2007 Internal Conference on Advanced Manufacture (ICAM2007)

A Study of Cutting Temperatures in Turning of Glass Fiber Reinforced Plastics Materials

Dept. of Mechanical & Mechtronic Engineering, National Ilan University, No. 1, Shen-Lung Road, I-Lan, Taiwan, R.O.C

Prof. Chung-Shin Chang

Nov. 26-30 2007, NCKU, Tainan, Taiwan
Abstract

1. Introduction

2. Theoretical Analysis

3. Experimental Method and Procedures

4. Results & Discussion

5. Conclusions

References

Acknowledgement
ABSTRACT

The main purpose of this report is to predict the cutting temperature of carbide tip's surface and study the cutting forces of GFRP with chamfered main cutting edge tools. The friction forces and heat generated on elementary cutting tools are calculated by using the measured cutting forces and the theoretical cutting analysis. The heat partition factors between the tip and chip are utilized temperature on the carbide tip’s surface measured by infrared instrument. The theoretical temperature of the carbide tip’s surface is solved by finite element analysis (FEA) and compared with those obtained from experimental measurements. A good agreement demonstrates the accuracy of the proposed model.
I. INTRODUCTION

The objective of this paper is to set up an oblique cutting GFRP model to study three-dimensional cutting temperature for a carbide tool with a chamfered main cutting edge.

The friction forces and heat generated on elementary cutting tools are calculated by using the measured cutting forces and theoretical cutting analysis. The energy method is also used to accurately predict cutting force.


II. THEORETICAL ANALYSIS

2.1 The shear and friction areas in the cutting for sharp tool *(Fig. 1)*

2.2 The energy method to predict cutting force *(Fig. 2)*

2.3 Solid modeling of carbide tip *(Fig. 5a)*

2.4 Finite element model *(Fig. 5b)*

2.5 Modified carbide tip’s temperature model

2.6 Heat transfer solution and validation *(Fig. 5)*
II. THEORETICAL ANALYSIS

- 2.1 Shear areas $A$ and friction areas $Q$ with a sharp chamfered edge tool can be calculated in Fig. 1 & Table 1
II. THEORETICAL ANALYSIS

Fig. 2 Shear plane area A (\( A = A_1 + A_2 + A_s \)) and friction area Q (\( Q = Q_1 + Q_2 + Q_3 \)), \( f > R, R \neq 0 \) (sharp tool without wear)
II. THEORETICAL ANALYSIS

Fig. 2-1 Calculation of friction force
II. THEORETICAL ANALYSIS

The cutting tools used in the experiments are Sandvik K10, type \textit{HIP} [14]. Carbide-tipped tools with following angles are used: Back rake angle $\alpha_b = 0^\circ$; The first and second side rake angle $\alpha_{s1} = -10^\circ, -20^\circ, -30^\circ$ and $\alpha_{s2} = 10^\circ, 20^\circ, 30^\circ$; end relief angle $= 7^\circ$; side relief angle $= 9^\circ$; end cutting edge angle $= 30^\circ$; side cutting angle $C_s = 20^\circ, 30^\circ, 40^\circ$, and nose radius $R = 0\text{ mm}$. Tool composition: WC85.5 \%, TiC 7.5 \%, TaC 1 \%, Co 6 \%, HV=1740, density $= 10.3\text{g/Cm3}$, thermal conductivity $= 25\text{W/m} - ^\circ\text{K}$ and heat capacity $= 200\text{J/kg} - ^\circ\text{K}$, The tool geometries are summarized in Table 1.
## II. THEORETICAL ANALYSIS

<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>$20^\circ$</td>
<td>1</td>
<td>$-10^\circ$, $10^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
<tr>
<td>$20^\circ$</td>
<td>2</td>
<td>$-20^\circ$, $20^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
<tr>
<td>$20^\circ$</td>
<td>3</td>
<td>$-30^\circ$, $30^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>4</td>
<td>$-10^\circ$, $10^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>5</td>
<td>$-20^\circ$, $20^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>6</td>
<td>$-30^\circ$, $30^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
<tr>
<td>$40^\circ$</td>
<td>7</td>
<td>$-10^\circ$, $10^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
<tr>
<td>$40^\circ$</td>
<td>8</td>
<td>$-20^\circ$, $20^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K100)</td>
</tr>
<tr>
<td>$40^\circ$</td>
<td>9</td>
<td>$-30^\circ$, $30^\circ$</td>
<td>sharp $(R=0)$, chamfered $(R=0, R=.3, R=.5, R=1.0)$</td>
<td>(K10)</td>
</tr>
</tbody>
</table>

