한국공작기계학회 2000년도 추계학술대회 논문집 pp.262~267

A Study on the Effect of Tool Thermal Deformation on Surface Roughness for Turning Process

Min Sung Hong*, Zhe Man Lian**, Dong Joon Kim**

* Division of Mechanical and Industrial Engineering, Ajou Univ.
** Department of Mechanical Engineering, Graduate School, Ajou Univ.

Abstract

During the turning of the workpiece, cutting heat causes thermal deformation of the cutting tool which influences the surface characteristics of the machined part. This paper presents a study of thermal deformation of the cutting tool. For this purpose, cutting tool is modeled based on Pro/Engineering and temperature and deformation are simulated by means of the finite element method. The thermal effect on the surface roughness profile is simulated by using surface-shaping system.

Key words: Surface roughness, Thermal deformation, FEM, Surface-shaping system.

1. Introduction

During the metal cutting energy is expended in deforming the chip and overcoming friction between the tool and the workpiece. Almost all of this energy is converted into heat.[1] Most of the heat is carried away by the chip while the rest is conducted through the tool and convected through the workpiece due to the movement of the workpiece relative to the cutting edge. The heat causes a rise in temperature and thermal deformation of the cutting tool. The deformation leads to displacement between cutting edge and surface of the workpiece which effects the surface roughness of the machined parts.

A number of experimental techniques and the finite element methods[2,3] have been applied to measure and calculate machining temperatures. The thermal deformations of the workpiece[4] due to the change in the temperature and the thermal deformation of the cutting tool in end milling[5] have been studied. However, the effect of thermal deformation of the cutting tool on the surface roughness in turning process has not been reported.

This paper presents a method for predicting the thermal deformation of the cutting tool in turning. Tool insert is modeled based on the Pro/Engineering and temperature and deformation are simulated by means of the finite element method. The effect of the deformation on the surface roughness is simulated by surface-shaping system.

2. Formulation of the Thermal Deformation of the Cutting Tool

A finite solid model, resembling the tool insert with dimensions $0 \le x \le L_x$, $0 \le y \le L_y$, and $0 \le z \le L_z$ is considered in this study. Since chip continuously flows on the rake face of cutting tool with a constant speed during machining, constant frictional heat is generated at the tool-chip interface. When the tool is assumed to have a sharp cutting edge, with negligible contact between the flank face and the workpiece, a heat source for the cutting tool exists at the tool-chip interface.

The governing equation and boundary condition, assuming temperature-independent thermal properties and ignoring radiations is written as:

$$\nabla^2 T = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

$$-k\frac{\partial T}{\partial z} = Q(x, y, t) \quad (2)$$

$$z=0; \quad 0 \le x \le a, 0 \le y \le b,$$

where T is the temperature, k is the thermal conductivity, α is the thermal diffusivity, a and b are tool-chip contact length representing the dimension of the heat source at the rake face, and Q is the heat source. This problem is most easily solved using Green's functions.[6,7,8] Figure 1 shows the coordinates of the cutting tool. The heat source has a rectangular shape with length a in x direction and length b in y direction. Heat transfer takes place at the surface of tool. The Green's function for the tool can be expressed as follows:

$$\theta_G = 8\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{p=1}^{\infty}[\exp(-\alpha(\beta_m^2+\upsilon_n^2+\eta_p^2)(t-\tau))]$$

$$\times\frac{h\sin\beta_m x+\beta_m\cos\beta_m x}{(h^2+\beta_m^2)L_x+2h}\times\frac{h\sin\upsilon_n y+\upsilon_n\cos\upsilon_n y}{(h^2+\upsilon_n^2)L_y+2h}$$

$$\times\frac{h\sin\eta_p z+\eta_p\cos\eta_p z}{(h^2+\eta_p^2)L_z+2h}\times(h\sin\beta_m x'+\beta_m\cos\beta_m x')$$

$$\times(h\sin\upsilon_n y'+\upsilon_n\cos\upsilon_n y')(h\sin\eta_p z'+\eta_p\cos\eta_p z') \quad (3)$$

