

Force Modeling in Shallow Cuts with Large Negative Rake Angle and Large Nose Radius Tools– Application to Hard Turning

Yong Huang, Research Assistant
Steven Y. Liang, Professor
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405, USA

Abstract

In finish turning, the applied feedrate and depth of cut are generally very small. In some particular cases, such as the finishing of hardened steels, feedrate and depth of cut are much smaller than tool nose radius. If the tool with large tool nose radius and large negative rake angle is used in finish turning, the ploughing effect is pronounced and needs to be carefully addressed. Unfortunately, the ploughing effect has not yet been systematically considered in force modeling in shallow cuts with large negative rake angle and large nose radius tools in 3-D oblique cutting. In this study, in order to model the forces in such shallow cuts, first the chip formation forces are predicted by transforming the 3-D cutting geometry into an equivalent 2-D cutting geometry, then the ploughing effect mechanistic model is proposed to calculate the total 2-D cutting forces. Finally, the 3-D cutting forces are estimated by a geometric transformation. The proposed approach is verified in the turning of hardened 52100 steel, in which cutting condition is typified as shallow cuts with negative rake angle and large nose radius tools. Here the workpiece material property of hardened 52100 steel is represented by the Johnson-Cook equation, which is determined from machining tests. The comparison between experimental results and model predictions is presented.

Nomenclature

$A_{cutting}$	Cutting cross section area
a_0, a_1, a_2, a_3	Constants of the ploughing effect coefficient K_c
b_0, b_1, b_2, b_3	Constants of the ploughing effect coefficient K_t
C_s	Side cutting edge angle
C_s^*	Equivalent side cutting edge angle
d	Depth of cut
F_c^*, F_t^*	Tangential and thrust chip formation forces
F_c, F_t	Total cutting forces with the ploughing effect considered
f	Feedrate
i^*	Equivalent inclination angle

K_c, K_t	Ploughing effect coefficients
P_1, P_2, P_3	Forces in cutting, feed and radial directions
$P_{1,m}, P_{2,m}, P_{3,m}$	Measured 3-D cutting forces
$P_{c,measure}, P_{t,measure}$	Measured 2-D cutting forces
$P_{1,p}, P_{2,p}, P_{3,p}$	Predicted 3-D cutting forces
$P_{c,prediction}, P_{t,prediction}$	Predicted 2-D cutting forces
r	Tool nose radius
t^*	Equivalent undeformed chip thickness
t_{max}	Maximum undeformed chip thickness along the tool nose
T	Temperature
T_m	Melting point temperature
T_r	Reference temperature for measuring σ_0
w^*	Equivalent width of cut
α_n	Cutting edge normal rake angle
α_n^*	Equivalent cutting edge normal rake angle
ε	Uniaxial (effective) strain
$\dot{\varepsilon}$	Strain rate
η_c^*	Equivalent chip flow angle
σ	Flow stress

1. Introduction

Force modeling in metal cutting is important for thermal modeling, tool life estimation, chatter prediction, and tool condition monitoring purposes. Numerous efforts have been devoted to capture the force profiles in metal cutting. Besides laborious experimental approaches, numerous numerical and analytical approaches are proposed to model the chip formation forces. Although some successes are gained in modeling the chip formation forces in metal cutting by finite element method (FEM), it is not readily applicable because it is laborious and not easy to be extended to practical 3-D turning cases [1,2]. Alternatively, analytical models have been favored as force models in metal cutting because they are easier to implement and can give much more insight about physical behavior in metal cutting. To analytically model the chip formation forces in metal cutting, two fundamental approaches have been extensively researched: minimum energy principle [3,4] and slip line field theory [5]. Numerous researchers have applied or modified these two approaches to model the forces in metal cutting on these bases.

In finish turning, feedrate and depth of cut are generally very small. In some particular cases, such as finishing hardened steels, feedrate and depth of cut are much smaller than tool nose radius and the ploughing effect (rubbing effect) is rather pronounced. Furthermore, when undeformed chip thickness is smaller enough, the ploughing effect contributes to a greater portion of the total cutting forces. Generally this critical chip thickness is defined by tool nose radius, machine tool system stiffness, and negative rake angle. The ploughing effect needs to be

carefully addressed under these cutting configurations. The first study on the ploughing effect in metal cutting was documented by Albrecht [6] in an attempt to estimate the real value of friction coefficient on the tool-chip interface and to explain the paradox of variation of the friction coefficient with variation of rake angle. After Albrecht's study, significant efforts have been devoted to model the ploughing force in orthogonal cutting [7-10]. Unfortunately, no documented effort has been found to deal with this ploughing effect in modeling forces in such shallow cuts with large negative rake angle and large nose radius under 3-D oblique cutting condition.

