Effect of Milling Vibration on The Machining Performance of 7075-T651 Aluminum Alloys

Miaoxian Guo (✉ miaoxian.guo@live.com)

University of Shanghai for Science and Technology

Jianming Wang

University of Shanghai for Science and Technology

Jin Liu

University of Shanghai for Science and Technology

Chao Huang

University of Shanghai for Science and Technology

Xiaohui Jiang

University of Shanghai for Science and Technology

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Effect of milling vibration on the machining performance of 7075-T651 aluminum alloys

Guo Miaoxian¹, Wang Jianming¹, Liu Jin¹, Huang Chao¹, Jiang Xiaohui¹

(1. College of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China)

Abstract: Milling of 7075-T651 is widely used in aerospace industry, however the process vibration restricts the machining performance in milling process. This paper puts forward a study on the effect of vibration on machining performance in milling to improve the machining quality. According to the characteristics of end milling, the process vibration is calculated and added based on the unformed chip thickness model of milling, and a milling simulation model considering vibration is established. Applying the finite element model and milling experiments, the simulation model is verified, the results proves the accuracy of the FEM models in predicting the milling force and milling temperature. Furthermore, the effect of milling vibration on machining performance is studied by numerical simulation, in which the relationship between amplitude-frequency characteristics and milling force-temperature fluctuation.

Keywords: 7075-T651 aluminum alloy; Milling Vibration; Unformed chip thickness; milling force; milling temperature;

1 Introduction

Aluminum alloys have been the primary material in aerospace industry for years because of their well-known performance [1]. Milling of the 7075-T651 aluminum alloys is studied by researches, which are required to have complex geometry and high surface quality. In order to improve the quality of machining, the machining performance should be studied. In the recent years, the control of the milling force and milling heat in process, and the optimization of the process parameters are the research focus in the field. In order to analyze and control milling force and milling heat in the machining process, the effective combination of finite element method, numerical analysis method and experimental verification is studied to predict milling force and milling heat, which provides a good reference for controlling milling force and milling heat and improving part machining quality [2-4].

In traditional machining techniques, such as grinding and milling, vibrations created in the milling process contribute significantly to machining accuracy and quality [5-8]. Vibration phenomenon in milling can lead to poor machining surface quality and impair machine life. Shtehin et al. [9] 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. [10] studied the problem of vibration during high-speed milling, considering regenerative vibration and frictional vibration. Liu et al. [11] introduce a time-change reliability analysis method to predict the stability and vibration reliability in milling process.

*Dr. MiaoXian Guo

University of Shanghai for Science & Technology, Shanghai 200093 China.

Tel: +86 18801918177, E-mail: guomx@usst.edu.cn

In other filed, it is common that ultrasonic vibration can improve the machining performance [12-13]. Vibration parameters are particularly important for milling forces during vibration-assisted milling. Verma et al.[14]using experimental research to evaluate the effect of process parameters on milling force, and carry out axial vibration of ultrasonic vibration auxiliary milling experiments, 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. [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. Kong et al. [16] 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. [17] 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. [18] 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. Most of the above studies focus on the effect of small ultrasonic amplitude on cutting force, but lack of comprehensive research on vibration parameters (vibration frequency and amplitude).

Furthermore, vibration in milling processing not only has an important effect on milling force, but also on milling heat. Feng et al. [19] 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. [20] 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. [21] 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. [22] developed a process physics-based equation to predict temperature rise in vibration-assisted milling. However, most of the researches are focused on the effect of ultrasonic vibration-assisted cutting on cutting temperature, and lack the research and analysis of cutting temperature from low frequency to ultrasonic vibration frequency.

The vibration characterization parameters (vibration frequency and amplitude) has a great impact on the machining performance, the researchers studied the vibration effect in conventional milling process and the ultrasonic vibration-assisted milling respectively. This paper systematically studied the effect of vibration frequency from low frequency to ultrasonic frequency on the milling performance. First, the milling process considering vibration is built based on the undeformed chip thickness calculation in milling process; Then, the Finite element analysis of AdvantEdge is conducted to analyze the impact of vibration characterization parameters on the milling performance of 7075-T651 aluminum alloy, and the experimental verification proves the accuracy of the FEM models in predicting the milling force and milling temperature. Finally, the effect of milling vibration (amplitude-frequency characteristics) on machining performance (milling force-temperature level and fluctuation) is studied, which provides a theoretical basis for improving milling performance of 7075-T651 aluminum alloy.