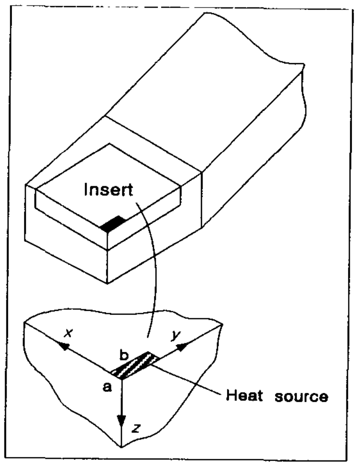


Fig. 1 Heat source of the rake face

Since heat source exists on the rake face of the tool. Temperature of the tool is:

$$T=\frac{\alpha Q}{\lambda}\int_0^a\int_0^b\int_0^t\theta_G d\tau dx' dy' = \frac{8Q}{\lambda}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{p=1}^{\infty}$$

$$\frac{\eta_p}{\beta_m^2+\upsilon_n^2+\eta_p^2}\times[1-\exp(-\alpha(\beta_m^2+\upsilon_n^2+\eta_p^2)t)]$$

$$\times C_x C_y C_z P_a P_b \quad (4)$$

where

β_m: m-th positive root of $\tan\beta Lx = 2\beta h/(\beta^2-h^2)$

υ_n : n-th positive root of $\tan\upsilon Ly = 2\upsilon h/(\upsilon^2-h^2)$

η_p : p-th positive root of $\tan\eta Lz = 2\eta h/(\eta^2-h^2)$

$$C_x=\frac{h\sin\beta_m x+\beta_m\cos\beta_m x}{(h^2+\beta_m^2)L_x+2h}$$

$$C_y=\frac{h\sin\upsilon_n y+\upsilon_n\cos\upsilon_n y}{(h^2+\upsilon_n^2)L_y+2h}$$

$$C_z=\frac{h\sin\eta_p z+\eta_p\cos\eta_p z}{(h^2+\eta_p^2)L_z+2h}$$

$$P_a=\frac{h}{\beta_m}(1-\cos\beta_m a)+\sin\beta_m a$$

$$P_b = \frac{h}{\upsilon_n}(1 - \cos \upsilon_n b) + \sin \upsilon_n b \qquad (5)$$

where $\beta_m, \upsilon_n, \eta_p$ are eigenvalues. h is relative coefficient of heat transfer. The thermal deformation of the tool in x direction can be expressed as follows:

$$\Delta x = \frac{8Q\eta}{\lambda} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{p=1}^{\infty} \frac{\eta_p}{\beta_m^2 + \upsilon_n^2 + \eta_p^2}$$
$$\times [1 - \exp(-\alpha(\beta_m^2 + \upsilon_n^2 + \eta_p^2)t)] \times C_x' C_y C_z P_a P_b \qquad (6)$$

where

$$C_x' = \frac{(h/\beta_m)(1 - \cos \beta_m L_x) + \sin \beta_m L_x}{(h^2 + \beta_m^2) L_x + 2h}$$

The thermal deformation Δy in the y direction and the Δz in the z direction are solved by using the same method, respectively. The tool thermal deformation in the direction of the depth of cut as shown in Fig. 2 can be written as follows:

$$\Delta l = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \times$$
$$\cos\left(\tan^{-1} \frac{\Delta z}{\sqrt{\Delta x^2 + \Delta y^2}} - \gamma_0\right) \times \cos\left(\tan^{-1} \frac{\Delta x}{\Delta y} - k_r'\right) \qquad (7)$$

where γ_0, k_r' are respectively rake angle and end cutting edge angle of the tool. The deformation is also observed in the following FEM model.

3. Surface Generation by Surface-Shaping System for Turning Process

Surface-shaping system[9], proposed by Hong, will be used to describe the generation and characteristics of engineering surface. It defines a generalized analytical framework and procedure

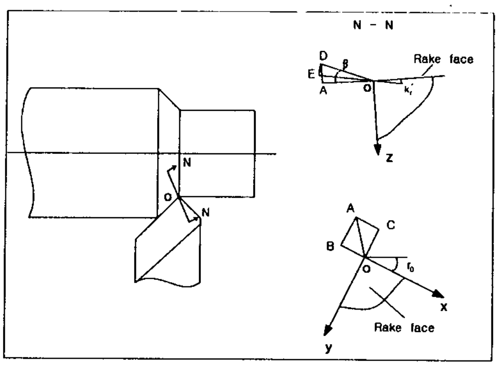


Fig. 2 The thermal deformation of the cutting tool

for the simulation of surface generation processes. The system incorporates not only the nominal cutting motions but also takes into account errors during machining such as spindle runout, machine deformation and vibration, as well as higher order motions. The surface-shaping system model also utilizes a precise description of the tool geometry. Therefore, this model provides a general mathematical basis for the prediction of the surface characteristics of metal removal manufacturing processes. The model of the surface-shaping system can be expressed as follows:

$$r_0 = B_{0,n} B_T e^4 \qquad (8)$$

Figure 3 shows the traditional turning process with a single-point tool. The radius vector r_0 of the surface-shaping points p_k on the cutting edge in the reference frame $\{S_0\}$ is derived as follows:

