An unformed chip thickness approach to study the influence of process vibration on machining performance in milling

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Abstract
The vibration in the milling process plays a key role in machining, which can significantly affect the machining quality of the workpiece. Some vibrations have negative influences on the workpiece surface, while other vibrations can improve machining stability. Therefore, it is critical to distinguish the influence of different types of vibration on machining quality. A simulation method of undeformed chip thickness considering process vibration is presented in this article, in which a finite element model is established to analyze the dynamic milling process of 7075-T651 aluminum alloy from the aspects of cutting force and temperature. A series of experiments are carried out to verify the effectiveness of the simulation model, and the results show that the proposed model is accurate in predicting both milling force and temperature. Furthermore, the effect of milling vibration on machining performance is studied with the proposed method, in which the relationship between the amplitude-frequency characteristics of vibration and milling force-temperature fluctuation is revealed. The results show that the proposed method can determine the influence of milling vibration and provide a basis for distinguishing favorable and unfavorable vibration parameters of machining quality in milling.

Keywords Amplitude-frequency characteristics · Milling vibration · Unformed chip thickness · Milling force · Milling temperature

1 Introduction

Precision milling processes have been widely applied in manufacturing parts including automotive, aerospace, and precision machinery. To improve the machining quality of the parts, the finite element method, numerical analysis method, and experimental method were applied to predict and evaluate the machining quality [1–3]. Process vibration has an important effect on the machining quality. As such, it is very important to distinguish which vibration parameters are favorable or unfavorable. Favorable vibration parameters refer to the conditions that can reduce the cutting force and temperature, which improves machining quality. Unfavorable vibration parameters refer to the conditions which would lead to poor surface quality, accelerate the cutting tool wear, and shorten the tool durability in cutting.

In grinding and milling processing technology, vibration generated from the processing process has a great impact on machining accuracy and quality [4–8]. The vibration phenomenon in the processing process will lead to poor surface quality and affect the machine life. Shitehin et al. [9] have carried out experimental research on low-frequency vibration when the spherical milling cutter is machining bevels. Their results show that the effect of low-frequency vibration on the processing surface is more significant than that of ordinary vibration. By taking regenerative vibration and frictional vibration into consideration, Kecik et al. [10] studied the problem of vibration during high-speed milling. Afazov and Uzunov [11] made a comparative study on the mathematical model of cutting force and the two flutter prediction models of directly-measured cutting force. It was found that the chatter model established by directly measuring the cutting force was in good agreement with the fast Fourier transform analysis. These studies are based on the process reliability study, so the vibration effect on the process performance requires further study.

In contrast, vibration in the process can also have a favorable effect on the machining quality. In this area,
ultrasonic-assisted vibration processing plays a crucial role in improving the processing quality of parts [12, 13]. The influence of the vibration parameters on milling force and heat is very important in vibration-assisted milling. Verma and Pandey [14] experimentally evaluated the effect of process parameters on milling force. The results showed that the most effective parameter of milling force is the feed, and axial vibration assistance also reduces the average milling force. Elhami et al. [15] studied the effect of mixed machining parameters on average milling force, and the results showed that the milling force of ultrasonic auxiliary milling could be reduced by about 27% compared to conventional milling. Through simulation and experimental studies, Shu and Sugita [16] found that the cutting force decreased with the increase of vibration frequency or amplitude in the cutting process of elliptical vibrating bone. Verma et al. [17] established a cutting force calculation model for an axial ultrasonic-assisted milling process based on process physics and carried out experimental research. It was found that the superposition of axial ultrasonic vibration in the milling operation could reduce the cutting force and improve the surface finish. Furthermore, it was determined that ultrasonic vibration-assisted milling can produce a periodic separation between the tooltip and the workpiece in the cutting process to reduce the milling force and produce the pulse cutting effect.

