Effects of chatter on workpiece surface topography during diamond turning

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During diamond turning of difficult-to-cut materials, a kind of self-excited vibration named chatter may occur mainly due to the regenerative effect. It usually leads to large cutting forces and vibrations of the workpiece/cutting tool, resulting in inferior workpieces and short tool lives. Thus, chatter phenomenon is analyzed for the ultra-precision diamond turning process in this study. Based on the regenerative effect, the turning force is modeled by considering the effect of chatter. The diamond turning experiment of titanium alloy is then carried out. The results on the measured cutting forces and the machined surface of the workpiece show that chatter not only affects the surface roughness (Sa and Sz values) of the workpiece, but also changes the surface pattern.

1. Introduction

Diamond turning of ultra-precision machining is an important method to machine difficult-to-cut materials. In order to obtain good surface quality of diamond turning, conservative cutting parameters are generally selected to avoid unstable vibration, i.e., chatter. Chatter is a self-excited vibration occurred between the cutting tool and workpiece [1]. It usually leads to large vibrations of the cutting tool and workpiece, reducing the surface quality and accelerating tool wear. Although conservative parameters are benefit to avoiding chatter, the machining efficiency is therefore low. Furthermore, the manufacturing of micro/nanostructures and curved surfaces frequently involves the use of tools featuring large clearance angles and occasionally lengthy overhangs, which can reduce the stiffness of the tool system. Additionally, ultra-precision machining often encompasses the processing of the thin-walled workpiece that lacks stiffness, as well as difficult-to-cut materials characterized by high strength. Both these scenarios, pertaining to the cutting tool and workpiece systems, are prone to induce chatter. Therefore, chatter during the ultra-precision machining such as diamond turning necessitates greater focus.

So far, only several studies on chatter in the ultra-precision machining process have been performed. For example, considering the tool wear effect, Li et al. [2] studied the chatter stability of fly cutting. Tan et al. [3] used ultrasonic elliptical vibration-assisted cutting technology to perform dry-ultra-precision cutting of Ti-6Al-4V alloy, and suppressed chatter during the machining process. Li et al. proposed a cutting force-based method to detect chatter [4] and also suppressed chatter using a developed magnetic field system in the diamond turning of Ti-6Al-4V alloy [5]. Considering the chatter effect, Ahemd et al. [6] tried to generate micro textures using controlled chatter during the diamond turning process. These studies mainly pay attention to stability analysis and suppression of chatter. Different from previous studies, this work focuses on the effect of chatter on surface topography of the workpiece. The relationship between the surface pattern and the cutting force is also studied, which helps to better reveal the impact of chatter on diamond turning.

2. Chatter phenomena

2.1 Chatter mechanism

As stated above, chatter is a kind of self-excited vibration occurred in the machining process due to the regenerative effect. As shown in Fig. 1, the nominal chip thickness is related with the preset feed rate and the depth of cut, which is usually constant during a certain turning process. It is impossible to completely avoid or mitigate vibrations of the cutting tool and the workpiece because of the excitation of cutting forces, imbalance of the spindle and so on. So, a wavy surface is generated in the turning process. As shown in Fig. 1, if the phases of the wavy surfaces generated by two consecutive cuttings are consistent, the chip thickness also keeps consistent. The cutting process is stable. However, when there are phase differences between the two consecutive wavy surfaces, chatter is easy to occur [7]. Chatter can increase the cutting forces and vibrations of the cutting system, which deteriorates the surface quality of the workpiece and may even produce an inferior workpiece.

