Mechanism of dual-direction vibration-assisted (DVA) micro-milling in surface formation considering the tool life-lengthening effect on the Co41Cr16Ni15 alloy: design and experiment

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Research Article

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Mechanism of dual-direction vibration-assisted (DVA) micro-milling in surface formation considering the tool life-lengthening effect on the Co41Cr16Ni15 alloy: design and experiment

Guo Li1 · YuHao Li1* · QiuYan Liao2 · JiaDai Xue2 · Bo Wang2

Abstract
Micro-milling is extremely paramount to fabricating micro-scaled components, requiring high quality and low setup cost. However, with the stiffness of low micro-milling systems, the uncontrolled surface and vulnerable wearing tools must be addressed to achieve ultra-precision processing for the thin-wall microstructure. This paper explored the mechanism of surface formation based on dual-direction vibration-assisted micro-milling, and verifies the effectiveness in back chipping, analyzing the impact on chips and tool life-lengthening effect. Initially, an active vibration-assisted signal was added to the feed direction, considering the impact on surface integrity and quality, and the integrity and quality of the machined surface model were examined. Furthermore, two groups of experiments assessing the micro-milling Co41Cr16Ni15 alloy were carried out, comparatively with conventional micro-milling, analyzing the effect of the vibration-assisted device on surface integrity and quality, and a deterministic vibration-assisted micro-milling system was established. Finally, the effects of vibration assistance on surface topography, chip topography and micro-milling tool runout were determined. As a result, vibration assistance improved the micro-step structure on both sides of the thin-wall microstructure surface caused by tool eccentricity, and changed the surface morphology of the groove bottom. The experiment results showed that the form deviation of the vibration-assisted micro-milling surface was less than 101 nm SPV and surface roughness was also below 25 nm RMS. Surface formation mechanism based on the vibration-assisted micro-milling system was explored to reveal that vibration assistance improves surface integrity and quality, and sharply reduces the tool’s runout rate.

Keywords Dual-direction vibration-assisted micro-milling. Surface formation mechanism. Thin-wall microstructure. Tool life lengthening effect

Nomenclature

\( r_e \quad \text{The radius of tool tip arc} \)
\( k' \quad \text{tool minor cutting edge angle} \)
\( K \quad \text{Equivalent stiffness coefficient of mechanical transmission part} \)
\( M \quad \text{Equivalent mass of mechanical transmission part} \)
\( B \quad \text{Equivalent viscous damping coefficient of mechanical transmission part} \)
\( x \quad \text{x-axis displacement} \)
\( Y_r \quad \text{The radial error} \)
\( Y_a \quad \text{The axial error} \)
\( A_r \quad \text{The amplitude of radial error} \)
\( A_a \quad \text{The amplitude of axial error} \)
\( \omega \quad \text{Angular velocity} \)
\( E_v \quad \text{The amount of environmental vibration} \)
\( f_{ev} \quad \text{The frequency of environmental vibration} \)

1 Introduction

Micro-machining has an increasingly widespread utilization in micro-scaled components, across aerospace national defense, electronics and biomedical industries. In the micro-machining field, micro-milling is widely used to achieve ultra-precision processing of thin-wall microstructure10-12 as shown in Fig.1, with the following characteristics: (1) a wide range of materials for the processed parts
M. Xiao et al. [19] presented a novel one-dimensional vibration assisted cutting technology, and the influence of vibration on the stability of the cutting system was deeply discussed. The experiment results showed that vibration assistance can favorably suppress the harmful vibration generated during the cutting process and significantly improve tool life extension. Moriwaki T and Shamoto E et al. [21] developed a greatly two-dimensional vibrating material technology, establishing the first elliptical vibration assisted cutting system. The vibration frequency of the system was increased from 20 kHz to 40 kHz, which greatly improves the performance of the vibration assisted system as well as surface integrity and quality. E. Shamoto and T. Moriwaki et al. [22] analyzed the effects of vibration on the side of a milling spindle. Under the elliptical vibration, diamond milling cutters can be used in the processing of hardened steel and other iron-based materials, and nano-level processing surface quality can be deterministically derived, which addresses technically a difficult task that diamond milling cutters cannot mill iron-based materials. However, to the best of our knowledge, it is difficult to achieve high-frequency vibration when vibration is applied to one side of the tool, owing to the rotating cutting state of the tool and large mass high-speed spindle in vibration-assisted micro-milling. E. Shamoto et al. [23] established a new three-dimensional elliptical vibration assisted cutting system, and the elliptical vibration trajectory in the plane was enhanced into spatial ones. Three-dimensional elliptical vibration is applied to the engraving and milling processes, which greatly improves the processing quality of complex three-dimensional structures. Nevertheless, a large amount of previous studies focused on the resonant mode in three-dimensional elliptical vibration assisted systems, and frequency is not adjustable with the vibration realized by the harmonic oscillator horn. The non-resonant vibration-assisted approach has the advantage of adjustable vibration frequency and amplitude, compared with the resonant mode, and widely uses the flexible hinge structure for the limited working frequency by the vibration mechanism. The working frequency of the vibrating mechanism based on the flexure hinge must be lower than the first-order resonance frequency of the mechanism for a feedback from the vibration action. Compared with the unidirectional mode, compound mode auxiliary vibration can simultaneously achieve high machining efficiency and good surface roughness. Therefore, the vibration frequency achieved in the vibration device of the flexible hinge mechanism is normally lower than those of the others, and the frequency and amplitude of the vibration action are both limited by the output power of the driving element and the driver.

