Characterization and functional evaluation of surface texture of micro eccentric shaft based on multi-index

Minghui Cheng¹, Li Jiao¹, Pei Yan¹, Zhongke Niu², Tianyang Qiu¹ and Xibin Wang¹

Abstract
Micro eccentric shaft has important application in many high-tech fields because of its small specific gravity, material, and energy saving. The machined surface texture has an indispensable influence on the surface integrity and the final functional capability. However, due to the micro scale and weak rigidity, it is difficult to characterize the surface texture and evaluate the functionality by traditional quantitative parameters. In order to comprehensively realize the surface texture characterization and functional analysis, a mathematical model is established to simulate the surface texture machined with different cutting tools. Then the surface microscopic profile and functional performance of the surface texture are analyzed by amplitude distribution function (ADF) and bearing area curve (BAC), and the surface texture is also evaluated by fractal dimension, which can avoid the negative effects of scale and resolution. Furthermore, power spectrum density (PSD) is utilized to analyze the relationship between the process dynamic state and geometrical specification of the surface texture. The validity of experimental results shown that the microscopic height distribution of surface machined by flat end milling cutter tends to be more random and there are more microscopic geometric features than that of the ball end milling cutter. The machined surface obtained by the flat end milling cutter has better load bearing, wear resistance, and liquid retention capability.

Keywords
Surface texture simulation, surface texture characterization, functional evaluation, spectral analysis, orthogonal turn-milling

Introduction
Micro eccentric shaft can render the conversion of rotary motion and linear motion, which is widely used in micro machinery. Because of the eccentric characteristic of the micro eccentric shaft, the process of machining is very complex, and the machining precision is difficult to guarantee. Turn-milling is suitable for machining micro eccentric shaft, due to small radial force during machining¹ and improved vibration characteristics compared with turning.² However, it is difficult to meet the requirements of evaluation length of the traditional surface characterization parameters, due to the small scale of the micro eccentric shaft, which makes it challenging to accurately characterize the actual surface quality.

Characterization of surface texture is an important aspect in the surface quality evaluation of parts. Modeling and simulation of the machined surface have become the research focus to characterize surface topography in recent years. Theoretically, surface topography simulation can be achieved by studying the tool’s motion trajectory and the residual height of the machined surface. During grinding process, Ding et al.³ reconstructed the measured surface topography of textured monolayer CBN wheels, and the machined surface topography was predicted based on the reconstructed wheel surface topology. In subsequent research, Ding’s group built an ultrasonic vibration plate device for creep-feed grinding⁴,⁵ and proposed an analytical model to clarify the generation mechanism of surface topography in tangential ultrasonic

¹Key Laboratory of Fundamental Science for Advanced Machining, Beijing Institute of Technology, Beijing, China
²Aerospace System Engineering Shanghai, Shanghai, China

Corresponding author:
Pei Yan, Key Laboratory of Fundamental Science for Advanced Machining, Beijing Institute of Technology, 5 South Zhongguancun Street, Haidian District, Beijing 100081, China.
Email: pyan@bit.edu.cn
vibration-assisted grinding.6 Dang et al.7,8 clarified the evolutionary process of surface topography under supercritical carbon dioxide-assisted grinding process. For milling process, Zhang et al.9 realized the simulation of machined surface topography based on cutter dynamic displacement response. In addition, the surface topography prediction model was established considering tool radial runout and axial drift in peripheral milling process.10 These studies showed that the surface topography can be accurately predicted or simulated in milling and grinding processes.

Turn-milling is different from milling or grinding process in that both the tool and workpiece are rotated simultaneously. For turn-milling process, Yuan and Zheng11 developed a geometrical model to analyze the influence degree of cutting parameters on surface roughness. Karagöz et al.12 studied the form errors of machined surface including circularity, cusp height, and circumferential surface roughness from the perspective of cutting mechanism. Zhu et al.13 built a mathematical model to characterize the theoretical surface topography based on locus function. Similarly, Döbbertin et al.14 established a function of surface micro height with respect to cutting parameters and realized the simulation of surface topography obtained by using flat end milling cutter. Overall, simulation of surface texture machined by different cutting tools has been achieved in orthogonal turn-milling. However, most researches model the surface texture from the perspective of the machined surface shape, which has a poor consistency with the actual machined surface. What’s more, few studies have further analyzed the specific microscopic geometrical feature and functional performance of surface texture in orthogonal turn-milling process.

