ORIGINAL ARTICLE

State-of-the-art review on vibration-assisted milling: principle, system design, and application

Wanqun Chen[1,2] · Dehong Huo[1] · Yilun Shi[1] · J. M. Hale[1]

Abstract

Vibration-assisted machining (VAM) is an external energy assisted machining method to improve the material removal process by superimposing high frequency and small amplitude vibration onto tool or workpiece motion. VAM has been applied to several machining processes, including turning, drilling, grinding, and more recently milling, for the processing of hard-to-machine materials. This paper gives a critical review of vibration-assisted milling (VAMilling) research. The basic kinematic equations of 1D and 2D VAMilling are formulated and three typical tool-workpiece separation types are proposed. State-of-the-art on the principle and structural design of VAM systems are reviewed. The benefits and applications of VAMilling are discussed with emphasis on machining of hard-to-machine materials. Finally, the paper concludes with future possibilities for VAMilling.

Keywords Vibration-assisted machining · Vibration-assisted milling · Vibration cutting · Vibration system design · Tool-workpiece separation

1 Introduction

High-accuracy precision components are increasingly in demand for various industries, such as biomedical engineering, MEMS, electro-optics, aerospace, and communications [1–4]. In addition to the aims of achieving tight tolerances and high-quality surface finishes, many applications also require the use of hard and brittle materials such as optical glass and technical ceramics, owing to their superior physical, mechanical, optical, and electronic properties [5–9]. Such applications range from biomedical devices such as neurosurgical brain implants made of semi-conductor materials (silicon, gallium nitride, silicon carbide) and bio-sensors made of piezoelectric materials (PZT, aluminum nitride, lithium niobate), to automotive and battery industries where quartz glass and silicon are widely employed [10, 11]. Therefore, the increasing demand for high-accuracy precision micro components in aforementioned industries has emphasized the importance of machining methods for hard and brittle materials to achieve tight tolerance and high-quality surface finish. However, due to their high hardness and usually rather low fracture toughness, the processing and fabrication of hard and brittle materials, has always been a challenge to the industries. Much more importantly, those devices usually possess complex feathers, further increasing the difficulty of high-precision machining.

Previously, non-conventional machining methods, such as EDM, ECM, laser machining, ion-beam machining, electrobeam machining, etc., were adopted to realize the processing of hard and brittle materials [12–16]. However, those methods have significant drawbacks on the machining of hard and brittle materials, including the long preparation time, low processing efficiency, high setup cost, and high environmental requirements. As for conventional milling or micro milling, owing to its high precision, superior flexibility, and simple setup [17–21], it is capable of generating a wide variety of complex components and structures from micro to macro scale. Since the scale of the edge radius of milling tool is approximately comparable to the uncut chip thickness, micro milling process exhibits different material removal mechanisms, compared with the conventional milling. That is the well-known size effects. Up to date, two issues which limit the further development of micro milling [22, 23] should be urgently solved. Firstly, the deformation and vibration between micro cutter and workpiece would interfere the machining accuracy.

✉ Dehong Huo
   dehong.huo@newcastle.ac.uk

[1] Mechanical Engineering, School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

[2] Center for Precision Engineering, Harbin Institute of Technology, Harbin 150001, People's Republic of China

To solve above problems, continuous efforts to enhance machining performance have been performed, and lots of breakthroughs have been achieved. One important breakthrough should be the finding of the vibration-assisted machining (VAM). The research results have clearly indicated that the surface quality of machined surface can be improved by applying high frequency vibration to the tool or workpiece. Vibration-assisted machining is an external energy assisted machining method in which high frequency and small amplitude vibration is superimposed on the tool or workpiece motion to improve the material removal process. With appropriate machining and vibration conditions, the tool periodically loses contact with the workpiece. This changes the cutting mechanics and can improve machining performance. VAM has been applied to several machining processes, including turning, milling, drilling, and grinding, for the processing of hard materials. Reported benefits include the following: reduction in machining forces [24–27]; improved surface finish and form accuracy [25, 28–30]; suppression of burr formation [23, 28]; reduction of tool wear and extension of tool life [30–32]. In the turning process, vibration assistance is relatively easy to implement on the cutting tool as it is stationary. Both 1D and 2D vibration-assisted systems for the turning process (linear vibration in the cutting direction and elliptical vibration motion in the plane of cutting and depth of cut directions, respectively) have been applied with success. However, due to the continually changing cutting velocity and uncut chip thickness in the milling process, the trajectory of the tool tip in VAMilling is more complex than that in vibration-assisted turning. Therefore, this paper is mainly focused on the working principle and state-of the-art of VAMilling.

The remainder of the paper is organized as follows: Sections 2 and 3 establish the kinematic models for both 1D and 2D VAMilling and generalize three types of typical tool-workpiece separation. Section 4 reviews the vibration application and actuation methods of vibration-assisted machining. Section 5 introduces the application and benefits of VAMilling.

2 Kinematics of vibration-assisted milling

According to the direction of the vibration applied, VAMilling can be divided into two main groups, i.e., 1D VAMilling where the vibration applies either in the feed direction, feed-directional vibration-assisted milling (FVAMill), or in the cross-feed direction, cross-feed-directional vibration-assisted milling (CFVAMill), and the 2D VAM milling (2DVAMill) where the vibration applies simultaneously in both the feed and the cross-feed directions [33].

Figure 1 shows a schematic diagram of vibration-assisted milling. The coordinate system used in this paper is defined as

follows: the workpiece feed is in x-axis; the cross-feed direction is in y-axis; and axial depth of cut is in z-axis.

The mathematical equation of the tool tip motion without vibration imposed is as follows:

$$\begin{cases} x = \mathrm{f}t + r\sin\left[\omega t - \dfrac{2\pi(z_i-1)}{Z}\right] \\ y = r\cos\left[\omega t - \dfrac{2\pi(z_i-1)}{Z}\right] \end{cases} \tag{1}$$

where f is feed velocity, r and ω are the radius and angular velocity of the cutter, z_i is the ith cutter tooth, and Z is number of flutes.

Assume that vibration is applied to the workpiece and the vibration trajectory is as follows:

$$\begin{cases} x_w = A\sin(2\pi f_x t + \phi_x) \\ y_w = B\sin\left(2\pi f_y t + \phi_y\right) \end{cases} \tag{2}$$

where A and B are the vibration amplitudes, f_x and f_y are the vibration frequencies, and ϕ_x and ϕ_y are the phase angles in the x- and y-directions, respectively. The relative displacement (x_i, y_i) of tool tip to workpiece in VAM milling can be obtained from Eqs. (1) and (2):

$$\begin{cases} x_i = ft + r\sin\left[\omega t - \dfrac{2\pi(z_i-1)}{Z}\right] + A\sin(f_x t + \phi_x) \\ y_i = r\cos\left[\omega t - \dfrac{2\pi(z_i-1)}{Z}\right] + B\sin\left(f_y t + \phi_y\right) \end{cases} \begin{pmatrix} CFVA & milling: A=0, B\neq0 \\ FVA & milling: A\neq0, B=0 \\ 2DVA & milling: A\neq0, B\neq0 \end{pmatrix} \tag{3}$$

Appropriate pattern of tool-workpiece separation (TWS) is the key to the success of VAM [34]. By definition, the separation we discuss in VAM is the rapid periodic interruption of constant tool-work piece contact. There are three different mechanisms that lead to the separation phenomenon, and each will be described below.
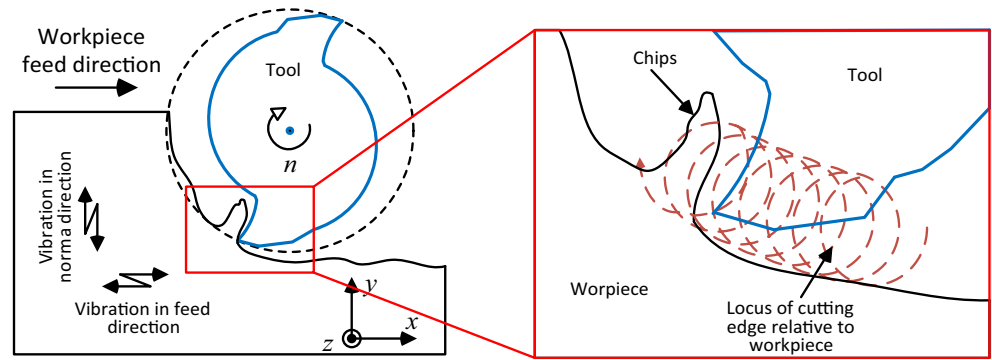
3 Tool-workpiece separation in vibration-assisted milling

3.1 Type I TWS

Figure 2 illustrates type I TWS in vibration-assisted milling. Type I separation occurs in the current tool path when the cutting direction component (i.e., tangential component) of the relative velocity between tool and workpiece is opposite to the tool rotation direction, resulting in the tool tip lagging behind the workpiece so that TWS occurs.

In position 1 of Fig. 2, the cutting direction component of the relative velocity between tool and workpiece is greater than zero, and the tool is in contact with the workpiece. When the tool advances to position 2, the cutting direction component of the relative velocity is equal to zero and it is

Fig. 1 A schematic diagram of VAMilling

about to break contact with the workpiece. In position 3, the cutting direction component of the relative velocity is negative, i.e., in the opposite direction to the tool rotation, and the tool separates from the workpiece. It can be seen that during the period when the tool and workpiece lose contact, the cutting direction component of relative velocity changes from zero to negative and back to positive. In position 4, the tool regains contact with the workpiece.