The contributions of this paper are as follows. Firstly, the study designed a deterministic device to correctively adjust vibration frequency and amplitude because of the non-resonant property called the dual-direction vibration-assisted device. The vibration device uses piezoelectric ceramics to drive a flexible hinge mechanism to achieve the vibration output and the pull-push working mode increases the input power of the vibration device to achieve non-resonant mode vibration. Compared with the traditional resonant auxiliary vibration device or the flexible hinge mechanism, this device applies vibration assistance on the workpiece to meet the requirement, changing the original micro-milling material removal mechanism and laying a foundation for subsequent experimental research.
The second contribution is establishing a machined surface integrity and quality model for the clarification of the effect of the low micro-milling system stiffness on micro-milling accuracy. The diameter of the micro-milling cutter and the cutting parameters have the same micron level, possessing the stiffness of the low micro-milling system, leading to severe tool wearing, and inevitably forming cutting and material extrusion traces. The ratio of trace scale to wall thickness for the part is much larger than that of the conventional scale part, which leads to poor processing consistency of thin-walled micro-components. Based on the machined surface integrity and quality model, the extrusion traces of the workpiece surface material are enhanced significantly, with the tool wear aggravated. A typical thin-wall microstructure of the alloy Co-Cr-Ni material elastic sensitive element is an experimental candidate in Fig.2, which is the core element of a new inertial guidance system. The side edge, bottom edge, and tip arc of the micro-milling cutter function together to complete the thin-wall microstructure, and the material’s removal mechanism becomes complicated while applying vibration assistance. This paper demonstrated that it is necessary to study the mechanism of surface formation of thin-walled micro-components under the non-resonant mode vibration, to improve the processing surface integrity and quality and consistency considering the tool life-lengthening effect.

2 Motion analysis of tool eccentric vibration assisted micro-milling machining

Modeling and effect of vibration-assisted micro-milling

In the micro-groove structure micro-milling process, the main factors that affect the bottom surface quality are the geometry and size of the tool, the movement state of the X axis, the movement state of the spindle (rotation speed, and axial and radial runout), and environmental factors such as vibration. In this topic, in order to improve the processing state of precision micro-milling, in the process of micro-milling, an active vibration auxiliary signal was added in the feed direction. The specific effect of each factor on the machined surface is shown in Figure 3.

When processing micro-groove structures, the main factors affecting the processing surface shape of the groove bottom surface include the structure size of the micro milling cutter, the characteristics of the linear guide, the characteristics of the vibrating table, the dynamic characteristics of the spindle, and the vibration of the environment, etc. The above factors have a certain impact on the processing quality of the micro-groove structure. Since the micro-milling process is a micro-scale effect, it is not suitable for the
"scenario" of conventional milling to identify the optimal cutting conditions, so it is necessary to establish a mechanical model considering factors of the micro-milling error\(^{[27]}\).

