An Unformed Chip Thickness Approach to Study the Influence of Process Vibration on Machining Performance in Milling

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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 milling process plays a key role in machining, which will significantly affect the machining quality of workpiece. Some vibrations have negative influences on the workpiece surface, while particular vibrations are able to improve machining stability. Therefore, it is critical to distinguish the influence of different types of vibration on the 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 milling force and temperature. Furthermore, the effect of milling vibration on machining performance is studied with the proposed method, in which the relationship between amplitude-frequency characteristics of vibration and milling force-temperature fluctuation is revealed. The results show that the proposed method can define 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. In order to improve the machining quality of the parts, 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, it is very important to distinguish favorable and unfavorable vibration parameters.

In the grinding and milling processing technology, vibration generated in the processing process has a great impact on the machining accuracy and quality [4-7]. Vibration phenomenon in the processing process will lead to poor surface quality and affect the machine life. Shtehin et al. [8] have carried out experimental research on low frequency vibration when the spherical milling cutter is machining bevels. The results show that the effect of low frequency vibration on the processing surface is more significant than that of ordinary vibration. Kecik et al. [9] studied the problem of vibration during high-speed milling, considering regenerative vibration and frictional vibration. Liu et al. [10] introduce a time-change reliability analysis method to predict the stability

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and vibration reliability in milling process. These researches are based on the process reliability study, the vibration effect on the process performance need further study.

In contrast, vibration in the process can also have a favorable effect on the machining quality. In the area, ultrasonic assisted vibration processing plays a crucial role in improving the processing quality of parts [11-12]. The influence of vibration parameters on milling force and heat is very important in vibration-assisted milling. Verma et al. [13] evaluated the effect of process parameters on milling force experimentally, the results show that the most effective parameter of milling force is the feed, and axial vibration assistance also reduces the average milling force. Elhami et al. [14] 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. Kong et al. [15] use finite element simulation technology to find that elliptical vibration milling has a lower milling force on 1045 steel than conventional milling. Chen et al. [16] studied the milling mechanism of magnesium alloy vibration-assisted micro-milling through finite element simulation and experiments and found that vibration frequency has a significant effect on machining mechanism, such as reducing milling force and tool wear. Tao et al. [17] have established an ultrasonic vibration-assisted milling mechanism model to calculate tangential, radial and axial milling forces. The results show that when ultrasonic vibration is applied in the feed direction, the milling force is reduced.

In addition, ultrasonic assisted vibration can not only reduce the milling force, but also play 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 is 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 of ultrasonic vibration-assisted milling of aluminum alloy 7075-T651, found 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 conventional milling process or ultrasonic vibration assisted milling process respectively. Most of the above studies focus on the specific frequency or amplitude range, it is important to comprehensive research on vibration parameters (wide vibration frequency range and multiple amplitude characteristics). The 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 cutting force, temperature and surface roughness is analyzed, and the accuracy of the model in predicting milling force and milling temperature was verified by experiments. Finally, the effect of milling vibration on machining performance is studied with the proposed method, and the relationship between amplitude-frequency characteristics of vibration and milling force-temperature fluctuation is revealed, which provide a basis for distinguishing favorable and unfavorable vibration parameters of machining quality.

2 Modelling of milling process considering vibration

2.1 Tool path in vibration condition

As shown in Figure 1, the vibration in process has significant effect on trajectory of tool. In milling, the workpiece feeds to the tool at a constant milling speed, while the tool makes periodic reciprocating movements the feed direction and vertical feed direction. In Figure 1(a), when the milling tool vibrates in the vertical feed direction, the milling 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:

$$\begin{cases} X = vt \\ y = asin(2\pi f_y t + \varphi_y) \end{cases} \tag{1}$$

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

$$\begin{cases} V_x = v \\ V_y = 2\pi f_y acos(2\pi f_y t + \varphi_y) \end{cases} \tag{2}$$

In Figure 1(b), 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:

$$\begin{cases} X = bsin(2\pi f_x t + \varphi_x) - vt \\ y = 0 \end{cases} \tag{3}$$

Where a and b are the amplitudes, fx and fy are the vibration frequencies in x and y direction, t is the time parameter, φx and φy are the initial angles, v is the feed rate. The speed of the tool relative to the workpiece can be expressed in the time derivative as follows:

$$\begin{cases} V_x = 2\pi f_x bcos(2\pi f_x t + \varphi_x) - v \\ V_y = 0 \end{cases} \tag{4}$$

When the tool vibrates in the feed direction and assuming that the variable k is the ratio of the maximum vibration speed of the tool to the milling speed v. And 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. Tool and chip separation can effectively reduce milling temperature and milling force.

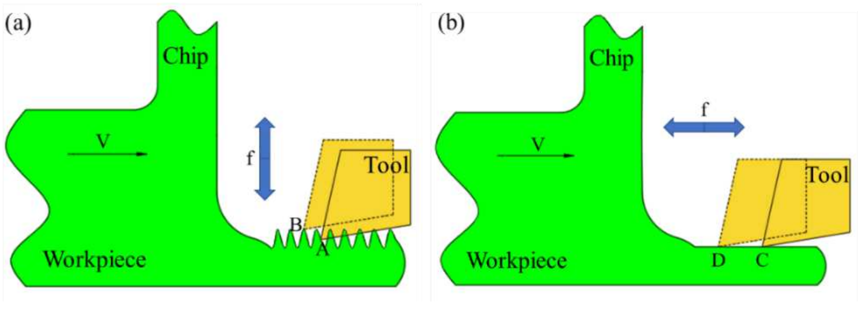

Figure 1 Tool path in vibration condition: **(a)** Vibration in vertical feed direction, **(b)** Vibration in feed direction

2.2 Unformed chip thickness considering vibration

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 Figure 2.