3.2 Type II TWS

Figure 3 illustrates type II TWS in vibration-assisted milling. Type II separation occurs in the current tool path, where vibration displacement in the instantaneous cutting thickness direction (i.e., tool radial direction) is larger than the instantaneous uncut chip thickness. This results in the tool cutting out of the workpiece so that tool-workpiece separation takes place.

In position 1 of Fig. 3, the vibration displacement in the tool radial direction is smaller than the instantaneous uncut chip thickness, so the tool is in contact with the workpiece. When the tool advances to position 2 where the vibration displacement in the tool radial direction is same as the instantaneous uncut chip thickness, and it is about to break contact

with the workpiece. In position 3, the vibration displacement exceeds the instantaneous uncut chip thickness, and the tool completely separates from the workpiece. When the vibration displacement is equal to the instantaneous uncut chip thickness in position 4, the tool regains contact with the workpiece.

3.3 Type III TWS

Contrary to vibration-assisted turning in which the influence of workpiece geometry can be ignored, the complex tool tip trajectories in vibration-assisted milling can result in a rather rugged surface, which in turn affects the cutting process. Figure 4 illustrates this effect and type III TWS in vibration-assisted milling. It can be seen that the current tool path with vibration assistance overlaps in some regions with the surface contour left by previous cutting path(s), so in these overlapping regions the cutting tool edge may break contact with the workpiece and discontinuous chips are generated. As part of the material in the current cutting path has been removed by previous cuts, periodical separation of tool-workpiece separation can take place.

It should be noted that in most cases during VAMilling, type I, II, and III separations could happen simultaneously. Tool-workpiece separation conditions are detailed in [35].
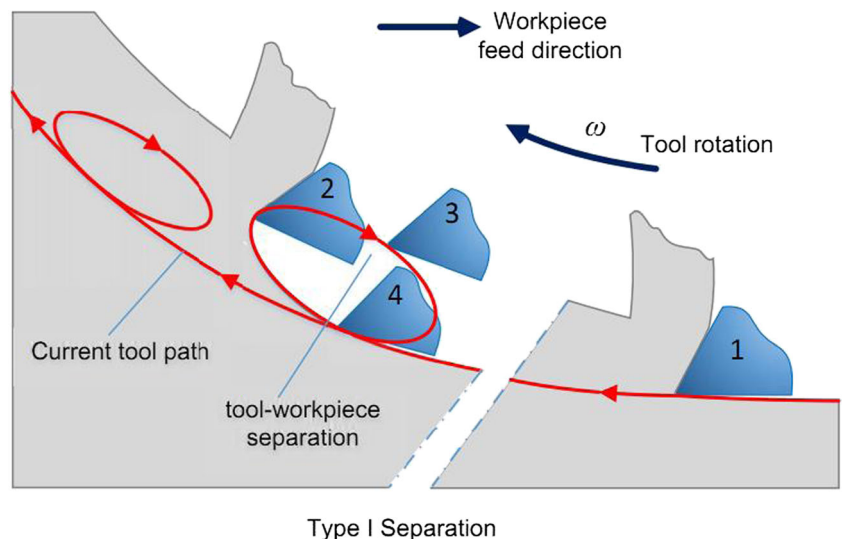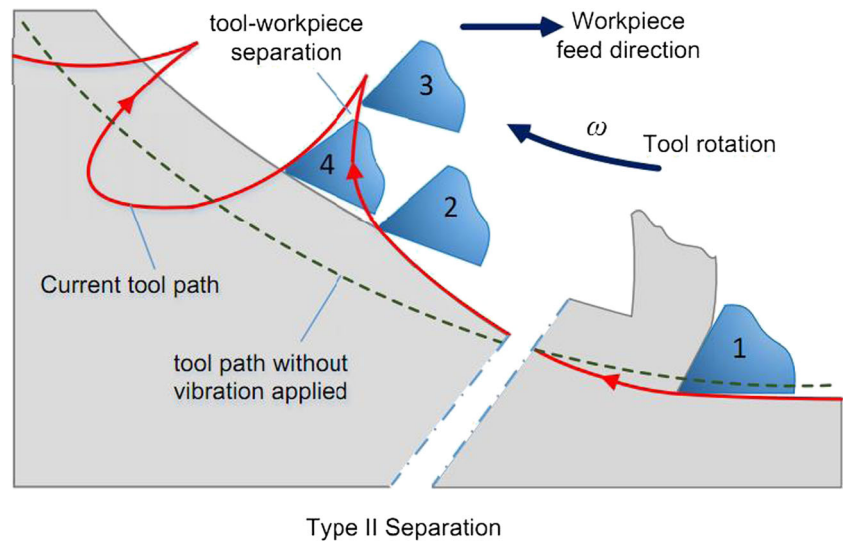
Fig. 2 Type I TWS during VAMilling process

Type I Separation

Fig. 3 Type II TWS during
VAMilling process

tool-workpiece
separation

Workpiece
feed direction

ω Tool rotation

Current tool path

tool path without
vibration applied

Type II Separation

4 Actuation methods in VAM

Archiving high frequency vibration is the key in realizing VAM. A brief review will be given regarding the various actuation methods that have been applied since the 1960s when the concept was first introduced. Some of the systems discussed in this section were developed for vibration-assisted turning, but in principle, these methods can be adopted for vibration-assisted milling.

4.1 Electromagnetic shaker

Sakaguchi et al. [36] developed the first prototype electromagnetic shaker to introduce vibration assistance in machining. The method was implemented in a grinding spindle, see Fig. 5, to excite the spindle magnetically as the current flow direction reverses rapidly in the coils (labeled as no. 5 in
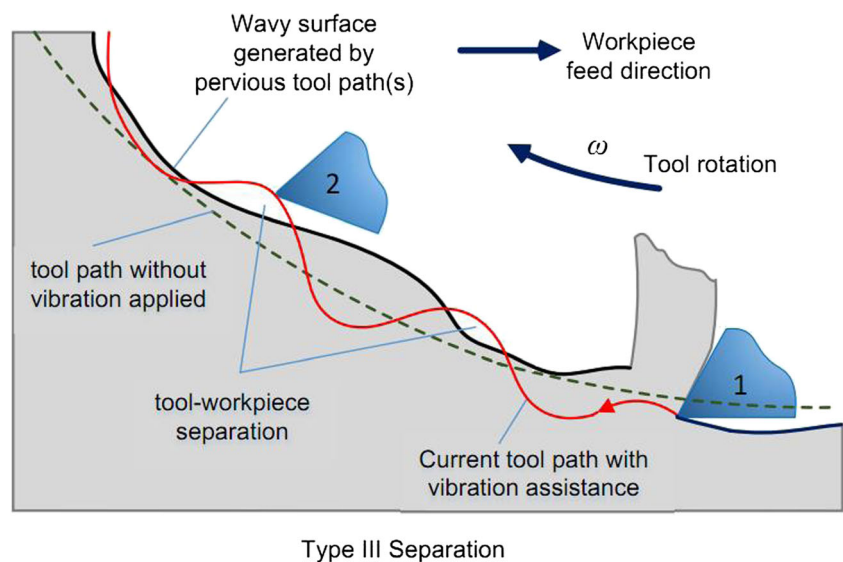
Fig. 5), thus achieving the longitudinal vibration at the grind (labeled as no. 1). This method could offer a vibration with frequency ranging from 20 to 200 Hz and an amplitude of up to 10 mm, at the cost of considerable power consumption (200 V, 17 kVA). The main drawbacks of such method include the following: the bulky size of the actuation apparatus which limits the vibration to be 1D longitudinal; the internal and external cooling required by the huge amount of heat generated during the process; and the fact that the vibration neutral point is prone to drift. Therefore, this type of actuation method is rarely used at present.

4.2 Magneto-strictive actuator

When it comes to meeting the requirement of ultrasonic vibrations (20 kHz or more), the most common methods are to utilize either piezoelectric actuators or magneto-strictive

Fig. 4 Type III TWS during
VAMilling process

Wavy surface
generated by
pervious tool path(s)

Workpiece
feed direction

ω Tool rotation

tool path without
vibration applied

tool-workpiece
separation

Current tool path with
vibration assistance

Type III Separation

Fig. 5 Section view of the design of a VAGrinding tool which utilizes an electromagnetic shaker as the source of vibration [36]
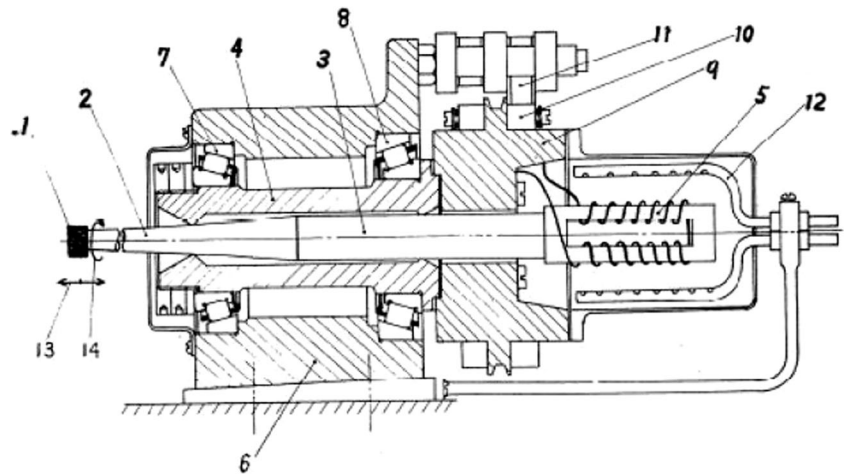
actuators, both of which can achieve ultra-high frequencies by utilizing the piezoelectric property or magneto-strictive property of the material to convert the input signal into mechanical output. Xiang et al. [37] developed a system as shown in Fig. 6 which combined the milling process with 35 kHz and 15 μm longitudinal vibration generated by a magneto-strictive actuator, and when milling SiCp/Al composites reduction in both cutting forces and crack growth were reported. However, the working principle of magneto-strictive actuation is that the input voltage signal must be first transduced into the intensity of magnetic field, and then through magneto-strictive effect to become mechanical output. The additional link in the chain of power transmission results in additional loss of energy,

therefore the performance is less desirable in regard of block force, maximum displacement, and no-load velocity when compared to PMN- or PZT-based piezoelectric actuators [38].