Table 1  Tool specifications
II. THEORETICAL ANALYSIS

Fig. 3  Force and temperature prediction flow chart
II. THEORETICAL ANALYSIS

- \( \tau_s = \tau_{\text{composite}} = \tau_{\text{fiber}} \ V_f \) (\( V_f \) is fiber contain) [B.W. Rosen, overview of composite materials in Engineered materials handbook, ASM, 1987]

- \( U_S = F_S V_S = \tau_s A V \cos \alpha_e / \cos(\varphi_e - \alpha_e) \)  \hspace{1cm} (1)

- \( U_f = F_f V_c = \tau_s \sin \beta V \cos \alpha_e Q / \cos(\varphi_e + \beta - \alpha) \)

\[ \cos(\varphi_e - \alpha_e) \]  \hspace{1cm} (2)

- \( U = U_S + U_f = V (F_H)_{\text{Umin}} \)  \hspace{1cm} (3)

- \( F_H = (F_H)_{\text{Umin}} = U_{\text{min}} / V \)  \hspace{1cm} (4)

- \( F_T = - N_t \sin \alpha_b \cos \alpha_{s2} + F_t (\cos \alpha_b \sin \eta_c - \sin \alpha_b \sin \alpha_{s2} \cos \eta_c) \)  \hspace{1cm} (5)
II. THEORETICAL ANALYSIS

\[ A_1 = \frac{t_3^2}{4\cos^2 \alpha_{s_2}} \left\{ \frac{4\cos^2 \alpha_e}{\sin^2 \varphi_e \cos^2 \eta_c} - \left[ 1 + \frac{\cos^2 \alpha_e}{\sin^2 \varphi_e \cos^2 \eta_c} \right] \right\} \]

\[ \left[ \sin^2 \eta_c + (\sin \alpha_e + \cos \alpha_e \cot \varphi_e)^2 - 2\sin \eta_c \sin \alpha_e \right]^{1/2} \]

\[ \left( \sin \alpha_e + \cos \alpha_e \cot \varphi_e \right) \right]^{2} \right\}^{1/2} \]

\[ A_2 = \frac{t_3 (2b / \cos \alpha_b - t_3 \tan \eta_c / \cos \alpha_{s_2})}{2 \sin \varphi_e \cos \alpha_{s_2} \cos \eta_c} \left\{ \cos^2 \alpha_e - 2 \sin \varphi_e \sin \eta_c \left[ \sin \eta_c - (\sin \alpha_e + \cos \alpha_e \cot \varphi_e \right) \sin \alpha_b] \right\}^{1/2} \]

\[ A_S = W_e^2 \cos^2 \alpha_{s_1} \tan C_S / 2 \cos \alpha_b \sin \varphi_e \]
II. THEORETICAL ANALYSIS

\[ Q_1 = 0.5(b_2 + b)t_3 / (\cos \alpha_b \cos \alpha_{s2}) \]  
(9)

\[ Q_2 = \frac{W_e b_2}{\cos \alpha_b} \]  
(10)

\[ Q_3 = W_e^2 \cos \alpha_{s1} \tan C_s / 2 \cos \alpha_b \]  
(11)

\[ N_S = F_c \sin \theta + F_t \cos \theta \]  
(12)

\[ F_S = F_c \cos \theta + F_t \sin \theta \]  
(13)

\[ U_f = F_t \cdot V_c = f_t \int_0^{B_1} db V_c = \]  
(14)
II. THEORETICAL ANALYSIS

\[ V_S = V \cos \alpha_e / \cos(\varphi_e - \alpha_e) \]  \hspace{1cm} (15)

\[ f_t = \tau_S t_1 \sin \beta / \cos(\varphi + \beta - \alpha) \sin \varphi \]  \hspace{1cm} (16)

\[ F_t = \tau_S \sin \beta \cos \alpha_e Q / \cos(\varphi_e + \beta - \alpha_e) \cos(\varphi_e - \alpha_e) \]  \hspace{1cm} (17)

\[ N_t = [(F_H)_{U_{\text{min}}} - (F_t)_{U_{\text{min}}} \sin \alpha_e] / \cos \alpha_{S_2} \cos \alpha_b \]  \hspace{1cm} (18)

\[ F_{HH} = (F_H)_M \]  \hspace{1cm} (19)

\[ F_{TT} = F_T \cos C_S + F_V \sin C_s \]  \hspace{1cm} (20)

\[ F_{VV} = F_V \cos C_S - F_T \sin C_s \]  \hspace{1cm} (21)
III. EXPERIMENTAL METHOD & PROCEDURE

