3D cutting force analysis in worn-tool finish hard turning

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Abstract: This study develops an analytical model for cutting force simulations in finish hard turning by a worn tool, which includes both chip formation and flank wear-land contact forces. Due to the 3D nature of the cutting zone, both the uncut chip area and wear-land contact are considered as numerous thin slices and individually analysed for cutting forces modelling. Using coordinate transformations, cutting forces due to individual slices can be projected and further integrated from the lead to tail cutting edge to calculate three components of cutting forces. The methodology was applied to simulate process parameter effects on cutting forces. The radial component is the most sensitive force to the change of process parameters, especially, flank wear-land and tool nose radius. Among all parameters tested, flank wear-land shows the most dominant effects on cutting forces and its existence will also augment the effects of other parameters, for example, the tool nose radius.

Keywords: cutting forces; finish hard turning; nose radius; tool wear.


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1 Introduction

Hard turning of precision steel components is considered as an alternative to some grinding applications. The cutting force information is important to part accuracy, tool wear and heat generations that may cause part thermal damages. Tool wear effects on cutting forces may limit the tool life and change the thermal conditions of the cutting tool. Cutting forces due to flank wear-land have been studied by several researchers. One school of thought claimed that chip formation is not coupled with the wear-land traction, which solely depends on the wear-land size and cutting conditions (Smithey et al., 2000; Waldorf et al., 1998, 2001). According to Waldorf et al. (1998), flank wear-land contact consists of both plastic flow region and elastic contact for a large wear-land. Smithey et al. (2000) further proposed that the stress distributions are different between the plastic flow region and the elastic contact. Once normal and shear stresses are determined, cutting forces due to tool wear can be obtained by integrating stresses over the flank wear-land area. The summation of sharp tool cutting forces and wear-land forces is the overall cutting forces in machining using a worn cutting tool. Elanayar and Shin (1996) also studied cutting forces due to wear-land using an indentation force model. The authors reported that wear-land effects on chip formation forces are insignificant. Huang and Liang (2004) have applied the worn-tool model from (Smithey et al., 2000; Waldorf et al., 1998, 2001), expanding to three-dimensional cutting, to model wear-land forces in hard turning and reported that model predictions agree with experimental results in a wide range of cutting conditions (Huang and Liang, 2004).

On the other hand, Wang and Liu (1999) suggested that the chip formation forces are affected by the wear-land interactions. The authors developed a method to decouple the wear-land force and chip formation force. A thermal model based on Green’s function was developed and, by using the white layer thickness in the chip (free surface side) as the thermal boundary condition of the machined surface, average stresses attributed to wear-land traction can be determined (Wang and Liu, 1999). The results indicate influence of wear-land to chip formation forces. In addition, Shi and Ramalingam (1991) applied a slip-line approach to study the tool wear effects. The authors demonstrated the interactions between the plastic region caused by the tool-wear land and the primary chip deformation region. The model captures largely uneven force increasing rates between the cutting and thrust components due to tool flank wear.

This study attempts to develop an analytical model for cutting force simulations in finish hard turning by a worn tool. Under the hypothesis that the chip formation and the wear-land traction are independent, the sum of both components establishes the overall cutting forces in worn-tool machining. The new-tool cutting forces were obtained using the mechanistic force model with variable uncut chip thickness and
integrated across the cutting edge. The wear-land contact was discretised and the differential forces over small individual contact areas can be transformed to the workpiece coordinates and integrated to obtain the wear-land forces. The model was employed to investigate the effects of machining parameters, tool nose radius and flank wear on cutting forces.

2 New tool force modelling

The chip formation forces in finish hard turning are modelled by a mechanistic approach. In finish cutting, the uncut chip area ($A_c$), the cutting edge Contact Length ($CL$), and the uncut chip thickness ($h_\theta$, a variable) across the cutting edge can be analysed and all related to process parameters and the tool nose radius (Asai and Kobayashi, 1990). As illustrated in Figure 1, the uncut chip area is considered as numerous thin slices, each with the dimensions of different uncut chip thickness ($h_\theta$) and an infinitesimally small width ($r\delta\theta$), where $r$ is the tool nose radius.