In addition, ultrasonic-assisted vibration can not only reduce the milling force but also plays an important role in reducing the milling heat. Feng et al. [18] proposed a model to analyze the ultrasonic vibration-assisted milling temperature, and the effect of milling parameters and vibration parameters on temperature was studied. Lu et al. [19] used finite element analysis techniques to study the effect of frequency and amplitude on milling temperature. The study found that the milling temperature increased with the increase of amplitude and decreased with the increase of frequency. Luo et al. [20] simulated and tested the ultrasonic vibration-assisted milling of aluminum alloy 7075-T651, finding that the milling temperature decreased accordingly with the increase of amplitude and frequency. Verma et al. [21] developed a process physics-based equation to predict temperature rise in vibration-assisted milling.

Researchers generally studied either the conventional milling process or the ultrasonic vibration-assisted milling process. Most of the above studies focused on the specific frequency or amplitude range, but it is important to conduct comprehensive research on the vibration parameters (wide vibration frequency range and multiple amplitude characteristics). A model with specific requirements needs to be developed to study the influence of process vibration on machining performance in milling.

In this paper, the effects of vibration frequency and amplitude on milling performance are systematically studied. Firstly, a simulation method of undeformed chip thickness considering process vibration is presented in this article, in which a finite element model is established. Taking 7075-T651 aluminum alloy as the object, the dynamic milling performance of the cutting force, temperature, and surface roughness are analyzed, and the accuracy of the model in predicting milling force and milling temperature was verified by experimentation. Finally, the effect of milling vibration on machining performance is studied with the proposed method, and the relationship between the amplitude-frequency characteristics of vibration and the milling force-temperature fluctuation is revealed, providing a basis for distinguishing the favorable and unfavorable vibration parameters of machining quality.

2 Modelling of a milling process considering vibration

2.1 Tool path in vibration condition

As shown in Fig. 1, the vibration in the process has a significant effect on the trajectory of the tool. In milling, the workpiece feeds the tool at a constant milling speed, while the tool makes periodic reciprocating movements to the feed direction and vertical feed direction. In Fig. 1a, when the milling tool vibrates in the vertical feed direction, the tool begins to move at point A, which is the midpoint of...
the previous cycle, and the tool moves to the vertex position of the next cycle when it moves to point B. The vibration trajectory of the milling tool relative to the workpiece can be described as follows:

\[
\begin{align*}
X &= vt \\
y &= asin(2\pi f_s t + \phi_y)
\end{align*}
\]  

(1)

The speed of the tool relative to the workpiece can be expressed in the time derivative of the tool position, as follows:

\[
\begin{align*}
V_x &= v \\
V_y &= 2\pi f_s, acos(2\pi f_s t + \phi_y)
\end{align*}
\]  

(2)

In Fig. 1b, when the milling tool vibrates in the feed direction, the milling tool starts to move at point C and reaches the end of a cycle at point D. The vibration trajectory of the milling tool relative to the workpiece is as follows:

\[
\begin{align*}
X &= bsin(2\pi f_s t + \phi_s) - vt \\
y &= 0
\end{align*}
\]  

(3)

where \(a\) and \(b\) are the amplitudes, \(f_x\) and \(f_y\) are the vibration frequencies in the \(x\)- and \(y\)-directions, \(t\) is the time parameter, \(\phi_x\) and \(\phi_y\) are the initial angles, and \(v\) is the feed rate. Figure 1 clearly demonstrates the meaning of the initial phase in the equation. The speed of the tool relative to the workpiece can be expressed in the time derivative as follows:

\[
\begin{align*}
V_x &= 2\pi f_s, bcos(2\pi f_s t + \phi_y) - v \\
V_y &= 0
\end{align*}
\]  

(4)

When the tool vibrates in the feed direction, it is assumed that the variable \(k\) is the ratio of the maximum vibration speed of the tool to the milling speed \(v\). Here, \(k\) is expressed as:

\[
k = \frac{v}{2\pi f_x, b}
\]  

(5)

When \(k < 1\), the tool is separated from the chips and workpieces. The separation of the tool and chip can effectively reduce both milling temperature and milling force.