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:

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

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

$$\begin{cases} V_x = v \\ V_y = 2\pi f_y a \cos(2\pi f_y t + \varphi_y) \end{cases} \quad (2)$$

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:

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

Where a and b are the amplitudes, f_x and f_y are the vibration frequencies in x and y direction, t is the time parameter, φ_x and φ_y 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:

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

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:

$$k = \frac{v}{2\pi f_x b} \quad (5)$$

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 end 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

$$R'^2 + f_z^2 - 2 \cdot f_z \cdot R' \cdot \cos(\alpha + 90^\circ) - R^2 = 0 \quad (6)$$

$$UCT = R - R' \quad (7)$$

Where f_z is the tool feed per tooth, R is the tool radius, α is the milling arc angle, UCT is the thickness of unformed chips [23]. It can be seen from the milling model and formula, the parameters affecting the thickness of unformed chips are tool diameter and feed per tooth. Furthermore, the vibration in process would also impact on the unformed chip thickness. Figure 3 presents as an example of calculated UCT with Vibration Considered when tool diameter is 8mm, the feed speed is 0.15mm/z, the vibration characteristics are amplitude of 20 μ m, frequency of 5000Hz. Applying the above unformed chip thickness theory in the software of AdvantEdge, the milling process can be simulated 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[21]. 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/K	2.52×10 ⁻⁵	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 [24]. For finite element simulation of material deformation processes, such as machining and plastic forming, the control equations are:

$$\sigma = (A + B\varepsilon^n) \left(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left[1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (8)$$

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[25].

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:

$$D = \sum \frac{\Delta \varepsilon}{\varepsilon^f} \quad (9)$$

Where ε^f is a failure strain; $\Delta \varepsilon$ 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 [26]:

$$\varepsilon^f = \left[d_1 + d_2 \exp \left(d_3 \frac{\delta_m}{\bar{\delta}} \right) \right] \left(1 + d_4 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left[1 + d_5 \left(\frac{T - T_r}{T_m - T_r} \right) \right] \quad (10)$$

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[25].

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 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 6, 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. 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, 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. 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

Measurements of milling forces and milling temperatures are shown in Figure 7. 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 F_x ,(b) Milling force F_y ,(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 by changing the acoustic system 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 $10\ \mu\text{m}$ was applied to the feed direction and vertical feed direction respectively. The simulation results are shown in Table 7.

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									
					Average		Average		temperature of		Fluctuation		Fluctuation	
					value of Fx		value of		the processed		value of		value of	
					(N)		Fy (N)		surface(°C)		Fx(N)		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

According to the results 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.

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.

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									
					Average value of Fx (N)		Average value of Fy (N)		Average temperature of the processed surface($^{\circ}\text{C}$)		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

According to the results 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.

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.

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									
					Average value of Fx (N)		Average value of Fy (N)		temperature of the processed surface($^{\circ}\text{C}$)		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

According to the results 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.

5 Conclusion

In this paper, a milling simulation model considering vibration is established. The effectively and accuracy of model is verified applying the milling experiments. And the effect of vibration on the milling performance of 7075-T651 aluminum alloy is finally studied. Based on the results of the analysis, the following conclusions are drawn:

- (1) Based on the unformed chip thickness model of ordinary milling, an unformed chip thickness simulation model considering milling vibration is established. Applying the model in the software, the machining performance can be analyzed through the milling force and milling temperature.
- (2) The experimental test is done to verify the perdition model, and the results show that the effectiveness and accuracy of the FEM models in predicting the milling force and milling temperature.
- (3) The effect of vibration frequency on milling force and temperature is studied. The results show that the tool vibration can effectively decrease the average milling force and temperature at ultrasonic frequency, but at the same time it increase the fluctuation value of milling force. Therefore, it is important to choose the vibration frequency in vibration-assisted process.
- (4) The effect of vibration amplitude on milling force and temperature is studied. The results show that when low frequency vibration in the vertical feed direction is applied, increasing the amplitude would result in the increase of the average milling force, temperature and milling force fluctuation values, which adversely affects the machining quality and system stability. 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. Effective selection of amplitude is important for improving process quality and system stability.

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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

Guo Miaoxian: Conceptualization, Methodology. Wang Jianming: Data curation, Validation, Writing-Original draft preparation. Liu Jin: Visualization, Investigation. Huang Chao: Reviewing and Editing. Jiang Xiaohui: Supervision.

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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