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ORIGINAL ARTICLE

A study of surface roughness variation in ultrasonic vibration-assisted milling

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Abstract The objective of this paper is to investigate the effects of assisted ultrasonic vibration on the surface roughness of machined surfaces in micro-end-milling. Series of slot-milling experiments were conducted with aluminum alloy as workpiece material. The surface roughness of slot bottom surface and vertical side wall surface of slot was studied, respectively. It is found that surface roughness of the machined slot bottom surface could increase to varying degrees because of ultrasonic vibration in most of the studied cases, and this deterioration becomes more apparent when large feed per tooth and low-spindle speed were adopted. As for the vertical side wall surface of the slot, there is an obvious improvement of surface roughness when ultrasonic vibration is applied. Based on analysis of variance analysis, further study indicates that the surface roughness of vertical side wall surface of the slot is determined by several key parameters including spindle speed, feed per tooth and amplitude in ultrasonic vibration-assisted milling. An optimal combination of these parameters is of great benefit to achieving small surface roughness.

Keywords Vibration cutting · End milling · Ultrasonic vibration · Surface roughness

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1 Introduction

Micro-end-milling has become one of the most important mechanical machining methods for microparts with the trend of product miniaturization. Micromilling tools with diameter less than 2 mm have been widely used by many manufactures. Micro-end-milling differs from conventional milling (CM) operation not just in their sizes. Miniaturized tool and low feed per tooth make its machining and tool failure mechanisms more complicated than those in macro-conditions. Given that small tools are more sensitive to vibration, machining quality and accuracy are much more difficult to obtain in micromilling. Hence, it is important to improve cutting conditions and machining technology when it comes to small-part machining.

Ultrasonic vibration cutting characterized by separate-type cutting is a cutting method in which vibration at a regular frequency within an ultrasonic range is imposed on the cutting tool or the workpiece to achieve better cutting effects. This technology has been widely used for different kinds of workpiece materials and lots of excellent cutting performances have been obtained. Kumabe and Sabuzawa firstly practiced ultrasonic vibration in the precision drilling of wood [1]. There have been also many research results in recent years. Jin and Murakawa found that precision cutting could be carried out for a workpiece with high hardness and the tool life could also be increased [2]. A conclusion that cutting force would be reduced in ultrasonic cutting glasses was drawn by Zhou et al. [3]. Xiao et al. pointed that chatter could be effectively suppressed irrespective of the tool geometry by ultrasonic vibration cutting [4]. Ductile machining of fused silica was achieved even for 2 μm depth of cut with ultrasonic vibration [5]. Shamoto et al. proposed an ultrasonic elliptical vibration cutting, which is a 2-D vibration cutting, and investigated its effect on

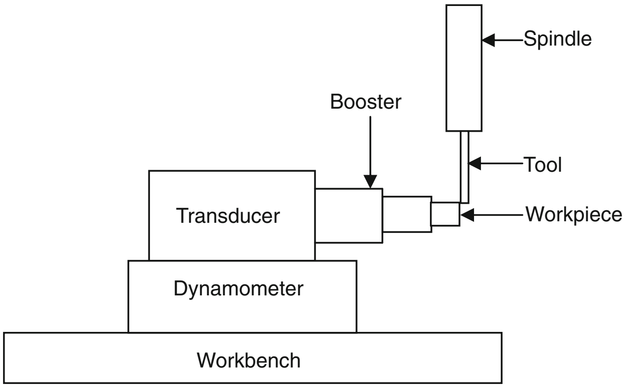


Fig. 1 Illustration of experimental setup

machining accuracy in turning [6, 7]. Ultrasonic vibration-assisted cutting was also proved to be able to improve the ductile mode cutting performance of tungsten carbide material [8]. Zhou et al. found that surface roughness of the aluminum-based metal matrix composite became better when being turned with ultrasonic vibration [9]. Better surface finish and low tool wear acceleration were obtained when ultrasonic vibration was used during low alloy steel cutting [10]. Nath et al. studied the effects of cutting parameters in the ultrasonic vibration cutting and found the cutting force, tool life, and surface roughness were all greatly improved when using ultrasonic vibration cutting for Inconel718 at low cutting speed [11]. The feed force was found to be decreased by 10–20% on average when ultrasonic vibration was applied for the drilling of titanium alloy [12].