The precision micro milling cutter model

In the process of milling the micro groove structure, the formation of the groove bottom surface is completed by the joint action of the tip arc of the milling cutter and the secondary cutting edge. The schematic diagram of the micro milling cutter model is shown in Figure 4. The cutting force and surface error can be predicted by the model implemented in the form of a computational program\(^{[24,25]}\). The model of the tip arc and the secondary cutting edge of the micro-milling cutter can be described by the following equation (2.1).

\[
y = \begin{cases} 
  r \cdot \frac{2 - x^2}{\sqrt{2 - x^2}} & \text{if } -r \cdot \sin k' \leq x < r \\
  r - r \cdot \cos k' \cdot (x + r \cdot \sin k') \tan k' & \text{if } x \leq -r \cdot \sin k'
\end{cases}
\]

(2.1)

Dynamic model of the X-axis motion guide

The vibration-assisted micro-milling processing motion of the micro-slot structure mainly includes the linear motion of the X-axis guide, the vibration of the vibration-assisted table, and the rotation of the air turbine high-speed spindle. The accuracy and disturbance of the X-axis directly affect the shape error and surface quality of the bottom surface of the micro-groove structure, and a mathematical model was established for the movement of the X-axis. The mathematical model of the X-axis mechanical transmission link G can be simplified as a second-order system, and its physical model is shown in Figure 5.

\[
m \frac{d^2 y}{dt^2} + c \frac{dy}{dt} + k_y y = k_i (x - y) - F
\]

(2.3)

Rotation Error of the Air Turbine High Speed Spindle

In the vibration-assisted micro-milling of the micro-slot structure, the spindle axial run-out error and radial run-out error exist in the form of sine waves, with frequency related to the spindle’s speed (2.4).
\[ Y_a = A_a \sin(\omega t) \]
\[ Y_r = A_r \sin(\omega t) \]  
(2.4)

Disturbance factors of the processing environment

The disturbing vibration of the surrounding environment also has a certain impact on the surface quality of the bottom surface of the processed micro-groove structure (2.5).

\[ E_v = 7.5 \sin(2 \pi f_v t) \]  
(2.5)

Modeling analysis of bottom surface profile of trough structures

According to the modeling process of the bottom surface of the microgroove structure in the previous section, cutting process parameters, tool parameters and the movement of the motion axis, the application of the vibration auxiliary signal, the interference of the external environment and other factors are used to affect the ordinary micro-milling surface simulation with the vibration-assisted micro-milling machined surface. The normal micro-milling machined surface profile is shown in Figure 7(a), and the vibration-assisted micro-milling machined surface profile is shown in Figure 7(b).

Fig. 7 Simulated topography of the bottom surface structure of the micro-groove a) Surface simulation topography of ordinary micro-milling b) Simulation topography of vibration-assisted micro-milling surface

As shown in Figure 8, application of the vibration assist signal remarkably complicates the knife pattern in the bottom surface of the micro groove structure. Due to the addition of the vibration assist signal, fluctuation of the processed surface is reduced, thereby improving the micro-milling micro-groove structure. The vibration signal improves the surface processing quality of the groove bottom surface. According to the experiments, periodic tool vibration can increase machining speed and reduce surface roughness\(^{29}\). Smaller feed per tooth, moderate back cut, high frequency and moderate amplitude can achieve low surface roughness, and the minimum achievable surface roughness Ra is 25nm; Tooth feed, small amount of back cutting, high frequency and small amplitude can achieve high surface accuracy SPV processing, and the surface accuracy SPV can reach up to 0.101\(\mu\)m.

3 Experimental results and analysis

3.1 Setup for experiments

The machining accuracy and surface quality of thin-walled micro-components require very high positioning accuracy and tracking accuracy of the micro-milling processing equipment, so the processing of this part requires a micro-milling processing system of ultra-precision processing level. At the same time, in order to improve the processing quality of thin-walled micro-components, this study integrates a vibration auxiliary table device on the basis of the ultra-precision micro-milling system. In order to study the impact of vibration assistance on the quality of micro-milling processing and simultaneously ensure the processing accuracy and surface quality of thin-walled micro-components, the vibration-assisted workbench device also needs to have high-precision vibration frequency and
vibration amplitude output capabilities. According to experiments it also needs to have a higher level of frequency and amplitude adjustment step. In response to the above requirements, this work developed a vibration-assisted micro-milling system composed of a precision micro-milling device and a vibration-assisted worktable. Figure 9 shows the three-axis linkage vibration-assisted micro-milling machine tool.

The main body of the ultra-precision micro-milling device adopts a vertical natural granite bed structure. The X and Y two-dimensional motion platforms in the device are composed of cross-type closed aerostatic guide rails and are driven by high-precision linear motors. The main components of the ultra-precision micro-milling device are as follows. The linear motor adopts a three-phase permanent magnet brushless linear servo motor (Kolemorgen’s PLATINUM-DDL series). The motor model was IL12-050, the stable working output was 122N, and the maximum output was 400N. A MicroE series linear grating ruler was used as the feedback element. The linear grating ruler has a resolution of 5 nm, which can meet the high-precision motion control requirements of the device. The main shaft adopts the high-speed electric main shaft with high-precision air bearing produced by British Loadpoint Company. The highest stable speed of the spindle is 120,000 rpm, and the axial and radial runout distances are both less than 0.125μm.

