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ORIGINAL ARTICLE

# Milling force vibration analysis in high-speed-milling titanium alloy using variable pitch angle mill

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**Abstract** Chatter may cause fast wear of tools and poor surface quality of the workpieces at high cutting speed and it will happen on different process parameters; how do we select the suitable cutting speed to suppress the chatter? In this paper, a signal analysis method for milling force and acceleration is adopted to identify chatter, which can obtain the results not only in frequency of chatter but also in the contribution for milling force at different frequencies. Through the milling experiment, the machining vibration behaviors of milling Ti–6Al–4V with variable pitch end mill were investigated. Milling force and acceleration signals obtained from experiment were analyzed and compared at stable and unstable milling processes. The experimental results show that when the chatter occurs, milling forces were found to increase dramatically by 61.9–66.8% compared with that of at stable cutting; machining surface quality became poor and machined surface roughness increases by 34.2–40.5% compared with that of at stable cutting.

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**Keywords** Titanium alloy · Surface quality · Chatter · Variable pitch mill

## 1 Introduction

Titanium alloys are extensively used in the aerospace industry due to their excellent performance in aerospace environment [1]. However, it is difficult to machine because of their poor thermal conductivity, low elastic modulus, and high chemical activation, which can result in high cutting temperature and tool vibration, consequently shortening tool life and decreasing machined surface quality [2–5]. When cutting titanium, tool life will dramatically decrease with cutting speed increasing for the onset of self-excited vibrations known as chatter. Therefore, cutting speeds for titanium alloy are often limited to 60 m/min [6]. Furthermore, most materials need to be removed from roughcast due to the characteristics of component design for titanium alloy. It leads to the machining cost increasing extremely with low cutting speed, which limits the development of aerospace industry.

Chatter is more serious especially when finishing machining titanium alloys because of low Young's modulus and the workpiece material's elasticity, which makes it spring away from the cutting tool, causing cutting edges to rub together; increasing friction; and further raising the temperature at the cutting area and dramatic vibrations [1]. Segmented chips further increases the fluctuations of cutting forces, finally causing vibration or chatter in the metal cutting process [7].

Many researchers have been looking for methods of chatter suppression. Ezugwu and Wang think that titanium alloy machining performance can be improved by employing very rigid machines, cutting tools, and set-ups, improving cutting tool materials and coatings, providing copious coolant flow, and designing special tools or non-conventional cutting methods, optimizing tool geometry and cutting parameters [1]. Tlust [8] presented to optimize the cutting conditions with the stability lobes which define regions of stable and unstable cutting zones as a function of axial depth of cut and spindle speed, and then the further researches were given in these documents [9–11]. Tarng and Li [12] changed spindle speed for avoidance of chatter in end milling. Slavicek [13] first proposed a variable pitch cutter design idea for chatter suppression, which disrupts the chatter by phase shifts between one flute and the next in successive tooth period [14]. In 1999, an analytical model in predicting the stability lobes of variable pitch mills was presented by Altıntas [15].

In this paper, a signal analysis method to identify chatter is presented under the milling experiment, which adopted variable pitch end mill to mill Ti–6Al–4V at different cutting speed varied from 80 to 360 m/min. Because the mill is less rigid in radial direction [16, 17], only through analysis of frequency spectra signals on the radial milling forces, $F_y$, and the accelerations, the cutting stability associated with the machined surfaces quality can be obtained from the comparison between stable and unstable milling conditions. Finally, the optimum cutting speed on milling Ti–6Al–4V was deduced by comprehensive analysis of the milling force and the machined surface quality under other given parameters' condition.