Generally speaking, the evaluation of surface texture includes two aspects. One is to evaluate the surface micro geometric features through some quantitative indexes, and the other is to select reasonable parameters to evaluate the functional properties of the machined surface.15 The quantitative characterization parameters include not only the two-dimensional (2D) amplitude parameters such as arithmetical mean height $R_a$ and root mean square height $R_q$, but also the three-dimensional (3D) amplitude parameters, spatial parameters, hybrid parameters, and functional parameters.16,17 Therefore, it is insufficient to characterize the surface texture just using the 2D amplitude parameters. 3D amplitude and functional parameters are required to characterize the surface texture and perform functional analysis. Eifler et al.18 realized the performance verification of areal surface texture based on the $S_p$-parameters associated with functional characteristic. Shi et al.19 proposed a 3D surface roughness evaluation method of surface quality based on sampling array. Liu et al.20 evaluated the surface topography by 3D surface roughness and fractal dimension in micro-milling. In addition, some statistical functions have been developed to describe the machined surface in other engineering fields. For example, amplitude distribution function is commonly used to describe the probability distribution of surface micro height and characterize the geometrical features.21,22 While bearing area curve as a statistical function has a superior performance in assessing the wear resistance, load bearing, and lubricant or oil retention capacity of the machined surface.23,24 Shi et al.25 revealed the inner characteristics of surface topography obtained by point grinding based on self-correlation and mutual correlation function. Furthermore, 3D amplitude and functional parameters belong to time-dominant quantification parameters, which cannot explain the dynamic frequency information of the machined surface. Therefore, some statistical functions such as power spectrum density and continuous wavelet transform have been used to analyze the spectral characteristic of microscopic profile.26,27 Through the above parameters or statistical functions, the characterization and functional analysis of the machined surface can be fully accomplished. However, the machined surface obtained by orthogonal turn-milling is regularly characterized by 2D amplitude parameters.28–31 It is inadequate for comprehensively describing the machined surface, especially for the micro parts.

In this paper, a mathematical model is firstly established to analyze the difference of surface texture obtained by different cutting tools. Then, the amplitude distribution function and bearing area curve are used to analyze the functional performance of the machined surface. What’s more, the fractal dimension is applied to analyze the surface texture, which can avoid the negative effects of scale and resolution compared with traditional quantitative statistical parameters. Finally, the spectral performance of surface texture is analyzed by combining power spectral density function with continuous wavelet transform. The characterization and functional performance of the surface texture obtained by different cutting tools are comprehensively analyzed.

**Theoretical analysis and experimental setup**

**The mathematical model of surface texture**

In order to analyze the difference of machined surface obtained by different cutting tools and realize the microscopic surface topography characteristics, the mathematical model of surface texture is first established according to the theoretical model of cutting edge trajectory.32,33 Figure 1 shows the geometric mathematical model of orthogonal turn-milling cylinder with ball end milling cutter. It is assumed that the workpiece is stationary and the tool rotates relative to the workpiece when constructing the model. Taking the ball end milling cutter as an example, the calculation process of the model is as follows:
The coordinates of any point on the helical edge of the ball end milling cutter under the tool static coordinate system \( O-X_{TS}Y_{TS}Z_{TS} \) are shown in equation (1):

\[
\begin{align*}
\mathbf{r}_i &= R_t \sin \alpha \cos \gamma (\cos \alpha/2) \\
\mathbf{w}_i &= R_t \sin \alpha \sin \gamma (\cos \alpha/2) \\
\mathbf{v}_i &= -R_t \cos \alpha \\
\end{align*}
\]

For flat end milling cutter, the coordinates of any point on the face edge in the tool static coordinate system \( O-X_{TS}Y_{TS}Z_{TS} \) can be expressed as:

\[
\begin{align*}
\mathbf{r}_i &= \varphi_0 + 2\pi(i - 1)/m - w_i t \\
\mathbf{w}_i &= \cos \varphi_i - \sin \varphi_i 0 \\
\mathbf{v}_i &= \sin \varphi_i \cos \varphi_i 0 \\
0 &\quad 0 0 1
\end{align*}
\]

Where \( R_t \) is the cutting tool radius, \( \alpha \) is the position angle of spiral edge, and \( \gamma \) is the helix angle of the ball end milling cutter.