4.3 Piezoelectric actuator

Piezoelectric actuators on the other hand, thanks to its superior features such as high energy efficiency, high precision, fast response, low friction and wear, as well as the compact size, have received an ever-increasing interest in most ultrasonic frequency applications, as well as at lower frequencies. There are two basic working modes of a piezo-actuation system, namely resonant mode and non-resonant mode.

Fig. 6 Schematic design of a vertical VAMilling, in which the coded vibration is generated by a magneto-strictive actuator [37]
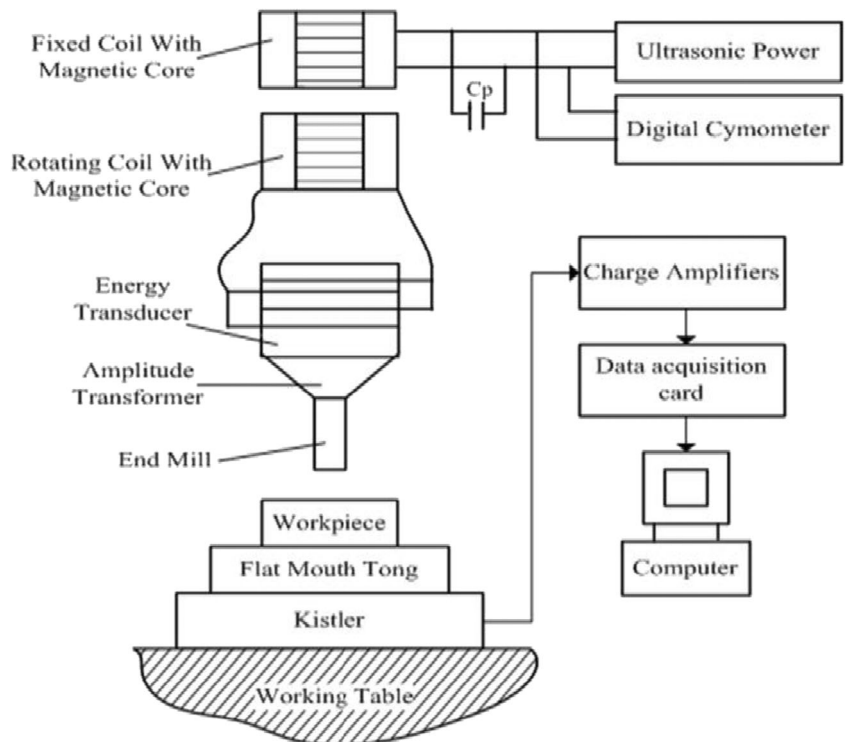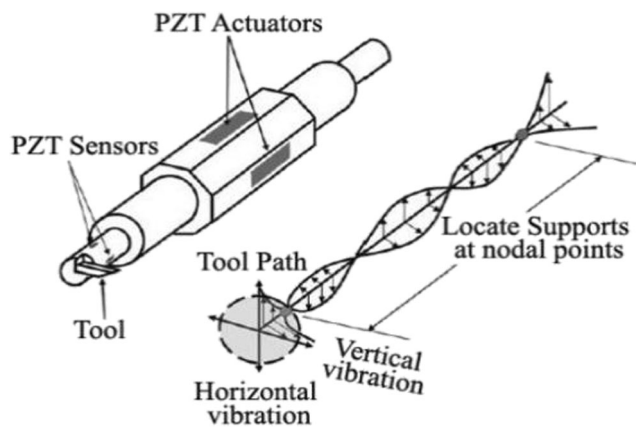
Fig. 7 A vibration-assisted lathe which utilized four PZT actuators to the turning tool, with 180° phase difference between each pair, causing 20 kHz (3rd grade resonant frequency) elliptical vibration at the turning tool [40]

4.3.1 Resonant mode

Resonant mode is where the piezo stack stretches and pulls back at a frequency close to the structure's resonance, so that a significantly large displacement can be obtained at high efficiency. In this mode, the losses of energy in electromechanical conversion and self-heating are quite low, and the vibration frequency can reach as high as several tens of kilohertz with the amplitudes ranging from several to several hundred microns. Numerous research groups have successfully developed resonant-mode vibration-assisted machining devices using piezoelectric actuators. Shamoto et al. [39, 40] developed a vibration-assisted device which utilized four PZT actuators on the turning tool, with 180° phase difference between each pair, causing 20 kHz (3rd resonant frequency) elliptical vibration at the turning tool, see Fig. 7.

Ko et al. [41], Razfar et al. and Zarchi et al. [42, 43] investigated the effect of cutting parameters on the machined surface. The cutting forces and the tool wear were measured on a similarl -designed system where 20–38.8 kHz 1D longitudinal

vibration is introduced to a horn and a "sandwich" transducer attached to the workpiece holder. The configuration of the modified tool holder is shown in Fig. 8. Attempts to apply 18 kHz vibration to the milling tool by modifying the spindle was made by Ostasevicius et al. [44], where the vibration milling tool was mounted on a standard Weldon holder. The configuration of the experimental setup is illustrated in Fig. 9.

In addition, Shen et al. [45], Zahedi et al. [46], Xing et al. [47], and Zhang et al. [48] also conducted similar experiments, i.e., attaching piezoelectric actuators to a specially designed horn, the structure of which shares the natural frequency by the piezoelectric actuator, to achieve ultrasonic vibration that aids the machining process.

Wang [49] designed a longitudinal-torsional compound vibration device. Ultrasonic longitudinal-torsional compound vibration is composed of vibration in the axial direction and in the tangential direction. Figure 10 showed a schematic of the device that converts longitudinal vibrations into longitudinal-torsional compound vibrations. The device on the left is the longitudinal vibration transducer, in the horn output connected with a chute of the transmission rod. Longitudinal vibration transmitted to the chute produces a torsional vibration component, to realize longitudinal and torsional vibration.

The principle of piezoelectric actuator driven resonant mode vibration devices limits their application to fixed high frequency use only. Due to this actuation method being based on the principle of resonance design, its performance relies greatly on the structural parameters. In addition, power dissipation and heating of piezoelectric ceramics working at high frequency and large amplitude are also major factors restricting their performance.

4.3.2 Non-resonant mode

The non-resonant mode is usually used for 2D VAMilling in the feed and cross-feed directions. This is usually

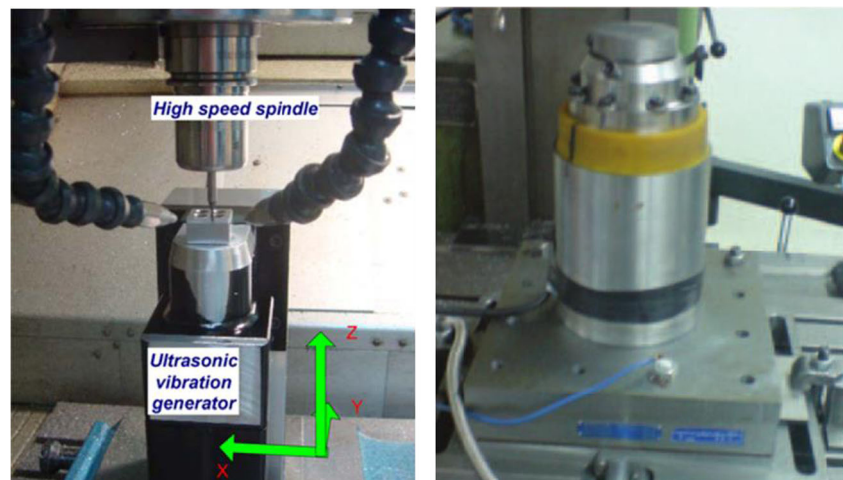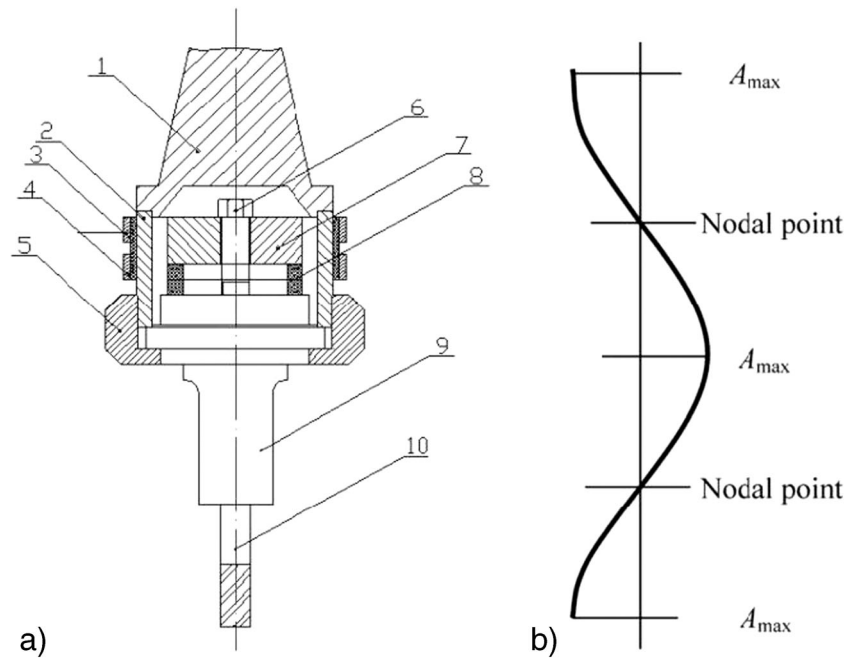**Fig. 8** Experimental setup of two VAM systems where the vibration is applied at the workpiece holder [42]