Ultrasonic vibration-assisted cutting is an effective method to obtain better cutting performance, and this combined machining technology has been widely used successfully in turning and drilling. However, only low frequency vibration-assisted micromilling was experimentally studied [13], ultrasonic vibration-assisted cutting technology has not yet been conducted in the field of milling. This paper investigates the effects of assisted ultrasonic vibration on surface finish in micro-end-milling

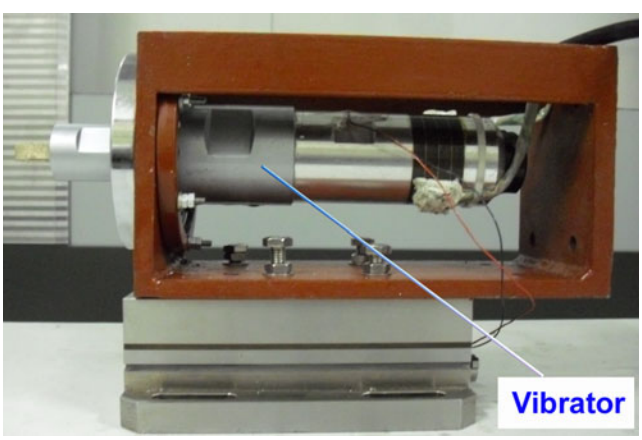


Fig. 2 Photo of vibrator and clamp

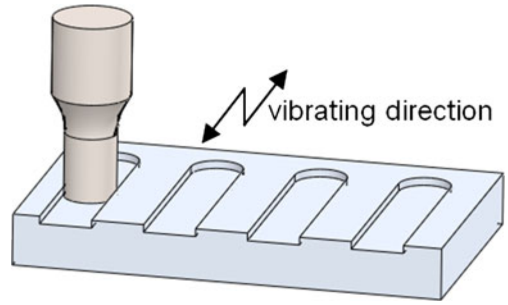


Fig. 3 Diagram of slot-milling process

through extensive slot-milling experiments with aluminum alloy as workpiece materials.

2 Experimental procedure

A DECKEL MAHO five-axis machining center was used to conduct the experiment. An ultrasonic vibrator composed of a transducer and a booster was employed to drive the workpiece to vibrate along the feed direction by converting high-frequency oscillation electric power into mechanical vibration. A sketch of the experimental setup is given in Fig. 1. The photo of vibrator and clamp is shown in Fig. 2. The slot-milling experiments were implemented as illustrated in Fig. 3. Note that it is necessary to cut a datum plane before machining real surfaces.

Following is a brief description of the experimental equipments involved in this study:

1. *Machining center*. DMU-70 V, the range of the spindle speed is 0–18,000 rpm, the repetitive positioning accuracy is ±0.001 mm.
2. *Driving source*. ZJS-1000, full automatic frequency tracking, 220 V, 50 Hz, 4A.
3. *Transducer*. YP-5020-4Z, used together with the driving source, the floating range of resonance frequency is ±200 Hz.
4. *Amplitude-monitoring system*, to realize real-time monitor of the vibrating amplitude by observing the voltage signal outputted by a strain gage.

Table 1 Experimental parameters

Cutting parameters	
Feed per tooth/f_z	2,4,6,8 μm/z
Spindle speed/n	1,000, 5,000, 9,000, 13,000 r/min
Depth of cut/a_p	0.5 mm
Vibrating parameters	
Vibrating type	workpiece vibrating along the feed direction
Amplitude/A	0,4 μm
Frequency/f	19.58 kHz

Table 2 Factors and levels

Parameter	Level		
	1	2	3
A—spindle speed (*r*/min)	5,000	9,000	13,000
B—feed per tooth (μm/z)	4	6	8
C—amplitude (μm)	4	7	10

5. *Scanning electron microscopy* (*SEM*). SM-6380LA, to observe the surface topography of machined surface.
6. *Optical interferometer.* Wyko NT9300, the vertical resolution is 0.1 nm, to measure surface roughness and observe the 3-D profiles of the machined surfaces.
7. *Milling tool*, two-flute end mill, made of carbide, with a diameter of 2 mm.
8. *Workpiece material*. Aluminum alloy 2A12.

2.1 Ultrasonic vibration-assisted milling experiment

The purpose of this experiment is to investigate the effects of assisted ultrasonic vibration on end-milling process by examining the surface roughness of machined surfaces, including bottom surfaces and vertical side wall surfaces of the machined slots. Detailed experimental parameters are given in Table 1. The axial cutting depth was chosen as 0.5 mm with spindle speed varying from 1,000, 5,000, 9,000, to 13,000 r/min and feed per tooth chosen as 2, 4, 6, and 8 μm/z. The required vibration was produced from the workpiece side along the feed direction with frequency of 19.58 kHz. The amplitude was set as 4 μm. Here, 0 μm means conventional milling. Each combination of cutting parameters was tested twice in this experiment to control the mismachining tolerance.

3-D roughness of the machined surfaces was measured accurately with an optical interferometer. All samples were cleaned three times by acetone and alcohol before being measured. Each surface was measured six times and their average value was determined as the measuring result. The slot bottom surfaces were first measured, and then the workpiece was properly cut by wire electrical discharge machining (WEDM) to measure the roughness of vertical side wall surfaces. Considered areas should be properly protected during WEDM cutting to avoid thermal burn. SEM photos for some machined surfaces were also taken for analysis.