During the cutting process, the angle between the \( \theta \)th blade and the \( X_{TS} \)-axis at any time can be expressed as equation (2), so the coordinate value \( (U, W, V) \) of any point on each helical edge under the tool motion coordinate system \( O-X_{TM}Y_{TM}Z_{TM} \) can be expressed as:

\[
\begin{align*}
\mathbf{r}_i &= \varphi_0 + 2\pi(i - 1)/m - w_i t \\
\mathbf{w}_i &= \cos \varphi_i - \sin \varphi_i 0 \\
\mathbf{v}_i &= \sin \varphi_i \cos \varphi_i 0 \\
0 &\quad 0 0 1
\end{align*}
\]

Where \( w_i \) is cutting tool angular velocity, and \( w_i t \) represents the angle that the cutting tool has turned at the current time \( t \).

In the next step, for any point on the cutting edge, the transformation of the coordinate from the tool motion coordinate system \( O-X_{TM}Y_{TM}Z_{TM} \) to the workpiece coordinate system \( O_w-X_wY_wZ_w \) is:

\[
T_S = \begin{bmatrix}
0 & \sin(\omega_wt) & \cos(\omega_wt) & 0 \\
0 & -\cos(\omega_wt) & \sin(\omega_wt) & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

The coordinate origin of the tool static coordinate system \( O-X_{TS}Y_{TS}Z_{TS} \) in the workpiece coordinate system \( O_w-X_wY_wZ_w \) is expressed as:

\[
\begin{align*}
x_0 &= R_t + R_w - a_p \\
y_0 &= 0 \\
z_0 &= f \cdot t
\end{align*}
\]

Where \( f \) represents the tool axial feed, \( R_w \) represents the radius of workpiece, and \( a_p \) represents the cutting depth.

When considering the kinematic error of machine spindle, the transformation matrix of ball end milling cutter center in the workpiece coordinate system \( O_w-X_wY_wZ_w \) can be expressed as equation (6):

\[
T_Q = \begin{bmatrix}
1 & 0 & f \cdot t + \Delta_d_l \cos(\delta_1 + \delta_2) \\
0 & 1 & \frac{\pi}{\Delta_d_l} \sin(\delta_1 + \delta_2) \\
0 & 0 & 1
\end{bmatrix}
\]

For flat end milling cutter, the coordinates of any point on the face edge in the tool static coordinate system \( O-X_{TS}Y_{TS}Z_{TS} \) can be expressed as:

\[
\begin{align*}
\mathbf{r}_i &= R_t \cos \alpha \\
\mathbf{w}_i &= R_t \sin \alpha \\
\mathbf{v}_i &= (R_i - t) \tan \lambda
\end{align*}
\]

On this basis, the cylindrical workpiece was meshed along the axial and circumferential direction. In order to simulate the surface texture, the machined surface, the cutting edge of the tool and the machining time were discretized. The coordinate points of the cutting edge in the workpiece coordinate system were compared with the corresponding coordinate points of the machined surface at different time to determine whether the tool has cut into the workpiece. Then the residual height on the workpiece surface was calculated. Finally, the 3D surface texture can be obtained according to the residual height of the machined surface. On the basis of the cutting edge trajectory model,
the surface texture can be predicted using the simulation software MATLAB R2018b. The flowchart of the simulation process is shown in Figure 2.

**Statistical analysis functions**

Normally, specific machining process corresponds to a certain surface with specific microscopic geometrical feature and functional performance. What’s more, when the value of surface roughness is greater than 0.1 \( \mu m \), the evaluation length should be greater than 4 \( mm \) to ensure the validity of the result. The size of micro eccentric shaft is difficult to meet the requirement of the evaluation length as shown in Figure 4, so it is insufficient to characterize the surface texture just with traditional quantitative parameters. Therefore, other functional statistical parameters are needed to characterize the surface texture and perform functional analysis. Amplitude distribution function is the commonly used to describe the probability distribution of surface micro height and characterize the geometrical features. In addition, the bearing area curve has a superior performance in assessing the wear resistance, load-bearing, and lubricant or oil retention capacity of the machined surface. The original surface profile and corresponding functional statistical parameters are shown in Figure 3 and Table 1, respectively.