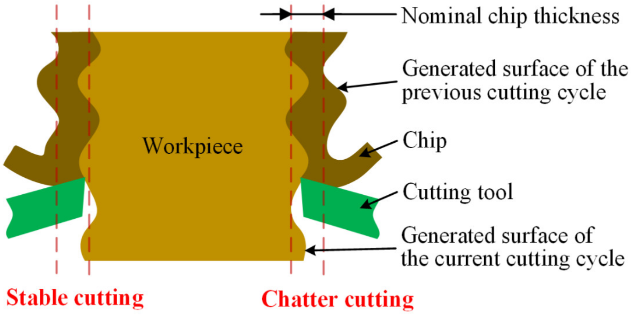

Fig. 1 Chip formation mechanism during turning

2.2 Turning forces considering chatter

Based on above chatter mechanism, diamond turning with and without chatter are described as Fig. 2. In the stable turning process, chip shape usually keeps constant. But during chatter turning, the chip shape changes periodically due to the regenerative effect.

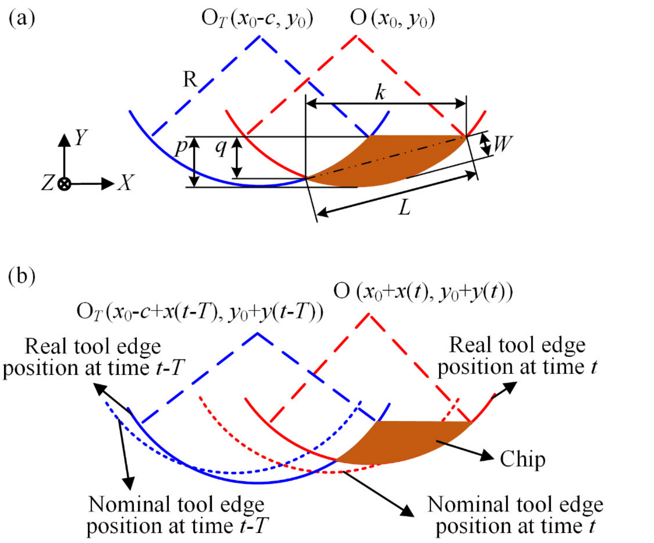

Fig. 2 Illustration graphs of diamond turning (a) without and (b) with chatter

It is known that the cutting force is closely related to chip cross-sectional area $S(t)=L(t)\cdot W(t)$ [8], where $L(t)$ and $W(t)$ are the chord length and corresponding equivalent chip thickness at time *t*. Based on the geometric relationship shown in Fig. 2, $L(t)$ and $W(t)$ can be calculated by Eq.(1).

$$\begin{aligned} &W(t)=c\cdot\sin\alpha(t)-\left[x(t)-x(t-T)\right]\cos\alpha(t)-\left[y(t)-y(t-T)\right]\sin\alpha(t)\\ &L(t)=\sqrt{q(t)^2+k(t)^2} \end{aligned} \quad (1)$$

where *c* is the feed per revaluation, $\alpha(t)=\arctan(k(t)/q(t))$, $x(t)$ and $y(t)$ are the vibration displacements of cutting tool/workpiece in the X and Y directions at time *t*, $x(t-T)$ and $y(t-T)$ are the vibration displacements of cutting tool/workpiece in the X and Y directions at time $t-T$ where *T* is the spindle rotation period. As for $q(t)$ and $k(t)$, they can be approximately described as Eq.(2).

$$\begin{aligned} q(t)&=p-y(t)-\left[R-\sqrt{R^2-(c/2+\Delta_q)^2}\right]\\ k(t)&=c/2+\Delta_k+\sqrt{R^2-\left[R-p+y(t)\right]^2} \end{aligned} \quad (2)$$

where *p* is nominal depth of cut, *R* is the radius of the tool nose, Δ_q and Δ_k are related with $x(t)$ and $x(t-T)$ and can be approximated to $\left[x(t)-x(t-T)\right]$ to a certain extent.

