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Force and spatial profile analysis of surface generation of single point diamond turning

W. Yuan[1], W.B.Lee[1], C.Y.Chan[1], L.H.Li[1]

1 The State Key Laboratory of Ultraprecision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong

15901591r@connect.polyu.hk

Abstract

In ultra-precision machining, the vibration sensors were conventionally mounted underneath the tool holder. In this paper, investigation has been made to study how representative the vibration signals captured could be by corresponding them with the arithmetic average value of surface profile in ultra-precision facing process. To correlate the surface profile data with the cutting process, a spatial profile retracing algorithm was developed to retrace the changes of profile along the cutting path from a measured 3D surface profile. By statically comparing the spatial and vibration signals, it was found that the tool-work vibration, which was along the cutting direction, was identified to be the most significant factor affecting surface generation. Even though the normal of the surface profile was parallel to the thrust force direction and was perpendicular to the cutting direction, the surface profile variation was found to bear more similarities to the tool-work vibration than that of the thrust force vibration.

Keywords: Ultra-precision machining, tool-work vibration, surface generation

1. Introduction

Ultra-precision diamond turning has been widely employed to fabricate high precision components with nano-metric surface roughness and sub-micrometric form accuracy. In order to obtain high surface quality on the machined surface, many factors were reported to be of prime importance including cutting conditions [1], crystal orientation [2] and tool vibration [3- 5].

Among all the above major factors, tool-work vibration has drawn much attention in recent years. The relative vibration between tool and workpiece is generally called tool-work vibration. Unfortunately, most of the researchers concurred that their measurement methods were along the thrust direction. To identify the actual tool-work vibration is very important because vibration describes precisely on how the tool moves relative to the workpiece. Besides, the surface roughness in the above studies is based on the profile of a machined surface, rather than the profile along the cutting trajectory. Unfortunately, only the variation of profile along the cutting trajectory could reasonable be matched with cutting force signals. It is expected that this relative movement would have direct impact on the cutting performance, the surface finish and the cutting forces. In this paper, a series of spiral cutting experiments was conducted. A retracing algorithm has been developed to retrace the surface profile along the cutting path and to investigate the variation of the retraced profile with surface finish.

2. Methodology

The surface profile was measured by Zygo NewView8000, a 3D optical surface profiler. However, the profiler cannot retrace the spatial helical profile along the cutting trajectory directly and precisely. Rather, the profile measurement was done by scanning the whole machined surface at identical distance intervals. To meaningfully correlate the scanning profile with the cutting force which was also recorded at the same time intervals, a retracing algorithm was developed. Due to the limitation of computation speed of our server, only the central area of the machined surface was investigated. The spatial helical profile was extracted through the following steps. All the vectors are represented in bold letters.

1) Read the set of all surface data-points $(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$and screen all the data points to computational load for next steps:

$$\{(\boldsymbol{x_1},\boldsymbol{y_1},\boldsymbol{z_1})|\,(\boldsymbol{x_1},\boldsymbol{y_1},\boldsymbol{z_1})\in(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}),\ z_{min}\le\boldsymbol{z_1}\le z_{min}+\tfrac{1}{3}(z_{max}-z_{min})\} \quad (1)$$

where z_{min} and z_{max} are the minimum and maximum values of $\boldsymbol{z}$ respectively. The central point $(\mathrm{a},\mathrm{b},\mathrm{c})$ is identified by equation (2) because in the facing experiments, a hole was pre-cut on every specimen to mark its center.

$$\{(a,b,c)|\,(a,b,c)\in(\boldsymbol{x_1},\boldsymbol{y_1},\boldsymbol{z_1}),\mathrm{c}=\ z_{min}\} \quad (2)$$

The screened surface data is shown in Figure.1 (1).

2) Generate the ideal spiral profile according to the cutting parameters. The ideal spiral was the profile of cutting trajectory on the surface sampled at the same time intervals. A lower sampling rate (500 Hz) was adopted because of the limitation of Zygo profiler in which the highest lateral resolution of surface measurement is 1.4749 µm. In the experiments, the tool tip moves 0.2 mm per revolution of the spindle. The ideal spiral profile $(\boldsymbol{\theta},\mathbf{R}\,(\boldsymbol{\theta}))$ in polar coordinate is:

$$\begin{cases}\boldsymbol{\theta}=\dfrac{\omega}{60}\times360\times\boldsymbol{t}\\ \mathbf{R}\,(\boldsymbol{\theta})=(y_{1max}-b)-\dfrac{20}{60}\times\boldsymbol{t}\end{cases} \quad (3)$$

where ω is the spindle speed; $\boldsymbol{t}$ is the discrete sampled time and y_{1max} is the maximum value of $\boldsymbol{y_1}$. The pole is at the center of the workpiece.

The ideal spiral profile $(\boldsymbol{x_2},\boldsymbol{y_2})$ in the Cartesian coordinate is:

$$\begin{cases} x_2 = \mathbf{R}(\boldsymbol{\theta}) \times \cos\left(\frac{\boldsymbol{\theta}}{180} \times \pi\right) + a \\ y_2 = \mathbf{R}(\boldsymbol{\theta}) \times \sin\left(\frac{\boldsymbol{\theta}}{180} \times \pi\right) + b \end{cases} \quad (4)$$

The ideal spiral profile is shown in Figure.1 (1).