implemented by using a flexible mechanism driven by piezo-electric actuators. A non-resonant vibration system is not limited to a fixed operating frequency and offers a more precise motion control. It is however difficult to produce a high operating frequency because of various technical limitations. The piezo stacks oscillate under forced vibration rather than resonance, and the frequencies of the sinusoidal excitation voltage signals can range from near DC (50 Hz) up to several thousand hertz, typically just below the first resonant frequency of the system. The displacement is usually subject to the input voltage and could reach the level of tens of microns due to the larger piezoelectric coefficient and higher strain of the "soft" PZT material. Although in theory it could operate at up to its first resonant frequency, the achievable vibration frequency is often much lower, since force and stroke requirement cannot be obtained at maximum frequencies. In practice, precision positioning setups with closed loop feedback control are usually operated well below the natural frequencies of a piezo-mechanical system to avoid feedback problems due to electro-mechanical phase shifting. In addition, when undergoing forced vibration, the piezo stack would suffer severe self-heating and cooling becomes a crucial problem. All piezo

ceramics possess ferroelectric property which only exists below its Currie temperature, and so cooling of piezo stacks operating at high power is crucial for their functioning.

Several two-dimensional vibration stages have been reported in the literature. Zhang et al. [50] developed a platform where piezoelectric actuators were used to generate different direction vibration to the table (Fig. 11a). The planar integrated structure has the characteristics of compact structure, zero clearance, and no mechanical friction. While, the piezoelectric actuators in X direction improved the moving mass of the vibration stage. Thus, the vibration frequency in Y direction is restricted, usually less than 1000 Hz.

An improved two-dimensional vibration stage was developed by Jin et al. [51] as shown in Fig. 11b. The piezoelectric actuators have been set beside of the hinge part, which transforms vibration to the workpiece access the face A and B of the flexible hinges. However, the structure only has one layer of flexible hinge around the platform. The piezoelectric actuator can generate the vibration to the vertical direction flexible hinges normally, but in the horizontal direction, the flexible hinge will be affected by the coupling stiffness, and the displacement of the platform will be uneven. Therefore, it is

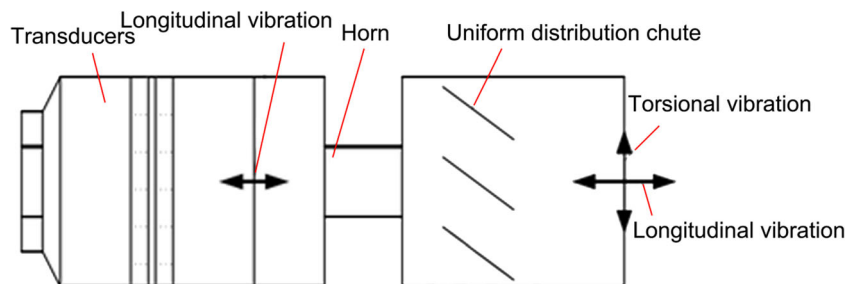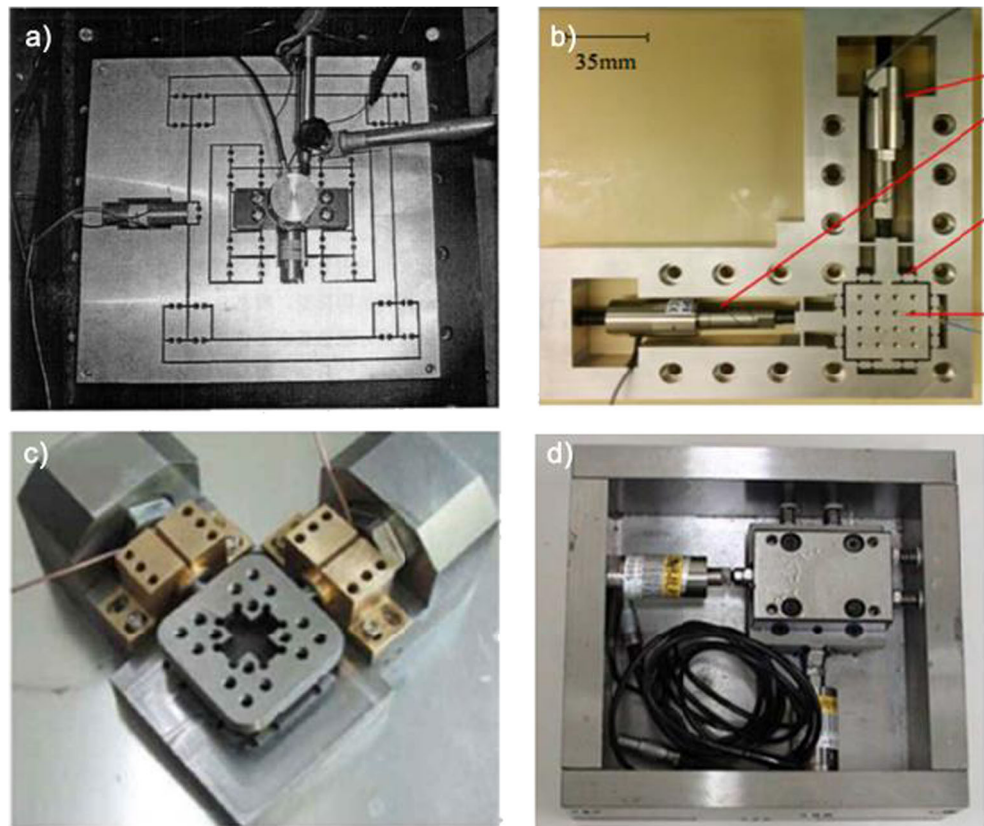Fig. 10 Longitudinal and torsional vibration device [49]

Fig. 11 Typical structure of the vibration stage. **a** Vibration stage proposed by Zhang et al. **b** Vibration stage proposed by Ji et al. **c** Vibration stage proposed by Li et al. **d** Vibration stage proposed by Chang et al.

difficult to control the displacement of the platform precisely. Li et al. [52] developed a two-dimensional vibration stage by using a single flexible four-bar mechanism as shown in Fig. 11c, but when the single flexible parallel four-bar mechanism vibrates at one direction, there will be a cross-coupling displacement in the another direction, which reduce the motion accuracy. Different to the typical two-dimensional vibration stages with flexible mechanism driven by piezoelectric actuators, a vibration worktable was designed by Chern et al. [53]. It is realized by employing piezoelectric actuators in conjunction with two slideways for generating the desired two-dimensional vibration as shown in Fig. 11d.

A novel structure of a two-dimensional vibration stage has been proposed by Chen et al. [54], as shown in Fig. 12. To reduce the displacement couple effect in the two moving directions, two-layer flexible hinges are adopted in the design. For each actuator direction, one pair of inner hinges and the opposite pair of outer hinges are flexible, and the other pairs are stiff, and vice versa for the other actuator. The outer and inner parts are combined with each other so that the vibration is transformed successfully, the 2D stage IS capable of independent vibration in the two directions, and 2 kHz vibration frequency with 10 μm vibration amplitude was achieved.

To improve high response frequency of 2D vibration stages, an active workpiece holder for the realization of vibration-assisted milling was developed as shown in Fig. 13. This stage enables highly dynamic horizontal vibration of a workpiece in two directions. It consists of a parallel

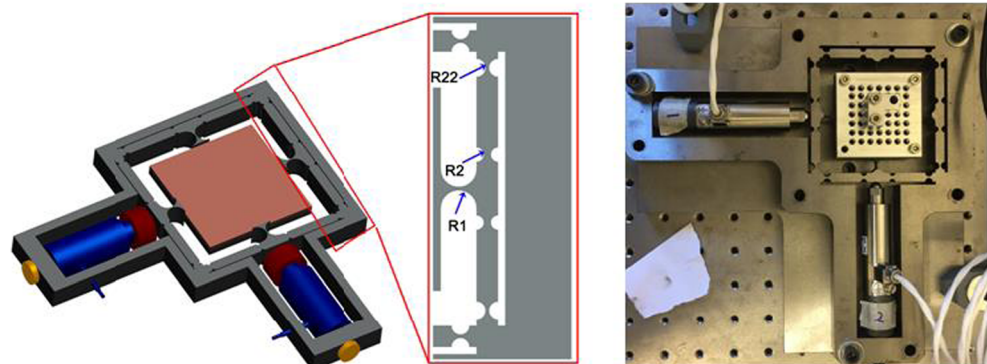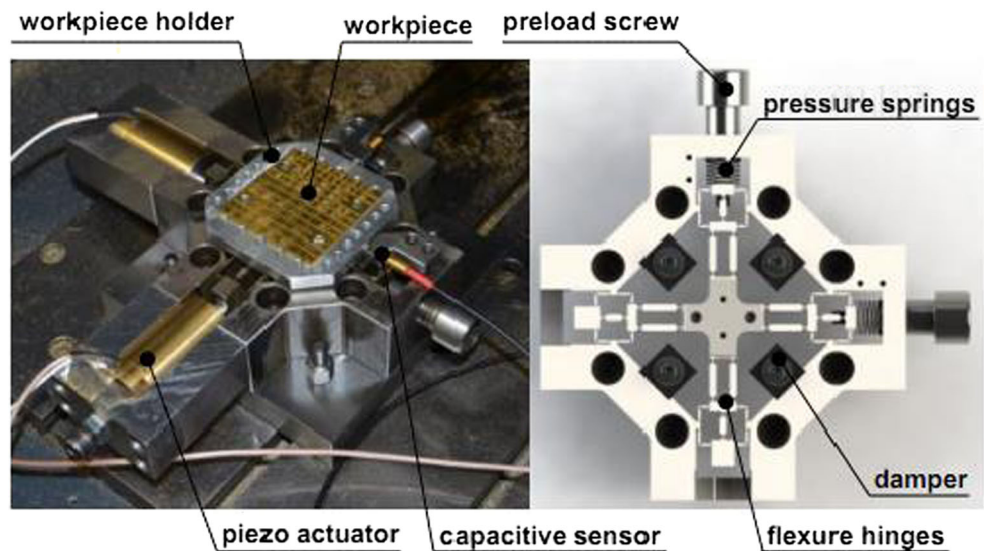**Fig. 12** A two-layer structure of vibration stage [54]