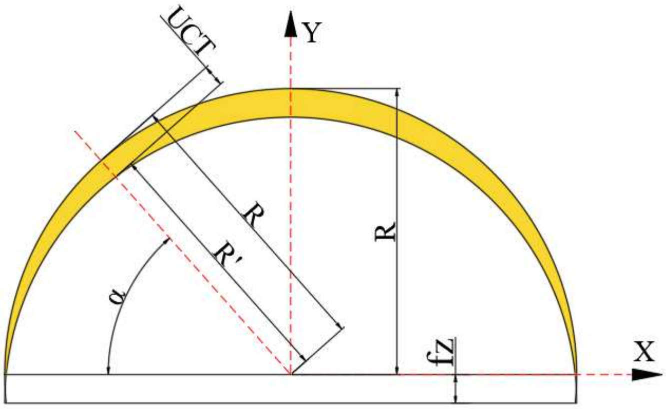

Figure 2 Unformed chip thickness model

$$R'^2 + f_z^2 - 2 \cdot f_z \cdot R' \cdot \cos(\alpha + 90°) - R^2 = 0 \tag{6}$$

$$UCT = R - R' \tag{7}$$

Where fz is the tool feed per tooth, R is the tool radius, α is the milling arc angle, UCT is the thickness of unformed chips [22]. It can be seen from the milling model and formula, the parameters affecting the thickness of unformed chips are tool diameter and feed per toot. Furthermore, the vibration in process would also impact on the unformed chip thickness. Figure 3 shows the variation of the thickness of the undeformed chip with the Angle of the arc zone without vibration and with vibration taken into account. The tool diameter is 8 mm, the feed speed is 0.15 mm/z, the amplitude is 20μm, and the frequency is 5000 Hz. The above undeformed chip thickness theory was applied to AdvantEdge software, and a milling model was established, as shown in Figure 4.

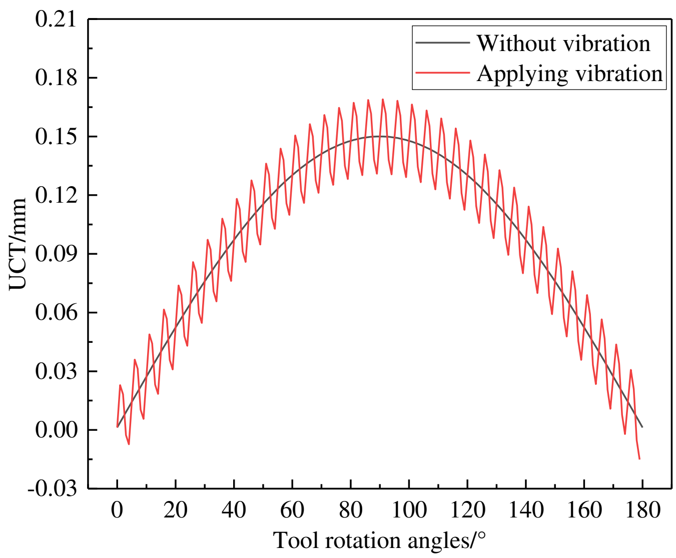

Figure 3 Unformed chip thickness for normal and vibration milling

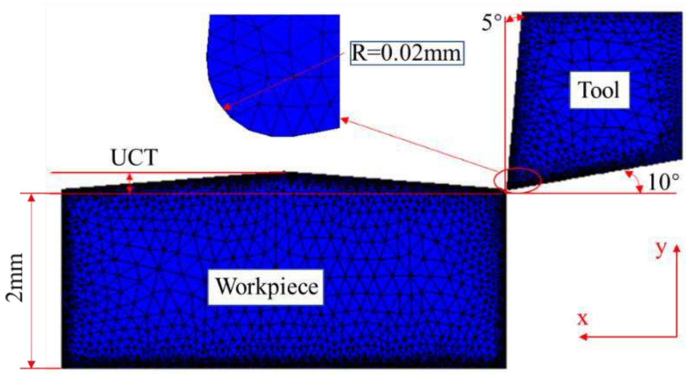

Figure 4 Milling simulation model

3 Finite element analysis and its verification

3.1 Simulation parameters

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

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

Table 2 Tool parameters

Tool diameter(mm)	Material	Rake angle(°)	Clearance angle(°)	Tool helix angle(°)	Tool flutes	Milling edge radius(mm)
8	Carbide-grade	5	10	30	3	0.02

Table 3 Material characteristic parameters of Aluminum alloy 7075-T651 and Carbide tool

Material parameters	Al7075-T651	Carbide tool
Density/(kg·m^{-3})	2810	15700
Elastic modulus(Gpa)	71.7	705
Poisson's ratio	0.33	0.23
Specific heat (J·kg^{-1}·K^{-1})	1075	178
conductivity/(W·m^{1}·K)	151.6	24
The coefficient of expansion/10·e^{-6}	25.2	5
melting point/K	908	

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

$$\sigma = (A + B\varepsilon^n)\left(1 + Cln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\left[1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \tag{8}$$

Where σ is the flow stress; ε is the effective plastic strain; $\dot{\varepsilon}$ is the effective plastic strain rate; $\dot{\varepsilon_0}$ is the reference 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; n is the strain hardening index. The J-C model parameters for 7075-T651 aluminum alloys are shown in Table 4[24].