- Dynamometer *(Kistler-9257B)*
- Tool tip: Sandvik *K10 (H1P)*
- Data acquisition system: *(Keithley Metrobyte Das-1600)*
- Workpiece: as Table 2
- CNC Turning Machine: SJ *(EL3807)*
- Block diagrams of performance are written and shown in Fig. 3
III. EXPERIMENTAL METHOD & PROCEDURE

The work material used was 0 ° unidirectional filament wound fiber of E-glass-fiber-reinforced plastics (GFRP) materials in the form of bars having a diameter of 40 mm and 500 mm length [20]. Table 2 shows the physical and mechanical properties of GFRP.

Table 2  Properties of the work materials GFRP [20]

<table>
<thead>
<tr>
<th>Nominal form</th>
<th>Density $g/cm^3$</th>
<th>Thermal conductivity $kcal/hr\cdot ^\circ C$</th>
<th>Fiber contain</th>
<th>Coefficient of thermal expansion $(10^{-6}/^\circ C)$</th>
<th>Thermo-setting resins</th>
<th>Hardness (Shore, $H_s$)</th>
<th>Tensile strength $(kg/mm^2)$</th>
<th>Compressive strength $(kg/mm^2)$</th>
<th>Modulus tensile $(kg/mm^2)$</th>
<th>Shear strength $(kg/mm^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roving continuous strand</td>
<td>1.8~2.1</td>
<td>0.21~0.28</td>
<td>75%</td>
<td>2~9</td>
<td>vinyl-ester</td>
<td>55~60</td>
<td>45~65</td>
<td>45~60</td>
<td>2000~4000</td>
<td>20</td>
</tr>
</tbody>
</table>
III. EXPERIMENTAL METHOD & PROCEDURE

Fig. 4 Rotation of cutting edge and positive directions of force components
III. EXPERIMENTAL METHOD & PROCEDURE

Fig. 5 Solid model and finite element mesh of chamfered main cutting edge tool
III. EXPERIMENTAL METHOD & PROCEDURE

Fig. 6 Experimental set-up
IV. RESULTS AND DISCUSSION

Fig. 7 The resultant cutting forces $F_r$ vs. $R$ and $C_s$ of unchamfered and chamfered tools at different $\alpha_{s1}$ and $\alpha_{s2}$ $d=3\text{mm}$, $V=252\text{m/min}$ (GFRP)

Experimental values, $F_r$ vs $R$, side rake angle, and $C_s$ of chamfered tools

<table>
<thead>
<tr>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
</tr>
<tr>
<td>340</td>
</tr>
<tr>
<td>320</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>280</td>
</tr>
<tr>
<td>260</td>
</tr>
<tr>
<td>240</td>
</tr>
<tr>
<td>220</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, no chamfer</td>
</tr>
<tr>
<td>0, chamfer</td>
</tr>
<tr>
<td>0.3, chamfer</td>
</tr>
<tr>
<td>0.5, chamfer</td>
</tr>
<tr>
<td>1.0, chamfer</td>
</tr>
</tbody>
</table>

$F_r$: experimental values vs $R$ of K type tool at side rake angle $-30$ & $30$, $C_s=40$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-30$ & $30$, $C_s=30$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-30$ & $30$, $C_s=20$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-20$ & $20$, $C_s=40$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-20$ & $20$, $C_s=30$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-20$ & $20$, $C_s=20$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-10$ & $10$, $C_s=40$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-10$ & $10$, $C_s=30$
$F_r$: experimental values vs $R$ of K type tool at side rake angle $-10$ & $10$, $C_s=20$
IV. RESULTS AND DISCUSSION

Fig. 8  The resultant cutting forces $F_r$ vs. $C_s$, $\alpha_1$ and $\alpha_2$ of chamfered cutting edge tools at $R=0.3$, $d=3\,\text{mm}$, $f=0.33\,\text{mm/rev}$, $V=252\,\text{m/min}$ (GFRP)
IV. RESULTS AND DISCUSSION

Fig. 9  Shape of chips with chamfered edge tool, $\alpha_{s1}, \alpha_{s2}$ (a) $-10^\circ, 10^\circ$, (b) $-20^\circ, 20^\circ$ and (c) $-30^\circ, 30^\circ$ at $Cs=20^\circ$, $d=3.0$, $R=0.3$, and $V=252$ m/min (GFRP) respectively (80X).
IV. RESULTS AND DISCUSSION