According to previous study [5], the cutting force can be calculated by Eq.(3). It can be seen that the process damping force component helps to reduce the total cutting force. And it increases with the decrease of the workpiece diameter at the cutting position. So, chatter is less likely to occur when cutting at the small diameter position of the workpiece.

$$\begin{bmatrix} F_x(t)\\ F_y(t)\\ F_z(t) \end{bmatrix}=\begin{bmatrix} C_x\\ C_y\\ C_z \end{bmatrix}L(t)W(t)-\frac{T\cdot L(t)}{\pi d(t)}\begin{bmatrix} C_{pdx}\dot{x}(t)\\ C_{pdy}\dot{y}(t)\\ C_{pdz}\dot{z}(t) \end{bmatrix} \quad (3)$$

where C_x, C_y ,and C_z are the cutting force coefficients in the X, Y and Z directions, C_{pdx}, C_{pdy} ,and C_{pdz} are the process damping coefficients, $\dot{x}(t)$, $\dot{y}(t)$,and $\dot{z}(t)$ are the velocity response of the cutting tool/workpiece in the X, Y, and Z directions, $d(t)$ is the diameter of the workpiece at the cutting position.

Based on Eqs.(1-3), during the chatter turning process, the cutting force consists of two main parts, which are the stable cutting force from feeding and the process damping effect and the chatter cutting force due to the regenerative effect (i.e., $x(t)-x(t-T)$ and $y(t)-y(t-T)$). The chatter cutting force causes extra vibrations of the cutting tool/workpiece, resulting in large surface roughness of the workpiece. In addition, it may also change the surface pattern of the workpiece when it is large enough.

3. Experimental analysis of diamond turning

3.1 Experimental procedure

As shown in Fig. 3, based on an ultra-precision machine tool (Moore Nano-tech 350 FG), diamond turning was carried out. In this experiment, cylindrical Ti6Al4V workpieces with a diameter of 15.8 mm were machined. Diamond cutting tools with rake and clearance angles of 0° and 12.5° were used for cutting. The radius of the tool nose was 1.16 mm. The overhang of the cutting tool was about 24 mm, which means that its stiffness is relatively low. Depth of cut and feed rate were set as 2 μm and 5 μm/rev, respectively. All experiments were performed at the spindle rotation speed of 1499 r/min. During the face diamond turning process, the cutting force was measured and recorded by a Kistler force sensor (Type: 9256C2). The sampling frequency was 50 kHz. After cutting, the surface topography and the roughness of the machined workpiece were measured by a Nexview 3D optical surface profiler.

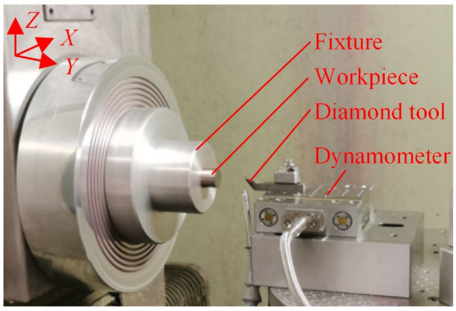

Fig. 3 The experimental setup of diamond turning

3.2 Experimental result and discussion

Although the sensitivity of cutting forces in the X (feeding), Y (normal), and Z (cutting) directions to chatter is different, all cutting forces in the three directions can reflect chatter information once it develops to a certain extent. Thus, taking the Y direction as an example, the cutting force during the whole diamond turning process is shown in Fig. 4. Turning starts at about 11.886s and ends at 75.145s. According to the cutting force-based chatter detection strategy developed in Ref.[4], it is judged that chatter occurs at about 12.65 s, weakens significantly from 55.180 s due to the process damping effect, and finally ends at 65.85 s. It is clear that chatter increases the fluctuation amplitude of the cutting force. Combing the cutting force and the machined surface of the workpiece, three representative time periods (i.e., [47 s, 49s], [58 s, 60 s], and [66 s, 68 s]) corresponding to different chatter statuses are selected for analysis, and the results are shown in Fig. 5 and Fig. 6.