Finish hard turning is a typical turning process of shallow cuts with negative rake angle CBN or ceramic tools. The cutter usually has a large nose radius compared with practical feedrate and depth of cut and has a large negative rake angle. Under these situations the ploughing effect can prevail. The material side flow can also be observed as the result of the ploughing effect in hard turning [11]. In this paper, to model cutting forces in such shallow cuts, first the chip formation forces are predicted by transforming the 3-D cutting geometry into an equivalent 2-D cutting geometry [5,12,13]. Then, the ploughing effect mechanistic model is proposed to calculate the total 2-D cutting forces. Finally, 3-D cutting forces are estimated by a geometric transformation. The proposed approach is verified in the machining test of finishing hardened 52100 steel. Here, the workpiece material property is represented by the Johnson-Cook equation, which is determined by independent machining tests.

2. Modeling the ploughing effect on cutting forces

Under the shallow cut condition, for a tool with large tool nose radius the shape of undeformed chip cross section is not ideally rectangular. By assuming zero rake and inclination angles for the tool, the typical cutting geometry in turning with shallow cuts is shown in Fig. 1. Fig. 2 displays the undeformed chip thickness versus the distance of an arbitrary location from point A to point D for a typical finish hard turning condition. The undeformed chip thickness varies around the cutting edge (arc AED) from zero (location A) to t_{\max} (location E) then to zero (location D) again. The maximum chip thickness t_{\max} can be calculated by Equ. (1) based on cutting geometry and tool geometry as shown in Fig. 1.

$$t_{\max} = r - \sqrt{r^2 + f^2 - 2f\sqrt{2rd - d^2}} \quad (1)$$

The ploughing effect contributes to a significant portion of the cutting forces where the undeformed chip thickness is smaller enough in comparison to a value, which is determined by tool nose radius, machine tool system stiffness, and tool rake angle. Until now, there has been no available model to predict this value in metal cutting. As seen from Fig. 2, some portions along the cutting edge are small enough for the ploughing effect to be pronounced. Without needing to know that value exactly, a mechanistic model is proposed herein to model the overall effect of the ploughing phenomenon on the total cutting forces. Suppose the tangential chip formation force F_c^* and thrust chip formation force F_t^* are the predicted chip formation forces without considering the ploughing effect, the total cutting forces in shallow cut are mechanistically modeled to include the ploughing effect as follows:

$$F_c = K_c F_c^*, F_t = K_t F_t^* \quad (2)$$

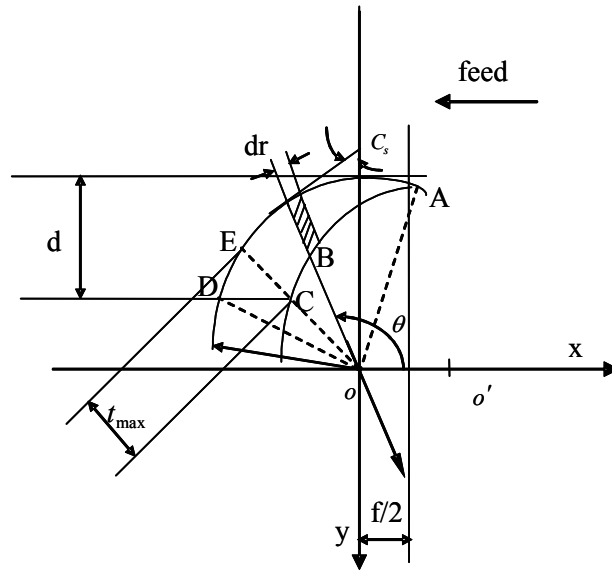


Fig. 1. Cutting geometric model under shallow cuts with a large nose radius tool (o' is the tool nose center of the previous revolution)

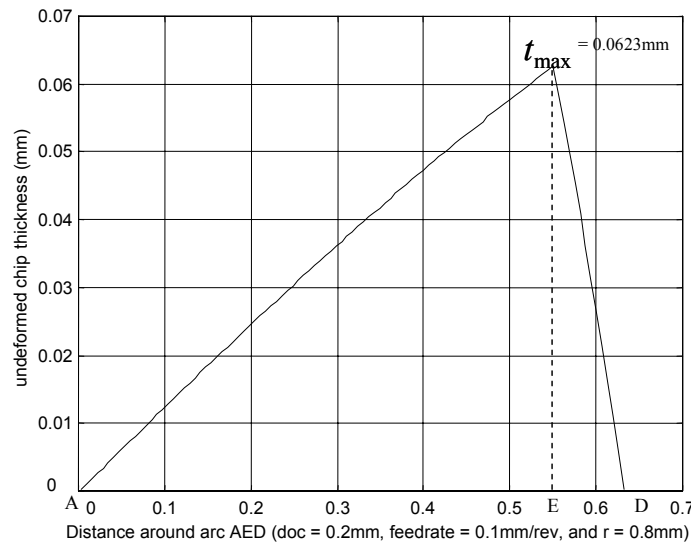


Fig. 2. The undeformed chip thickness around the tool cutting edge AED for one cutting condition