In addition, considering the fractal dimension is an independent parameter for scale, which is not affected by the sampling length, box fractal dimension is introduced in this paper to evaluate the surface quality.\(^{36}\) The detailed implementation process of the box fractal dimension can be referred to our previous research.\(^{37}\)

**Spectral analysis methods**

The machined surface contains a lot of dynamic frequency information, such as the trajectory of the tool path and machine vibration, but the time-dominant quantification parameters are lack of the quantitative spectrum analysis. Therefore, power spectral density (PSD) and wavelet analysis are combined to analyze and evaluate the frequency structure of the machined surface. The PSD method can obtain the frequency structure characteristics of the spatial wavelength from the surface micro-contour and reflect its distribution. PSD is calculated from the surface micro-contour data, as shown in equation (10):

\[
PSD(f) = \lim_{L \to \infty} \left( \frac{|z(f, L)|^2}{L} \right)
\]

(10)

Where \( f \) represents the spatial frequency, \( L \) is the sample length, and \( z(f, L) \) is the Fourier transform of the two-dimensional contour data \( z(x) \), the expression of which is shown in equation (11):

\[
z(f, L) = \int_{-L/2}^{L/2} z(x) \exp(-j2\pi fx)dx
\]

(11)
To clarify the effect of various frequency characteristics on the surface texture, it is necessary to analyze the multi-scale property of the machined surface. Wavelet transform can be utilized to analyze the multi-scale property of surface topography, due to the flexible time-frequency resolution. Wavelet transform generally includes continuous wavelet and discrete wavelet. Continuous wavelet transform (CWT) is capable of arbitrarily extracting the frequency characteristics of the original machined surface texture compared with discrete wavelet. Therefore, the CWT is used to analyze the two-dimensional surface contour and its expression is shown in equations (12) and (13):

$$ W_c(f) = \int f(t) \psi \left( \frac{t-b}{a} \right) dt $$

$$ \psi^{a,b}(x) = |a|^{-1/2} \psi \left( \frac{x-b}{a} \right) (a, b \in \mathbb{R}, a > 0) $$

Where $W_c$ represents continuous wavelet coefficients, $a$ represents scale factor, and $b$ represents translation factor.

When using the CWT to analyze the surface texture features, the wavelet basis function and scale factor $a$ need to be determined. Here, the Mexican Hat Wavelet function is used and its expression is shown in equation (14). The scale factor $a$ is determined through equations (15) and (16):

$$ \psi(t) = 2\sqrt{3}\pi^{-1/4}(1-t^2)e^{-t^2/2} $$

$$ f_s = 2f_L/N $$

$$ a = f_c/f_s\Delta $$

Where, $\psi(t)$ denotes Mexican Hat Wavelet function, $f$ represents the actual frequency characteristics of the machined surface, $L$ represents the sample length, $N$
represents the number of sample points, $f_c$ is the center frequency of the wavelet basis function, and $\Delta$ represents the sampling period.

**Experimental setup**

The micro eccentric shaft with an eccentricity of 0.15 mm was machined through self-centering three jaw chuck with gasket, as shown in Figure 4. The material of the workpiece is 310S stainless steel and the properties are shown in Table 2.

Figure 5 and Table 3 show the micro milling cutters used in the paper and the corresponding technical parameters, respectively.

CNC turn-milling machining center KNC-50FS was used to machine the micro eccentric shaft. The machined surface texture was measured by KEYENCE VK-100 confocal laser scanning microscope, as shown in Figure 6. Based on the cutting parameter range recommended by the tool supplier, the cutting parameters were determined by trial tests, as shown in Table 4.

**Results and discussion**

**The simulation and experimental results of surface texture**

At a rotation speed of cutting tool of 4000 r/mm, a rotation speed of workpiece of 30 r/mm, a depth of cut of 0.05 mm, an axial feed rate of 0.02 mm/r, the simulation and experimental results of surface texture profile with different cutting tools are shown in Figure 7. The surface texture profiles of simulations and experiments are in good agreement, which confirms that the mathematical model is effective for surface morphology simulation. In addition, it is worth noting that there is a large difference in the height of surface texture profiles of simulations and experiments. According to the mathematical model established in section 2.1, the most obvious difference lies in the contact form of different tools and workpiece, as shown in equations (1) and (8). The position angle mainly reflects the different contact form and the maximum position angle directly determines the contact range of the tool and workpiece. The maximum position angle of ball end milling cutter is $\cos((R_t - a_p)/R_t)$, and $\cos$ represents the arc cosine function. For flat end milling cutter, first of all, it is necessary to determine whether only the face edge of cutter participates in cutting or the face and side edge participate in cutting at the same time. According to previous

| Tool type            | Tool materials              | Tool diameter (mm) | Holder diameter (mm) | Edge number | Rake angle (°) | Clearance angle (°) | Helix angle (°) |
|----------------------|-----------------------------|--------------------|----------------------|-------------|----------------|---------------------|----------------|
| Flat end milling cutter | WC-TiC-Co cemented carbide | 0.2                | 4                    | 2           | 3              | 7                   | 30             |
| Ball end milling cutter | WC-TiC-Co cemented carbide | 0.2                | 4                    | 2           | 5              | 7                   | 55             |
research, it can be determined by the following formula:

\[
R_t < \sqrt{R_w^2 - (R_w - \alpha_p)^2}
\]