Table 4 J-C model parameters for 7075-T651 aluminum alloys

$A(MPa)$	$B(MPa)$	C	m	n	$\dot{\varepsilon_0}(s^{-1})$	$T_r(K)$	$T_m(K)$
527	575	0.017	1.61	0.72	1	298	908

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 Johnson-Cook 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:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f} \tag{9}$$

Where ε^f is a failure strain; Δε indicates an increase in effective plastic strain at a unit load. According to the Johnson-Cook fault guidelines, the fault failure strain of the material is calculated as follows [25]:

$$\varepsilon^f = \left[d_1 + d_2 exp\left(d_3 \frac{\delta_m}{\bar{\delta}}\right)\right]\left(1 + d_4 ln \frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\left[1 + d_5\left(\frac{T-T_r}{T_m-T_r}\right)\right] \tag{10}$$

In which δ_m represents the mean of positive pressure; $\bar{\delta}$ is effective; d_1-d_5 is the material failure parameter, the J-C damage model parameters for the 7075-T651 aluminum alloy are shown in Table 5[24].

Table 5 J-C damage model parameters for 7075-T651 aluminum alloys

d_1	d_2	d_3	d_4	d_5
0.11	0.572	-3.446	0.016	1.099

The software usually sets the relationship between the tool workpiece (rigid elastic-plastic) to ensure that the simulation process of the tool mesh does not distort the iteration. The friction factor between the tool and the workpiece (set this to 0.5 for this article) plays a decisive role in the final simulation results, and the software in this paper uses the friction relation as coulomb formula. As shown in the following formula:

$$F_f \leq \mu \cdot F \tag{11}$$

Where F is the force between the tool and the workpiece surface, μ is the friction factor, F_f is the friction force caused by friction.

The main simulation parameters were shown in Table 6.

Table 6 Main simulation parameters

	Spindle speed(r/min)	Milling depth (mm)	Feed speed(m/min)	Frequency (kHz)	Amplitude (μm)
(I)	4000	0.6	0.8	0	0
(II)	4000	0.6	0.8	20	10

3.2 Simulation results and analysis

As shown in Figure 5, the simulation result of milling force in non-vibration and vibration condition is present. It can be found that the milling forces both obviously showed 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 the inherent characteristics 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 Figure 5c, in which the band-pass filtering is applied to calculate the periodic fluctuation curve, and the force fluctuations after filtering is 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 milling force affects the stability of the machining system.

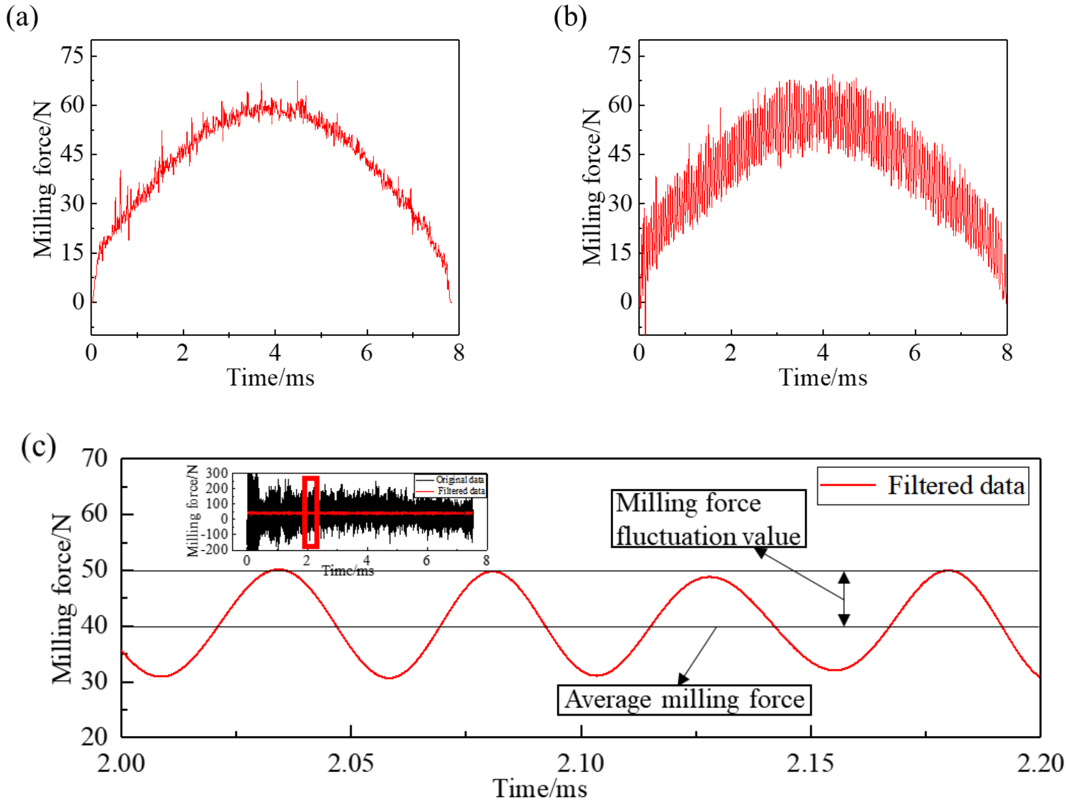

Figure 5 Milling force simulation results:**(a)** Milling without vibration (Parameter I), **(b)** Milling with vibration (Parameter II), **(c)** Average and fluctuation value of milling force (Parameter II)

As shown in Figure 6, the results of the milling temperature simulation in non-vibration and vibration condition is present respectively. 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 of 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 vibration machined surface appear undulating wave, which matches with the movement between the tool and the workpiece. In 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 mainly generated by the friction of the rear face. A gradient from high to low temperature is formed inside the workpiece, which has an important effect on the surface temperature of the processed workpiece.