Table 3 Designed header of orthogonal array

Factor and interaction	A	B	(A×B)$_1$	(A×B)$_2$	C	(A×C)$_1$	(A×C)$_2$	(B×C)$_1$	(B×C)$_2$
Column number	1	2	3	4	5	6	7	8	11

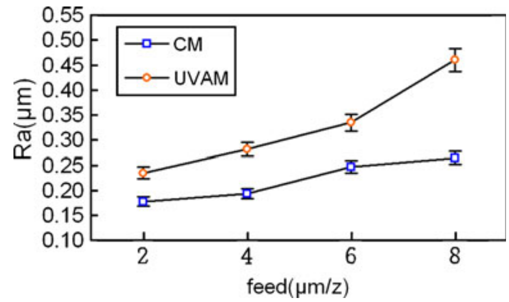


Fig. 4 Surface roughness of slot bottom vs. feed (n=5,000 r/min)

2.2 Orthogonal experiment with ANOVA

In this section, an orthogonal experiment was conducted to get small surface roughness of vertical side wall surface of slot in ultrasonic vibration-assisted milling (UVAM) by optimizing the machining parameters. The chosen process parameters for optimizing were spindle speed, feed per tooth, and amplitude. A L27 orthogonal array was used to arrange the test. The analysis of variance (ANOVA) was performed to analyze the effects of the chosen parameters and their interactions on the test index. An optimal combination of machining parameters in this experiment was predicted and confirmed.

The levels of the chosen parameters are summarized in Table 2. The designed header of the orthogonal array is shown in Table 3. Other machining parameters not mentioned here are the same as those described in Table 1.

3 Results and discussion

3.1 UVAM experiment

3.1.1 Surface roughness variation of the machined slot bottom surface

Figures 4 and 5 show the respective values of surface roughness of slot bottom surfaces against feed per tooth and spindle speed for CM and UVAM. In most cases, it can be seen that the values of surface roughness increase more or

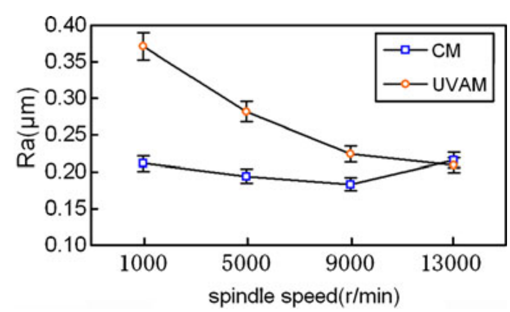


Fig. 5 Surface roughness of slot bottom vs. spindle speed (f_z=4 μm/z)

less after ultrasonic vibration is applied. This deterioration of surface roughness is mainly attributed to the complexity of the relative motion between the tool and the workpiece after ultrasonic vibration is applied. Figure 6 describes the trajectories of two tool tips of a two-flute end-milling tool with a diameter of 2 mm in one cutting cycle. Calculation of the trajectory of tool tip of an end-milling tool has been described in detail in the reference [14] and will not be elaborated upon here. It is very clear that ultrasonic vibration greatly changes the movement pattern of tool tips, causing the tool tips to separate from the workpiece repeatedly and regularly. In UVAM, the tool/workpiece will produce nearly 20,000 vibrations within 1 s, leaving much more tool marks on slot bottom surface than that in CM and producing more complicated surface, which results in the rise of surface roughness. Comparing the two SEM photos in Fig. 7, we also note that scaly surface is produced in UVAM, which is in accordance with the calculated trajectory of tool tip.

Figure 8 shows the increment of surface roughness against spindle speed after ultrasonic vibration is applied. It can be seen that under the same vibrating conditions, the increment of surface roughness decreases with the increase in spindle speed. This is because when other cutting parameters are given, spindle speed affects the exact trajectory of tool tips as shown in Fig. 9. Under a certain vibrating frequency, the spindle speed is higher, the cutting period is shorter, and less tool marks will be left on machined surface as shown in Fig. 10. Thus, in UVAM, selection of cutting parameters and vibrating parameters affects the topography of machined surface and has a direct impact on surface roughness. The effect of ultrasonic vibration on cutting process is more obvious when the ratio of vibrating frequency to the gyro-frequency of spindle is larger.