Figure 1 A sketch showing uncut chip geometry in finish turning

A mechanistic approach is applied to each uncut chip slice to relate normal and friction forces ($\delta F_n$ and $\delta F_f$) at the rake face with uncut chip area ($\delta A_c$) and two specific cutting pressure constants, $K_n$ and $K_f$.

$$\delta F_n = K_n r h_\theta \delta \theta$$

$$\delta F_f = K_f r h_\theta \delta \theta$$

Using coordinate transformation, cutting forces due to an individual uncut chip slice at $\theta$ can be projected to the workpiece coordinated system, that is, tangential, radial and axial components. Further integrating forces from the lead to tail cutting edges gives overall three components of chip-formation forces as below (Chou and Song, 2003).
\[
\begin{bmatrix}
F_r \\
F_t \\
F_a
\end{bmatrix} = \begin{bmatrix}
\cos \alpha & \sin \alpha & 0 \\
-\sin \alpha & \cos \alpha & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & \tilde{A}_c \cos \gamma & \sin c \\
0 & 0 & 1 & \sin \gamma & \cos c \\
-A_c & -A_c & 0 & \tilde{A}_c & \sin \gamma \cos c
\end{bmatrix}
\begin{bmatrix}
K_s \\
K_t \\
K_a
\end{bmatrix}
\] (2)

where

\[
\tilde{A}_c = \sqrt{\int h_y \sin (\theta) d\theta}^2 + \int h_y \cos (\theta) d\theta^2
\]

and the equivalent lead angle, \( \gamma_e \), is defined as:

\[
\gamma_e = \sin^{-1} \left( \sin \left( \tan^{-1} \left( \frac{1}{h_y \cos \theta d\theta} \right) \right) \right)
\] (3)

with \( n \) as an empirical exponent, about 0.63 (Chou and Song, 2003).

A set of hard turning experiments was conducted with force measurements to calibrate \( K_s \) and \( K_t \). Ceramic cutting tools (AlTiC) with 20° × 0.1 mm chamfer were used. Cutting geometry was -5° nominal rake angle, 5° relief angle, and 15° both side and end cutting edge angles. Tool nose radii tested included 0.8 mm, 1.6 mm and 2.4 mm. Workpieces were solid round bars made of hardened AISI 52100 steel, 60 to 62 HRc. Machining parameters ranged from 1 to 4 m/sec of cutting speed, 0.025 to 0.6 mm/rev feed, and 0.05 to 0.4 mm depth of cut.

Using the least square regression method, all the coefficients of \( K_s \) and \( K_t \) can be determined. The regression results suggested \( K_s \) and \( K_t \) being formulated as

\[
\ln(K_s) = 7.54 - 0.329 \ln(V) - 0.022 \ln(V) - 0.229 \ln(\gamma_e) - 0.06 \ln(CL)
\]

\[
\ln(K_t) = 5.72 - 0.515 \ln(V) + 0.123 \ln(V) - 0.474 \ln(\gamma_e) - 0.142 \ln(CL)
\] (4)

where \( \frac{V}{h_y} = A_c / CL \) is the average uncut chip thickness. The mechanistic model above shows R-squared values of 93.9% and 90.4%, respectively.

For the verification purpose, another set of experiments (18 conditions) have been conducted and compared to the model predictions. It includes a range of parameters: 0.8 to 2.4 mm tool nose radius, 2 to 3 m/sec cutting speed, 0.05 to 0.6 mm/rev feed, and about 0.2 mm depth of cut. The predicted tangential forces (\( F_t \)) agree with the experimental data fairly well, mostly less than 10%, Figure 2. Errors of the radial (\( F_r \)) and axial (\( F_a \)) components are relatively larger, with the maximum about 20 to 30%. The relative errors of the model predictions have been compared against average uncut chip thickness of each cutting condition. It is also noticed that large errors mostly occur at conditions with a smaller average uncut chip thickness.