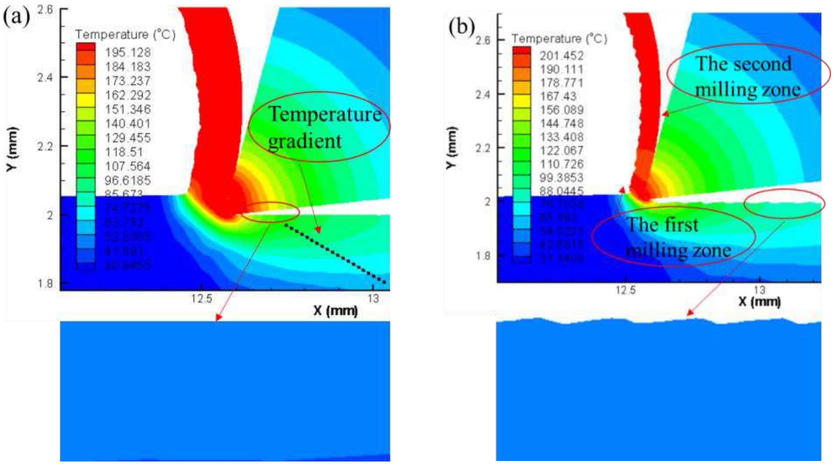

Figure 6 Milling Temperature Simulation Results:**(a)** Milling without vibration (Parameter I), **(b)** Milling with vibration (Parameter II)

3.3 Experimental setup

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

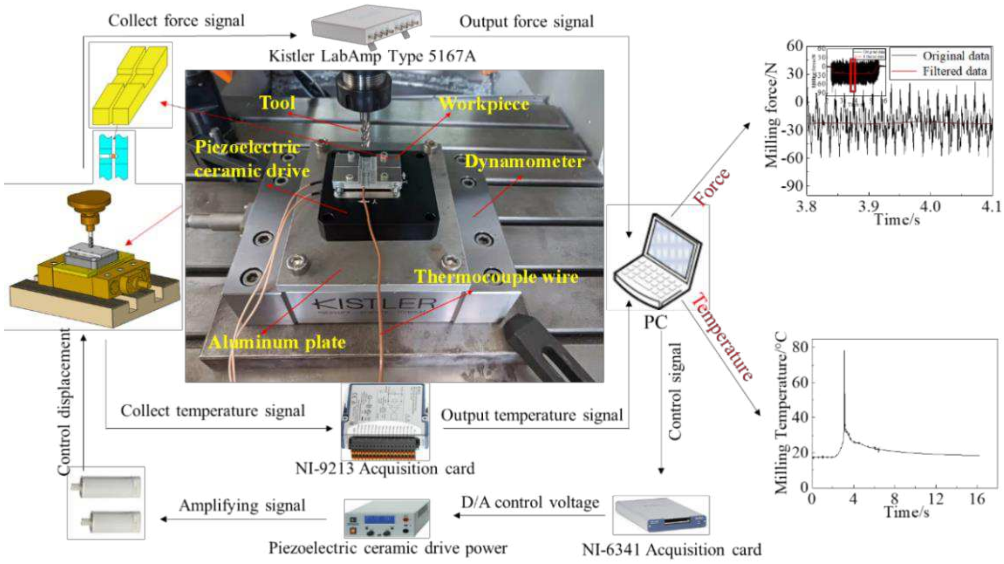

Figure 7 Verification test setup

3.4 Experimental verification results

The Measurement results of milling forces and milling temperatures are shown in Figure 7. The milling parameters are as follows: spindle speed 4000r/min, milling depth 0.6mm, feed speed 0.8m/min. The vibration parameters are as follows: amplitude 10μm, frequency 2kHz. The finite element simulation model is experimentally verified from the milling force and milling temperature, and the results are shown in Figure 8. It can be found that the maximum error of force between the experimental and simulation is 12%, while the maximum error of temperature is 15.7%. The simulation results had good agreement with the experiment observations, which proves the accuracy of the simulation model, and can realize the simulation prediction of the milling force and temperature.