In order to ensure the dimensional accuracy and surface quality of thin-walled micro-components, an ultra-precision vibration-assisted micro-milling system was built in this work. The ultra-precision vibration-assisted micro-milling device is composed of a micro-milling device and a vibration-assisted worktable in Fig 10.

Considering the dimensional accuracy of thin-walled micro-components and the structural characteristics of ultra-precision micro-milling devices, this study adopted a 1D non-resonant vibration-assisted working mode with active vibration control. It needs to realize the following functions:

(1) Precise control of active vibration frequency $f$

For turning and planing processing methods that do not rotate the tool, vibration-assisted cutting shows that the higher the frequency, the better the processing quality. However, in the field of micro-milling processing, there is no research showing that the higher the vibration frequency, the better the outcome, justifying the design of this study. The vibrating table adopts a non-resonant frequency adjustable working mode. According to the driving ability of the driving components used and the response frequency of the mechanical structure of the vibrating table, the output frequency range of the selected vibrating auxiliary table’s driving power supply is 0–10 kHz, and the control accuracy is 100 Hz.

(2) Precise control of active vibration amplitude $A$

Since micro-milling is a weak-rigidity cutting, the cutting characteristics are significantly different from those of high-rigidity cutting methods. The main factors that affect amplitude output include the output power of the driver (W) and the stiffness of the mechanical structure of the vibration auxiliary table ($k$). The former directly determines the magnitude of the input energy, and the latter determines the response ability of the vibrating structure to the input energy. The piezoelectric ceramics in the vibration auxiliary workbench are both elastic bodies as the functional components and the mechanical structure that responds to vibration. The interaction of these two parts is a process in which the elastic bodies are connected in series, and the stiffness of both parts directly affects the amplitude output characteristics of the vibrating table. Combined with the experimental requirements and the output power of the vibration auxiliary workbench, the output amplitude of the vibration auxiliary workbench developed in this work was selected to be 0–4μm, and the control accuracy was 0.1μm.

3.2 The effect of vibration on surface topograph

In preliminary experiments assessing hard aluminum alloy materials, a VHX-1000E ultra-depth-of-field three-dimensional microscope was used as the inspection instrument for the surface morphology of thin-walled micro-components.

By comparing the surface morphologies of the groove bottom obtained by vibration-free micro-milling and vibration-assisted micro-milling with amplitude vibration of 2μm and 4μm, it can be seen that
vibration assistance significantly affected the processing quality, and the processing quality of the processed surface increased with the vibration amplitude (Figure 11). The addition of vibration-assisted cutting produces more complex-shaped primary microtextures compared with conventional micro-milling, which can simultaneously construct desired secondary textures by controlling the intersections with adjacent vibration-assisted cutting trajectories\(^{[32]}\). Therefore, the vibration auxiliary device needs to have an adjustable amplitude output function.

![Fig. 11](a) No vibration (b) With 2 μm amplitude vibration (c) With 4 μm amplitude vibration

In order to assess the effect of vibration on surface topography, this study used a confocal microscope to detect the bottom topography of the groove. The parameters used in this experiment were: spindle speed, 30000 rpm; back-cutting amount, 6μm; feed rate per tooth, 2μm/z; tool diameters, 200μm, 300μm and 500μm; output amplitude, 0-4μm; cutting material, Elgiloy. The test results are shown in Figure 12.

![Fig. 12](a) Groove machined with 200 μm diameter tool and step size (b) Groove machined with 300 μm diameter tool and step size (c) Groove machined with 500 μm diameter tool and step size

As shown in Figure 12, there were obvious stepped structures on both sides of the groove under different tool diameters. By measuring the step structure on both sides of the groove, it was found that the widths of the step structure obtained by micro-milling tools of different diameters were basically 5~7μm, indicating that the step width has nothing to do with tool diameter, spindle speed and the amount of back cutting. It is only related to the eccentricity of the tool and the feed per tooth.

![Fig. 13](a) Conventional micro-milling (b) Vibration assisted micro-milling

The results of vibration-assisted micro-milling in Figure 13 b) showed that after vibration-assisted application, the tiny steps on both sides of the bottom surface of the groove structure were basically invisible. In conclusion, through comparative experiments, it can be found that vibration assistance can effectively suppress the generation of step morphologies on both sides of the groove structure by complicating the motion trajectory and significantly improve the tiny step defects of thin-walled micro-components.