## 2 Milling dynamic theory and the signal analysis method

Because the whole tool system of mill/toolholder/machine is more flexible than the workpiece, a 2-degree-of-freedom milling system representative of workpiece–mill system is shown in Fig. 1, where the axis direction ($z$ axis) is supposed as rigid compared with the other two directions. $x$ and $y$ are the directions of mill feed and perpendicular to the machined surface, respectively. $k_x$, $k_y$ are equivalent

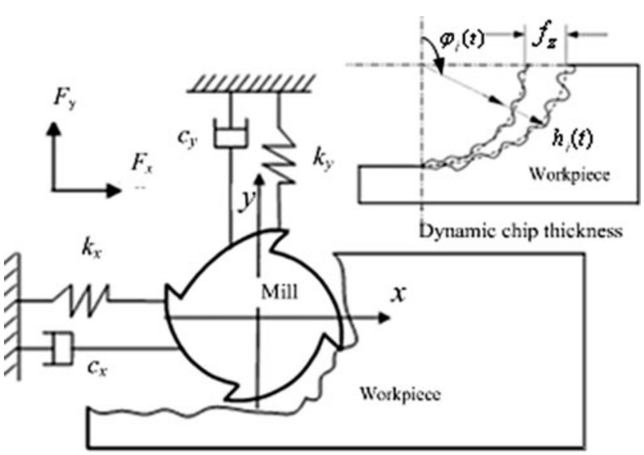


**Fig. 1** Dynamic milling model

elastic coefficients respectively and $c_x$, $c_y$ are equivalent damping coefficients at the two directions respectively, $f_z$ is feed per tooth and $h_i(t)$ is dynamic chip thickness, $\phi_i(t)$ is the position angle of number $i$ cutting edge.

The dynamics of the system are described by following differential equations:

$$\begin{cases} m_x\,\ddot{s}_x + c_x\dot{s}_x + k_x s_x = F_x(t) \\ m_y\,\ddot{s}_y + c_y\dot{s}_y + k_y s_y = F_y(t). \end{cases} \tag{1}$$

where, $m_x$, $m_x$ are equivalent modal mass of the milling system at $x$ and $y$ directions, respectively; $F_x(t)$, $F_y(t)$ are dynamic milling forces at the two directions, respectively, which are the functions of the dynamic chip thickness referring to the documents[18]. They are a periodic function and their period is:

$$T' = \frac{T}{N} \tag{2}$$

Where, $T$ is the period of spindle rotation, $N$ is the number of cutting edge.

Frequency analysis is particularly useful for distinguishing cutting stability status, it is well known that in a stable cutting process, peak values of milling force always occurs at the integral multiple of tooth passing frequencies ($z\times$ tooth passing frequency (TPF), $z$=1,2,3…), but because of the tool runout during the milling, the peak value of milling force will appear at the multiple of spindle frequency ($z\times$ spindle frequency (SF), $z$=1,2,3…) .

SF is defined as

$$\mathrm{SF} = \frac{n}{60} = \frac{1000v}{60\pi D} \tag{3}$$

Where, $n$ and $v$ are the spindle speed (revolutions/min) and linear speed (m/min) respectively, $D$ is the diameter of the mill.

TPF is defined as

$$\mathrm{TPF} = N \times \mathrm{SF} = \frac{1000Nv}{60\pi D} \tag{4}$$

On the contrary, if milling force peak values occur at some different frequencies from the multiple of spindle frequency (z×SF), then it can be deduced that chatter have occurred.

## 3 Experimental procedure

### 3.1 Experimental setup, workpiece material, and mill

The experiments were performed in a vertical CNC machine center (Daewoo ACE-V500) with 15 kW of power as shown in Fig. 2. The milling forces data were obtained by the dynamometer (Kistler 9257B) and the sampling frequency was set to 7,000 Hz to see the change in 3,500 Hz. The mill vibrations were monitored using piezoelectric accelerometers mounted on the spindle head and the sampling frequency was set to 2,000 Hz. The workpiece material was titanium alloy Ti–6Al–4V. The mill was solid cemented carbide end mill with variable pitch angle, whose distribution is shown in Fig. 3. The mill diameter ($D$) is 20 mm with its overhang length 74.3 mm, tooth number ($N$) 4 and helix angle 42°.