Fig. 10  Shape of chips with chamfered edge tool, $\alpha_{s1}, \alpha_{s2}$ (a) $-10^\circ, 10^\circ$, (b) $-20^\circ, 20^\circ$ and (c) $-30^\circ, 30^\circ$ at $Cs=30^\circ$, $d=3.0$, $R=0.3$, and $V=252$ m/min (GFRP) respectively (80X)
IV. RESULTS AND DISCUSSION

Fig. 11 Cutting temp. vs. time for unchamfered and chamfered tool $C_s=20$

Temperature values, $T_e$, vs unchamfered and chamfered cutting edge tools

$T_e$: degree

---

- $T_e$: measured values (unchamfered tool vs cutting time at $C_s=20$, rake angle -30 & 30)
- $T_e$: calculated values (unchamfered tool vs cutting time at $C_s=20$, rake angle -30 & 30)
- $T_e$: measured values (unchamfered tool vs cutting time at $C_s=20$, rake angle -10 & 10)
- $T_e$: calculated values (unchamfered tool vs cutting time at $C_s=20$, rake angle -10 & 10)
- $T_e$: measured values (chamfered tool vs cutting time at $C_s=20$, rake angle -30 & 30)
- $T_e$: measured values (chamfered tool vs cutting time at $C_s=20$, rake angle -10 & 10)
- $T_e$: calculated values (chamfered tool vs cutting time at $C_s=20$, rake angle -10 & 10)
- $T_e$: calculated values (chamfered tool vs cutting time at $C_s=20$, rake angle -30 & 30)
IV. RESULTS AND DISCUSSION

Fig. 12  Cutting temp. vs. time for unchamfered and chamfered tool Cs=40°

Temperature values, 

- measured values (unchamfered tool vs cutting time at Cs=30, rake angle -30 & 30)
- calculated values (unchamfered tool vs cutting time at Cs=30, rake angle -30 & 30)
- measured values (unchamfered tool vs cutting time at Cs=30, rake angle -10 & 10)
- calculated values (unchamfered tool vs cutting time at Cs=30, rake angle -10 & 10)
- measured values (chamfered tool vs cutting time at Cs=30, rake angle -30 & 30)
- measured values (chamfered tool vs cutting time at Cs=30, rake angle -10 & 10)
- calculated values (chamfered tool vs cutting time at Cs=30, rake angle -10 & 10)
- calculated values (chamfered tool vs cutting time at Cs=30, rake angle -30 & 30)
IV. RESULTS AND DISCUSSION

4.1 The cutting force (Figs. 7, 8)

4.2 The shape of chips (Figs. 9, 10)

4.3 Temperature of tip surface

(1) Based on Li and Albert [13], the flowchart for inverse heat transfer solution of $K$ is described in Fig. 2. After finding the value of $K$, the finite element model can be applied to calculate temperature at tips, the results are shown in Figs. 11-13.

(2) Figs. 11-12 show the cutting temperatures vs cutting time for different values $\alpha_{s1}$ and $\alpha_{s2}$ with chamfered and unchamfered sharp tool at $d=2.0\text{mm}, f=0.33\text{mm/rev}, V=120\text{m/min}$ at $Cs=20^\circ$, and $Cs=30^\circ$, respectively. Fig. 13 shows the temperatures vs $Cs$ for different values $\alpha_{s1}$ and $\alpha_{s2}$ with chamfered and unchamfered sharp tool at $d=2.0\text{mm}, f=0.33\text{mm/rev}, V=120\text{m/min}$ respectively. Fig. 14 shows the temperatures distribution with chamfered main cutting edge tool at, $\alpha_{s1}=-30^\circ$, $\alpha_{s2}=30^\circ$, and $Cs=20^\circ$, $d=2.0\text{mm}$, $f=0.33\text{mm/rev}$, and $V=120\text{m/min}$. 
IV. RESULTS AND DISCUSSION

(3) From Figs. 11-13, it proved that the cutting edge temperature of the chamfered main edge tool was lower than unchamfered main cutting edge tool.

(4) According to Figs. 11-13, the tip temperatures of chamfered main cutting edge tool were very low and the inverse data correlates closely with the experimental values.