kinematic two DOF stage with flexure hinges, on which a workpiece holder is mounted. The flexure hinges are set into motion by two high voltage piezo actuators, and the system enables 2 DOF vibration-assisted milling up to 10 kHz with a maximum amplitude of 7.5 μm [55]. This actuation method has a simple structure and is easy to realize multi-dimensional vibration. However, the size of the piezoelectric actuators is long; hence, it requires large installation space. In addition, the amplitude and the frequency are limited mutually in this actuation method, making it difficult to obtain larger amplitudes at high frequency.

4.4 Mechanical actuation methods

According to Section 2.1, the relative two-dimensional vibration between the cutting tool and the workpiece is actually an elliptical motion. Therefore, instead of applying vibration on both directions at the same time, an alternative is to aim directly at the elliptic trajectory instead of trying to achieve

vibrations on two directions. Moriwak et al. [56] implemented this idea, by applying the double-spindle mechanism and using two separate sets of AC servo motors together with eccentric sleeves to generate an elliptical locus of the tool shank, as shown in Fig. 14.

The developed machine generates circular vibratory motion of the cutting tool mechanically by rotating an eccentric sleeve with a built-in motor as shown in Fig. 14. This mechanical vibrator consists of a unique double structure spindle system with a built-in motor for tool vibration and a servo motor for rotation of the tool spindle. The tool spindle is inserted within the eccentric sleeve and connected to the servo motor via a flexible coupling. By rotating the sleeve with the built-in motor, the tool spindle within the sleeve is vibrated mechanically to form a circular locus. The circular vibration can be added while the inside tool spindle is rotated. Both spindles can then be mechanically clamped individually. Consequently, the following four cutting modes can be realized by installing the mechanical vibrator into the spindle of

Fig. 14 Schematic design and experimental setup of a VAMilling system using the mechanical approach, a double-spindle design as the source of vibration [56]
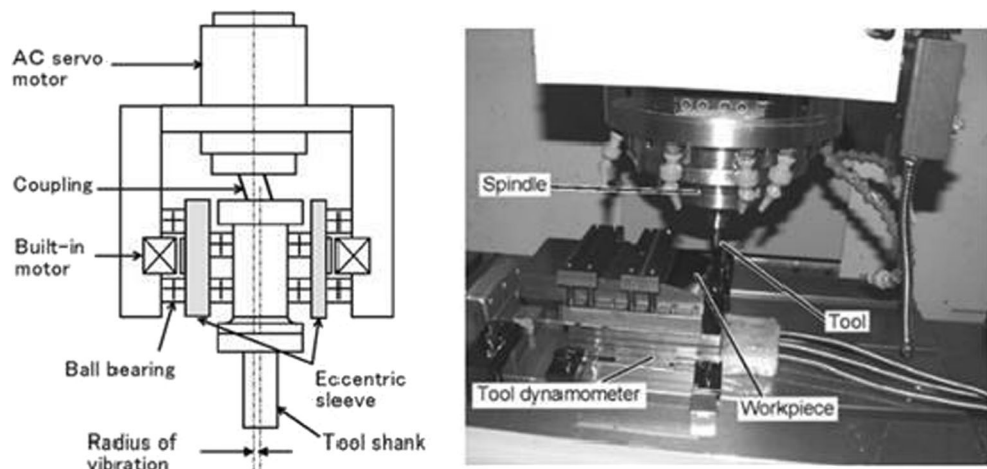
Table 1 Actuation methods of vibration in VAM

Source of vibration	Achievable frequency	Achievable amplitude	Applications	Limitations
Electromagnetic shaker	20~200 Hz	Up to 10 (mm)	Large load situations (frame planer, etc.)	Open loop, cooling, base point drifting
Magneto-strictive actuator	Ultrasonic	15 (μm)	Vertical and horizontal ultrasonic vibrations	Fixed frequency, low efficiency
Piezo-actuator (resonant)	Ultrasonic	0~20 (μm)	Vertical and horizontal ultrasonic vibrations	Fixed frequency, bulky size (horn)
Piezo-actuator (non-resonant)	0~10,000 Hz	0~20 (μm)	Vertical and horizontal non-ultrasonic vibrations	Relatively lower frequency. Cooling
AC servo motors	0~200 Hz	0~10 (μm)	Vertical planar vibration with fixed trajectory	Open loop, low frequency

an ordinary milling machine. The equivalent vibration frequency is 167 Hz at an amplitude of 4.4 μm. This approach can generate repetitive oscillation without piezoelectric actuators, and the vibration parameters can be altered subject to the rotational speed of the motor and the eccentricity of the sleeve. However, this method is limited to vertical machining centers only and it is limited to very low frequency.

4.5 Summary of actuation methods

A summary of the different actuation methods of the vibration stage is given in Table 1. It can be seen that the vibration devices driven by electromagnetic shaker, hydraulic servo valve, and AC servo motors cannot generate high frequency vibration. Magneto-strictive actuators and piezoelectric actuators can achieve ultrasonic vibration, which is used in one-dimensional vibration at resonant mode. The piezoelectric actuators are also used at non-resonant mode two-dimensional vibration stage with frequencies up to 10 kHz.

5 Application and benefits of VAMilling

Vibration-assisted milling has been applied to cutting various metals, including aluminum alloys [43, 57–59] and more difficult to machine metallic materials such as nickel-based super

alloys [60], stainless steel [47, 61–63], hardened tool steel [64–66], and other alloys [67, 68]. It has also been applied to glass [69] and composite materials [70–73]. Reported benefits include improving machining surface quality, tool life extension, and surface texture generation. This section summarizes these applications and the benefits obtained.

5.1 Surface improvement

5.1.1 Helical milling

Composite materials, titanium alloys, and ceramic aerospace materials have been widely used in aerospace structures because of their superior performance. In the structure assembly process, a large number of holes need to be machined and traditional machining processes do not easily meet the quality requirements. Recently, spiral milling technology was successfully applied to hole cutting of difficult to machine materials. In order to further improve the accuracy and efficiency of processing hard materials, ultrasonic vibration cutting technology has been applied in spiral milling hole by using longitudinal or longitudinal-torsional compound vibration milling methods [49].

In the helical milling process, the cutting tool moves in a spiral and mills holes that are larger than the tool diameter, as shown in Fig. 15 [74]. Ishida et al. [75]

Fig. 15 Kinematics of helical milling [74]

v_c : Cutting speed
a_p : Pitch per revolution
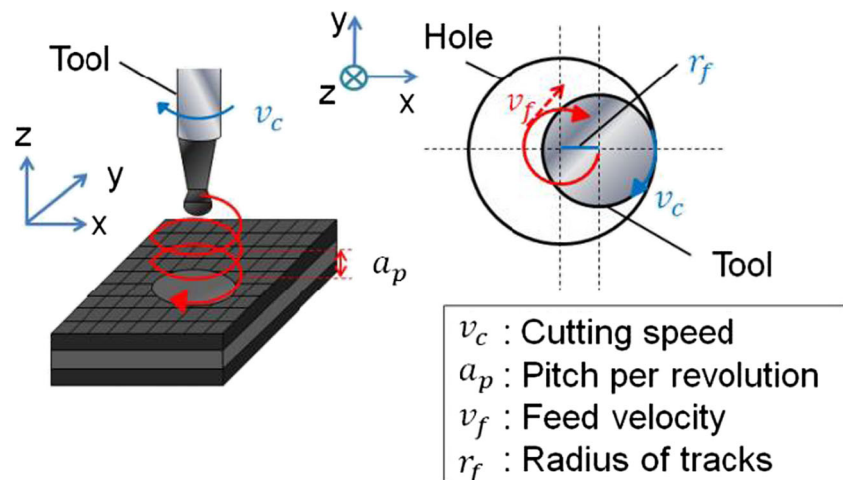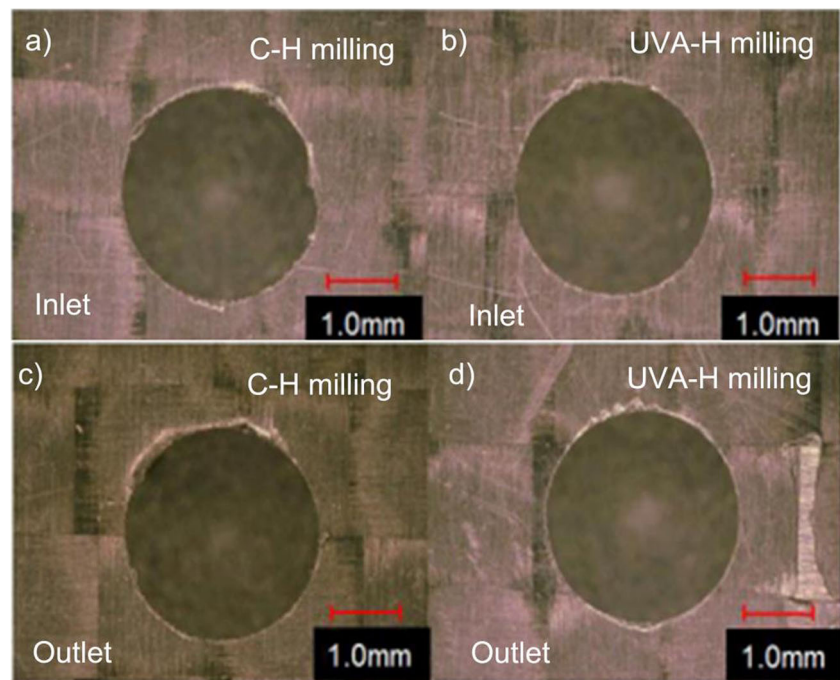v_f : Feed velocity
r_f : Radius of tracks