In Fig. 4, it is observed that surface roughness increases with the rising feed per tooth both for CM and UVAM, very

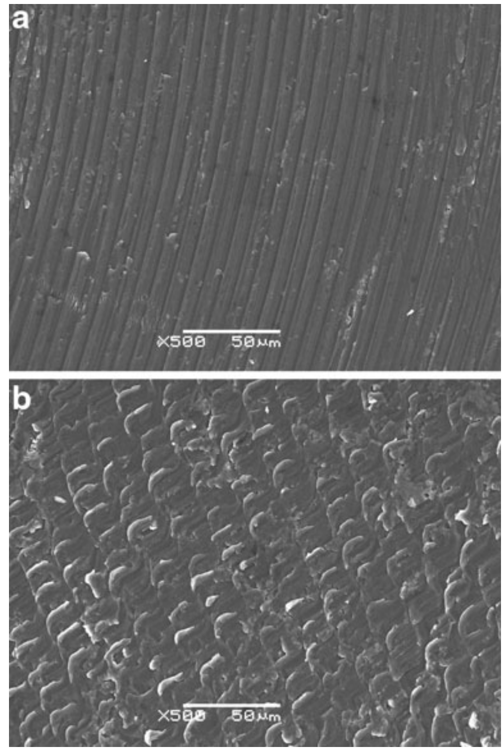


Fig. 7 SEM photos of slot bottom surfaces (n=5,000 r/min, f_z=4 μm/z, A=4 μm)

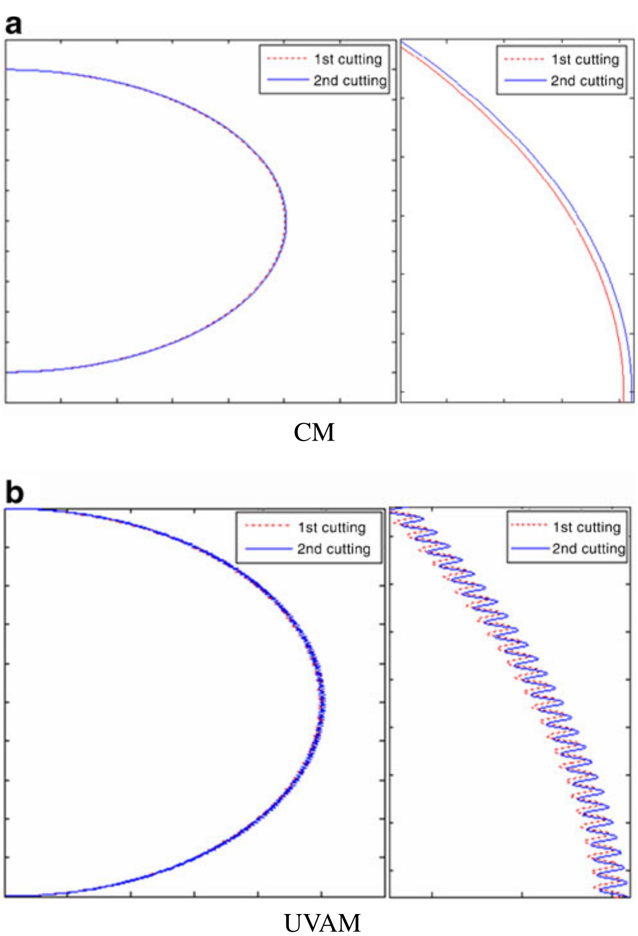


Fig. 6 Trajectories of tool tips in a cutting cycle

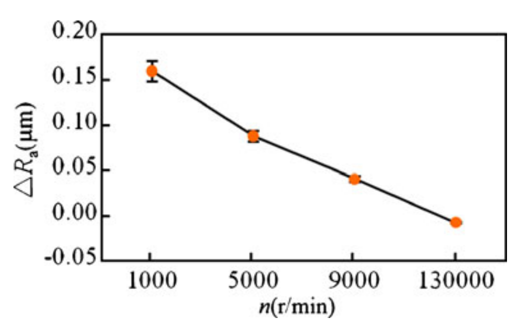
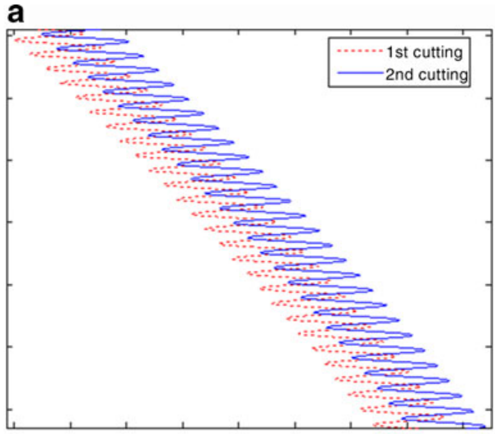
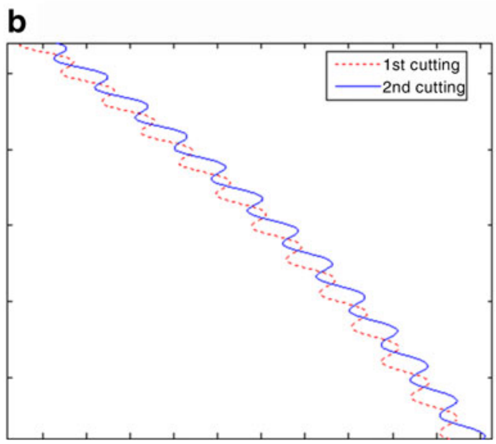