### 2.2 Unformed chip thickness considering vibration

The undeformed chip thickness has an important influence on the cutting force and temperature in machining. According to the study of Li et al. [22], it is impossible to establish the relationship between the cutting force and temperature in the tool feed direction and vertical feed direction, and the undeformed chip thickness. Therefore, according to the cutting motion direction of the tool and the undeformed chip thickness value direction, as well as based on the characteristics of slot milling, a semicircular model was established by considering the machining paths of two adjacent cutter teeth along the feed direction, as shown in Fig. 2. According to the undeformed cutting thickness model shown in Fig. 2, the mathematical model shown in Eq. (6) is established, and the undeformed cutting thickness is obtained by solving Eq. (7).

\[
R^2 + f_z^2 - 2 \cdot f_z \cdot R' \cdot \cos(\alpha + 90^\circ) - R^2 = 0
\]  

(6)

\[
UCT = R - R'
\]  

(7)

where \(f_z\) is the tool feed per tooth, \(R\) is the tool radius, \(\alpha\) is the milling arc angle, and \(UCT\) is the thickness of undeformed chips [22]. It can be seen from the milling model and formula that the parameters affecting the thickness of undeformed chips are tool diameter and feed per tooth. Furthermore, the vibration in the process would also impact the undeformed chip thickness. Accordingly, an undeformed chip thickness model considering vibration is established. Figure 3 shows the variation of the thickness of the undeformed chip with...
the angle of the arc zone with and without vibration is considered. The tool diameter is 8 mm, the feed speed is 0.6 m/min, the amplitude is 20 µm, and the frequency is 5000 Hz. The undeformed chip thickness analysis model considering vibration is applied to the finite element software, and the corresponding finite element simulation model is established, as shown in Fig. 4.

3 Finite element analysis and its verification

3.1 Simulation parameters

The aluminum alloy 7075-T651 has good fatigue resistance, with its chemical composition being shown in Table 1 [20]. Carbide tools have the advantages of high hardness, good temperature hardness, and good wear resistance. The parameters of the tool are recorded in Table 2. The material characteristic parameters of the workpiece and tool are recorded in Table 3.

The Johnson–Cook (JC) model is a good reflection of the high-temperature deformation of metals at high strain, high strain rate, and high temperature [23]. For the finite element simulation of material deformation processes, such as machining and plastic forming, the control equations are:

\[
\sigma = (A + Be^n) \left( 1 + Cln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left[ 1 - \left( \frac{T - T_\text{r}}{T_m - T_\text{r}} \right)^m \right]
\]  

where \(\sigma\) is the flow stress; \(\varepsilon\) is the effective plastic strain; \(\dot{\varepsilon}\) is the effective plastic strain rate; \(T\) is the ambient temperature; \(T_m\) is the melting point temperature of the material; \(A\) is the yield stress of the material; \(B\) is the processing hardening parameter of the material; \(C\) is the strain rate reinforcement index; \(m\) is the temperature change rate index; and \(n\) is the strain hardening index. The JC model parameters for 7075-T651 aluminum alloys are shown in Table 4 [24].

In the finite element model of the milling process, the critical value reached by plastic strain accumulation is often used as a criterion for chip damage, and the JC fracture criterion is used as the failure criterion in this study. The failure criterion provides a calculation method for the equivalent plastic strain when the material reaches the failure point, and the fracture failure parameter \(D\) is applied to determine the removal of the material:

\[
D = \sum \frac{\Delta \varepsilon}{\varepsilon'} 
\]

where \(\varepsilon'\) is a failure strain, while \(\Delta \varepsilon\) indicates an increase in effective plastic strain at a unit load. According to the JC fault guidelines, the fault failure strain of the material is calculated as follows [25]:

\[
\varepsilon_f = d_1 + d_2 \exp \left( d_3 \frac{\delta_m}{\bar{\sigma}} \right) \left[ 1 + d_4 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right] \left[ 1 + d_5 \left( \frac{T - T_\text{r}}{T_m - T_\text{r}} \right) \right]
\]

where \(\delta_m\) represents the mean of positive pressure; \(\bar{\sigma}\) is effective; and \(d_1-d_5\) is the material failure parameter. The JC damage model parameters for the 7075-T651 aluminum alloy are shown in Table 5 [24].

