10, 2004. In this letter, my papers abstract entitled “Turning of glass fiber reinforced plastics materials with chamfered main cutting edge carbide tools-code Number 2204,” has been accepted by 8th PCMM 2004. Now I have completed my paper on CD pdf. File and a hard copy. I send you the mail, please check it. If there are any questions, please inform me. Thank you for your help.

Your assistance is deeply appreciated.

Best Regards

Prof. Chung-Shin, Chang  
Dept. of Mechanical Engineering  
National Ilan University  
No. 1, Shen-Lung Rd.  
I-Lan city, Taiwan, R.O.C
Mr. Sam H. Salem
General Manager PCMM
P.O. Box 267
Box Hill, Victoria, Australia, 3128
Fax:+61 3 9897 1147
E-mail:SHSalem@netspace.net.au