Fig. 16 Digital microscope image of delamination at the inlet and outlet of the conventional and ultrasonic assisted helical milling [75]

demonstrated helical milling of carbon fiber reinforced plastics using ultrasonic vibration with cryogenic tool cooling. High-precision holes were obtained at the inlet of the machined holes and the delamination size at the outlet was reduced as shown in Fig. 16. Zemann et al. [11] studied vibration-assisted milling on machining of carbon fiber reinforced polymers. It was shown that by optimizing the vibration characteristics of form, frequency, and amplitude, the fraying behavior could be improved. Bachrathy et al. [76] studied a one degree of freedom mechanical model of the milling process for helical mills, and found that for appropriate axial immersion parameters, if the cutting was stable the surface quality parameters will also be optimal, even in those spindle speed domains where the system was near to resonance which improved the cutting efficiency.

5.1.2 End milling

One of the characteristics of VAM is improvement of surface finish. But it should also be noted that the surface roughness of the workpiece machined with ultrasonic vibration-assisted machining is larger than that machined with conventional milling at certain spindle speeds, and the surface roughness increases with the increase of the ultrasonic vibration amplitude. Ko and Shaw [77] shown that inducing ultrasonic vibration during high-speed milling of small metal products can lead to smoother, higher quality surfaces. Kim and Choi [78] found the crest from the surface of 2D VAMilling (feed and cross-feed directions) has been eliminated by the alternating cycles phenomenon. From this, it is concluded that good surface is achieved by cutting the crests and peaks on the surface with the vibratory tool. Figure 17a shows the surface

Fig. 17 Effect of VAM in surface tool produced **a** without VAM, **b** with VAM [66]
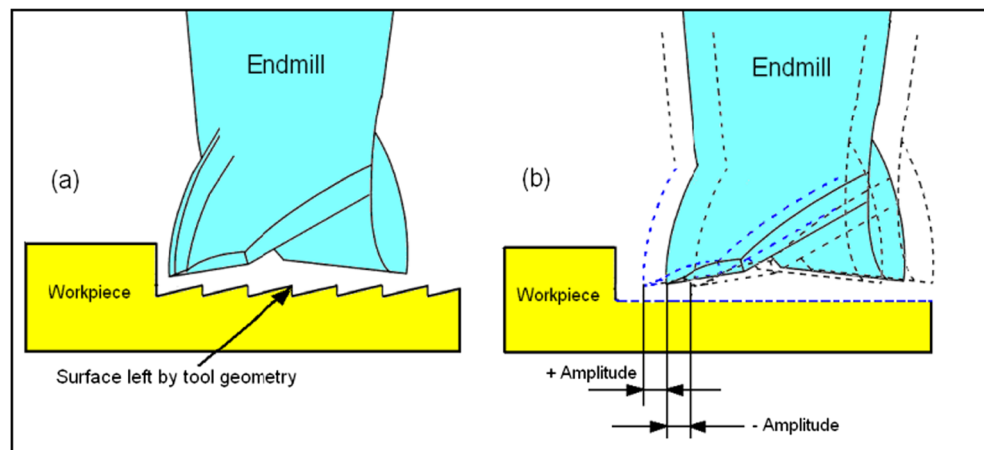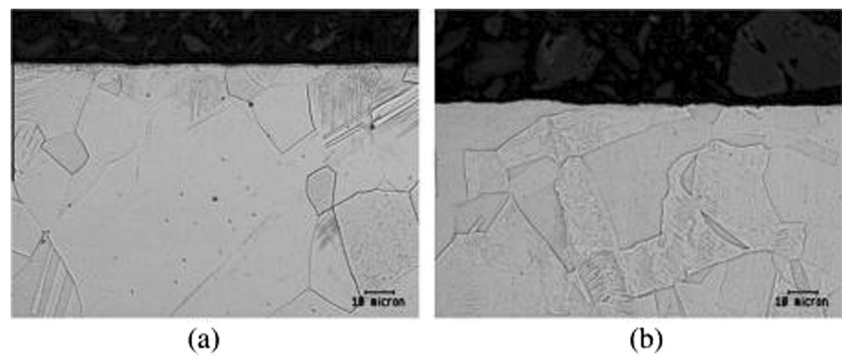
(a)　　　　　　　　　　(b)

generation by conventional milling, with peaks and valleys left by the cutter. In VAMilling, vibration makes the tool cutting point traverse the cut area from the preceding cycle and remove the material peaks and valleys left by it as shown in Fig. 17b. The higher the frequency of vibration, the more chance there is of the tool cutter reducing these peaks and valleys to obtain a good surface result [66]. Ko et al. [41] investigated the effect of ultrasonic vibration assistance in the axial direction of the tool. The machining experiments demonstrated that this method can improve the machined surface with reduction of chatter marks. Shen et al. [45] also showed that ultrasonic vibration in the feed direction has a positive effect on the surface roughness when the vibrating frequency is far higher than the gyro-frequency of the spindle.

Ko and his co-workers [79] found that the height of the remnant material, called "cusp," can be reduced by applying ultrasonic vibration during high-speed milling with narrow tool paths and removal depths of less than 1 mm, improving the quality of the milled surface considerably. For plastic metal machining with VAMilling, vibration assistance in the feed and cross-feed directions was carried out separately to understand the mechanism of directional effects for producing better machined surface quality. The machined surface quality measurement revealed that the effect was greater when feed-directional vibration was applied to the material than when the vibration was applied across or perpendicular to the feed, since the latter resulted in the formation of wavy burrs. The level of surface roughness is dependent on a combination of factors including feedrate and tool profile, in addition to vibration and tool speed, so in order to obtain better machined surface the vibration machining parameters should be

optimized [59, 80–82]. Ding et al. [83] found that feed per tooth has a significant effect on the height of the top burr, and the use of vibration-assisted cutting in micro end milling could minimize the size effect and improve the cutting performance, thereby reducing the height of the top burr by 80%. Tsai et al. [84] investigated the machining of hard mold steel by ultrasonic assisted end milling, and found that a positive rake angle and a large helix angle gave improved surface finish. Maurotto and Wickramarachchi [85] investigated the effects of frequency in ultrasonically assisted end milling on grain sizes of AISI 316L. They found that grain sizes appeared comparable with conventional milling and there was no sign of grain rotations, grain refinements, or strongly deformed areas indicative of significant machining abuse, as shown in Fig. 18. The hardness of the hardened subsurface layer (average 3.98 GPa) from vibration-assisted machining is 16% lower than that of conventional machining [86]. The control of burr formation in micro milling was investigated by Chen et al. [23]. They found that due to the vibration assistance in the feed direction, up milling and down milling take place periodically on both of the cutting-in and cutting-out sides. This results in a reduction of burr formation.

5.2 Tool life extension

Machining processes are inherently involved with tool wear, which is an influential factor in cutting forces, surface roughness, and machining costs. Vibration-assisted machining improves the milling cutter life when machining hard materials. The hardening effect, which influences material removal in terms of increasing the shear angle (reducing the shear plane

Fig. 19 Carp surface and SEM photo of the VAMilling surface [95]
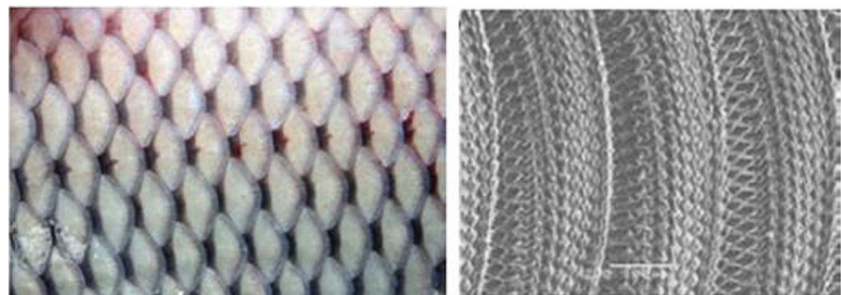
length) and consequently reducing tool contact length, is recognized as one of the main reasons to reduce the cutting force [87]. During the elliptical motion of tool tip in VAM, the average force is reduced and this reduced tool cutting force has also been shown to reduce chatter [88] on the surface produced.