The software sets the relationship between the tool and workpiece (rigid elastic–plastic) to ensure that the simulation process of the tool mesh does not distort the iteration. According to Coulomb friction law, the friction factor between the tool and the workpiece plays a decisive role in the final simulation results. Based on the research of Bil et al. [26], the friction coefficient is taken as 0.5 in the present study. The software in this paper uses the friction relation as the Coulomb formula. As shown in the following formula:

\[
F_f \leq \mu \cdot F
\]

where \(F\) is the force between the tool and the workpiece surface, \(\mu\) is the friction factor, and \(F_f\) is the friction force caused by friction.

The main simulation parameters are shown in Table 6.

---

### Table 1 Chemical composition of aluminum alloy 7075-T651 (wt%)

|   | Al    | Zn    | Mg    | Cu    | Fe    | Si    | Mn    | Ti    | Cr    |
|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|   | 87.1~91.4 | 5.1~6.1 | 2.1~2.9 | 1.2~2 | 0.5   | 0.4   | 0.3   | 0.2   | 0.18~0.28 |

---
3.2 Simulation results and analysis

As shown in Fig. 5, the simulation results of milling force in both non-vibration and vibration conditions are presented. It can be found that both milling forces noticeably showed a parabolic trend, which is in line with the change law of unformed chip thickness in slot milling. Furthermore, while in milling without vibration, the milling force has only a small range of fluctuations, which is an inherent characteristic of milling. In milling with vibration, the milling force will produce periodic large-scale fluctuations with vibration, which is mainly due to the periodic movement of the tool. To obtain the force values, the force data is post-processing, as shown in Fig. 5c, in which the band-pass filtering is applied to calculate the periodic fluctuation curve, and the force fluctuations after filtering are consistent with the applied vibration signal. The average milling force is obvious in the figures, and the milling force fluctuation is the value of function amplitude. The average milling force directly affects the machining quality, while the fluctuation value of the milling force affects the stability of the machining system.

As shown in Fig. 6, the results of the milling temperature simulation in non-vibration and vibration conditions are presented. It can be found that the highest temperature in the milling area is at the tip of the tool, and the maximum temperature of milling with vibration is higher than that without milling. Furthermore, from the partial amplification of the machining workpiece surface, it can be found that the non-vibration machined surface is relatively flat, while the vibration machined surface appears as an undulating wave, which matches with the movement between the tool and the workpiece. In the milling process, the milling temperature is mainly concentrated in the first and second milling areas. In the first milling area, the temperature is mainly caused by the plastic deformation of metal materials. In the second milling area, the temperature is mainly generated by the friction of the rear face. A gradient from high to low temperature is
Fig. 5  Milling force simulation results. (a) Milling without vibration (parameter I). (b) Milling with vibration (parameter II). (c) Average and fluctuation value of milling force (parameter II).

Fig. 6  Milling temperature simulation results. (a) Milling without vibration (parameter I). (b) Milling with vibration (parameter II).
formed inside the workpiece, which has an important effect on the surface temperature of the processed workpiece.

### 3.3 Experimental setup

This verification experiment was carried out on the carved Carver S600A vertical milling machine, as exhibited in Fig. 7. With specially designed workpieces fixed on the piezoelectric ceramic driver platform (model specification PT1500707301), the piezoelectric ceramic driver was fixed on the dynamometer to produce a certain vibration frequency and amplitude. The milling temperature was measured by the K-type thermocouple using the NI 9213 acquisition card. The milling forces were measured by a Kistler Force Dynamometer (Type 9139AA) mounted at the machine bed, for which the sampling rate was set to 2500 Hz. In the test, the tool and workpieces’ material were chosen as in Tables 1 and 2, which are the same as that in the simulation.