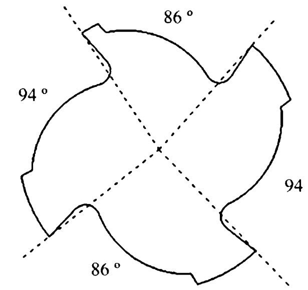


Fig. 3 Variable pitch angle distribution

### 3.2 Experimental design

All experiments were conducted in dry and down milling. Milling route was shown in Fig. 4, where $n$ is the spindle speed, $F_z$ is the milling force at the axial direction ($z$ axis). The cutting speeds ($v$) were varied from 80 to 360 m/min in steps of 40 m/min with constant feed per tooth, axial depth of cut, and radial depth of cut in the experiments, which are listed on Table 1. Experimental number is shown in Fig. 4.

Where,

$$v = \frac{\pi D n}{1000} \qquad (5)$$

## 4 Stability analysis and experimental results

### 4.1 Experimental phenomenon

During the milling process, very harsh noise was heard when cutting speed is 240 m/min and extreme vibration was observed in whole milling system; but, at this moment, the mill does not wear. When cutting speed is increased to 360 m/min, similar or even more serious noise was heard; meanwhile, breakage occurs on the mill tip shown in Fig. 5.

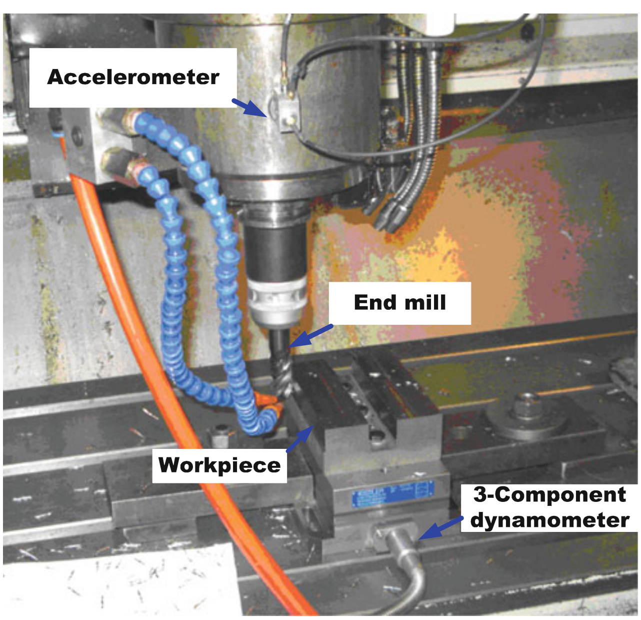


Fig. 2 Experimental setup

### 4.2 Analysis of acceleration signal

The measured frequency spectra of radial accelerometer signal are shown in Fig. 6a–d, meanwhile, the frequency spectrum diagrams at cutting speed varied from 80 to 200 m/min are similar to Fig. 6b and c.

From Fig. 6a and d, it was observed that the milling force peak value occurs at 734 Hz when cutting speed is 240 m/min and 730 Hz at 360 m/min. Combined with those sharp noises when cutting speeds are 240 and 360 m/min, it can be deduced preliminary that chatter had occurred at those two cutting speeds and its occurred frequencies are 734 and 730 Hz, respectively as shown in Fig. 6a and d.

### 4.3 Analysis of radial milling force

In order to further analyze vibration of the milling system, fast Fourier transform (FFT) of the radial milling force was treated using MATLAB software, time rectangular window was set to 2 s.