Numerous researchers studied the tool wear in VAM [89–92]. At lower spindle speeds, due to lower cutting temperature, the dominant wear mechanism is abrasive wear. Because of mechanical and impact contacts between workpiece and flank surface in VAM, tool life is less than that in the conventional process. At higher cutting speed, temperature activated wear mechanisms including diffusion, chemical wear, and thermal wear occur. On the other hand, because of intermittent separation of workpiece and tool, the temperature in the cutting zone in VAM is lower than that in conventional process, which tends to increase tool life. Another reason for reduced temperature in VAM can be attributed to the change in friction coefficient from semi-static to dynamic [25, 92], which results in reduced friction coefficient in the VAM process and changes the chip formation mechanism. As cutting speed increases, there is an increase in the degree of tool-workpiece engagement per tool revolution. As a result, the effect of vibration on the milling process decreases and cutting forces in vibration-assisted milling and conventional milling processes become closer to each other. Gong et al. [93] found that the increase in vibration amplitude increases the rate of reduction of cutting forces in the ultrasonic assisted milling process compared with conventional milling process. However, Lucas et al. [94] studied ultrasonic cutting of three very different materials, and found that the coefficients of friction were significantly reduced by ultrasonic excitation but unaffected by ultrasonic amplitude.

**Fig. 20** Surface topography with vibration-assisted micro milling [55]
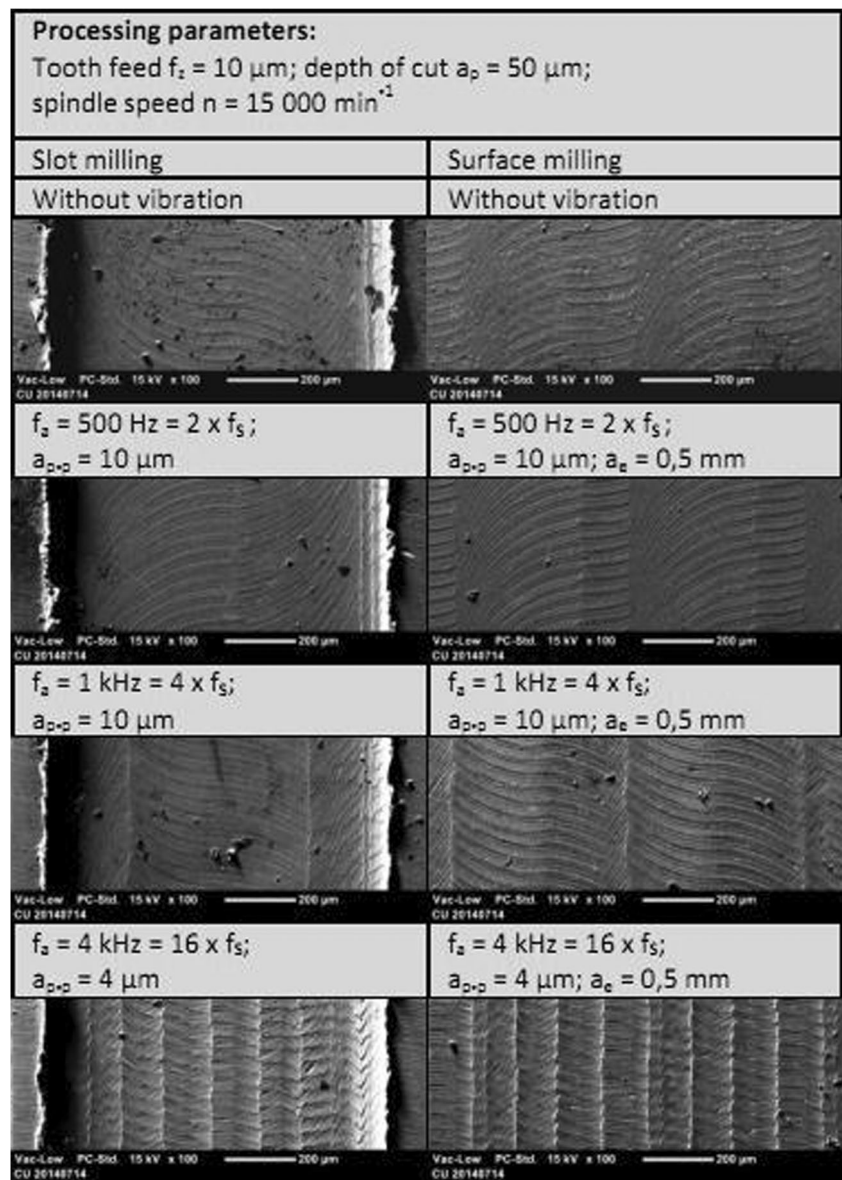
5.3 Surface texture generation

Engineered textured surfaces have the characteristics of regular texture structure and high aspect ratio, enabling the component surface to have certain specific functions, such as reducing adhesion friction, improving lubricity, increasing wear resistance, changing the hydrophilic performance, and enhancing optical properties. It was proved that VAMilling in either single direction or two directions can form certain surface textures [30, 31] depending on its defined cutting edge geometry and kinematics. There is an emerging trend to obtain biomimetic surface texture and certain surface performance through VAM. Tao et al. [95] produced the squamous surface by VAMilling as shown in Fig. 19. Uhlmann et al. [55] found that surface topography in the process of micro milling can be achieved by means of targeted high frequency vibration of a

Fig. 21 Wettability of the different topography: **a** no vibration; **b** 2 kHz; **c** 2.2 kHz; **d** 3.4 kHz [33]
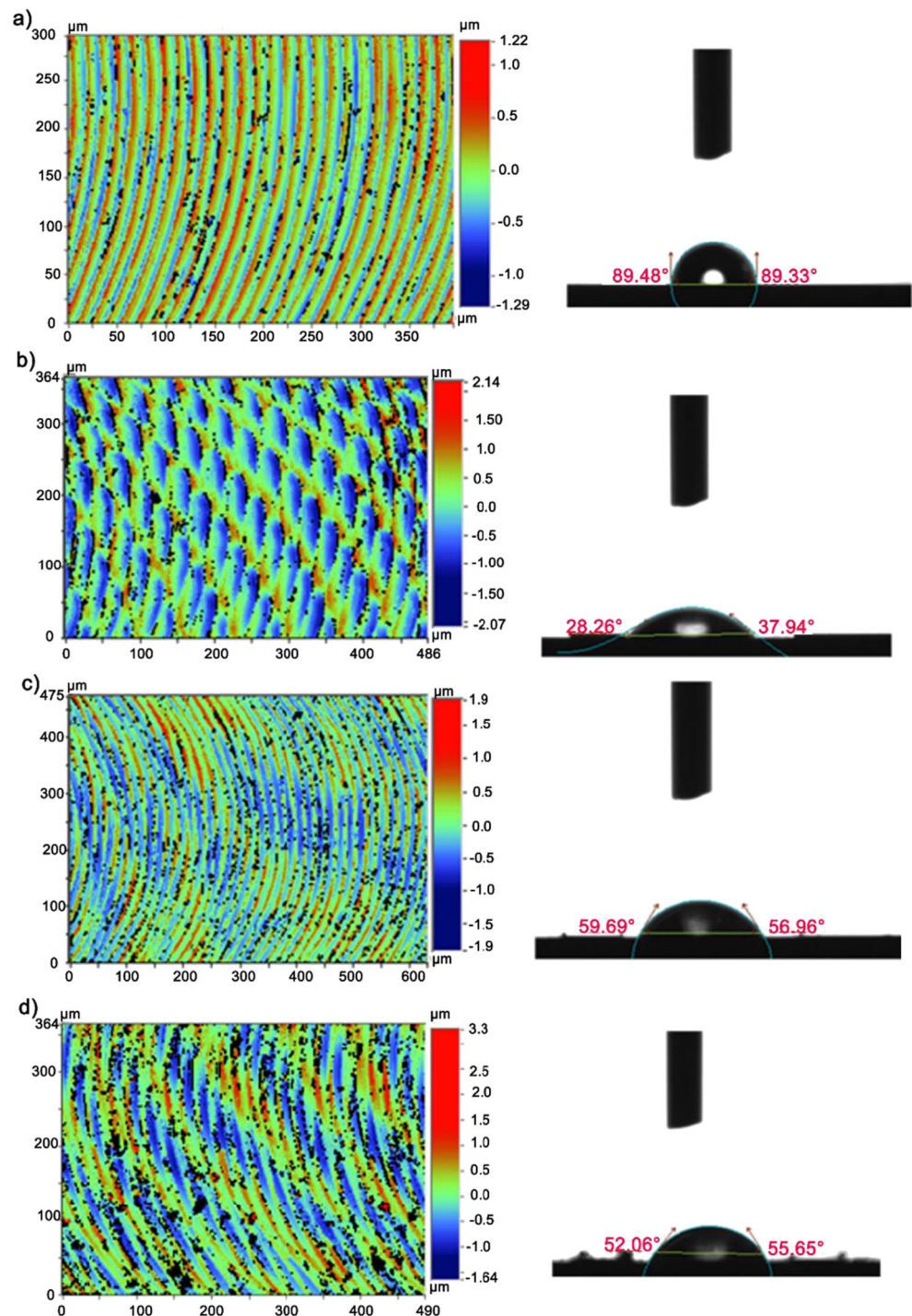
workpiece, and the different surface topographies were obtained with different vibration frequencies as shown in Fig. 20.