Fig. 8 Increment of surface roughness vs. spindle speed (f_z=4 μm/z)



n=1000r/min

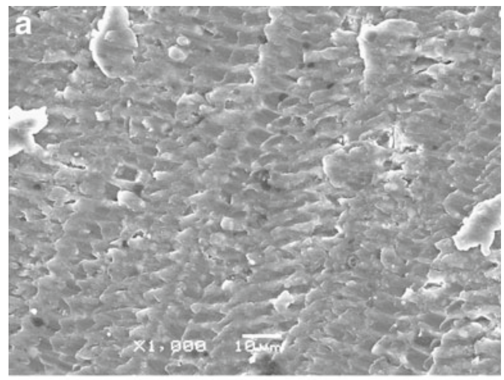


n=5000r/min

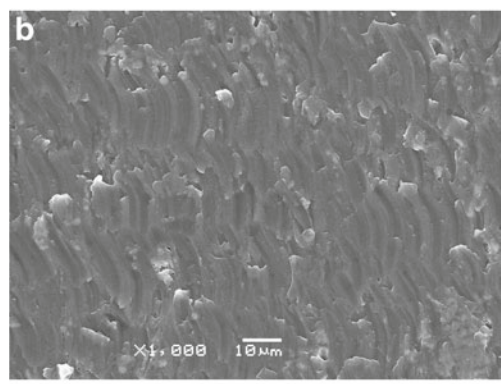
Fig. 9 Trajectories of tool tips under different spindle speed (partial enlarged view)

similar to that of the macro-milling condition. With feed per tooth increasing, this negative effect of vibration becomes more apparent.

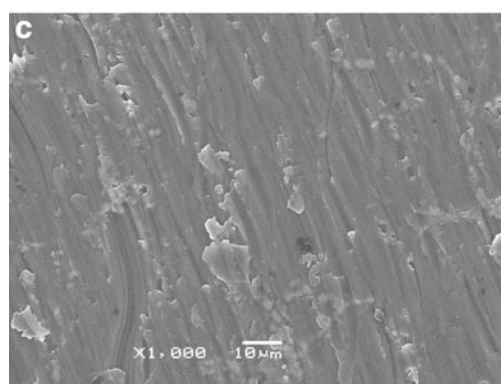
In Fig. 5, for CM, it can be seen that the surface roughness has a tendency of slow decrease with the spindle speed increasing from 1,000 to 9,000 r/min. But the measured value of surface roughness increases from 0.183 to 0.216 μm with the spindle speed changing from 9,000 to 13,000 r/min. This is because, in case of conventional milling with a miniaturized end mill, high speed generates high-frequency vibration, thus causing the quality of surface to become lower. In addition, higher cutting temperature produced under the condition of higher spindle speed builds up plastic deformation of the metal materials, which also goes against surface quality. However, this increase at high spindle speed never happens for UVAM. In comparison, the measured value of surface roughness at spindle speed of 13,000 r/min for UVAM is slightly smaller than that for CM. The reasons are as follows. Firstly, as stated above, with the spindle speed increasing, the cutting period becomes shorter so that less tool marks will be left on the slot bottom surface in UVAM. Secondly, ultrasonic vibration causes the workpiece to depart from the tool constantly. This separation of the cutting tool and the workpiece allows cutting fluid to reach the processing area and carry away more cutting heat, which favors chip flowing and can effectively prevent the accumulation of cutting heat. Moreover, according to the insensitive vibration-cutting mechanism [15, 16], the forced vibration at a frequency within an ultrasonic range suppresses the dynamic change of tool/workpiece in cutting process.



n=1000r/min



n=5000r/min



n=13000r/min

Fig. 10 SEM photos of slot bottom surfaces under two different spindle speed (f_z=2 μm/z, A=4 μm)

3.1.2 Surface roughness of vertical side wall surface of slot

Figures 11 and 12 show the values of surface roughness of vertical side wall surfaces against feed per tooth and spindle speed for CM and UVAM, respectively. In most of the cases, it can be seen that the value of surface roughness is dramatically decreased after ultrasonic vibration is applied. Experiment results show that ultrasonic vibration in the feed direction has a positive effect on the surface roughness of vertical side wall surface. For example, as seen in Fig. 11, when the feed per tooth is 8 μm/z, the measured value of surface roughness is 1.990 μm without vibration. This value drops to only 0.545 μm when vibration is applied, with an improvement of about 265%.