$$r_0 = B_{0,5} r_5$$
$$= {}^N A^6(\theta) {}^N A^1(x) {}^N A^2(y) {}^N A^3(z) {}^E A^1(e_{th}) r_5 \qquad (9)$$

where ${}^N A^6(\theta)$ represents the nominal rotation of the frame {S1} about the Z-axis and ${}^{N}A^{1}(x)$, ${}^{N}A^{2}(y)$, and ${}^{N}A^{3}(z)$ are the nominal translations x, y, and z of the different frames in the X, Y, and Z directions with respect to frame {S0}, respectively. ${}^{E}A^{1}(e_{th})$ represents the thermal deformation. r_5 is the radius vector of the surface-shaping points of the tool in frame{S5} which can be written as:

$$r_5 = {}^{N}A^{5}(\psi){}^{N}A^{1}(\rho){}^{N}A^{2}(p_{yk})e^{4} \quad (10)$$

where ${}^{N}A^{5}(\psi)$ is the nominal rotation of the radius vector r_5 about the Y-axis and ${}^{N}A^{1}(\rho)$ and ${}^{N}A^{2}(p_{yk})$ are the nominal translations ρ and p_{yk} of the radius vector r_5 in the direction of the X and Y axes with respect to frame {S5}, respectively.

4. FEM Analysis

In order to observe thermal deformation of the cutting tool, the cutting tool is modeled by using Pro/E 2000i and the FEM package ANSYS 5.6 is used. The material properties of tool and cutting parameters used in the simulation are tabulated in Table 1 and 2, respectively. Figure 4 shows the FEM model of the tool insert. The temperature distribution of the tool insert is shown in Figure 5a and the temperature distribution measured in the direction of the chip flow is shown in Figure 5b. The thermal deformation of the tool tip is 41 μm as shown in Figure 6.

5. Results and Discussion

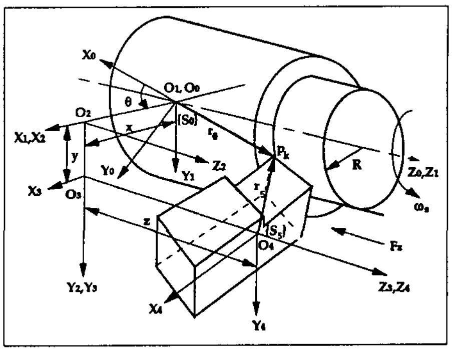


Fig. 3 Surface-shaping system of the turnig process

Table 1. Material properties of tool

Young's Modulus	517 GPa
Coefficient of Thermal Expansion	6.0×10^{-6}/ ℃
Thermal Conductivity	48 W/m ℃

Table 2. Cutting parameters

Spindle Speed (rpm)	600
Feed (mm)	0.2
Depth of Cut (mm)	1
End Cutting Edge Angle	35°
Rake Angle	-5°
Tool	Carbide Insert

Based on the surface-shaping system, computer simulation for the surface roughness is conducted. Figure 7 shows the methodology to simulate a machined surface. From the above simulation results, the deformation of tool influences the surface roughness profile of the machined workpiece. The difference of surface profiles between ideal and thermal deformation is shown in Figure 8. The surface profiles varied along feed direction. This is due to thermal

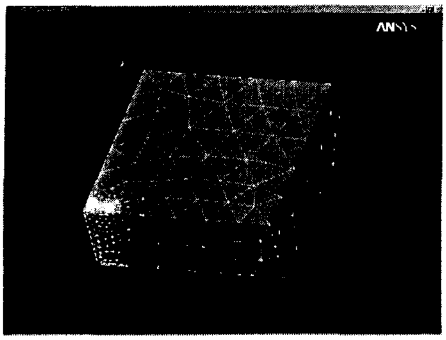
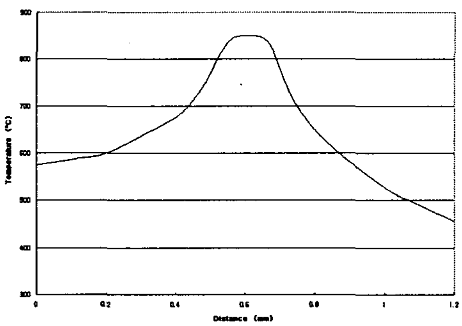