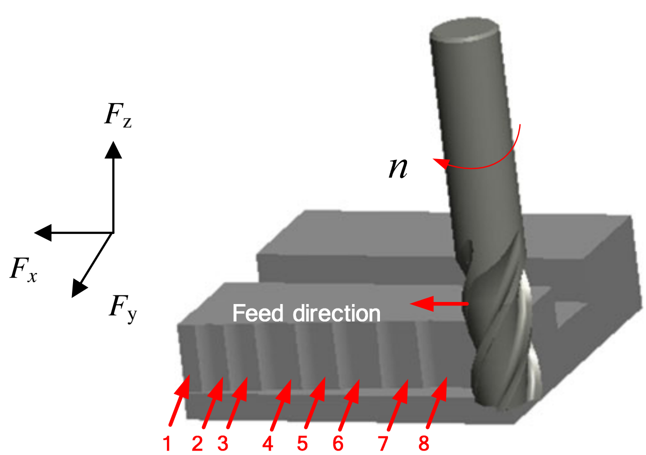


Fig. 4 Milling route

**Table 1** Cutting parameters

| Experimental no | Cutting speed $v$ (m/min) | Spindle frequency SF(Hz) | Feed per tooth $f_z$ (mm/tooth) | Axial depth of cut $a_p$ (mm) | Radial depth of cut $a_e$ (mm) |
|---|---|---|---|---|---|
| 1 | 80 | 21.22 | | | |
| 2 | 120 | 31.83 | | | |
| 3 | 160 | 42.44 | | | |
| 4 | 200 | 53.05 | 0.08 | 20 | 0.5 |
| 5 | 240 | 63.66 | | | |
| 6 | 280 | 74.27 | | | |
| 7 | 320 | 84.88 | | | |
| 8 | 360 | 95.49 | | | |

Figure 7 shows a three-dimensional diagram of the frequency spectra analysis of $F_y$ at different cutting speeds. It is shown that the peak values of milling force are larger when the cutting speeds are 240, 280, and 360 m/min than those at other cutting speeds. But when cutting speed is 280 m/min, its frequency spectra distribution are periodic, on the contrary, when cutting speeds is 240 and 360 m/min, there are uneven frequency interval zones pointed out by arrows in Fig. 7.

In order to further analyze chatter, frequency spectra analysis is used for the radial force at different cutting speeds; the results are shown in Fig. 8. When cutting speeds are 80 and 120 m/min, the dominant peak value occurs at the low multiples of SF (1× and 4×); but when cutting speeds are 160, 200, 280, 320 m/min, besides at the low multiples of SF (1× and 4×), high multiples of SF occur. Milling force peak values are shown in Fig. 8c, d, f, g. From Fig. 8f, a significant amplitude occurs at 816 Hz (11× SF), the smaller amplitude occurs at 1,114 Hz (15× SF), which can be deduced to high-frequency energy increase with wear of mill during cutting.

When cutting speeds are 240 and 360 m/min, milling force peak values occur also at different frequencies from multiples of TPF and SF, such as 734 Hz at 240 m/min, 730 Hz, 1,111 Hz, 1,268 Hz, 1,363 Hz, and 1,459 Hz at 360 m/min. From the former analysis, it is known that chatter can be assessed from the newly occurred frequency which is different from multiples of TPF and SF, so chatter occurs when cutting speeds are 240 and 360 m/min, and caused severe friction, squeeze, and slit between mill and workpiece, consequently leading to too-fast wear of the mill shown in Fig. 5.

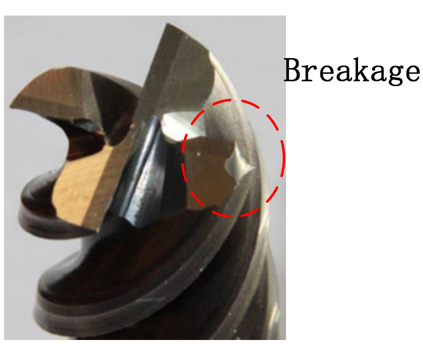


**Fig. 5** Mill wear

Figure 9 presents the effect of cutting speed on the maximum radial milling force $F_y$. It was observed that milling forces increase slightly when cutting speed varied from 80 to 160 m/min, it only increased by 9.8% and 18.9% when cutting speeds are increased from 80 to 120, to 160 m/min, respectively. It is because the impact force and strain hardening rate of the materials increase with the interrupted milling speed growing, which cause increasing milling force. Meanwhile, the cutting temperature also increases with increasing cutting speed, which, however, results in thermal softening of the workpiece material and causes the decreasing of milling force. Finally, milling forces only slightly increases under the combined effects of those two sides.