The reason of this improvement mainly lies in the following aspects: on the one hand, ultrasonic vibration changes the mechanism of chip producing. The mental material of processing area is pried off the matrix little by little in UVAM owing to the rapid separation of the tool and the workpiece, and therefore more uniform surface can be obtained than that in CM; as shown in Figs. 13 and 14 shows, the SEM photos of the machined surfaces with respective magnification times of 500 and 2,000. We can also find the separate-type cutting trace by comparing these photos. On the other hand, because the vibrating direction is parallel to the vertical side wall surface of slot and the vibrating frequency is far more than the gyro-frequency of the spindle, the cutting surface will be ironed to and fro by the cutting edge as illustrated in Fig. 15. This kind of repetitive cutting also helps to get good surface finishing. Besides, as stated above, owing to the separate-type milling at a high frequency, the prevention of cutting heat accumulation and the improvement of the dynamic change of tool/workpiece may also be helpful.

In Fig. 11, for CM, the surface roughness increases with the increase in feed per tooth. However, this tendency becomes very inconspicuous for UVAM. In Fig. 12, for CM, it is found that the surface roughness has a clear tendency of decrease when the spindle speed increases from 1,000 to 13,000 r/min. But for UVAM, the surface roughness has no obvious change with spindle speed.

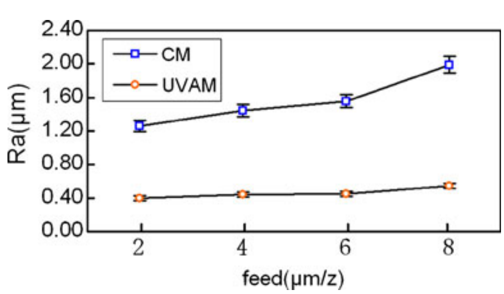


Fig. 11 Surface roughness of side wall vs. feed (n=5,000 r/min)

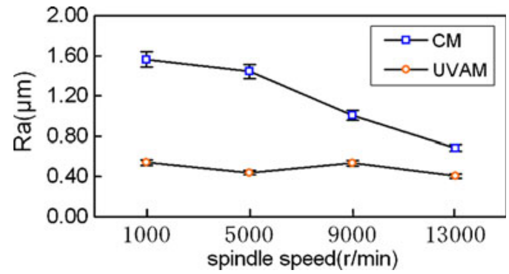


Fig. 12 Surface roughness of side wall vs. spindle speed (f_z=4 μm/z)

According to the test results, for UVAM, the surface roughness of vertical side wall surface of slot appears unapparent change against feed per tooth or spindle speed in this experiment, further study is therefore carried out to investigate the influence of parameter matching on the surface roughness in the following part.

3.2 Orthogonal experiment with ANOVA

In this part, ANOVA method is used to reveal the main and interactive effects of the chosen parameters on the surface roughness of vertical side wall surface of the machined slot.

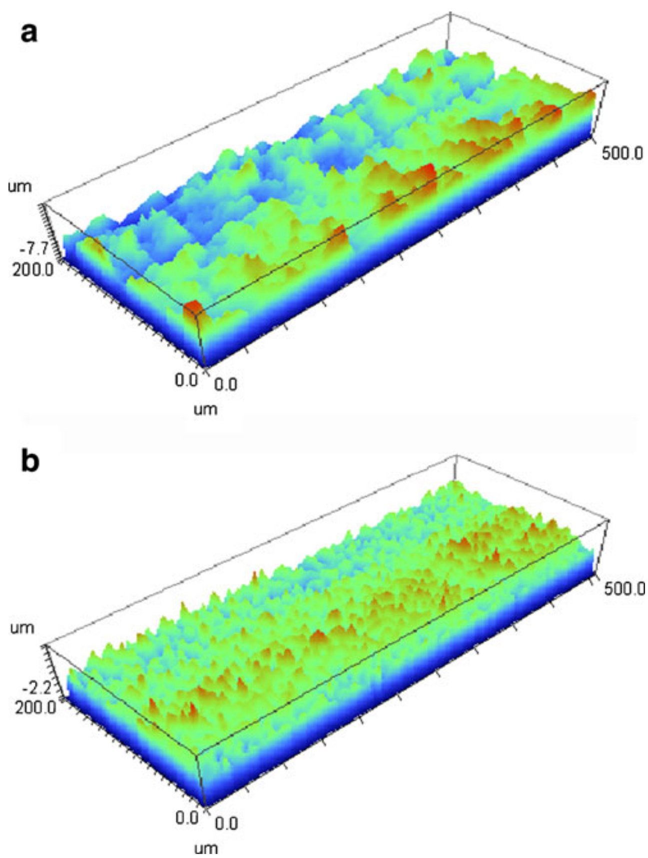


Fig. 13 3D plot of machined surfaces (n=5,000 r/min, f_z=6 μm/z, A=4 μm)