Fig. 4 FEM model of tool insert

(a) Tool insert



(b) Measured in the direction of chip flow

Fig. 5 Temperature distribution

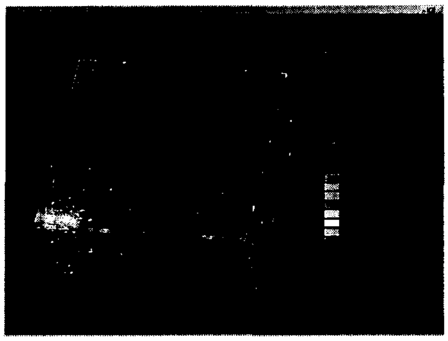


Fig. 6 The thermal deformation of the tool insert

error of tool. Figure 9 shows the thermal error of the tool. The surface roughness average S_a and root mean square S_q are 1.61 μm and 1.99 μm under the ideal conditions, and 1.91 μm and 2.27 μm considering the thermal deformation of the cutting tool, respectively.

6. Conclusions

This paper presents a study of thermal deformation of the cutting tool. The thermal effect on the surface roughness is simulated based on the surface-shaping system. From this study, the following conclusions can be drawn:

1. The temperature distribution of the rake face of the tool and thermal deformation have been observed based on the finite element method for the tool insert.
2. Through FEM analysis model and simulated results based on the surface-shaping system, the thermal deformation of the cutting tool influences the surface roughness profile.
3. By using the general model of the surface -shaping system, the surface roughness can be predicted for turning process.

References

[1] David, A. S., and John, S. A., *Metal Cutting Theory and Practice*, MARCEL DEKKER, 1997.

[2] Tay, A. O., Stevenson, M. G., and de Vahl Davis, G., "Using the Finite Element Method to Determine Temperature Distributions in Orthogonal Machine," Proc. Inst. of Mech. Engrs., Vol. 188, pp. 627~638, 1974.

[3] Stephenson, D. A., and Ali, A., "Tool Temperatures in Interrupted Metal Cutting," ASME Journal of Engineering for Industry, Vol. 114, pp. 127~136, 1992.

[4] Stephenson, D. A., and Barone, M. R., " Thermal Expansion of The Workpiece in Turning," ASME Journal of Engineering for Industry, Vol. 117, pp. 542~550, 1995.

[5] Hong, M. S., "A Study on The Thermal Deformation of A Cutting Tool in End Milling," Journal of the Korean Society of Machine Tool Engineers, Vol. 8, pp. 25~29, 1999.

[6] Carslaw, H. S., and Jaeger, J. C., *Conduction of Heat in Solids*, Clarendon Press, Oxford, 1959.

[7] Beck, J. V., Cole, K. D., Haji-Sheikh, A., and Litkouhi, B., *Heat Conduction Using Green's Functions*, HEMISPHERE, 1992.

[8] Ozisik, M. N., *Boundary Value Problems of Heat Conduction*, DOVER PUBLICATIONS, New York, 1968.

[9] Hong, M. S., "Generation, Characterization and Synthesis of Engineering Surfaces," Ph.d Thesis, Northwestern University, 1993.

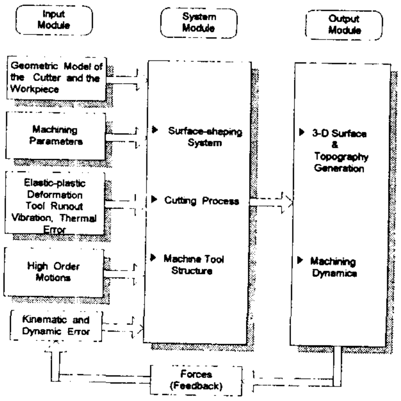


Fig. 7 Methodology to simulate a machined surface

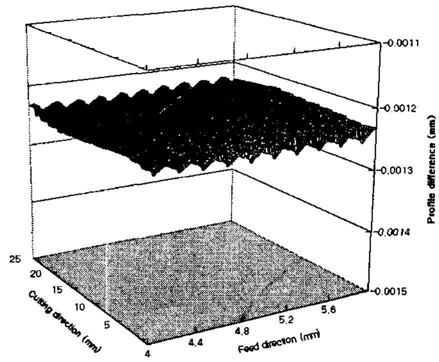


Fig. 8 The difference of surface profiles between ideal and thermal deformation

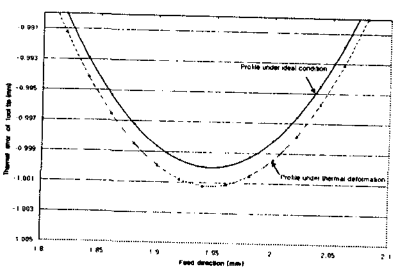


Fig. 9 Thermal error of the tool tip