As shown in Fig. 8, the milling workpiece is divided into two parts. The end and bottom of workpiece 1 are provided with grooves, and the thermocouple is arranged in the grooves between workpiece 1 and workpiece 2, which are connected by bolts.

During the temperature measurement in milling, when the tool cuts the aluminum alloy material in the thermocouple test position, the temperature increases sharply and then falls, which produces a peak temperature, called the maximum temperature. The thermocouple measurement area is on the milling workpiece surface.
The processing parameters of the validation experiment are shown in Table 7. The measurement results of the milling forces and milling temperatures are shown in Fig. 7. The milling parameters are as follows: spindle speed 4000 r/min, milling depth 0.6 mm, and feed speed 0.8 m/min. The vibration parameters are as follows: amplitude 10 µm and frequency 2 kHz. The finite element simulation model is experimentally verified from the milling force and milling temperature, and the results are shown in Fig. 9. It can be found that the maximum error of force between the experiment and simulation is 12%, while the maximum error of temperature is 15.7%. The simulation results in present good agreement with the experimental observations, which proves the accuracy of the simulation model and can realize the simulation prediction of the milling force and temperature.

4 Effect of vibration characterization parameters on machining performance

In the milling of 7075-T651 aluminum alloys, the vibration characterization parameters (amplitude and frequency) have an impact on the milling force and temperature, it cannot be ignored in the precision manufacturing process. It is very difficult to obtain different vibration characterization parameters in experiments, the simulation method is applied to analyze the effect of vibration characterization parameters on the processing results.

4.1 Effect of vibration frequency on milling force and temperature

The single factor test of frequency was conducted in simulation, as presented in Table 8. The vibration of the amplitude of 10 µm was applied to the feed direction and...
vertical feed direction, respectively. The simulation results are shown in Table 8, and the relationship between vibration frequency, milling force, and milling temperature was analyzed, as shown in Fig. 10. As in Fig. 10a, b, while the vibration frequency in the feed direction increases, the average milling force in the x- and y-directions varies little when the frequency is below 20 kHz and decreases gradually when the frequency is greater than 20 kHz. The average surface temperature of the workpiece increases and then gradually decreases with frequency. Furthermore, the milling force fluctuation value of vibration in the x-direction gradually increased when the frequency was more than 20 kHz.

As in Fig. 10c, d, while the vibration frequency in the vertical feed direction increases, the average milling force of vibration in the x- and y-directions varies little when the frequency is below 20 kHz and decreases gradually when the frequency is greater than 20 kHz. The average surface temperature of the workpiece increases and then gradually decreases with frequency. Furthermore, the milling force fluctuation value of vibration in the y-direction gradually increased when the frequency was more than 20 kHz.

### 4.2 Effect of amplitude on milling force and temperature

#### 4.2.1 Effect of amplitude on milling force and temperature at low-frequency vibration

The single factor test of amplitude was conducted in simulation as processing parameters in Table 9, and the vibration frequency of 2 kHz was applied to the feed direction and vertical feed direction. The simulation results are shown in Table 9. The relationship between the amplitude, milling force, and milling temperature was analyzed, as shown in Fig. 11. As presented in Fig. 11a, b, with the increase of the amplitude in the feed direction, the average milling forces of vibration in the x- and y-directions remain basically unchanged, while the average temperature of the surface of the workpiece decreases gradually. As shown in Fig. 11c, d, with the increase of the amplitude in the vertical feed direction, the average milling force of vibration in the x- and y-directions and the average surface temperature of the workpiece show an increasing trend. Additionally, the milling force fluctuation value of vibration in the x- and y-directions gradually increases.
In summary, in the situation of low-frequency vibration in the vertical feed direction, the vibration amplitude will increase the average milling force, temperature, and milling force fluctuations, resulting in poor machining quality and machining system stability.