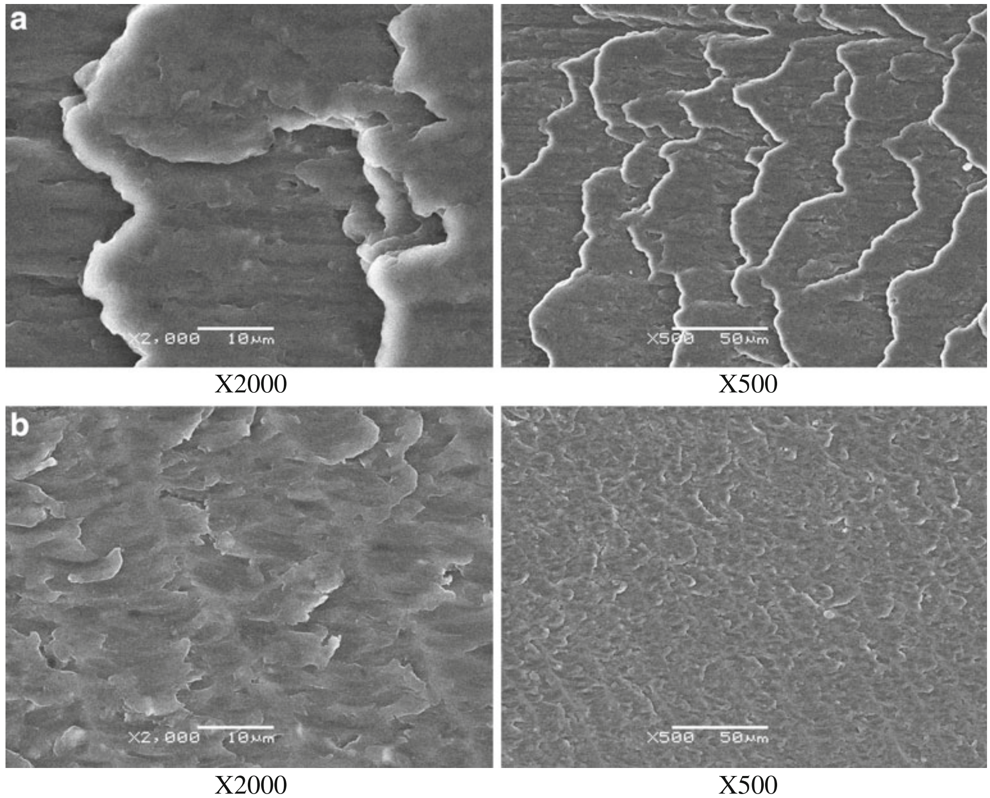


Fig. 14 SEM photos of vertical side surfaces of slot (n=5,000 r/min, f_z=6 μm/z, A=4 μm); **a** CM, **b** UVAM

Table 4 shows the actual data for surface roughness along with the computed value of the sum of square deviation for each factor. In this table, K is the sum of the measured values for each level; Q is the average value of the quadratic sum of K_1, K_2, and K_3; T is the total sum of all measured values; and S is defined as the sum of square deviation.

Table 5 shows the results of ANOVA for surface roughness. As seen in the ANOVA table, the values of the sum of square deviation of both $A\times C$ and $B\times C$ are very small, so they are counted together as error term. The F ratio of each factor is also given in the table. Comparing the F ratio with the corresponding critical value at confidence coefficient of 0.01, it can be seen that spindle speed, feed per tooth, amplitude, and the interaction between spindle speed and feed are all significant influential factors for surface roughness. Judging from the F ratio, it is found that spindle speed has the most prominent effect on surface roughness of vertical side wall surface for UVAM, the next are amplitude, the interaction between spindle speed and feed per tooth, feed per tooth consequently.

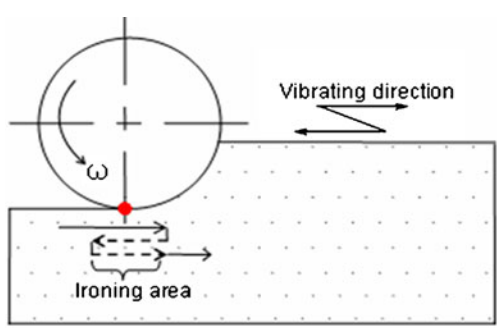


Fig. 15 Diagram of repetitive cutting

Because the index of this test is surface roughness, the smaller the better, the optimal level of factor C is C_2 by selecting the smallest value of K. As the interaction of A and B also has significant influence on surface roughness and it cannot be easily and directly analyzed, we summarize all their combinations in Table 6. It can be seen clearly that the smallest value of surface roughness is obtained when factor A and factor B are at level 1 and level 2, respectively. So, the optimal parameter combination is $A_1B_2C_2$ in this test. The measured value of surface roughness under the condition of this optimal combination is 0.387 μm, the smallest one in Table 4.

From the result of ANOVA, it can be concluded that the surface roughness of vertical side wall surface of slot is determined by several key parameters including spindle speed, feed per tooth, and amplitude in UVAM. As shown in the measured results, optimal combination of these parameters can ensure excellent improvement in surface finishing.