In micro-milling, the amount of feed per tooth has a direct impact on the topography of the machined surface. With the feed per tooth, the tool deformation of a micro-milling cutter increases significantly, which in turn deteriorates the quality of the machined surface. In order to ensure the effect of vibration, it is also necessary to consider the influence of the number of cutting edges for micro-milling cutters and the rotation frequency of the spindle. Compared with conventional milling, due to the small diameter of the developed micro-milling cutter, tool deformation during the milling process accounts for a large proportion of the tool’s diameter, so the milling rigidity of the micro-milling cutter is low. When the amplitude is too large, the undeformed cutting thickness also increases accordingly. In addition, the milling force increases, which causes vibration and impact between the cutting elements...
edge of the milling cutter and the workpiece. At the same time, the vibration also causes obvious friction between the bottom edge of the milling tool and the machined surface, which affects the surface topography of the thin-walled micro-components. Therefore, under different tooth feeds, vibration frequencies and amplitudes, the surface topography of the thin-walled micro-components was machined, and the effect of vibration on the surface topography is depicted in Figure 14.

Figure 14 a) and b) show micrographs of the surface of thin-walled micro-components when the feed per tooth are 0.5μm/z and 2μm/z, respectively. The results showed that with increasing feed per tooth, the cutting pattern of surface milling becomes more and more obvious. At a feed rate per tooth of 2μm/z, the material’s cutting marks caused by machining were more obvious; at 0.5μm/z, in addition to the cutting marks, there were obvious marks on the surface of thin-walled micro-components as traces of repeated cutting.

3.3 The effect of vibration on chip morphology

In this section, the chip was taken as the research object, and experimental research on chip morphology obtained by conventional micro-milling and vibration-assisted micro-milling was carried out, and chip fracture morphology at the bottom of the groove was analyzed. The mechanism of material removal and the effect of groove bottom topography. An SEM image of the micro-milling cutter used in the experiment is shown in Figure 15. The shapes of both sides of the chip are shown in Figure 16.

The micro-milling chip morphology is shown in Figure 16. The morphology of the chip shows that the surface of the chip in contact with the tool replicates the traces on the rake face of the micro-milling cutter, while the surface of the chip not contacting the rake face of the tool forms denser folds, which reflects the fracture of the material during the milling process. In this way, when the material accumulates to a certain extent, it breaks with the matrix material, and the cycle is repeated; finally, the entire chip is removed at the edge of the material’s matrix.

The following is a detailed analysis of chip morphology in conventional micro-milling and vibration-assisted micro-milling. The chip morphologies obtained by both processing methods are shown in Figure 17.
3.4 Effect of vibration parameters on surface roughness and form accuracy

In this study, the processing quality of thin-walled micro-components was assessed from the two aspects of vibration frequency and amplitude. Using 3D-OLS4000 with three-dimensional imaging function, the surface quality and surface shape accuracy of thin-walled micro-components can be accurately detected.

The surface topography of thin-walled micro-components was examined. The red frame area in Figure 4-7 represents the data acquisition and detection area for surface roughness and surface shape accuracy, and the size of this area was 100μm×100μm. The filtered surface in Figure 18 clearly shows that the surface topography caused by tool deformation during the milling process has reduced and high structural characteristics in the middle and at both ends, respectively. The following is a detailed analysis of the detection results, which are obtained after filtering the detected data.

Figure 18 shows the detection results of surface roughness Ra and surface shape accuracy SPV under the effects of different frequencies and amplitudes. It was found that the milling marks on the surface of thin-walled microcomponents were replaced by vibration-assisted vibration lines. The detection results of surface roughness showed that with the increase of vibration frequency, the high point area of the detection surface was continuously reduced, that is, the red area increasingly became small. At a vibration frequency of 10 kHz, the surface quality had the best results in the range of vibration parameters applied in this paper. With the continuous increase of amplitude, the vibration pattern on the surface became more and more obvious. At a large amplitude, there were more and more high-point areas in the structure, that is, the red area in the detection results was larger and larger, with deteriorated surface shape accuracy. In summary, different process parameters affect the surface roughness and surface shape accuracy of the machined surface. These findings also verified that vibration application has a positive effect on the machining quality of micro-milling.