4.2.2 Effect of amplitude on milling force and temperature at ultrasonic vibration

The single factor test of amplitude was conducted in simulation as processing parameters in Table 10, and a vibration

Table 9 Effect of different amplitudes (low-frequency vibration) on processing results

| No. | Spindle speed (r/min) | Feed rate (mm/t) | Milling depth (mm) | Amplitude (µm) | The average value of $F_x$ (N) | The average value of $F_y$ (N) | The average temperature of the processed surface (°C) | Fluctuation value of $F_x$ (N) | Fluctuation value of $F_y$ (N) |
|-----|---------------------|-----------------|-------------------|---------------|-------------------|-------------------|---------------------------------|-------------------|-------------------|
| 1   | 10,000              | 0.1             | 0.2               | 10            | 19.3              | 19.7              | 182.4                           | 2.5               | 5.0               |
| 2   | 10,000              | 0.1             | 0.2               | 20            | 19.3              | 19.3              | 176.5                           | 2.4               | 7.2               |
| 3   | 10,000              | 0.1             | 0.2               | 30            | 19.4              | 19.7              | 170.3                           | 2.3               | 9.1               |
| 4   | 10,000              | 0.1             | 0.2               | 40            | 19.4              | 20.2              | 166.7                           | 2.3               | 11.8              |
| 5   | 10,000              | 0.1             | 0.2               | 50            | 19.5              | 23.4              | 165.2                           | 2.2               | 18.6              |
| 6   | 10,000              | 0.1             | 0.2               | 60            | 19.3              | 27.1              | 163.8                           | 2.2               | 26.5              |
| 7   | 10,000              | 0.1             | 0.2               | 70            | 19.2              | 29.1              | 160.5                           | 2.2               | 30.9              |
| 8   | 10,000              | 0.1             | 0.2               | 80            | 19.1              | 30.3              | 159.2                           | 2.3               | 33.7              |
| 9   | 10,000              | 0.1             | 0.2               | 90            | 19.0              | 32.5              | 157.3                           | 2.2               | 37.5              |
| 10  | 10,000              | 0.1             | 0.2               | 100           | 19.1              | 33.2              | 155.2                           | 2.2               | 40.8              |

$F$ applying feed direction vibration, $v$ applying vertical feed direction vibration

Fig. 10 Effect of vibration frequency on the average milling force, temperature, and milling force fluctuation values. 

(a) Average milling force and temperature applying feed direction vibration. 

(b) Milling force fluctuation value applying feed direction vibration. 

(c) Average milling force and temperature applying vertical feed direction vibration. 

(d) Milling force fluctuation value applying vertical feed direction vibration.
frequency of 20 kHz was applied to the feed direction and vertical feed direction. The simulation results are shown in Table 10. The relationship between the amplitudes, milling force, and milling temperature was analyzed, as exhibited in Fig. 12. As shown in Fig. 12a, b, with the increase of the amplitude in the feed direction, the average milling force of vibration in the x- and y-directions and the average temperature of the surface of the workpiece decreases gradually. This is because the ultrasonic vibration causes intermittent milling of the tool, decreasing both the average milling force and milling temperature. The milling force fluctuation value gradually increases with the amplitude increase. Therefore, the selection of amplitude is very important to the stability of the system in ultrasonic-assisted milling.

As can be seen from Fig. 12c, d, with the increase of the amplitude in the vertical feed direction, the average milling force fluctuation value gradually increases with the amplitude increase. Therefore, the selection of amplitude is very important to the stability of the system in ultrasonic-assisted milling.