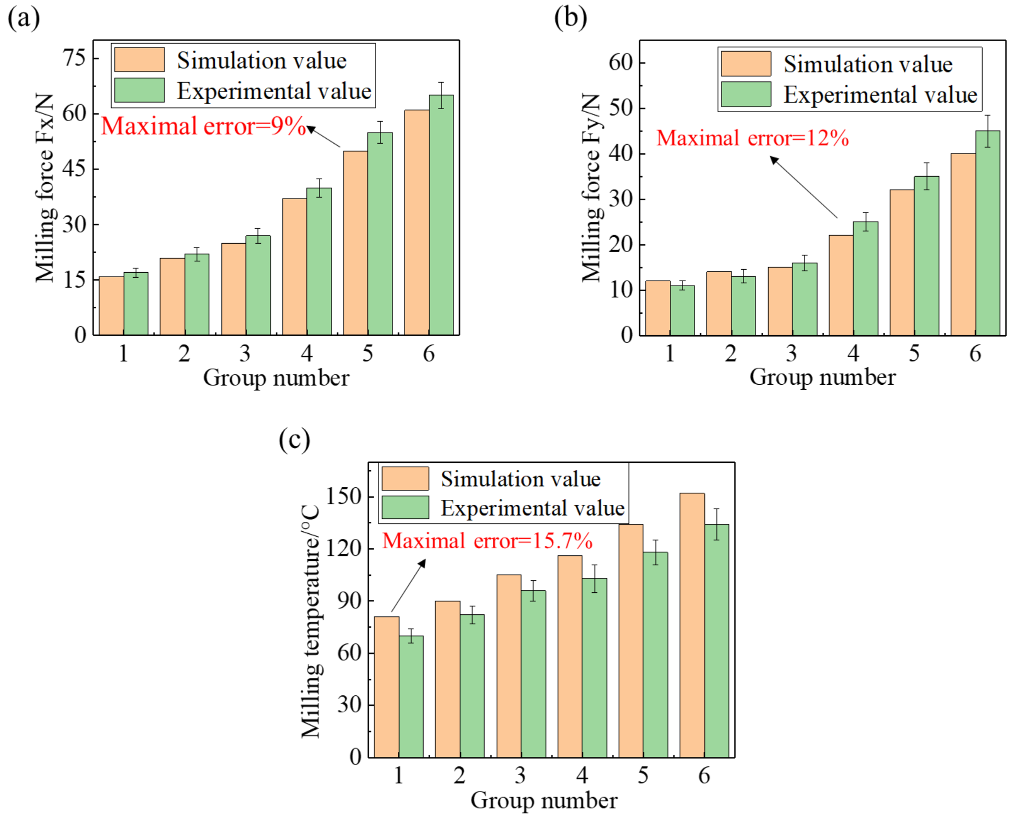

Figure 8 Verification results of milling force and milling temperature:**(a)** Milling force Fx,**(b)** Milling force Fy,**(c)** Milling temperature

4 Effect of Vibration characterization parameters on machining performance

In milling of 7075-T651 aluminum alloys, the vibration characterization parameters (amplitude, frequency) have impact on milling force and temperature, it cannot be ignored in 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 processing results.

4.1 Effect of vibration frequency on milling force and temperature

The single factor test of frequency was conducted in simulation as in Table 7, vibration of amplitude of 10 μm was applied to the feed direction and vertical feed direction respectively. The simulation results are shown in Table 7, the relationship between vibration frequency and milling force and milling temperature is analyzed as shown in Figure 9. As in Figure 9a and Figure 9b, 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 20kHz, and decreases gradually when the frequency is greater than 20kHz. The average surface temperature of the workpiece increases and then gradually decrease with the frequency. Furthermore, the milling force fluctuation value of vibration in the x directions gradually increased when the frequency is more than 20kHz.

As in Figure 9c and Figure 9d, while the vibration frequency in the vertical feed direction increases, the average milling force of vibration in the x and y directions varies when the frequency is lower than 20kHz, and decreases gradually when the frequency is greater than 20kHz. The average surface temperature of the workpiece increases and then gradually decrease with the frequency. Furthermore, the milling force fluctuation value of vibration in the y directions gradually increased when the frequency is more than 20kHz.

Table 7 Effect of different vibration frequencies on processing results

NO.	Spindle speed (r/min)	Feed rate (mm/t)	Milling depth (mm)	Frequency (Hz)	Average value of Fx (N)		Average value of Fy (N)		Average temperature of the processed surface(°C)		Fluctuation value of Fx(N)		Fluctuation value of Fy(N)	
					F	V	F	V	F	V	F	V	F	V
1	10000	0.1	0.2	1000	19.5	19.2	9.2	8.8	182.2	165.7	3.5	9.1	1.3	2.4
2	10000	0.1	0.2	2000	19.3	19.7	9.1	8.9	183.8	172.4	2.5	5.3	1.1	1.5
3	10000	0.1	0.2	3000	19.9	19.2	9.2	8.7	185.6	178.6	2.0	3.6	0.9	1.7
4	10000	0.1	0.2	4000	19.5	19.3	9.3	8.6	188.1	188.2	1.2	3.7	0.6	1.6
5	10000	0.1	0.2	5000	20.1	19.4	9.1	9.0	190.3	188.5	1.0	2.5	0.5	2.0
6	10000	0.1	0.2	6000	19.8	19.6	9.2	8.8	187.7	191.3	0.6	2.4	0.4	1.1
7	10000	0.1	0.2	7000	19.8	19.7	9.1	8.9	186.7	190.2	1.1	1.3	0.5	0.8
8	10000	0.1	0.2	8000	20.2	19.3	9.1	9.5	186.8	188.7	0.5	2.8	0.3	4.2
9	10000	0.1	0.2	9000	19.5	19.9	9.0	9.4	184.4	192.6	0.7	1.2	0.2	2.0
10	10000	0.1	0.2	10000	19.1	19.5	9.0	9.8	183.2	189.7	2.2	3.2	1.0	5.3
11	10000	0.1	0.2	20000	19.0	20.4	8.7	12.0	182.9	188.1	5.1	4.6	1.4	7.5
12	10000	0.1	0.2	30000	19.1	19.0	8.8	12.0	180.1	182.3	10.2	4.0	1.8	11.4
13	10000	0.1	0.2	40000	18.4	19.5	8.6	11.7	178.0	185.5	13.3	3.1	2.0	18.3
14	10000	0.1	0.2	50000	18.0	18.7	8.5	11.0	177.5	180.3	17.5	3.5	2.5	20.6
15	10000	0.1	0.2	60000	17.5	18.3	8.2	10.3	176.7	178.4	22.1	2.5	2.2	35.4
16	10000	0.1	0.2	70000	17.3	17.8	8.2	10.2	175.7	168.7	24.0	2.8	2.1	40.2
17	10000	0.1	0.2	80000	17.2	17.3	8.1	9.7	172.5	160.5	28.3	3.0	2.2	45.8
18	10000	0.1	0.2	90000	15.7	16.5	7.6	9.3	170.5	155.7	30.1	3.5	3.2	48.5
19	10000	0.1	0.2	100000	15.3	16.0	7.0	8.5	169.6	150.4	35.2	4.2	4.1	50.2