(17)

If the inequality holds, only the face edge of flat end milling cutter is in cut. Thus, it can be inferred that only the face edge is in cut for flat end milling cutter, and the maximum position of flat end milling cutter is \(R_t\). Therefore, from Figure 7(a) and (b), it can be seen that the height of surface profiles of ball end milling cutter is directly related to cutting depth, but the simulation results of the flat end milling cutter have no direct relationship. What’s more, different deformation, material flow direction, residue distribution, and hardness values of workpiece all affect the surface quality of micro structures. Finally, the workpiece shows different surface texture profiles and residual heights. The surface texture obtained by the flat end milling cutter is arranged in wavy stripes, and there are many sharp peaks formed on the surface. The surface texture obtained by the ball end milling cutter is arranged in a spiral shape (ring-shape pit) and many small peaks appear on the edge of ring-shape pit. Therefore, it is of great significant to analyze the dynamic characteristics and functional performance of different surface texture.

### Surface texture characterization and functional performance analysis

As can be seen from Figure 7, there is a clear difference in the height of the surface microscopic profile. The analysis results of different cutting tools under intermediate level combination of cutting parameters are shown in Figure 8, and the statistical parameters of the ADF under all cutting parameter combinations are shown in Figure 9.

As shown in Figures 8 and 9(a), when machining with flat end milling cutter, the skewness values of the surface are approximately zero, which means that the microscopic height distribution of the surface is much closer to Gaussian distribution and the surface texture tends to be more random (more micro geometrical

| No. | Rotation speed of cutting tool (rpm) | Rotation speed of workpiece (rpm) | Depth of cut (mm) | Axial feed rate (mm/r) |
|-----|-----------------------------------|-----------------------------------|------------------|-----------------------|
| 1   | 4000, 4500, 5000, 5500             | 30                                | 0.05             | 0.020                 |
| 2   | 4500                              | 25, 30, 35, 40                    | 0.05             | 0.020                 |
| 3   | 4500                              | 30                                | 0.04, 0.05, 0.06, 0.07 | 0.020                 |
| 4   | 4500                              | 30                                | 0.05             | 0.018, 0.02, 0.022, 0.024 |

Figure 7. Surface texture profiles with different cutting tools: (a) the simulation results of surface texture of flat end milling cutter, (b) the simulation results of surface texture of ball end milling cutter, (c) experimental results of flat end milling cutter, and (d) experimental results of ball end milling cutter.
features). The ADF of the machined surface obtained by the ball end milling cutter are positively deviated from Gaussian distribution, which indicates that the surface height region above the mean line has a higher probability density. In addition, the leptokurtic surface has a high Sku value ($>3$), while the platykurtic surface has a low Sku value ($<3$). Thus, it can be inferred from Figure 9(b), there are more sharp peaks on the surface machined by flat end milling cutter, which corresponds to the previous research and the simulation results, as shown in Figure 9(a).

Conventional surface texture evaluation parameters are rarely associated with functionality-related performance. It is necessary to propose functional statistical parameters to characterize the corresponding functionality-related performance of the machined surface. In general, different microscopic height of the surface texture corresponds to different performance of the part. Therefore, the functional performance of the surface texture is evaluated through the bearing area curve (BAC), as shown in Figure 10.

Functionally, reduced peak height $R_{pk}$ is directly related to the initial mechanical contact in the running-in period, which affects the time for the part to enter the normal working state. The larger value of $R_{pk}$ means the poor running-in performance. Core height $R_k$ directly sustains the corresponding loads and determines the wear resistance of the machined surface. Higher value of $R_k$ indicates the longer service life of the part. Reduced dale height $R_{vk}$ is used to characterize the fluid retention property of the machined surface. Higher value of $R_{vk}$ represents a better fluid retention capacity. Functional statistical parameters of the machined surface under all cutting parameter combinations are shown in Figure 11.