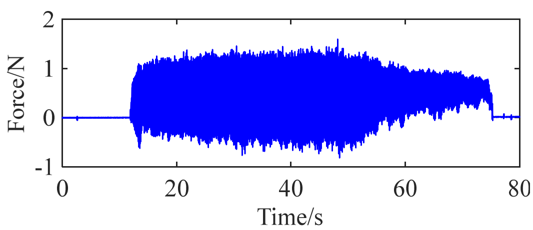

Fig. 4 The cutting force in the Y direction during the whole diamond turning process

As shown in Fig. 5 (c), there are only spindle rotation frequency and its harmonics (i.e., stable frequencies) in the frequency spectrum of the cutting force at time period [66 s, 68 s], corresponding to a workpiece diameter of approximately 2.02 mm at the cutting position. It means that the cutting is stable and the cutting force is only composed of stable frequency components. For a determined cutting system, vibrations of the cutting tool/workpiece and cutting forces usually have the same frequency composition and are positively correlated in amplitude. Thus, no chatter marks occur on the machined surface, as shown in Fig. 6 (c). The surface topography and its cross-sectional profile from point E to F are uniform, which are mainly determined by the replica effect of the tool edge on the workpiece surface and the stable vibration of the cutting tool/workpiece. The fluctuation period of the cross-sectional profile is consistent with the feed rate *c*. In this case, values of roughness Sa and Sz are 14.59 nm and 197 nm, respectively.

When cutting at a position with a diameter of 4 mm on the workpiece (i.e., cutting at about [58 s, 60 s]), chatter component with a frequency of 3754.5 Hz appears in the cutting force, as shown in Fig. 5 (b). The amplitude of the chatter component is similar to that of the maximum stable component. It means that mature chatter occurs in this cutting process. The corresponding surface topography is shown in Fig. 6 (b). It can be seen that both Sa (17.96 nm) and Sz (235 nm) values are increased compared to those obtained in the stable cutting at [66 s, 68 s], which is caused by chatter. In addition, chatter pattern appears on the workpiece surface near point C. According to the chatter mechanism, the phase of the surface fluctuation generated in the current cutting cycle lags behind that generated in the adjacent previous cutting cycle. The chatter frequency is a fractional multiple of the spindle rotation frequency, as shown in Fig. 5 (b). When the amplitude of the chatter cutting force component is larger than that of the stable cutting force component, the surface topography is mainly affected by the chatter force component. Thus, chatter pattern due to phase lag occurs on the surface. The cross-sectional profile also changes due to the chatter pattern, which will be discussed in detail in the next.

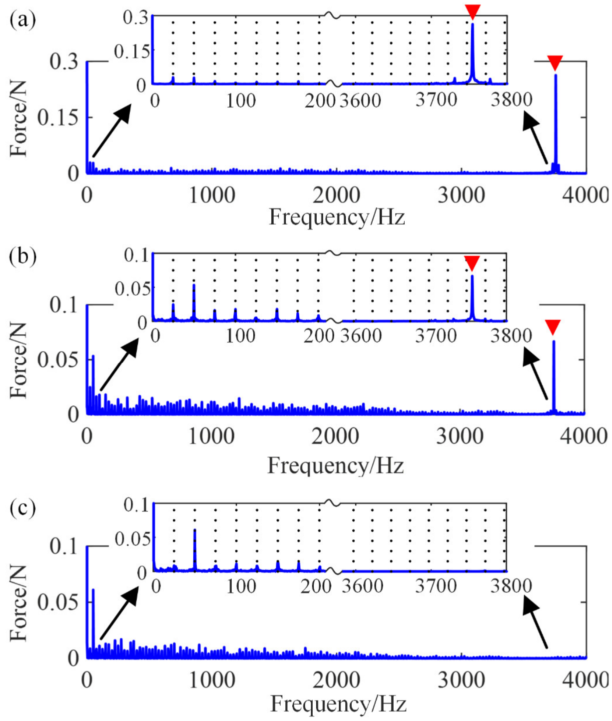

Fig. 5 Frequency spectra of the cutting forces in the Y direction during the time periods of (a) [47 s, 49 s], (b) [58 s, 60 s], and (c) [66 s, 68 s]. ▼, chatter frequency (3754.5 Hz). Dots, lines composed of dots represent the spindle rotation frequency and its harmonics.