(5) From Figs. 11-13, the temperatures of chamfered main cutting edge tool is the lowest, when $Cs=20^\circ$, $\alpha_s1=-10^\circ$ & $\alpha_s2=10^\circ$, and the temperature is not exceed 220 $^\circ$C

(6) From Fig. 14, it proved that the distribution of chamfered main cutting edge tool’s temperature was close the Fig. 11.
IV. RESULTS AND DISCUSSION

Fig. 11 Cutting temp. vs. time for unchamfered and chamfered tool Cs=20°

Temperature values, Te, vs unchamfered and chamfered cutting edge tools

Te: degree

- ■ - Te:measured values (unchamfered tool vs cutting time at Cs=20, rake angle -30 & 30)
- ○ - Te:calculated values (unchamfered tool vs cutting time at Cs=20, rake angle -30 & 30)
- ● - Te:measured values (unchamfered tool vs cutting time at Cs=20, rake angle -10 & 10)
- ◊ - Te:calculated values (unchamfered tool vs cutting time at Cs=20, rake angle -10 & 10)
- ▲ - Te:measured values (chamfered tool vs cutting time at Cs=20, rake angle -30 & 30)
- □ - Te:measured values (chamfered tool vs cutting time at Cs=20, rake angle -10 & 10)
- ◀ - Te:calculated values (chamfered tool vs cutting time at Cs=20, rake angle -10 & 10)
- ◊ - Te:calculated values (chamfered tool vs cutting time at Cs=20, rake angle -30 & 30)
IV. RESULTS AND DISCUSSION

Fig. 12 Cutting temp. vs. time for unchamfered and chamfered tool $Cs=30^\circ$

Temperature values, $Te$, vs unchamfered and chamfered cutting edge tools

$Te$: degree

- $Te$ measured values (unchamfered tool vs cutting time at $Cs=30$, rake angle $-30$ & $30$)
- $Te$ calculated values (unchamfered tool vs cutting time at $Cs=30$, rake angle $-30$ & $30$)
- $Te$ measured values (unchamfered tool vs cutting time at $Cs=30$, rake angle $-10$ & $10$)
- $Te$ calculated values (unchamfered tool vs cutting time at $Cs=30$, rake angle $-10$ & $10$)
- $Te$ measured values (chamfered tool vs cutting time at $Cs=30$, rake angle $-30$ & $30$)
- $Te$ measured values (chamfered tool vs cutting time at $Cs=30$, rake angle $-10$ & $10$)
- $Te$ calculated values (chamfered tool vs cutting time at $Cs=30$, rake angle $-30$ & $30$)
- $Te$ calculated values (chamfered tool vs cutting time at $Cs=30$, rake angle $-10$ & $10$)
IV. RESULTS AND DISCUSSION

Fig. 13 Cutting temp. vs. Cs for unchamfered and chamfered tool  \( R = 0.3 \)

Temperature, \( T_e \), vs Cs of unchamfered & chamfered cutting edge tools

- \( T_e \): calculated values vs Cs of unchamfered tool at side rake angle -30 & 30
- \( T_e \): measured values vs Cs of unchamfered tool at side rake angle -30 & 30
- \( T_e \): calculated values vs Cs of unchamfered tool at side rake angle -10 & 10
- \( T_e \): measured values vs Cs of unchamfered tool at side rake angle -10 & 10
- \( T_e \): calculated values vs Cs of chamfered tool at side rake angle -30 & 30
- \( T_e \): measured values vs Cs of chamfered tool at side rake angle -30 & 30
- \( T_e \): calculated values vs Cs of chamfered tool at side rake angle -10 & 10
- \( T_e \): measured values vs Cs of chamfered tool at side rake angle -10 & 10
IV. RESULTS AND DISCUSSION

Fig. 14 Tool tip’s temperature of FEM method near tool nose at $Cs=20^\circ$
IV. RESULTS AND DISCUSSION

Fig.14 Tool tip’s Temperature of FEM Method, Heat flux at $Cs=20^\circ$
V. CONCLUSIONS

Good correlations between predicted values and experimental results of forces and temperatures during machining with sharp tools in cutting GFRP. The new tool model with chamfered cutting edge has been developed by including the variation of shear plane areas. In this model, the energy method is also used to accurately predict cutting force.
V. CONCLUSIONS

The FEM and Inverse heat transfer solution in tool temperature in GFRP turning is obtained and compared with experimental measurements. The good agreement demonstrates the accuracy of proposed model. This model can be extended to on-line control domain in addition to the factors of time and thermal effect. The above results demonstrate that the predicted values matched with the experimental values very well.


REFERENCES


14 M. E. Merchant,”Basic mechanics of the metal cutting process,” J. of Applied Mechanics, Trans of ASME, 66(1944), pp. 267
Acknowledgement

- This work was supported by National Science Council, Taiwan, R.O.C. under grant number NSC 95-2622-E-197-001-CC3
Welcome visit at National Ilan University (NIU)

Thank you for listening
Question and Answer?

Thank you for listening