As shown in Figure 11(b) and (c), values of $R_k$ and $R_{vk}$ of the surface machined by the flat end milling cutter are much larger than that of the ball end milling cutter under the same cutting parameters, which indicates that the surface machined by the flat end milling cutter has better load bearing, wear resistance, and lubricant or oil retention capability. This is mainly
because that the cross section of the surface machined by the flat end milling cutter is not an ideal circle but a polygonal shape, which means that the height difference of the microscopic profile varies widely according to previous research. Moreover, wave-shaped peaks and valleys staggered with each other are formed on the surface, as shown in Figure 7(a). Such a surface has a better lubricant retention structure in sliding friction.
pair. However, scallops are formed on the surface machined by ball end milling cutter and circular dimples exist at the bottom of valley, as shown in Figure 7(b), which accounts for the mediocre performance of the surface. The values of $R_{pk}$ is slightly different as shown in Figure 11(a), which manifests that there is no significant distinction in the running-in performance of the surface.

Considering that micro eccentric shaft belongs to micro-small parts, the surface texture is often affected by the scale or resolution. Therefore, the surface texture is analyzed by the fractal dimension, as shown in Figure 12.

It can be found that the value of the fractal dimension obtained by the ball end milling cutter is slightly larger than that of the flat end milling cutter. This suggests that the micro profile obtained by the ball end milling cutter is more regularity, while the profile morphology of the flat end milling cutter is more complex, and the surface profile has overall fluctuation.

**Spectral analysis of the surface texture**

Traditional surface evaluation parameters can’t explain the exact relations between process dynamic state and geometrical specification of the machined surface, so the functional parameter PSD is introduced to study the spectral properties of the machined surface. The spectrum analysis process of surface texture is similar for each set of cutting parameters. Therefore, the cutting parameter combinations under variable axial feed rate are selected for analysis, as shown in Figure 13.

As can be seen from Figure 13, in addition to the vicinity of the peak, the PSD curve of the surface obtained by the flat end milling cutter fluctuates in a zigzag manner, and the PSD curve of the surface obtained by the ball end milling cutter is relatively flat. It shows that the surface texture obtained by the flat end milling cutter has more micro geometrical features than that of the ball end milling cutter, which is consistent with the results of Figure 11(a) and the chatter is slightly larger in the orthogonal turn-milling process. Furthermore, both of the PSD have a dominant spatial frequency, which indicates that the surfaces have periodic microscopic structure, as shown in Figure 7.

From the results of PSD analysis, there are three apparent actual frequency characteristics corresponding to the surface obtained by different cutting tools, as shown in Figure 14. Furthermore, Continuous wavelet analysis can remedy the shortcoming of PSD in analyzing the continuity of frequency features, so the wavelet coefficients are extracted from the actual frequency characteristics using continuous wavelet analysis (CWT), and the frequency components are determined. The effect of cutting parameters on the microscopic profile is mainly reflected by the wavelength and amplitude of frequency characteristics. Corresponding to the
flat end milling cutter, the frequency characteristic of 0.0092 μm⁻¹ is the main factor affecting the surface texture. Similarly, the frequency characteristic of 0.0184 μm⁻¹ is the main factor affecting the surface texture for ball end milling cutter, as shown in Figure 15. In addition, intermediate frequency characteristic is the most important factor to reflect the influence of cutting parameters and cutting vibration.

**Conclusions**

Surface texture characterization plays an important part in describing surface micro geometrical features and determining surface functionality-related properties. In this paper, the surface texture obtained by different cutting tools during turn-milling of micro eccentric shaft is analyzed from the perspective of functional characterization parameters and statistical functions. The main conclusions can be summarized as follows:

1. The simulation of surface texture was carried out based on the theoretical model of the cutting edge trajectory model. The simulation results are in good agreement with the experimental results, which gives a satisfactory prediction of the real surface texture;
2. The microscopic height distribution of the surface machined by flat end milling cutter is much closer to Gaussian distribution, and there are more microscopic geometric features than that of the ball end milling cutter;
3. Compared with ball end milling cutter, the machined surface obtained by the flat end milling cutter has better load bearing, wear resistance, and lubricant or oil retention capability based on the BAC-related functional statistical parameters;
4. The influence of cutting parameters and vibration on machined surface can be reflected by intermediate frequency characteristic during machining process.