The coefficients K_c and K_t in Equation (2) are termed ploughing effect coefficients. Experimental evidence has shown that the dependence of the specific cutting energy on the chip thickness can be well described by a power law relationship [14,15]. Here the power law relation is assumed between the ploughing effect coefficients and t_{\max} also on the basis that t_{\max} is

dependent on undeformed chip thickness. Furthermore, a linear relationship between the ploughing effect coefficients and t_{\max} is included. Thus, K_c and K_t are defined as

$$K_c = a_0 - a_1 t_{\max} - a_2 t_{\max}^{a_3}, K_t = b_0 - b_1 t_{\max} - b_2 t_{\max}^{b_3} \quad (3)$$

The effect of rake angle is neglected for simplicity since rake angle in this study is fixed. The different rake angle value will change a 's and b 's. K_c and K_t are not sensitive to tool material properties, but are dependent on workpiece material properties.

3. Modeling forces in 3-D oblique cutting condition

3.1. Equivalent 2-D oblique cutting geometry for 3-D oblique cutting condition

In typical finish turning, the orthogonal cutting condition no longer holds in the presence of substantial tool nose radius and the 3D oblique cutting configuration. By considering the equivalent 2-D oblique cutting geometry in finish turning, the force model for orthogonal cutting [16] is extended to model the chip formation forces. The equivalent cutting geometry, including the equivalent cutting edge normal rake angle α_n^* , the equivalent inclination angle i^* , and the equivalent side cutting edge angle C_s^* , can be calculated from the 3-D oblique cutting geometry transformation model as documented in [5,12,13]. For cutting tools with substantial tool nose radius, C_s is calculated as the angle between the center line and tool nose tangential line, which is tangential to the intersection point between half depth of cut and the tool. The use of these equivalent cutting geometries for the development of a 3-D force model is discussed below.

3.2. Three-dimensional oblique force model

Based on Stabler's flow rule [17], the equivalent chip flow angle is:

$$\eta_c^* = i^* \quad (4)$$

In determining turning forces, the orthogonal cutting model can be applied by assuming that inclination angle is zero irrespective of its actual value and rake angle is taken as α_n^* [12]. The equivalent undeformed chip thickness t^* and the equivalent width of cut w^* can be calculated by:

$$t^* = f \cos C_s^*, \quad w^* = d / \cos C_s^* \quad (5)$$

Based on transformed equivalent cutting conditions t^* and w^* , and the transformed equivalent tool normal rake angle α_n^* , the tangential chip formation force F_c^* and the thrust chip formation force F_t^* are calculated based on the orthogonal cutting force model as documented in [16]. With the consideration of the ploughing effect on the total cutting forces, the total cutting forces

F_c and F_t within the 2-D equivalent cutting geometry can be calculated based on Equ. (2). As shown in Equ. (1), t_{\max} is determined by given process attributes, r , f , and d .

Referring to [12,13] with a single-point cutting tool, the forces acting in the cutting, axial, and radial directions can be calculated respectively from

$$P_1 = F_c, \quad P_2 = F_t \cos C_s^* + F_r \sin C_s^*, \quad P_3 = F_t \sin C_s^* - F_r \cos C_s^* \quad (6)$$

where

$$F_r = \frac{F_c (\sin i^* - \cos i^* \sin \alpha_n^* \tan \eta_c^*) - F_t \cos \alpha_n^* \tan \eta_c^*}{\sin i^* \sin \alpha_n^* \tan \eta_c^* + \cos i^*} \quad (7)$$

4. Experimental validation

All machining experiments discussed below are carried out on a horizontal Hardinge lathe with 7.5 KW spindle power, and the workpiece is hardened 52100 bearing steel with hardness of HRC 62. The forces are measured with a Kistler 9257B dynamometer.

4.1. Determination of the workpiece material properties

The workpiece material property as a function of temperature, strain, and strain rate in the primary and secondary shear zones is needed to model the chip formation forces. Regarding the material property of hardened 52100 bearing steel, several models were researched [18,19]. But these models lead to certain contradictions. Poulachon *et al.* [18] neglected the effect of strain rate for the constitutive relation, but Guo *et al.* [19] considered strain rate as a dominant factor. The Johnson-Cook equation is used in this study to represent the workpiece material constitutive property and its constants (σ_0, B, n, c, m) are determined based on machining tests. The experimental data is collected by simulating orthogonal cutting hardened 52100 steel. Kennametal KD120 CBN grooving insert with 0° rake angle and straight cutting edge is used. To satisfy the plain strain condition, depth of cut is chosen as 0.889mm (0.035inch). The experiment is designed based on changing feedrate from 0.0762mm to 0.1778mm at the interval of 0.0254mm for both cutting velocities of 2.032m/s (400sfm) and 3.048m/s (600sfm). Since the orthogonal chip formation force model [16] is not analytically differentiable to provide a set of normal equations, the conventional curve fitting method based on least squares method cannot be used here. To overcome this difficulty, the determination of the constants is treated as an optimization problem by using a genetic algorithm [20]. Based on the experimental cutting force results, the constants of the Johnson-Cook equation are determined by minimizing the difference between measured cutting forces and predicted cutting forces as