### 3 Wear-land force modelling

A typical worn cutting tool in finish hard turning has a constant wear-land width, \( VB \), over the entire wear-land except around the lead and tail cutting edges. To determine cutting forces in three directions, the wear-land contact is discretised into a number of small slices, Figure 3.
According to Waldorf et al. (1998), flank wear-land contact consists of plastic flow region and elastic contact if the wear-land width, \( VB \), is greater than a critical size \( VB_{cr} \). Smithey et al. (2000) further proposed that the width of plastic flow region (\( VB_P \)) linearly increases with \( VB \) and the proportionality is solely a function of the workpiece and cutting tool materials. Following the assumption of the linear growth of the plastic zone, stresses are modelled as constant in the plastic flow region, \((\sigma_0, \tau_0)\), and as a quadratic distribution in the elastic contact. \( \sigma_0 \) and \( \tau_0 \) are determined from the slip-line field theory, derived from the shear angle, the slip-line field angle, and the shear flow stress on the shear plane (Waldorf et al., 1998). Differential cutting forces, \( \delta F_{rr} \) and \( \delta F_{qq} \), due to a small wear-land contact slice can be calculated by integrating normal and shear stresses over the contact area.

\[
\delta F_{rr} = VB_P \delta w \tau_0 + \int_{VB}^{VB+\delta w} \delta w \tau_0(x) \, dx \\
\delta F_{qq} = VB_P \delta w \sigma_0 + \int_{VB}^{VB+\delta w} \delta w \sigma_0(x) \, dx
\]  

(5)
In the elastic contact, the stresses decrease parabolically towards the end of contact (Smithey et al., 2000):

$$\sigma_0(x) = \sigma_0 \left( \frac{V_B - x}{V_B - V_B_p} \right)^2, \quad \tau_0(x) = \tau_0 \left( \frac{V_B - x}{V_B - V_B_p} \right)^2$$  (6)

$\sigma_0$ and $\tau_0$ are determined from the slip-line field theory (Smithey et al., 2000). When $V_B < V_B_p$,

$$\sigma_0 = \tau_0 \left[ 1 + \frac{v}{2} - 2\phi + 2\gamma + \sin(2\gamma - 2\phi) \right]$$  (7)

$$\tau_0 = \tau_s \cos(2\gamma - 2\phi)$$

where $\tau_s$ is the shear flow stress of the shear plane, $\gamma = \cos^{-1}m_s/2 + \phi$, and $\phi$ is the shear angle.

When $V_B \geq V_B_p$,

$$\sigma_0 = \tau_0 \left[ 1 + \frac{v}{2} + \cos^{-1}m_s + \sin\left(\cos^{-1}m_s\right) \right]$$

$$\tau_0 = \tau_s m_m$$

$m_s$ and $m_m$ are two friction factors, close to one (Smithey et al., 2000), at the cutting edge and flank wear-land, and are estimated to be 0.9 in this study.

Differential forces due to stresses over the wear-land slice can then be transformed to the global coordinate system (workpiece) and integrated to obtain three components of wear-land forces, that is, radial ($F_{r,w}$), tangential ($F_{t,w}$) and axial ($F_{a,w}$) components.

$$F_{r,w} = \int_0^\theta \delta F_{r_w} d\theta = \int_0^\theta \left[ V_B \gamma r_{t_0} + \int_{v_B}^{v_B} r_{w} (x) dx \right] d\theta$$

$$F_{t,w} = \int_0^\theta \delta F_{t_w} \cos\theta d\theta = \int_0^\theta \left[ V_B \gamma r_{t_0} + \int_{v_B}^{v_B} r_{w} (x) dx \right] \cos\theta d\theta$$  (9)

$$F_{a,w} = \int_0^\theta \delta F_{a_w} \sin\theta d\theta = \int_0^\theta \left[ V_B \gamma r_{t_0} + \int_{v_B}^{v_B} r_{w} (x) dx \right] \sin\theta d\theta$$

Equations (9) above and the chip formation forces establish the total machining forces in finish hard turning using a worn-tool.

The wear-land dimensions are defined by $CL$, $V_B$, as well as two angles at lead and tail cutting edges ($a$ and $b$ in Figure 2), assumed to be 65° and 55° per experimental observation. The shear flow stress on the shear plane at different machining conditions has been established from the mechanistic force model in new tool cutting. Based on the experiments, the entire wear-land has only elastic contact when $V_B$ is less than 0.3 mm. Wear-land forces predicted show linearly increasing with $V_B$.