Figure 13. PSD analysis results under different cutting parameters: (a) PSD analysis results of flat end milling cutter and (b) PSD analysis results of ball end milling cutter.

Figure 14. PSD analysis under different cutting tools: (a) PSD analysis of flat end milling cutter and (b) PSD analysis of ball end milling cutter.
Declaration of conflicting interests

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ORCID iDs

Minghui Cheng https://orcid.org/0000-0001-8135-2443
Pei Yan https://orcid.org/0000-0001-6004-5532

References

1. Otalora-Ortega H, Osoro PA and Arrazola Arriola PJ. Analytical modeling of the uncut chip geometry to predict cutting forces in orthogonal centric turn-milling operations. Int J Mach Tools Manuf 2019; 144: 103428.
2. Sun T, Qin LF, Fu YC, et al. Chatter stability of orthogonal turn-milling analyzed by complete discretization method. Precis Eng 2019; 56: 87–95.
3. Ding W, Dai C, Yu T, et al. Grinding performance of textured monolayer CBN wheels: undeformed chip thickness nonuniformity modeling and ground surface topography prediction. Int J Mach Tools Manuf 2017; 122: 66–80.
4. Cao Y, Zhu Y, Ding W, et al. Vibration coupling effects and machining behavior of ultrasonic vibration plate device for creep-feed grinding of Inconel 718 nickel-based superalloy. Chin J Aeronaut 2022; 35(2): 332–345.
5. Miao Q, Ding W, Xu J, et al. Creep feed grinding induced gradient microstructures in the superficial layer of turbine blade root of single crystal nickel-based superalloy. Int J Extrem Manuf 2021; 3(4): 045102.
6. Qiu Y, Yin J, Cao Y, et al. Generation mechanism modeling of surface topography in tangential ultrasonic vibration-assisted grinding with green silicon carbide abrasive wheel. Proc IMechE, Part B: J Engineering Manufacture 2021; 2021: 09540542110406.
7. Dang J, Zhang H, An Q, et al. On the microstructural evolution pattern of 300 M steel subjected to surface cryogenic grinding treatment. J Manuf Process 2021; 68: 169–185.
8. Dang J, Zhang H, An Q, et al. Surface modification of ultrahigh strength 300M steel under supercritical carbon dioxide (scCO2)-assisted grinding process. J Manuf Process 2021; 61: 1–14.
9. Zhang X, Zhang W, Zhang J, et al. Systematic study of the prediction methods for machined surface topography and form error during milling process with flat-end cutter. Proc IMechE, Part B: J Engineering Manufacture 2019; 233(1): 226–242.
10. Chen HQ and Wang QH. Modelling and simulation of surface topography machined by peripheral milling considering tool radial runout and axial drift. Proc IMechE, Part B: J Engineering Manufacture 2019; 233(12): 2227–2240.
11. Yuan SM and Zheng WW. The surface roughness modeling on turn-milling process and analysis of influencing factors. Appl Mech Mater 2011; 117–119: 1614–1620.
12. Karagüzel U, Uyusl E, Budak E, et al. Analytical modeling of turn-milling process geometry, kinematics and mechanics. Int J Mach Tools Manuf 2015; 91: 24–33.
13. Zhu L, Li H and Wang W. Research on rotary surface topography by orthogonal turn-milling. Int J Adv Manuf Technol 2013; 69(9–12): 2279–2292.
14. Döbbertin C, Taschenberger S, Welzel F, et al. Modelling of turn-milled surfaces. Int J Adv Manuf Technol 2019; 101(1–4): 849–857.

Figure 15. Wavelet analysis results under different scale factors: (a) CWT analysis of flat end milling cutter and (b) CWT analysis of ball end milling cutter.
15. De Chiffre L, Lonardo P, Trumpold H, et al. Quantitative characterisation of surface texture. CIRP Ann Manuf Technol 2000; 49(2): 635–652.

16. Gadelmawla ES, Koura MM, Maksoud TM, et al. Roughness parameters. J Mater Process Technol 2002; 123(1): 133–145.

17. Liang X, Liu Z, Yao G, et al. Investigation of surface topography and its deterioration resulting from tool wear evolution when dry turning of titanium alloy Ti-6Al-4V. Tribol Int 2019; 135: 130–142.

18. Eifler M, Klauer K, Kirsch B, et al. Performance verification of areal surface texture measuring instruments with the Sk-parameters. Measurement 2021; 173: 108550.