F --- Applying Feed direction vibration; v--- Applying Vertical feed direction vibration

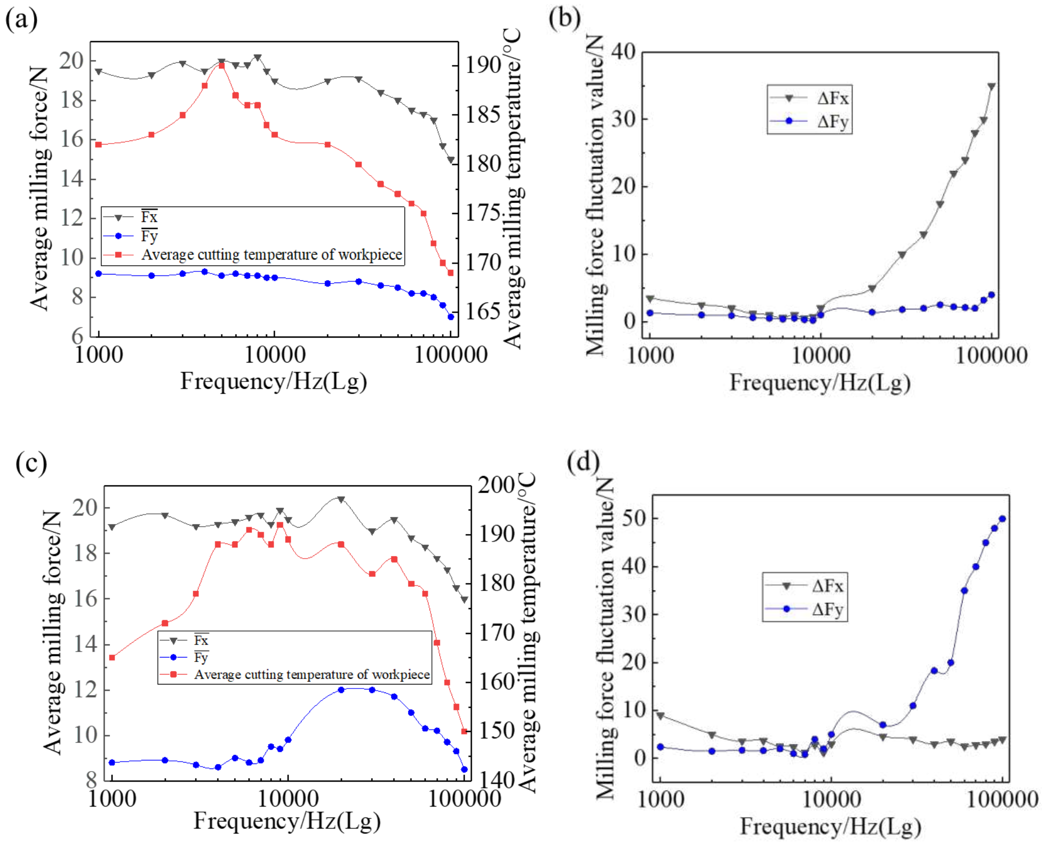

Figure 9 Effect of vibration frequency on the average milling force, temperature and milling force fluctuation values:**(a)** Average milling force and temperature applying feed direction vibration, **(b)** Milling force fluctuation value applying feed direction vibration, **(c)** Average milling force and temperature applying vertical feed direction vibration, **(d)** Milling force fluctuation value applying vertical feed direction vibration

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 8, and vibration frequency of 2kHz was applied to the feed direction and vertical feed direction. The simulation results are shown in Table 8, the relationship between amplitude and milling force and milling temperature is analyzed as shown in Figure 10. As in Figure 10a and Figure 10b, with the increase of the amplitude in the feed direction, the average milling forces of vibration in x and y directions remain basically unchanged, while the average temperature of the surface of the workpiece decreases gradually. As shown in Figure 10c and Figure 10d, With the increase of the amplitude in the vertical feed direction, the average milling force of vibration in x and y directions and the average surface temperature of the workpiece show an increasing trend, the milling force fluctuation value of vibration in the x and y directions are gradually increasing.

In summary, in the situation of low frequency vibration in 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.