$$\min \left\{ \sqrt{\sum [(F_{c,measure} - F_{c,prediction})^2 + w_1 (F_{t,measure} - F_{t,prediction})^2]} \right\}. \text{ Both } P_{c,prediction} \text{ and } P_{t,prediction} \text{ are}$$

determined by using the orthogonal force model [16]. Since the thrust force is relatively small compared with the tangential cutting force, to compensate the error that may be generated in optimization, a weight w_1 is added to the thrust force component. In this case, w_1 is specified as 1.2. In this study, the cutting forces when feed rate is 0.1270 mm/rev and 0.1778mm/rev for both

test velocities are used in determining the unknown constants of the Johnson-Cook equation. The resulting Johnson-Cook equation of hardened 52100 bearing steel is

$$\sigma = \left(774.78 + 134.46\varepsilon^{0.3710}\right) \left(1 + 0.0173 \ln \dot{\varepsilon}\right) \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{3.1710}\right) (Mpa) \quad (8)$$

where $T_m = 1487^\circ\text{C}$ (1760K) and $T_r = 25^\circ\text{C}$.

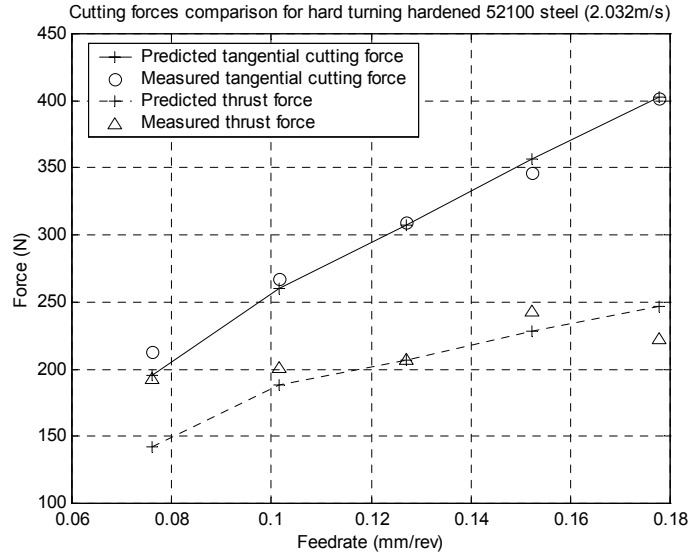


Fig. 3. Cutting forces comparison when turning hardened 52100 steel (Velocity = 2.032m/s and depth of cut = 0.889mm)

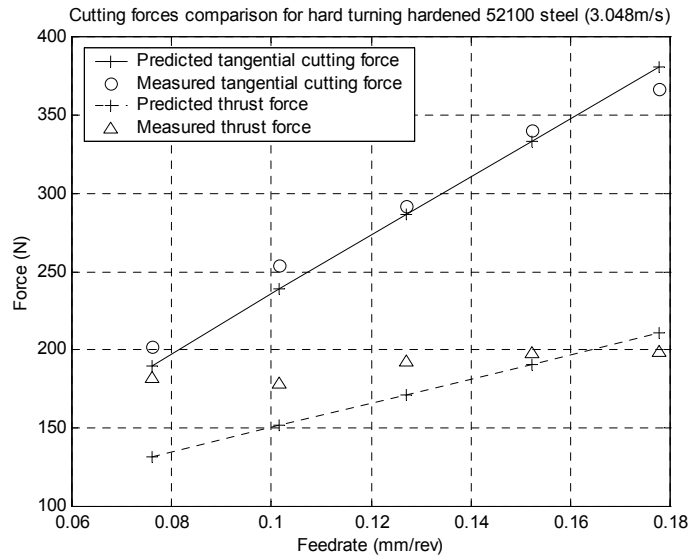


Fig. 4. Cutting forces comparison when turning hardened 52100 steel (Velocity = 3.048m/s and depth of cut = 0.889mm)

Based on the determined Johnson-Cook equation, the cutting forces are predicted by using the orthogonal cutting chip formation force model [16] and are compared with the measured cutting forces in this experiment, which are not used in calibrating coefficients of Equ. (8). The comparisons are shown in Fig. 3 and Fig. 4. In Fig. 3 and Fig. 4, the data points for feed rate of 0.1270 mm/rev and 0.1778mm/rev are the results of calibration and the others are of validation. The deviation at feedrate of 0.0762mm is believed to result from the cutting edge hone of the grooving insert. Since the used grooving inserts have a straight cutting edge, the undeformed chip thickness is uniform along the cutting edge and believed to be large enough (except for feedrate of 0.0762mm) that the ploughing effect will not happen here. No ploughing effect is considered for this grooving process. The comparisons are within 15% of error when feedrate is large.