Then, the radial milling force increase by 36.1% at 200 m/min compared with that of at 80 m/min, the reasons are shown in Fig. 8d; a bigger milling force peak value occurs at 790 Hz (15× SF), so the energy in high frequencies increase amplitude of the milling force.

The first peak value occurs at 240 m/min, there is an increase of 61.9% compared with that of at 80 m/min. Then, an obvious decrease followed when cutting speeds are 280 and 320 m/min. After that, the milling force got augmented again, achieving another peak value at 360 m/min, which increases by 66.8% compared with that of at 80 m/min. Chatter is the main reason that causes a significant increase of milling force; an increase of the high-frequency energy for mill wear is another reason.

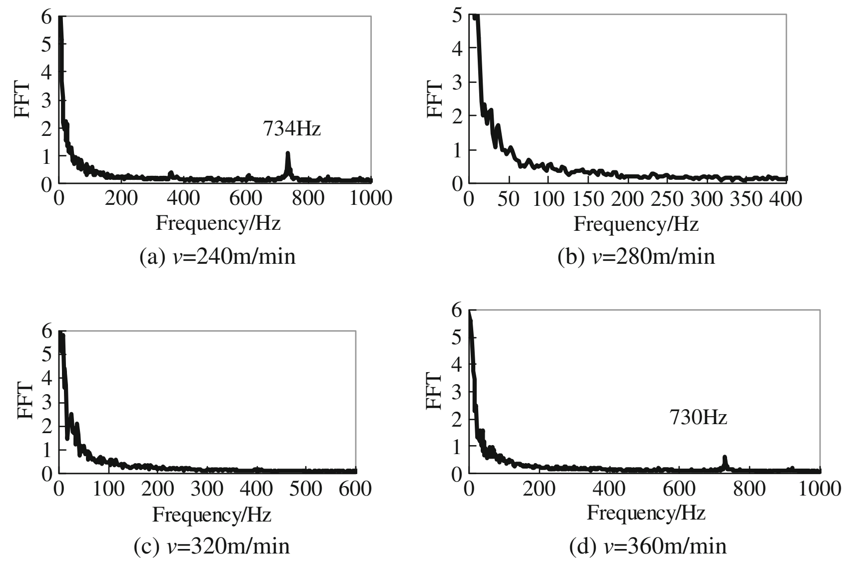


**Fig. 6** The measured frequency spectra of radial accelerometer signal

4.4 Analysis of surface quality

Typically, the machined surfaces are specified using the mean roughness $S_a$; it is evaluated over the complete 3D surface. Mathematically, the $S_a$ can be evaluated as follows:

$$S_a = \iint_a |Z(x,y)| dxdy \quad (6)$$

Where $Z(x,y)$ is the height of sample points.

Figure 10 gives the surface roughness curve measured at different cutting speeds. It shows that the increasing cutting speeds caused the slight decline of roughness value when cutting speed vary from 80 to 160 m/min, followed by a climb and up to the summit at 240 m/min by 34.2% compared with that of at 80 m/min. Then, the curve bends downward slightly, ending with an increase again at 360 m/min by 40.5% compared with that of at 80 m/min. The reasons leading to this trend of roughness curve is similar to the reasons of milling force; namely, the chatter and the increase of high frequencies energy for the mill wear.