A cutting test with 3 m/sec of cutting speed, 0.2 mm depth of cut, 0.05 mm/rev feed and 0.8 to 2.4 mm tool nose radius was used to verify the analytical predictions. Cutting forces due to wear-land were obtained by subtracting the corresponding fresh tool cutting forces from measured total cutting forces. Figure 4 compares experimental results and model predictions of cutting forces due to wear-land, tangential and radial components, respectively. Machining tests were repeated twice. Error bars in the figures represent the range of experimental data. The experimental results of tangential wear-land forces show linear correlation with $V_B$ and agree well with the predictions, with relative errors less
than 15 %, Figure 4(a). Comparing to the tangential component, the errors of radial forces are relatively large, though still less than 30%. Also noted is that the model predictions always underestimate radial component, Figure 4(b). It seems to indicate that large flank wear-land sizes may result in even more deviations that will limit the model capability. Some systematic errors may result from the assumptions associated with radial force modelling. Another observation is that wear-land forces increase with tool nose radius.

Figure 4  Comparison of cutting forces due to wear-land between model and experiments (3 m/sec cutting speed, 0.2 mm depth of cut and 0.05 mm/rev feed) (a) tangential force and (b) Radial force
4 Simulation results

The model was applied to study machining parameter effects on cutting forces. The cutting speed (V) ranged from 1 m/sec to 5 m/sec, feed (f) from 0.02 mm/rev to 0.38 mm/rev, depth of cut (d) from 0.05 mm to 0.38 mm, and wear-land width (VB) from 0 mm to 0.2 mm. In addition, the tool nose radius (r) was varied from 0.4 mm to 3.2 mm. Figure 5 shows flank wear-land effects on cutting forces. Among three components, the radial force increases most rapidly with the wear-land size, about 100% from 0 to 0.2 mm VB. On the other hand, tangential and axial forces increase less than 50% from 0 to 0.2 mm VB.

Figure 5 Flank wear-land effects on cutting forces ($F_r$: radial component, $F_t$: tangential component, $F_a$: axial component, $V$: 3 m/sec, $r$: 0.8 mm, $f$: 0.2 mm/rev, $d$: 0.2 mm)

Figure 6 shows parameter effects on cutting forces at both new and worn-tool conditions. As known in common machining practices, cutting forces slightly decrease with increasing cutting speed, but are seemingly linear to the feed. The depth of cut effects on cutting forces are also close to linear at large depths of cut, but deviated from linearity at small depths, especially at a large VB. In addition, the wear-land size has the dominant effect, forces increasing significantly. In general, the wear-land does not alter the behaviour of other process parameter effects, noting the close-to-parallel lines between new and worn-tool cases.

On the other hand, the tool nose radius effects, Figure 7, seem to be augmented by the wear-land. In new tool cutting, both $F_r$ and $F_t$ increase gradually with the tool nose radius. However, with 0.2 mm VB, the increasing rate of the radial force with the tool nose radius is particularly high compared to other two components. This may imply that using a larger tool nose radius for better part surface finish may result in poor part accuracy or even adverse effects on the surface finish due to a higher radial cutting force when flank wear increases.

Analysis of variance has also been conducted and confirms that the wear-land is the most significant factor to cutting forces among all parameters tested, augments the effects of other parameters and has two-way interactions with other parameters to affect the cutting forces.
Figure 6  Process parameter effects on cutting forces ($F_r$: radial component, $F_t$: tangential component, $V$: speed, $f$: feed, $d$: depth of cut). (a) Cutting speed effect ($f$: 0.2 mm/rev, $d$: 0.2 mm), (b) Feed effect ($V$: 3 m/sec, $d$: 0.2 mm) and (c) Depth of cut effect ($V$: 3 m/sec, $f$: 0.2 mm/rev)
5 Conclusions

A 3D analytical model was developed for cutting force simulations in finish hard turning using a worn-tool. The model includes the chip formation forces and the wear-land traction forces, assumed to be independent. The uncut chip area and the wear-land contact are discretised to evaluate the differential cutting forces, and then coordinate-transformed and integrated to obtain three-components of cutting forces. The model has been used to study the process parameter effects on cutting forces. The results show that the wear-land is the most significant factor and generally does not alter the effects from other parameter, however, amplifies the tool nose radius effects dramatically.

References