4.2. Calibration of the ploughing effect

A Kennametal CBN tool insert (KD050) is used in turning hardened 52100 steel. The tool has a nose radius of 0.8mm, chamfer length of 0.1mm, and chamfer angle of -20° . The expressed normal rake angle on chamfered face is -25° , the normal rake angle is -5° , and the inclination angle is -5° . The testing conditions are selected based on the tool manufacturer's recommended range. Two sets of cutting experiment are performed: 1). Changing feedrate from 0.0508mm to 0.1778mm at the interval of 0.0127mm by specifying depth of cut at 0.127mm and cutting velocity at 2.13m/s; and 2). Changing depth of cut from 0.1016mm to 0.3048mm at the interval of 0.0254mm by specifying feedrate at 0.0762mm/rev and cutting velocity at 2.13m/s. Because of the difficulty in generating the normal equations for the least squares method, the determination of the constants of the ploughing effect coefficients is treated as an optimization process. Six groups of experiment results (the 3-D cutting forces when depth of cut is specified at 0.127mm and velocity at 21.3m/s, but feedrate is 0.0508mm/rev, 0.0762 mm/rev, 0.1016 mm/rev, 0.1270 mm/rev, 0.1524 mm/rev, and 0.1778 mm/rev) are used to determine the constants of the ploughing effect coefficients (a 's and b 's in Equation (3)) and are solved by minimizing the difference between measured forces and predicted forces as $\min\left\{\sqrt{\sum[(P_{1,m} - P_{1,p})^2 + (P_{2,m} - P_{2,p})^2 + (P_{3,m} - P_{3,p})^2]}\right\}$. The cutting forces $P_{1,p}$, $P_{2,p}$, and $P_{3,p}$ are predicted based on Equ. (6). Again, the genetic algorithm is used in this calibration. The ploughing effect coefficients of K_c and K_t are determined as

$$K_c = 3.0759 - 1.7424t_{\max} - 6.1909t_{\max}^{0.6592} \quad \text{and} \quad K_t = 5.7836 - 2.5969t_{\max} - 14.5324t_{\max}^{0.6246} \quad (9)$$

4.3. Model validation

As discussed in Section 4.2, six groups of experiment results of experimental design set one are used in calibrating the ploughing effect coefficients. The remaining data points of experimental design set one (the 3-D cutting forces when depth of cut is specified at 0.127mm and velocity at 21.3m/s, but feedrate is 0.0635mm/rev, 0.0889 mm/rev, 0.1143 mm/rev, 0.1397 mm/rev, and 0.1651mm/rev) are used for model validation. These measured cutting forces are compared with the model predictions. As shown in Fig. 5, the comparisons are within 15% of error.

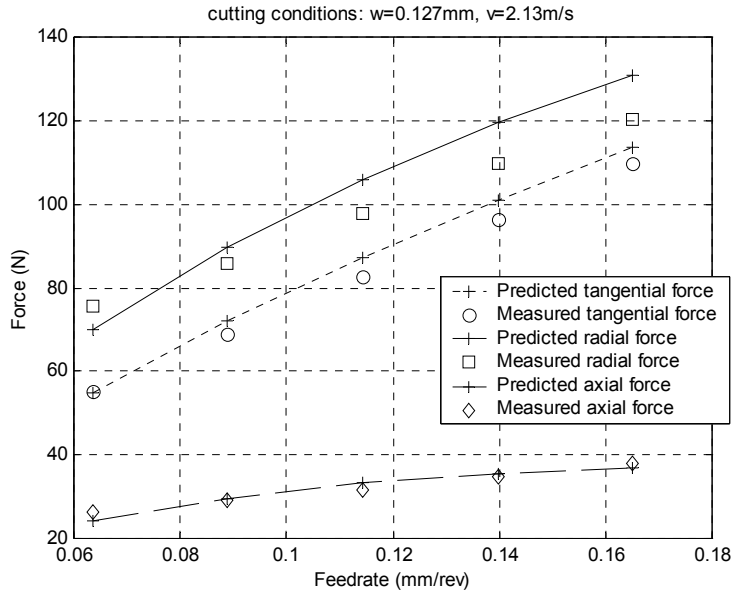


Fig. 5. Cutting forces comparison as feedrate changes (Velocity = 2.13m/s and depth of cut = 0.127mm)

No experimental data points of experimental design set two are used in calibration in Section 4.2. To test the feasibility of the proposed mechanistic modeling, the determined ploughing effect mechanistic model (Equ. (9)) is further used to predict the total cutting forces for the conditions specified by experimental design set two, where depth of cut is changed. The predicted forces match well with the experimental data as shown in Fig. 6. The force comparisons are within 15% of error.