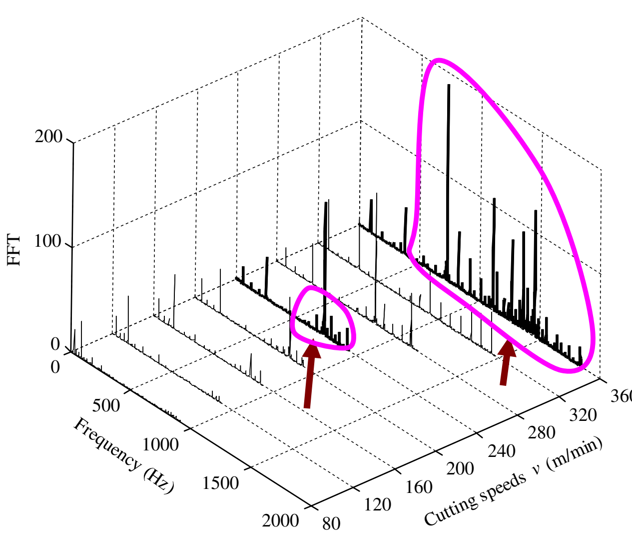


**Fig. 7** FFT of the radial force versus the cutting speed ($f_z$=0.08 mm, $a_e$=0.5 mm, $a_p$=20 mm)

Figure 11a–h presents the surface topography measured with white light interferometers (WYKO NT9300) at different cutting speeds. From Fig. 11e and h, it is shown that large areas of material loss happened at the machined surface zone pointed out by an arrow, there are possibly the following two reasons:

1. Unstable cutting conditions play strong roles in milling between workpiece and the mill, accordingly produce excessive cut at workpiece surface.
2. Intense vibration brings high cutting temperature, so there are some adhesions at touch part of the mill's flank and workpiece; then, some materials were taken away by the mill from workpiece with the spindle rotation.

Table 2 shows experimental phenomenon and results at different milling speeds. Experimental number corresponds to Fig. 4 and Table 1. From Table 2, it is shown that the chatter results in harsh noise in milling, dramatic increasing of milling force, and very poor machined surface quality. So, chatter must be suppressed during the milling process.