19. Shi H, Yuan S, Li Z, et al. Evaluation of surface roughness based on sampling array for rotary ultrasonic machining of carbon fiber reinforced polymer composites. Measurement 2019; 138: 175–181.

20. Liu J, Cheng K, Ding H, et al. An investigation of influence of cutting parameters on three-dimensional surface topography in micromilling SiCp/Al composites. Proc IMechE, Part B: J Engineering Manufacture 2021; 235(3): 829–838.

21. Yang D and Liu Z. Surface topography analysis and cutting parameters optimization for peripheral milling titanium alloy Ti-6Al-4V. Int J Refract Metals Hard Mater 2015; 51: 192–200.

22. Zeng Q, Yin Q, Chang W, et al. Correlating and evaluating the functionality-related properties with surface texture parameters and specific characteristics of machined components. Int J Mech Sci 2018; 149: 62–72.

23. Dong WP, Sullivan PJ and Stout KJ. Comprehensive study of parameters for characterizing three-dimensional surface topography I: some inherent properties of parameter variation. Wear 1992; 159(2): 161–171.

24. Dong WP, Sullivan PJ and Stout KJ. Comprehensive study of parameters for characterizing three-dimensional surface topography II: statistical properties of parameter variation. Wear 1993; 167(1): 9–21.

25. Shi X, Xiui S, Meng Z, et al. Research on machining topography of point grinding based on correlation function method. Proc IMechE, Part B: J Engineering Manufacture 2019; 233(3): 850–862.

26. Cheung CF and Lee WB. Characterisation of nanosurface generation in single-point diamond turning. Int J Mach Tools Manuf 2001; 41(6): 851–875.

27. Zahouani H, Mezghani S, Vargiolo R, et al. Identification of manufacturing signature by 2D wavelet decomposition. Wear 2008; 264(5–6): 480–485.

28. Booazarpour M, Teimouri R and Yazdani K. Comprehensive study on effect of orthogonal turn-milling parameters on surface integrity of Inconel 718 considering production rate as constrain. Int J Lightweight Mater Manuf 2021; 4(2): 145–155.

29. Choudhury SK and Bajpai JB. Investigation in orthogonal turn-milling towards better surface finish. J Mater Process Technol 2005; 170(3): 487–493.

30. Choudhury SK and Mangrulkar KS. Investigation of orthogonal turn-milling for the machining of rotationally symmetrical work pieces. J Mater Process Technol 2000; 99(1): 120–128.

31. Jin CZ and Fang R. Research on surface topography and roughness of micro parts by high speed turn-milling. Mater Sci Forum 2014; 800–801: 607–612.

32. Hu HCJ. Research on surface micro pattern generation in turn-milling considering ball-end milling cutter eccentricity. Adv Eng Rev 2018; 149: 855–863.

33. Peng Z, Jiao L, Yan P, et al. Simulation and experimental study on 3D surface topography in micro-ball-end milling. Int J Adv Manuf Technol 2018; 96(5–8): 1943–1958.

34. ISO 4287. Geometrical product specifications (GPS)–surface texture–profile method–terms, definitions and surface texture parameters. Geneva, Switzerland: ISO, 1997.

35. ISO 25178-3. Geometrical product specifications (GPS)-Surface texture: Areal-part3: Specification operations. Switzerland, https://www.iso.org/obp/ui/#iso:std:iso:25178:en (2018, accessed 10 September 2018).

36. Li J, Du Q and Sun C. An improved box-counting method for image fractal dimension estimation. Pattern Recognit 2009; 42(11): 2460–2469.

37. Niu Z, Jiao L, Chen S, et al. Surface quality evaluation in orthogonal turn-milling based on box-counting method for image fractal dimension estimation. Nanomanuf Metrol 2018; 1(2): 125–130.

38. Karaguel S, Uysal E, Budak E, et al. Effects of tool axis offset in turn-milling process. J Mater Process Technol 2016; 231: 239–247.

39. Zhu L, Jiang Z, Shi J, et al. An overview of turn-milling technology. Int J Adv Manuf Technol 2015; 81(1–4): 493–505.

40. Kaibu S, Ikeda A and Ihara Y. Study on cutting marks by turn mill process. Procedia CIRP 2018; 77: 251–254.

41. Nieslony P, Kroloczyk GM, Wojciechowski S, et al. Surface quality and topographic inspection of variable compliance part after precise turning. Appl Surf Sci 2018; 434: 91–101.