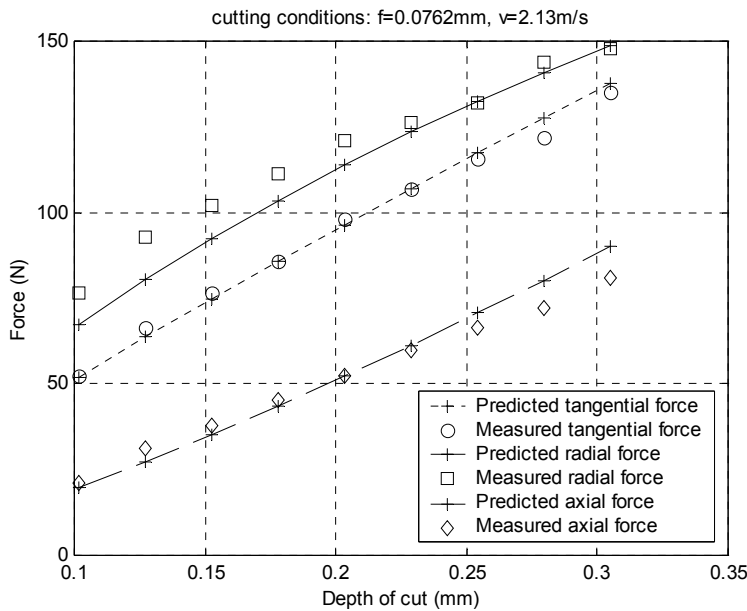


Fig. 6. Cutting forces comparison as depth of cut changes (Velocity = 2.13m/s and feedrate = 0.0762mm/rev)

To appreciate the importance of ploughing effect coefficients, force predictions without considering the ploughing effect are shown in Figs. 7 and 8 for both of the two validation cases. It can be seen that there is a large difference between force predictions and measurements if the ploughing effect is ignored. The values of ploughing effect coefficients K_c and K_t with respect to feedrate (when depth of cut = 0.127mm) and depth of cut (when feedrate = 0.0762mm/rev) are shown respectively in Figs. 9 and 10. As expected, K_c and K_t decrease as feedrate or depth of cut increases because the ploughing effect turns less significant when maximum undeformed chip thickness increases. For shallow cuts, the ploughing forces contributes to the dominant portion of the total cutting forces and cannot be ignored as seen from Figs. 9 and 10.

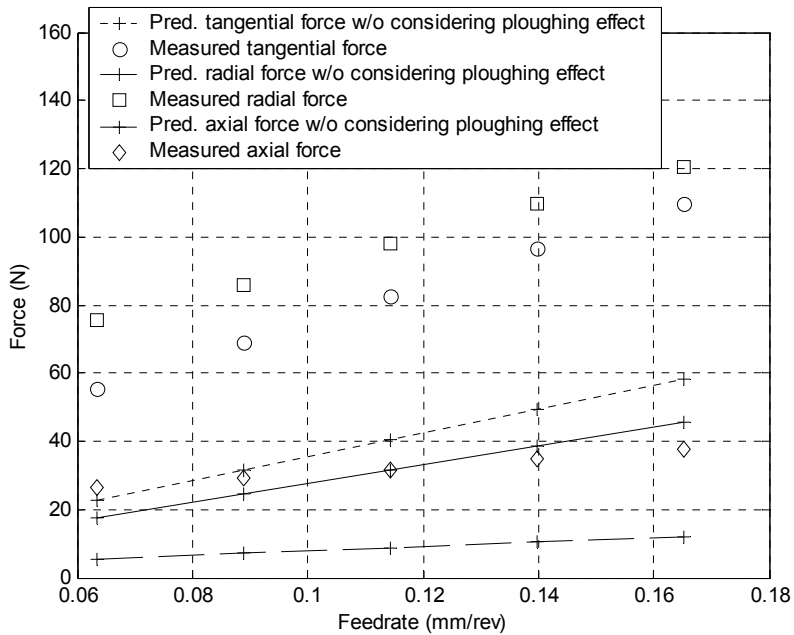


Fig. 7. Cutting forces comparison as feedrate changes without considering the ploughing effect (Velocity = 2.13m/s and depth of cut = 0.127mm)