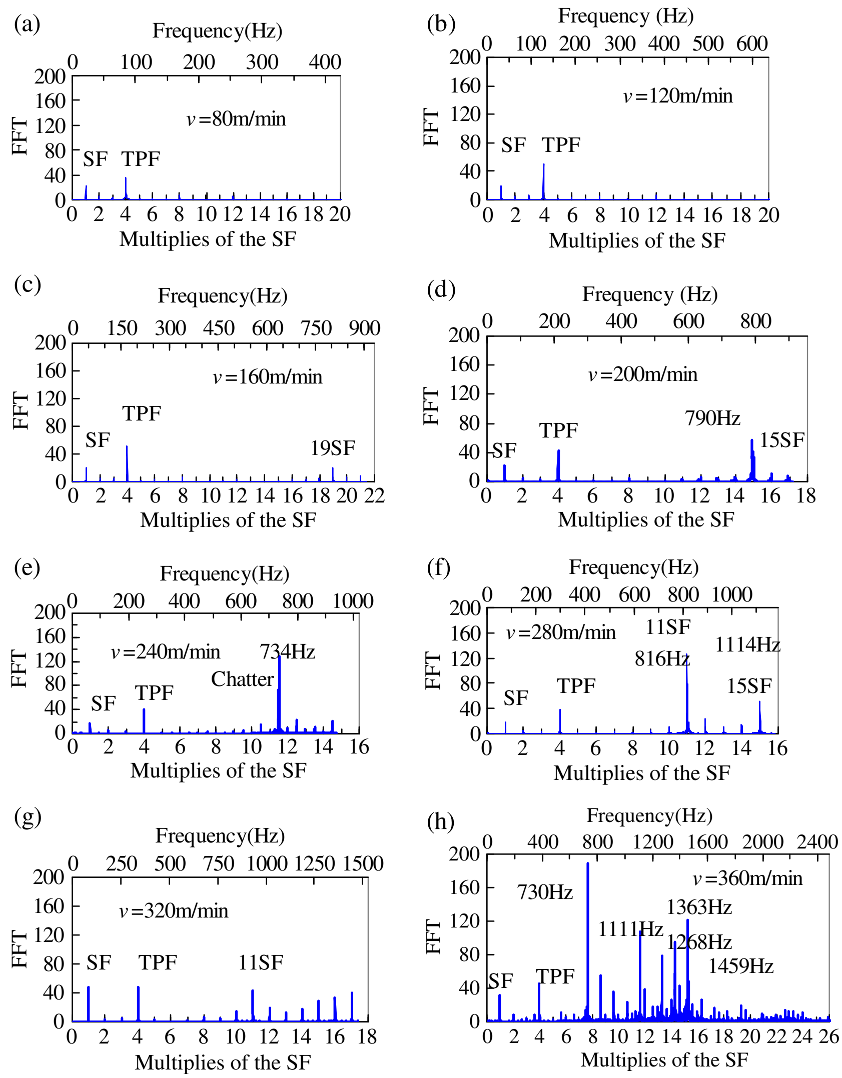


**Fig. 8** FFT analysis on the radial force $F_y$. **a** $v$=80 m/min; **b** $v$=120 m/min; **c** $v$=160 m/min; **d** $v$=200 m/min; **e** $v$=240 m/min; **f** $v$=280 m/min; **g** $v$=320 m/min; **h** $v$=360 m/min

## 5 Conclusions

1. Chatter happens when milling speeds are 240 and 360 m/min, Main chatter frequencies of the milling system are about 730 Hz, 816 Hz, 1,111 Hz, 1,363 Hz, and 1,459 Hz.
2. At high multiples of SF, there are many milling force peak values because high-frequency energy results in increasing of the mill wear during milling course.
3. Milling forces, $F_y$, increase slightly with cutting speed growing varied from 80 to 160 m/min under the action of two factors which are increasing strain hardening