Table 4 Experimental results for surface roughness

No.	A	B	$(A\times B)_1$	$(A\times B)_2$	C	$(A\times C)_1$	$(A\times C)_2$	$(B\times C)_1$	$(B\times C)_2$	Ra (μm)
1	1	1	1	1	1	1	1	1	1	0.440
2	1	1	1	1	2	2	2	2	2	0.500
3	1	1	1	1	3	3	3	3	3	0.547
4	1	2	2	2	1	1	1	2	3	0.450
5	1	2	2	2	2	2	2	3	1	0.387
6	1	2	2	2	3	3	3	1	2	0.420
7	1	3	3	3	1	1	1	3	2	0.545
8	1	3	3	3	2	2	2	1	3	0.400
9	1	3	3	3	3	3	3	2	1	0.660
10	2	1	2	3	1	2	3	1	1	0.535
11	2	1	2	3	2	3	1	2	2	0.450
12	2	1	2	3	3	1	2	3	3	0.793
13	2	2	3	1	1	2	3	2	3	0.533
14	2	2	3	1	2	3	1	3	1	0.529
15	2	2	3	1	3	1	2	1	2	0.787
16	2	3	1	2	1	2	3	3	2	0.622
17	2	3	1	2	2	3	1	1	3	0.487
18	2	3	1	2	3	1	2	2	1	0.618
19	3	1	3	2	1	3	2	1	1	0.407
20	3	1	3	2	2	1	3	2	2	0.590
21	3	1	3	2	3	2	1	3	3	0.823
22	3	2	1	3	1	3	2	2	3	0.667
23	3	2	1	3	2	1	3	3	1	0.620
24	3	2	1	3	3	2	1	1	2	0.764
25	3	3	2	1	1	3	2	3	2	0.887
26	3	3	2	1	2	1	3	1	3	0.807
27	3	3	2	1	3	2	1	2	1	1.105
K_1	4.329	5.085	5.265	6.135	5.086	5.650	5.593	5.027	5.301	T=16.353
K_2	5.354	5.157	5.834	4.804	4.750	5.649	5.426	5.573	5.565	
K_3	6.670	6.111	5.254	5.414	6.517	5.054	5.334	5.753	5.487	
K_1^2	18.740	25.857	27.720	37.638	25.867	31.923	31.282	25.271	28.101	
K_2^2	28.665	26.595	34.036	23.078	22.563	31.911	29.441	31.058	30.969	
K_3^2	44.489	37.344	27.605	29.311	42.471	25.543	28.452	33.097	30.107	
Q	3.403	3.326	3.310	3.334	3.367	3.310	3.303	3.312	3.303	
S	0.306	0.073	0.124		0.196	0.031		0.037		

Table 5 ANOVA analysis for surface roughness

Source	Sum of square	Degree of freedom	Mean square	F ratio	Critical value	Significance	Optimal
A	0.306	2	0.153	42.207	$F_{0.01}(2,16)=6.23$	**	A1
B	0.073	2	0.037	10.069		**	B1
C	0.196	2	0.098	27.034	$F_{0.01}(4,16)=4.77$	**	C2
A×B	0.124	4	0.031	17.103		**	A1B2
A×C	0.031	4	0.0073				
B×C	0.037	4					
Error	0.048	8					

Table 6 The AB two-way table

B	A		
	1	2	3
1	0.500	0.387	0.400
2	0.450	0.529	0.487
3	0.590	0.620	0.807

4 Conclusions

In this paper, through a series of slot-milling experiments, we studied the effects of vibration on the surface roughness of the machined surfaces when using feed direction ultrasonic vibration-assisted micro-end-milling. As a summary, we draw three conclusions as follows.

1. In most cases, the forced feed direction ultrasonic vibration has a negative effect on the surface roughness of slot bottom surface in the UVAM experiment. This is mainly because more tool marks are left on the slot bottom surface in UVAM resulting from the more complicated relative motion between the tool and the workpiece. However, it is also noted that the surface roughness of slot bottom surface appears no obvious change after ultrasonic vibration is applied at a high speed of 13,000 r/min.
2. According to the experimental results, ultrasonic vibration makes a brilliant contribution to the improvement of the surface roughness of vertical side wall surface of slot. Much more uniform surface is produced in UVAM than that in CM, which is originated from the effect of separate-type cutting.
3. The result of ANOVA shows that the surface roughness of vertical side surface of slot is determined by the combined action of spindle speed, feed per tooth, and amplitude in UVAM. Optimal combination of these parameters can ensure excellent improvement in surface finishing. According to F test, spindle speed has the most significant influence with amplitude, the interaction between spindle speed and feed per tooth, feed per tooth being the second, the third, and the fourth, respectively.

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