When cutting at a position with a diameter of 6.6 mm on the workpiece (i.e., cutting at about [47 s, 49 s]), the amplitude of chatter cutting force component with a frequency of 3754.5 Hz is much larger than that of the stable cutting force component, as shown in Fig. 5 (a).

It means that severe chatter occurs in this cutting process. So, the surface topography is mainly determined by the chatter cutting force component. In this case, chatter pattern covers the whole workpiece surface, as shown in Fig. 6 (a). It can be seen the cross-sectional profile from A to B fluctuates at a larger period, which is determined by the ratio of the chatter frequency to the spindle rotation frequency and the feed rate *c*. Of course, the surface fluctuation due to replica effect of the tool edge still exists. Affected by the chatter pattern, the surface roughness Sa (22.92 nm) and Sz (271 nm) further increase. The physical properties of the workpiece surface may also change as a result, which will be further studied in the future.

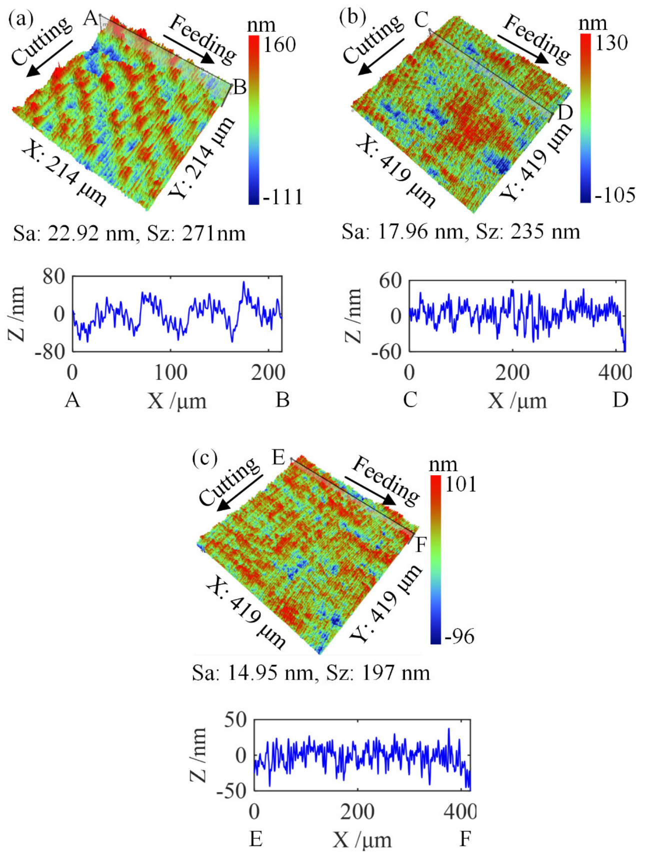

Fig. 6 Surface topographies and cross-sectional profiles of the machined workpiece corresponding to cutting time periods (a) [47 s, 49 s], (b) [58 s, 60 s], and (c) [66 s, 68 s].

4. Conclusions

Aim at diamond turning, effects of chatter on the cutting force and surface topography of the workpiece are analyzed in this work. It is found that chatter usually increases the fluctuation amplitude of the cutting force by adding a chatter cutting force component. Combining the cutting force and surface topography of the workpiece during chatter diamond turning process, it is concluded that chatter can increase the surface roughness Sa and Sz, and the increase is positively related to the amplitude of the chatter cutting force component. In addition, if the chatter cutting force component is larger than that of the stable cutting force component, chatter pattern with a large fluctuation period occurs on the surface topography due to phase lag effect, which may change the physical properties of the workpiece surface.

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