In the process of studying the vibration-assisted precision micro-milling process, detection of the roughness and surface accuracy of the bottom surface of the micro-groove structure was carried out along the direction of the groove length by using the Taylor Hobson profiler. The measurement range was 1 mm, and the feed rate was 0.25 mm/s; the pressure of the probe was moderate. Orthogonal experiments were carried out according to different feeds, frequencies and amplitudes. The range of vibration frequency was 0.028 and that of amplitude was 0.063. It can be seen that the amplitude of the vibration signal had the greatest influence on surface roughness.

As shown in Figure 18, when vibration frequency was in the range of 0~2 kHz, with increasing vibration frequency, the surface roughness decreased, and the surface roughness decreased from 137 nm to 91 nm. However, when the vibration frequency reached 2~4 kHz, surface roughness worsened and rose to 101 nm. The analysis found that since the maximum speed of the air-float electric spindle used in the machine tool in this paper was 120000 rpm, the maximum vibration frequency of the spindle rotation was 2 kHz, and its double frequency was 4 kHz. Therefore, a vibration frequency of 2~4 kHz had an adverse effect on the main shaft and worsened the surface roughness (Ra). As the frequency further increased in the range of 4~10 kHz, surface roughness was reduced from 101 nm to 25 nm. It can be seen that the influence on surface roughness is that at frequency exceeding 4 kHz, as vibration frequency further increased, surface roughness was improved. The analysis showed that the higher the vibration frequency, the more obvious the “micro-grinding” effect of the flank of the cutting bottom edge of the micro-milling cutter on the machined surface during the processing of thin-walled micro-components, and the better the surface roughness of the machined surface.

As shown in Figure 18, the influence of amplitude on the shape accuracy SPV is shown in Figure 18. As the amplitude increased in the range of 0~1μm, the surface shape accuracy SPV decreased, from 0.237μm to 0.189μm. When vibration frequency was increased from 2 kHz to 6 kHz, the surface shape accuracy SPV was deteriorated again and increased to 0.275μm. When vibration frequency was increased from 6 to 10 kHz, the surface shape accuracy was gradually increased, and the SPV was decreased to 0.121μm. The analysis found that with increasing vibration frequency, the cutting force is decreased, and the SPV of the surface shape accuracy is improved to a certain extent; however, in the range of 2~6 kHz, with a further increase of vibration frequency, due to the highest rotation frequency of the spindle, uncontrollable chattering occurs in the whole micro-milling process, and the cutting process shape is extremely complicated at this time, so it also has an adverse effect on SPV.

The influence of amplitude on the shape accuracy SPV is shown in Figure 18. As the amplitude increased in the range of 0~1μm, the surface shape accuracy SPV decreased, from 0.237μm to 0.101μm. Further increase in the range of ~4μm resulted in gradually deteriorated surface shape accuracy, and the surface shape accuracy SPV increased from 0.101μm to 0.275μm. The behavior of the amplitude completely differed from the vibration-assisted application in turning or planing. In vibration-assisted turning or planing, the larger the amplitude, the better the surface shape accuracy (SPV). The micro-milling cutting system is a typical weak-stiffness system. Too large amplitude results in increased milling force and impact on tool deformation. Therefore, in order to ensure the surface accuracy of thin-walled micro-components, large amplitude cutting parameters cannot be used.

3.5 Tool wear patterns in micro-milling titanium alloy

Our previous work demonstrated that our developed cutting force model considering tool runout has a better effect in investigating the influence of vibration parameters on the surface quality, which can be
well predicted by the change in milling force. The established three-directional micro-milling force model has strong robustness, which can be used for vibration-assisted slot milling of titanium alloy materials, helping assess the influence of tool runout on the surface quality of workpieces [34].

SEM micrographs of the worn tool at different vibration frequencies and amplitudes after machining for 45 min are given in Fig. 18. When the tool tip was worn at a spindle speed of 30,000 r/min, a back-cutting amount of 6 μm and a feed rate per tooth of 2 μm/rev, wear modes such as microcracks and fractures emerged, but no tool breakage was present for the Elgiloy micro-milling cutter. Ti6Al4V is an alpha-beta titanium alloy but has a specific strength, which can generate stress that can wipe off the tip of the Elgiloy micro-mill. Meanwhile, this process causes metals, such as chromium, cobalt and nickel, to fall out of the metal bond of the tool, and the workpiece material accumulates and fills the cavity formed by these dislodged metals.

At a low feed, the more chrome, cobalt, nickel and other metals fall off the tool tip, the more workpiece material accumulates on the tool tip, which generates higher stress under the action of micro-milling and eventually causes attrition wear. Research on tool wear was carried out under two distinct regimens, including reduced spindle speed with low feed and increased spindle speed with high feed. The first regimen had a higher attrition wear rate and severe wear, accompanied by wear patterns such as cracks, chipping, sticking and chipping, as shown in Figure 19 a). The brittle fracture occurred in this mode, allowing easier material removal and lower cutting forces being required to remove the material [33].