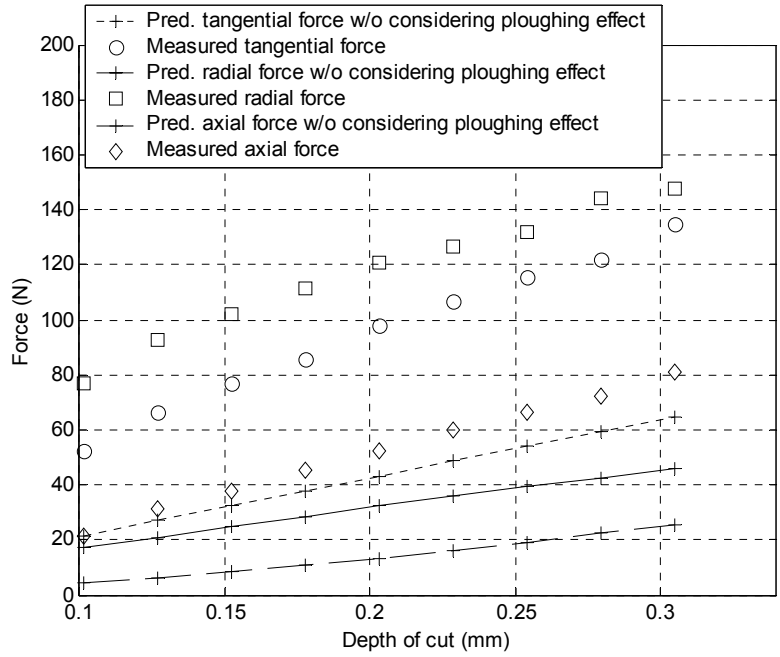


Fig. 8. Cutting forces comparison as depth of cut changes without considering the ploughing effect (Velocity = 2.13m/s and feedrate = 0.0762mm/rev)

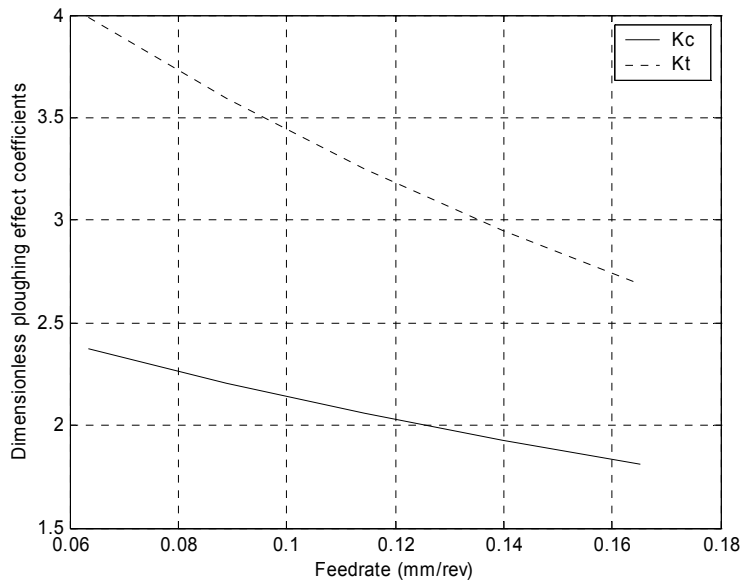


Fig. 9. Ploughing effect coefficients vs. feedrate (Depth of cut = 0.127mm and tool nose radius = 0.8mm)

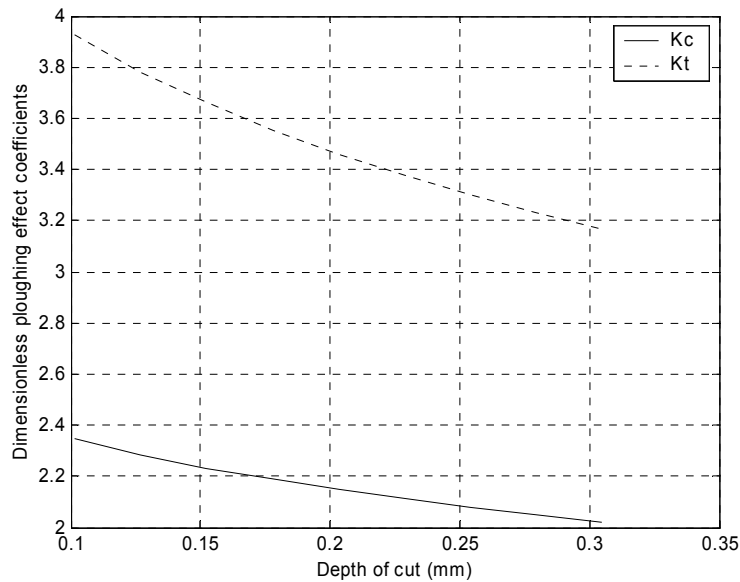


Fig. 10. Ploughing effect coefficients vs. depth of cut (Feedrate = 0.0762mm/rev and tool nose radius = 0.8mm)

5. Conclusion

The ploughing effect is common in shallow cuts with large negative rake angle and large nose radius tools, such as in finish hard turning. To model cutting forces in such shallow cuts in this paper, first the chip formation forces are predicted by transforming the 3-D cutting geometry into the equivalent 2-D cutting geometry, then the ploughing effect mechanistic model is proposed to calculate the total 2-D cutting forces. Finally, 3-D cutting forces are estimated by the geometric transformation. The proposed model is calibrated and validated through the experimental machining data of finish turning hardened 52100 steel. The Johnson-Cook equation is used to represent the workpiece material property of hardened 52100 steel. The total cutting forces match measurements within 15% error. The comparison also shows the validity of the ploughing effect mechanistic model as applied to the broader cutting conditions.