Table 8 Effect of different amplitudes (low frequency vibration) on processing results

NO.	Spindle speed (r/min)	Feed rate (mm/t)	Milling depth (mm)	Amplitude (μm)	Average value of Fx (N)		Average value of Fy (N)		Average temperature of the processed surface(°C)		Fluctuation value of Fx(N)		Fluctuation value of Fy(N)	
					F	V	F	V	F	V	F	V	F	V
1	10000	0.1	0.2	10	19.3	19.7	9.1	8.9	182.4	193.4	2.5	5.0	1.0	1.5
2	10000	0.1	0.2	20	19.3	19.3	9.0	8.3	176.5	190.6	2.4	7.2	1.1	3.0
3	10000	0.1	0.2	30	19.4	19.7	9.0	8.3	170.3	206.2	2.3	9.1	1.1	3.1
4	10000	0.1	0.2	40	19.4	20.2	9.1	10.5	166.7	213.8	2.3	11.8	1.2	8.2
5	10000	0.1	0.2	50	19.5	23.4	9.1	20.5	165.2	218.5	2.2	18.6	1.2	27.5
6	10000	0.1	0.2	60	19.3	27.1	9.0	30.1	163.8	219.3	2.2	26.5	1.1	43.9
7	10000	0.1	0.2	70	19.2	29.1	9.0	35.8	160.5	221.6	2.2	30.9	1.2	55.2
8	10000	0.1	0.2	80	19.1	30.3	8.9	40.6	159.2	223.4	2.3	33.7	1.3	63.4
9	10000	0.1	0.2	90	19.0	32.5	8.8	46.6	157.3	225.8	2.2	37.5	1.4	73.4
10	10000	0.1	0.2	100	19.1	33.2	8.8	49.5	155.2	228.7	2.2	40.8	1.5	80.5

F --- Applying Feed direction vibration; v--- Applying Vertical feed direction vibration

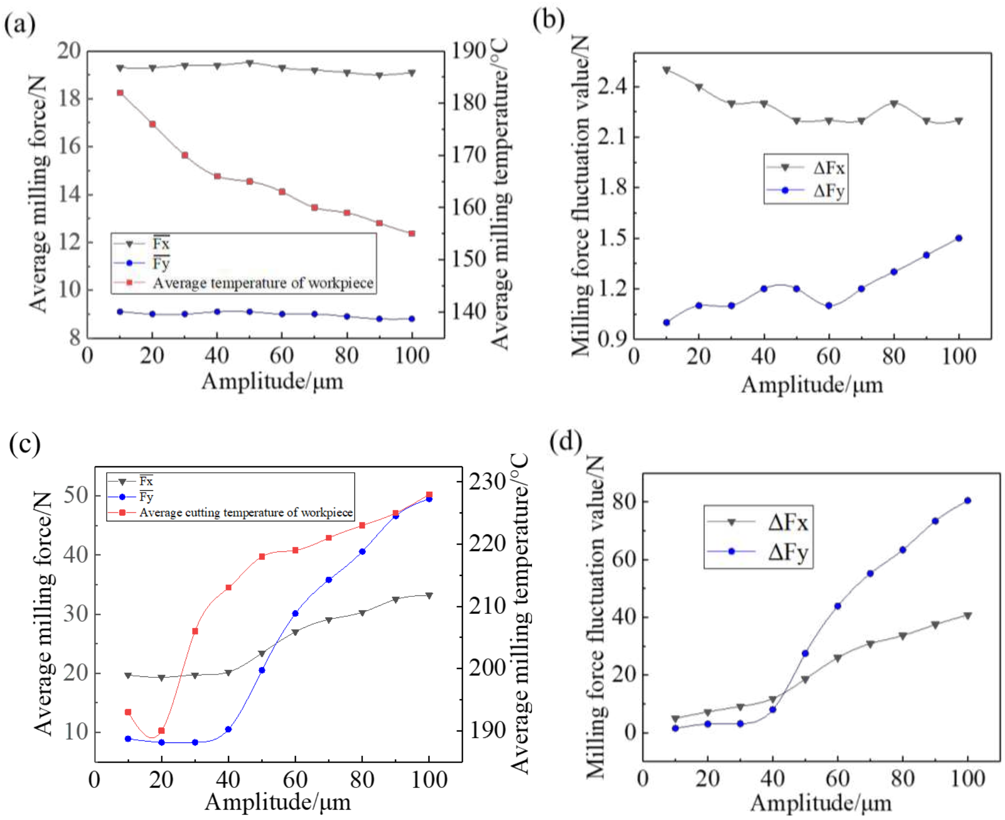

Figure 10 Effect of amplitude（2kHz）on average milling force, temperature, and milling force fluctuations: **(a)** Average milling force and temperature applying feed direction vibration,**(b)** Milling force fluctuation value applying feed direction vibration,**(c)** Average milling force and temperature applying vertical feed direction vibration,**(d)** Milling force fluctuation value applying vertical feed direction vibration

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 9, and vibration frequency of 20kHz was applied to the feed direction and vertical feed direction. The simulation results are shown in Table 9, the relationship between amplitudes and milling force and milling temperature is analyzed as shown in Figure 11. As in Figure 11a and Figure 11b, with the increase of the amplitude in the feed direction, the average milling force of vibration in x, y direction and the average temperature of the surface of the workpiece decreases gradually, it is because that the ultrasonic vibration causes intermittent milling of the tool, decreasing the average milling force and milling temperature. The milling force fluctuation value is gradually increasing 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 Figure 11c and Figure 11d, with the increase of the amplitude in the vertical feed direction, the average milling 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 workpiece surface decreases at first stage and then increases gradually. The change in temperature is due to the change in the dominance position of cutter-workpiece discontinuous milling and increased milling area. The milling force fluctuation values of vibration in x and y directions gradually increase, and the amplitude of the milling force fluctuation value in y direction increases more obviously.