3) Find the spatial helical profile (x_s, y_s, z_s) on the surface such that

$$\{(x_s, y_s, z_s)\,|\,(x_s, y_s, z_s) \in (x, y, z), x_s = x_2, y_s = y_2\} \quad (5)$$

4) Calculate the arc length $\boldsymbol{S}$ of the ideal profile such that

$$S_{[n]} = \sum_{i=1}^{n} \sqrt{(x_{s[i]} - x_{s[i-1]})^2 + (y_{s[i]} - y_{s[i-1]})^2}$$

where *i* is index of $\boldsymbol{S}$. *n=1,2,3,…N***,** and *N* is the length of x_s .
The $\boldsymbol{S}$-z_s profile is shown in figure 1(2).

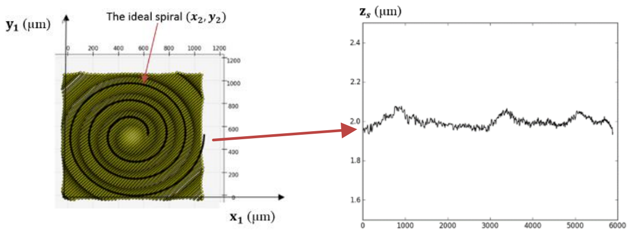

Figure 1. (1) Ideal cutting trajectory on the screened surface profile (2) The $\boldsymbol{S}$-z_s profile.

3. Experiment setup

The spiral-cutting experiments as shown in figure. 2(1) were conducted on a Nanotech 350FG ultraprecision machine. X, Y, Z shown in figure. 2(1) represent feed direction (FD), cutting direction (CD) and thrust direction (TD) respectively. The material used was aluminum alloy 6061. Before the spiral-cutting tests, all the specimens were prepared by ultraprecision turning and flattened by the same machine. , a hole was pre-cut on every specimen to mark its center. The specimen were cut under the conditions shown in Table 1. During the experiments, the cutting forces in the FD, CD and TD are measured by a Kistler 9258B force transducer with a sampling rate of 50 kHz. The machined surface is shown in figure. 2 (2).

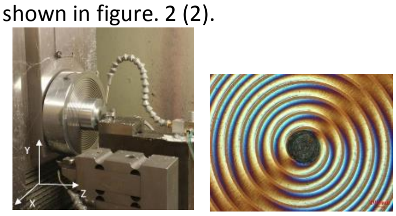

Figure 2. (1) Spiral-cutting experiment setup (2) Machined surface.

Table 1. Cutting conditions

parameters	value
spindle speed	100 rpm
feedrate	20 mm/min
depth of cut	1,2,5,10,15 um
tool noise radius	2.54 mm
lubricant	No

4. Results and discussion

Test results of the surface roughness (Ra) of helical profile z_s and arithmetic average value (Ra) of cutting forces along TD, FD and CD are shown in figure 3. Ra value is calculated using the following equation (6), where y_i is the i^{th}magnitude of helical profile z_s or cutting force.

$$R_a = \frac{1}{n}\sum_{i=1}^{n} |y_i| \quad (6)$$

As shown in the figure. 3, the Ra value of helical profile and cutting force in cutting direction are both increasing as the depth of cut is larger. While those values of cutting force in thrust and feed direction are not correlated well with depth of cut. Therefore, the force in cutting direction is the dominant factor in the surface generation along the cutting trajectory rather than the force in thrust or feed direction. As the surface profile and force in the cutting direction has the prominent positive correlation relationship, the tool-work vibration along the cutting direction is probably the prime factor most closely correlated with the variation of surface profile along cutting trajectory. When the depth of cut decreased to 1 µm, the surface roughness is relatively large which is not compatible with forces in any direction.

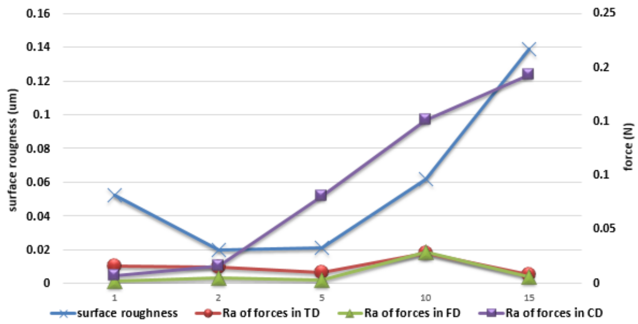

Figure 3. Surface roughness and arithmetic average value (Ra) of cutting forces.

5. Conclusion

In this paper, a retracing algorithm was developed to extract the surface profile along the cutting trajectory so as to investigate the property of surface generation and its correlation to cutting forces along thrust, feed and cutting directions. It was found that the arithmetic average value of surface profile has a strong positive correlation relationship with force along cutting direction when the depth of cut was in the range of 2 to 15 µm.

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