Adhesive wear was indicated by EDS analysis in Fig 19 b), as it was found that the majority of the Ti, Al and V deposited on the exposed tool tip were mainly composed of workpiece materials (Table 1). The adhesive on the tool tip was dislodged during the micro-milling process as evidenced by tool tip cracking producing chips and carrying away some of the tool’s materials. In the second regimen, severe flank wear occurred, and severe friction occurred with the bottom layer of chips, so that the contact surface has a certain temperature and pressure, resulting in cold welding and staying on the rake face. Then, the atoms on the surface of the workpiece material are captured and gradually formed into a built-up edge. The built-up edge replaces the original tool tip, which is beneficial in protecting the cutting edge and increasing the rake angle; however, once it is separated from the tool tip, the machined surface roughness becomes larger and is prone to vibration.
Table 1: The analysis results of material composition at point A in Fig. 19(a).

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
<th>At%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>05.65</td>
<td>18.40</td>
</tr>
<tr>
<td>AlK</td>
<td>07.47</td>
<td>10.82</td>
</tr>
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</table>

3.6 Effect of Vibration Auxiliary Action on Wear of Micro-milling Tool

In micro-milling, tool wear is faster and more severe than in conventional milling because the size of the tool tip arc is in an order of magnitude with the back-engagement and feed. The state and morphology of wear were studied.

Effect of tool eccentricity on tool wear pattern

It is well known that the surface structure of a workpiece processed by micro-milling limits a certain proportion of oil droplets to reach the cutting edge, causing tool wear\[26\]. However, as a cutting factor that cannot be ignored in micro-milling, tool eccentricity also exerts a different effect on tool wear than conventional cutting conditions. The eccentricity of the tool increases the length between collets and tooltip, which affects the tool runout and aggravates the tool wear pattern\[29\]. Figure 20 shows the SEM pictures of the micro-milling tool before and after the micro-milling process.

(a) New micro milling cutter  (b) Worn tool
(c) short blade tip wear     (d) long blade tip wear

Figure 20 a) is the SEM inspection image of the new micro milling cutter. Figure 20 b) is the SEM inspection image of the worn micro-milling cutter. It can be seen from the figure that one cutting edge of the double-edged end mill is more worn, while the other cutting edge is less worn. Figure 20 c) is the inspection diagram of the cutting edge with less wear in the micro-milling cutter. Figure 20 d) is the inspection diagram of the cutting edge with greater wear in the micro-milling cutter. It can be seen from the test results that in the process of micro-milling, the eccentricity of the tool is real, and it also has an adverse effect on the tool wear of the two cutting edges, which will lead to serious tool wear on the long cutting edge and affect the service life of the tool.

Effect of vibration on tool wear pattern

The following is an experimental study of tool wear under conventional micro-milling and vibration-assisted micro-milling conditions. Figure 21 shows the changing patterns of tool wear for conventional micro-milling and vibration-assisted micro-milling as the cutting distance increases. Cutting distances were 0 mm, 1884 mm, 3768 mm and 7536 mm, respectively, were used to detect tool wear.

As shown in Figure 21 above, wear of conventional micro-milling tools is mainly in the form of adhesive wear of the tool tip. After continuous cutting for a period of time, due to the high temperature and high pressure, the cutting edge of the tool is damaged, thereby losing the ability to cut materials. However, the flank of the micro-milling cutter is relatively clean, with no material adhesion. The tool wear pattern of vibration-assisted micro-milling is significantly different from that of conventional micro-milling. A large amount of material is adhered to the flank of the cutting bottom edge, and the tool wear pattern is the material adhesion wear of the flank of the cutting bottom edge. From the perspective of tool wear, it was confirmed that the material removal mechanism under vibration-assisted conditions is fundamentally different from that of conventional micro-milling. During the cutting process, a large amount of material adheres to the flank of the cutting bottom edge, resulting in the “micro-grinding” effect, so that the flank of the cutting bottom edge participates in cutting, which is also the reason why vibration assistance can improve the quality of the machined surface.

It can also be seen from the wear picture of the tool that when the cutting distance is the same, after applying vibration assistance in conventional micro-milling, the wear rate of the tool, i.e., the damage degree of the tool tip area, is significantly lower than that of vibration-assisted micro-milling. Therefore, vibration assistance can significantly increase the tool’s life of micro-milling cutters.