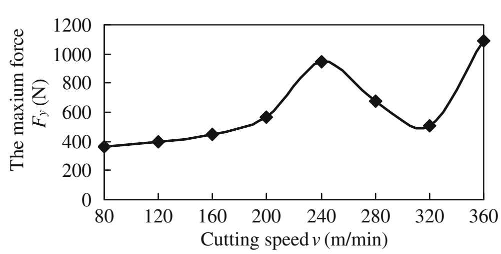


**Fig. 9** Maximum radial force versus cutting speed. ($f_z$=0.08 mm, $a_e$= 0.5 mm, $a_p$=20 mm)

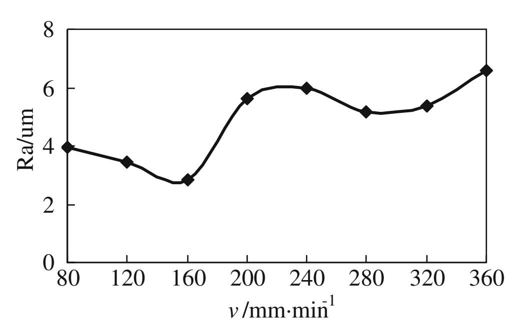


**Fig. 10** Surface roughness versus cutting speed

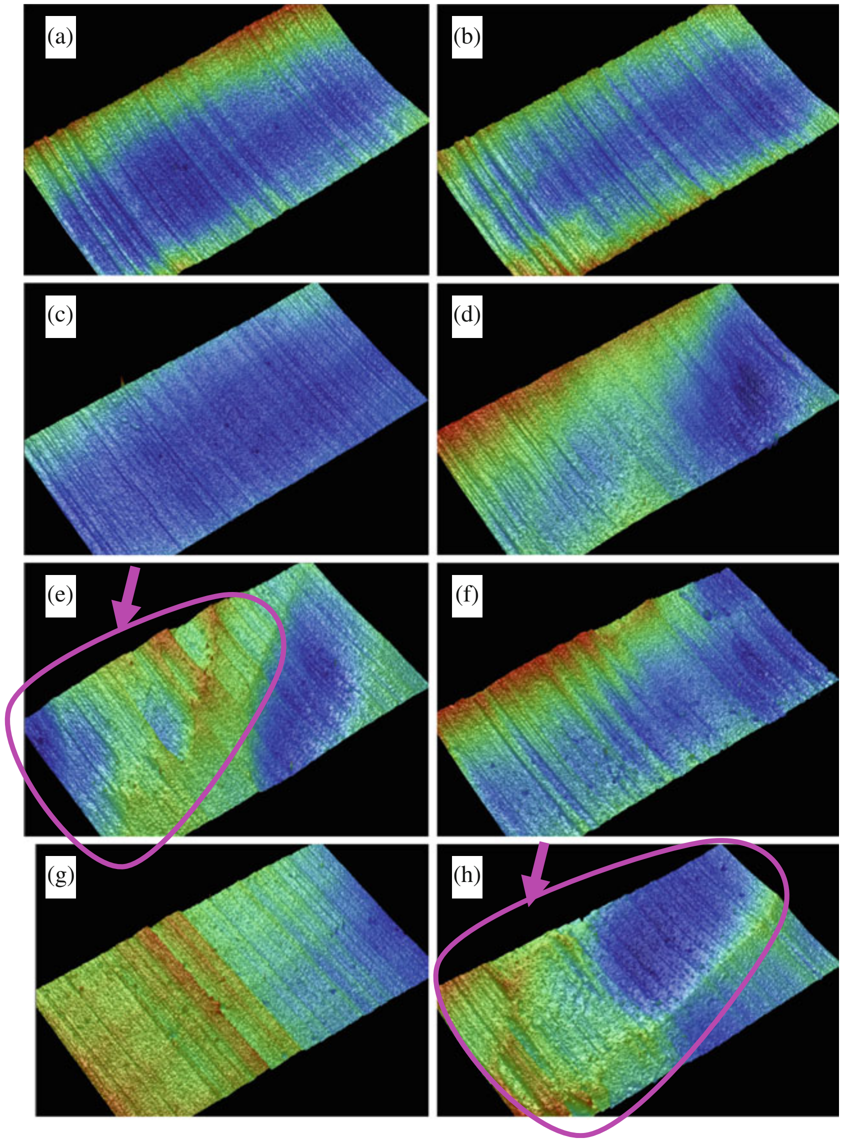


**Fig. 11** Surface topography measured with WYKO NT9300 white light interferometers ($f_z$=0.08 mm, $a_e$=0.5 mm, $a_p$=20 mm). **a** $v$=80 m/min; **b** $v$=120 m/min; **c** $v$=160 m/min; **d** $v$=200 m/min; **e** $v$=240 m/min; **f** $v$=280 m/min; **g** $v$=320 m/min; **h** $v$=360 m/min

rate of the workpiece material under the growing impact forces and thermal softening of the workpiece material with increasing milling temperature.

4. Chatter is the main reason for a significant increase of milling force and poor machined surface quality; an increase of the high-frequency energy for mill wear is another reason. Chatter can cause the mill wear.
5. Under the other cutting parameters mentioned in Table 1, the optimal cutting speed is recommended with 160 m/min because it has good machined surface quality and smaller milling force at this cutting speed.

**Table 2** Experimental phenomenon and results

| Experiment no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Cutting voice | Normal | Normal | Normal | Normal | Harsh noise | Normal | Normal | Harsh noise |
| The maximum value of $F_y(N)$ | 361.4 | 400.9 | 445.8 | 566 | 948 | 675.6 | 506.3 | 1088.2 |
| Machined surface quality | Medium | Medium | Good | Medium | Very poor | Poorer | Poorer | Very poor |
| conclusion | Stable | Stable | Stable | Stable | Chatter | Stable | Stable | Chatter |

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