Table 10 Effect of different amplitudes (ultrasonic vibration) on processing results

| No. | Spindle speed (r/min) | Feed rate (mm/t) | Milling depth (mm) | Amplitude (µm) | The average value of $F_x$ (N) | The average value of $F_y$ (N) | The average temperature of the processed surface (°C) | Fluctuation value of $F_x$ (N) | Fluctuation value of $F_y$ (N) |
|-----|----------------------|------------------|--------------------|----------------|-----------------------------|-----------------------------|----------------------------------|-----------------------------|-----------------------------|
| 1   | 10,000               | 0.1              | 0.2                | 10             | 19.1                        | 20.4                        | 8.7                              | 12.1                        | 4.6                         |
| 2   | 10,000               | 0.1              | 0.2                | 20             | 18.6                        | 20.2                        | 8.6                              | 16.3                        | 6.2                         |
| 3   | 10,000               | 0.1              | 0.2                | 30             | 18.4                        | 20.1                        | 8.4                              | 19.5                        | 8.0                         |
| 4   | 10,000               | 0.1              | 0.2                | 40             | 15.0                        | 19.0                        | 7.5                              | 21.6                        | 9.1                         |
| 5   | 10,000               | 0.1              | 0.2                | 50             | 12.5                        | 18.7                        | 6.0                              | 23.5                        | 9.5                         |
| 6   | 10,000               | 0.1              | 0.2                | 60             | 10.5                        | 17.8                        | 5.4                              | 24.2                        | 10.3                        |
| 7   | 10,000               | 0.1              | 0.2                | 70             | 9.8                         | 17.6                        | 4.6                              | 25.6                        | 11.2                        |
| 8   | 10,000               | 0.1              | 0.2                | 80             | 8.6                         | 17.0                        | 4.2                              | 26.0                        | 11.3                        |
| 9   | 10,000               | 0.1              | 0.2                | 90             | 8.2                         | 16.6                        | 4.0                              | 26.5                        | 12.0                        |
| 10  | 10,000               | 0.1              | 0.2                | 100            | 7.2                         | 16.5                        | 3.3                              | 27.2                        | 13.2                        |

$F$ applying feed direction vibration, $v$ applying vertical feed direction vibration
force of vibration in the $x$-direction decreases gradually, while the average milling force in the $y$-direction increases gradually. The average milling temperature of the workpiece surface decreases at the first stage and then increases gradually. The temperature change is due to the change in the dominant position of cutter-workpiece discontinuous milling and increased milling area. The milling force fluctuation values of vibration in the $x$- and $y$-directions gradually increase, and the amplitude of the milling force fluctuation value in the $y$-direction increases more obviously.

5 Conclusion

In this paper, a simulation method of milling considering process vibration is presented by considering the undeformed chip thickness. Additionally, the effectiveness of the simulation method and model are verified by milling experiments. The influence of vibration parameters on milling performance is studied by using the simulation model. According to the analysis results, the following conclusions can be drawn as follows:

1. Based on the theory of undeformed chip thickness in the milling process, a simulation method of undeformed chip thickness considering vibration was proposed. The machining performance under different vibration parameters can be studied with the proposed model.

2. Experimental tests were performed to verify the simulation method and model, and the results show that the effectiveness of the finite element method (FEM) models in predicting the milling force and milling temperature. Therefore, the simulation model can define the influence of milling vibration on machining quality and can be applied to distinguish the favorable and unfavorable vibration parameters.

3. The influence of vibration frequency on the milling force and temperature was studied by the simulation model. The results indicate that the tool vibration can effectively decrease the average milling force and temperature at an ultrasonic frequency, though it simultaneously increases the fluctuation degree of the milling force. Therefore, it is important to choose the vibration frequency in the vibration-assisted process.

4. When low-frequency vibration in the vertical feed direction is applied, increasing the vibration amplitude will increase the average milling force, temperature, and milling force fluctuation values, which adversely affects the machining quality. When the ultrasonic vibration in the feed direction is applied, increasing the amplitude would reduce the average milling force and temperature, but increase the milling force fluctuation value.
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