Acknowledgements:

The authors wish to express their gratitude to Mr. Anand Ramesh at Georgia Tech for the orthogonal hard grooving data and Mr. Ty G. Dawson at Georgia Tech for his discussion during the machining experiments. The authors also thank the reviewers for their inputs and comments.

References:

- [1] B. P. Wang, A. B. Sadat, and M. J. Twu, Finite Element Simulation of Orthogonal Cutting – A Survey, Materials in manufacturing processes, MD-vol. (8), ASME WAM, Chicago, IL, pp. 87-91, Dec. 1988.

- [2] E.G. Ng, D.K. Aspinwall, D. Brazil, and et al., Modeling of Temperature and Forces when Orthogonally Machining Hardened Steel, *Int. J. Mach. Tools Manufact.*, 39, pp. 885-903, 1999.
- [3] M.E. Merchant, Mechanics of the Metal Cutting Process, Part 2: Plasticity Conditions in Orthogonal Cutting, *J. Appl. Phys.*, 16, pp. 318-324, 1945.
- [4] E.H. Lee and B.W. Shaffer, Theory of Plasticity Applied to Problems of Machining, *ASME J. of App. Mechanics*, 18(4), pp. 104-113, 1951.
- [5] P.L.B. Oxley, *Mechanics of Machining, an Analytical Approach to Assessing Machinability*, Ellis Horwood Limited, West Sussex, England, 1989.
- [6] P. Albrecht, New Developments in the Theory of the Metal-cutting Process, Part 1: The Ploughing Process in Metal Cutting, *J. of Eng. for Ind.*, pp. 348-358, 1960.
- [7] D.W. Wu, Application of a Comprehensive Dynamic Cutting Force Model to Orthogonal Wave-generating Process, *Int. J. Mech. Sci.*, 30(8), pp. 581-600, 1988.
- [8] C. Rubenstein, The Edge Force Components in Oblique Cutting, *Int. J. Mach. Tools Manufact.*, 30(1), pp. 141-149, 1990.
- [9] S. Elanayar and Y.C. Shin, Modeling of Tool Forces for Worn Tools: Flank Wear Effects, *ASME J. of Manuf. Sci. and Eng.*, 118(3), pp. 359-366, 1996.
- [10] D.J. Waldorf, R.E. DeVor and S.G. Kapoor, A Slip-line Field for Ploughing during Orthogonal Cutting, *ASME J. of Manuf. Sci and Eng.*, 120(4), pp. 693-699, 1998.
- [11] H.A. Kishawy and M.A. Elbestawi, Effects of Process Parameters on Material Side Flow during Hard Turning, *Int. J. Mach. Tools Manufact.*, 39, pp. 1017-1030, 1999.
- [12] J.A. Arsecularatne, P. Mathew and P.L.B. Oxley, Prediction of Chip Flow Direction and Cutting Forces in Oblique Machining with Nose Radius Tools, *Proc. Inst. Mech. Engrs.*, 209(B), pp. 305-315, 1995.
- [13] J. A. Arsecularatne, P. Mathew and P.L.B. Oxley, Modeling Approach, Its Applications and Future Directions, *Machining Science and Technology*, 4(3), pp. 363-397, 2000.
- [14] A.J.P. Sabberwal, Chip Section and Cutting Forces during the Milling Operation, *Annals of CIRP*, 10, pp. 197-203, 1961.
- [15] P.L.B. Oxley, Rate of Strain Effect in Metal Cutting, *ASME J. of Eng. for Industry*, 85, pp. 339-345, 1963.
- [16] Y. Huang and S.Y. Liang, Force Modeling Considering the Effect of Tool Thermal Property-Application to CBN Hard Turning, to appear in *Int. J. of Mach. Tools Manufact.*, 2002.
- [17] G.V. Stabler, The Fundamental Geometry of Cutting Tools, *Proc. Inst. Mech. Eng.*, 165, pp. 14-21, 1951.
- [18] G. Poulachon, A. Moisan and I.S. Jawahir, On Modeling the Influence of Thermo-Mechanical Behavior in chip Formation during Hard Turning of 100Cr6 Bearing Steel, *Annals of CIRP*, 50(1), pp. 31-36, 2001.
- [19] Y.B. Guo and C.R. Liu, Mechanical Properties of Hardened AISI 52100 Steel in Hard Machining Processes, *ASME J. of Manufacturing Science and Engineering*, 124(1), pp. 1-9, 2002.
- [20] D.E. Goldberg, *Genetic algorithm in search, optimization, and machine learning*, Addison Wesley, Reading, MA, 1989.