Table 9 Effect of different amplitudes (ultrasonic vibration) on processing results

NO.	Spindle speed (r/min)	Feed rate (mm/t)	Milling depth (mm)	Amplitude (μm)	Average value of Fx (N)		Average value of Fy (N)		Average temperature of the processed surface(°C)		Fluctuation value of Fx(N)		Fluctuation value of Fy(N)	
					F	V	F	V	F	V	F	V	F	V
1	10000	0.1	0.2	10	19.1	20.4	8.7	12.1	166.8	192.5	5.2	4.6	1.1	7.2
2	10000	0.1	0.2	20	18.6	20.2	8.6	16.3	155.5	190.3	6.2	6.1	1.4	13.4
3	10000	0.1	0.2	30	18.4	20.1	8.4	19.5	148.4	187.4	8.0	8.0	2.0	21.3
4	10000	0.1	0.2	40	15.0	19.0	7.5	21.6	141.6	192.6	9.1	8.7	3.2	26.2
5	10000	0.1	0.2	50	12.5	18.7	6.0	23.5	135.0	200.2	9.5	9.5	4.0	30.5
6	10000	0.1	0.2	60	10.5	17.8	5.4	24.2	132.8	213.2	10.3	9.8	4.6	35.6
7	10000	0.1	0.2	70	9.8	17.6	4.6	25.6	130.3	224.3	11.2	10.2	5.4	38.6
8	10000	0.1	0.2	80	8.6	17.0	4.2	26.0	128.6	240.5	11.3	10.3	5.8	38.9
9	10000	0.1	0.2	90	8.2	16.6	4.0	26.5	125.2	245.2	12.0	10.6	6.2	40.5
10	10000	0.1	0.2	100	7.2	16.5	3.3	27.2	120.3	255.3	13.2	11.2	7.1	40.8

F --- Applying Feed direction vibration; v--- Applying Vertical feed direction vibration

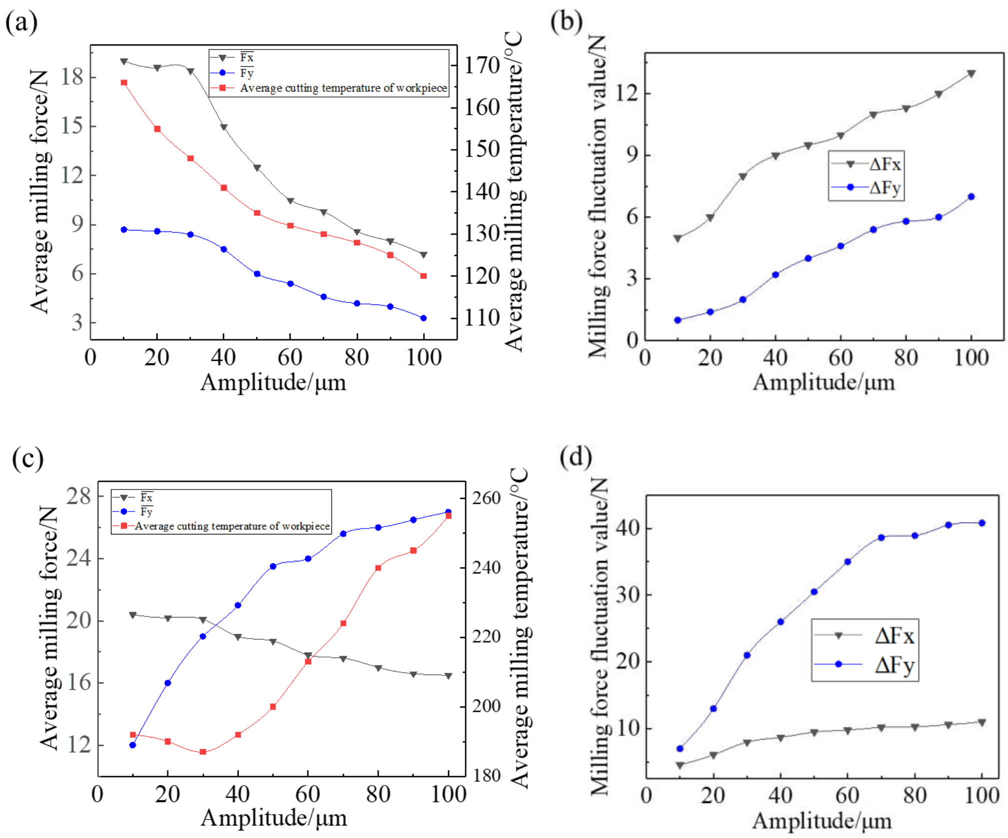

Figure 11 Effect of amplitude (20kHz) on average milling force, temperature, and milling force fluctuations: **(a)** Average milling force and temperature applying feed direction vibration,**(b)** Milling force fluctuation value applying feed direction vibration,**(c)** Average milling force and temperature applying vertical feed direction vibration,**(d)** Milling force fluctuation value applying vertical feed direction vibration

5 Conclusion

In this paper, a simulation method of milling considering process vibration is presented by taking the undeformed chip thickness into account, and 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 are drawn as follow:

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

(2) The experimental tests are performed to verify the simulation method and model, and the results show that the effectiveness of the 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 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 ultrasonic frequency, but at the same time it increases the

fluctuation degree of milling force. Therefore, it is important to choose the vibration frequency in vibration-assisted process.

(4) When low frequency vibration in the vertical feed direction is applied, increasing the vibration amplitude will result in the increase of 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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Ethical Approval

Compliance with ethical standards.

Consent to Participate and Publish

Conflict of interest

The authors declare that they have no conflict of interest.

Authors Contributions

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Weicheng Guo: Methodology, Editing, Corresponding.
Jin Liu: Visualization, Investigation.
Xiaohui Jiang: Supervision, Reviewing.

Availability of data and materials

The data and materials that support the findings of this study are available from the corresponding author upon reasonable request.

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