4 Conclusions

Thin-walled micro-components are more and more widely used in the fields of national defense and aviation, and the requirements for their processing quality and performance are showing an increasing trend. Although the traditional micro-milling technology can realize the processing of thin-walled micro-components, it has disadvantages such as low surface quality, severe tool wear and poor dimensional accuracy consistency. The following specific conclusions were drawn from this investigation:

1. Design and building of a new vibration-assisted workbench. The vibration table works in an active vibration mode and is driven by two sets of piezoelectric ceramics with a difference of 180° to achieve a vibration output with a frequency of 0–10 kHz and an amplitude of 0–4μm. In addition, the vibrating table utilizes the piezoelectric effect of piezoelectric ceramics, which enables real-time dynamic monitoring of the micro-milling process. After filtering the detected vibration signal, the tool wear state could be judged according to the change trend of the signal strength of spindle and active vibration frequencies with the cutting process.
2. Based on the orthogonal experiment method, the effect of vibration assistance on the machining quality of thin-walled micro-components was studied. The experimental results show that vibration assistance can improve the defects of micro-step structure at both ends of the micro-groove structure caused by the eccentricity of the tool. At the same time, the effects of the feed per tooth, the amount of back engagement, and the frequency and amplitude on surface quality and surface shape accuracy were studied. The results show that at a feed per tooth of 0.1μm/z, an amount of back cutting of 3μm, a vibration auxiliary frequency of 10 kHz and a vibration amplitude of 1μm, surface roughness was best, reaching 25 nm. In machining, at a feed rate per tooth of 1μm/z, a back cutting amount of 3μm, a vibration auxiliary frequency of 10 kHz and a vibration amplitude of 1μm, the surface shape accuracy was the best, reaching an SPV of 0.101μm. At the same time, at an amplitude of 4μm and a frequency of 10 kHz, the cutting burr at the bottom of the groove was basically invisible. In addition, this paper also conducted an experimental research on tool wear. The experimental results show that vibration assistance can significantly reduce the wear rate of the tool. In addition, the wear pattern of the tool is significantly different from that of conventional micro-milling tools. The material was sticky, resulting in sticky wear of micro-milling cutters. No obvious burrs were found on all channel bases. The surface roughness of channel base was dependent on cavities, which is controlled by the cutting conditions. At cutting parameters of 10,000–20,000 r/min spindle speed, 0.5–1.0μm/z feed and 125–150 mm cut depth, massive cavities appeared on the channel base to deteriorate the surface quality. The lower feed rate was also prone to higher surface roughness because of intensive plowing of the tool on aluminum caused by rapid tool wear.

3. A new type of multi-ceramic push-pull multi-functional workpiece vibration-type vibration auxiliary workbench was designed and built. The worktable adopts the active vibration mode driven by bidirectional piezoelectric ceramics, which can realize the adjustable vibration output of high frequency and large amplitude, which effectively avoids the defect that the conventional flexible hinge mechanism hardly achieves high frequency and large amplitude. By studying the burr shape and tool wear mechanism in the groove bottom of thin-walled micro-components by vibration-assisted micro-milling, the effects of process parameters and vibration factors on the machining accuracy and quality of thin-walled micro-components were deeply analyzed, and the effects of vibration-assisted parameters on the micro-milling groove bottom were revealed. The effects of cutting burr and tool wear provide a basis for realizing high-quality machining of thin-walled micro-components.

4. Further research is needed to investigate the extent of the effect of vibration assistance on the surface metamorphic layer of thin-walled micro-components. The material of the thin-walled micro-component studied in this paper has high-elasticity, i.e., poor machinability. Compared with other materials, the cutting force during the cutting process was also larger. At the same time, the structural size of its functional area is about 10μm. Basically, the mechanical properties of the entire structure are affected by cutting parameters and cutting methods. At present, this paper only examines the influence of vibration assistance on thin-walled micro-components by studying the improvement of the macroscopic mechanical properties. It is still necessary to continue to quantitatively study the influence of vibration assistance on the surface metamorphic layer at the microscopic scale. The effect of performance can be used to better understand the influence of different processing methods on the mechanical properties of thin-walled parts.
Declarations

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b. Conflicts of interest/Competing interests
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Not applicable

d. Code availability
Not applicable

e. Ethics approval
Not applicable

f. Consent to participate
I agree to participate.

g. Consent for publication
I agree to publish.

h. Authors' contributions
Theory, experiment and writing.

References