Xing [96] investigated the tribology properties of the surfaces generated by ultrasonic VAMilling. The results showed that in the breaking-in stage, compared with traditional milling surface, vibration machined surfaces reduced friction coefficient curve fluctuations and had better friction stability even with no obvious transition. In normal wearing stage, for a specific vibration amplitude, the surface roughness, load carrying capacity of oil film, and wear rate all had a significant improvement with the increase of the feed per tooth. Chen et al. [33] proposed a surface texture formation method by non-resonant vibration-assisted milling and studied the effects of the vibration and machining parameters on the surface texture generation, as shown in Fig. 21. They found that controllable wettability of the machined surface can be realized by combining different machining and vibration parameters. It is desirable to control the wettability of the machined surface, e.g., in microfluidic channels, since different regions need different wettability to control the flow rate and mixing efficiencies of different fluids. Conventional processing methods cannot achieve controllable wettability, while vibration-assisted milling provides a viable solution for such application.

6 Conclusion

As a non-traditional external energy assisted machining method, vibration-assisted machining has been applied successful in turning, grinding, drilling, and more recently milling operations. Recently, vibration-assisted milling has been attracting more attention from both academia and industry. This paper reviewed the latest developments and applications in vibration-assisted milling. Since cutting velocity and uncut chip thickness change continuously in the milling process, the trajectory of tool tip in vibration-assisted milling becomes more complex than other vibration-assisted machining operations. Some observations and future work are proposed as follows to unleash the potential of vibration-assisted milling.

1. Fundamental studies on the material removal mechanisms of vibration-assisted milling difficult-to-machine materials are limited. The machining physics and mechanics are unclear. Finite element simulation will be an effective way to investigate these issues.

2. To date, two-dimensional vibration-assisted milling studies have been limited to frequencies below 3 kHz, which is unsuitable for the micro milling process where high spindle rotational speeds are required to achieve even modest machining efficiency and the tooth passing frequency is typically above 1 kHz. Preliminary simulation shows that to achieve proper periodical tool/chip separation in one tooth/workpiece engagement cycle, vibration frequency should be an order of magnitude higher than the tooth passing frequency. Therefore, a higher vibration frequency above 20 kHz is required for micro milling. Development of a two-dimensional vibration stage with high vibration frequency is a challenge.

3. Compared with vibration-assisted turning processes, the vibration-assisted milling process is more complex. Tool tip trajectory, instantaneous uncut chip thickness, dynamic cutting forces, VAM duty cycle, micro tool wear, etc. are difficult to determine, so that accurate kinematic and dynamic models are needed to guide vibration-assisted milling.

4. Special milling tools for vibration-assisted machining should be designed to further enhance the machining performance and extend tool life.

5. Hybrid machining technology needs to be combined with vibration-assisted machining to reduce the process forces, allow very fine structures, increase process reliability, and extend tool life.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

1. Qin Y, Brockett A, Ma Y et al (2009) Micro-manufacturing: research, technology outcomes and development issues. Int J Adv Manuf Technol 47:821–837

2. Weule H, Hüntrup V, Tritschler H (2001) Micro-cutting of steel to meet new requirements in miniaturization. Ann CIRP 50(1):61–64

3. Liu X, DeVor RE, Kapoor SG, Ehmann KF (2004) The mechanics of machining at the microscale: assessment of the current state of the science. J Manuf Sci Eng, Trans ASME 126:666–678

4. Brinksmeier, E., Riemer, O. and Stern, R. (2001) Machining of precision parts and microstructures. Proceedings of the 10th International Conference on Precision Engineering (ICPE), Initiatives of Precision Engineering at the Beginning of a Millennium, Yokohama, Japan: S. 3–11

5. Debnath K et al (2014) Rotary mode ultrasonic drilling of glass fiber-reinforced epoxy laminates. J Compos Mater 49(8):949–963

6. Hitoshi O, Nakagawa T (1995) Analysis of mirror surface generation of hard and brittle materials by ELID (electronic in-process

dressing) grinding with superfine grain metallic bond wheels. CIRP Ann Manuf Technol 44(1):287–290

7. Sakamoto, Satoshi, et al. Fundamental micro-grooving characteristics of hard and brittle materials with a fine wire tool. Adv Mater Res (2016):1136

8. Cui, Ying, et al. Study on electroplating technology of diamond tools for machining hard and brittle materials. *Eighth International Symposium on Advanced Optical Manufacturing and Testing Technology (AOMATT2016)*. International Society for Optics and Photo-Dermatology, 2016

9. Zhang X et al (2013) A model to predict the critical undeformed chip thickness in vibration-assisted machining of brittle materials. Int J Mach Tools Manuf 69:57–66

10. Chae J, Park SS, Freiheit T (2006) Investigation of micro-cutting operations. Int J Mach Tools Manuf 46(3–4):313–332

11. Zemann R, Kain L, Bleicher F (2014) Vibration assisted machining of carbon fibre reinforced polymers. Proc Eng 69:536–543

12. Sarkar, B. R., B. Doloi, and B. Bhattacharyya. Electrochemical discharge micro-machining of engineering materials. Non-traditional Micromachining Processes Springer International Publishing, 2017. 367–392

13. Manjaiah M, Narendranath S, Basavarajappa S (2014) Review on non-conventional machining of shape memory alloys. Trans Nonferrous Metals Soc China 24(1):12–21

14. Agarwal N et al (2015) Investigation of material removal method in EDM for non-conductive materials. Eur J Adv Eng Technol 2(4): 11–13

15. Guénolé J, Prakash A, Bitzek E (2017) Atomistic simulations of focused ion beam machining of strained silicon. Appl Surf Sci 416: 86–95

16. Parandoush P, Hossain A (2014) A review of modeling and simulation of laser beam machining. Int J Mach Tools Manuf 85:135–145

17. Cheng K, Huo D, ed. (2013) Micro-cutting: fundamentals and applications. Wiley

18. Rahman M, Senthil Kumar A, Prakash JRS (2001) Micro milling of pure copper. J Mater Process Technol 116(1):39–43

19. Suzuki H et al (2007) Precision cutting of aspherical ceramic molds with micro PCD milling tool. CIRP Ann Manuf Technol 56:131–134

20. Uhlmann E, Piltz S, Schauer K (2005) Micro milling of sintered tungsten–copper composite materials. J Mater Process Technol 167(2):402–407

21. Friedrich CR, Coane PJ, Vasile MJ (1997) Micromilling development and applications for microfabrication. Microelectron Eng 35(1–4):367–372

22. Mohammadi MM (2011) A review on micro fabrication methods to produce investment patterns of microcasting[J]. J Nat Sci Res 1(2): 5–13

23. Wanqun Chen, Xiangyu Teng, Lu Zheng, et al. (2018) Burr reduction mechanism in vibration-assisted micro milling, Manufacturing letter,in press

24. Zhou M, Eow Y, Ngoi B, Lim E (2003) Vibration-assisted precision machining of steel with PCD tools. Mater Manuf Process 18:825–834

25. Amini S et al (2017) Effect of longitudinal−torsional vibration in ultrasonic-assisted drilling. Mater Manuf Process 32(6):616–622

26. Li C et al (2017) Material removal mechanism and grinding force modelling of ultrasonic vibration assisted grinding for SiC ceramics. Ceram Int 43(3):2981–2993

27. Weremczuk A, Rusinek R, Warminski J (2015) The concept of active elimination of vibrations in milling process. Proc CIRP 31: 82–87

28. Moriwaki T, Shamoto E (1991) Ultraprecision turning of stainless steel by applying ultrasonic vibration. Ann CIRP 40:559–562

29. Shamoto E, Suzuki N, Naoi Y (2002) Development of ultrasonic elliptical vibration controller for elliptical vibration cutting. Ann CIRP 51:327–330

30. Xiao M, Sato K, Karube S, Soutome T (2003) The effect of tool nose radius in ultrasonic vibration cutting of hard metal. Int J Mach Tools Manuf 43:1375–1382

31. Shamoto E, Moriwaki T (1999) Ultraprecision diamond cutting of hardened steel by applying elliptical vibration cutting. Ann CIRP 48:441–444

32. Liu K, Li XP, Rahman M, Liu XD (2004) Study of ductile mode cutting in grooving of tungsten carbide with and without ultrasonic vibration assistance. Int J Adv Manuf Technol 24:389–394

33. Chen W, Zheng L, Huo D, Chen Y (2018) Surface texture formation by non-resonant vibration assisted micro milling. J Micromech Microeng 28(2):025006

34. Abootorabi Z, Mohammad M, Mohammad RR et al (2017) Research on the importance of tool workpiece separation in ultrasonic vibration assisted milling. Proc IMechE Part B: J Eng Manuf 226(7):1185–1191

35. Chen, Wanqun, et al. 2018 Kinematics and tool-workpiece separation analysis of vibration assisted milling. Int J Mech Sci, 136:169–178

36. Katsumi S, Junichiro K (1975) Impact properties of the ultrasonic vibrating grinding wheel. J Japan Soc Precis Eng 41(485):559–564

37. Xiang, D., et al. (2011) Study on cutting force and tool wear of high volume SiC/Al MMCs with ultrasonic vibration high speed milling. *Key Engineering Materials*. Vol. 455. Trans Tech Publications,

38. John S, Sirohi J, Wang G, Wereley NM (2007) Comparison of piezoelectric, magnetostrictive, and electrostrictive hybrid hydraulic actuators. J Intell Mater Syst Struct 18(10):1035–1048

39. Shamoto E, Suzuki N, Moriwaki T, Naoi Y (2002) Development of ultrasonic elliptical vibration controller for elliptical vibration cutting. CIRP Ann Manuf Technol 51(1):327–330

40. Shamoto E, Suzuki N, Tsuchiya E, Hori Y, Inagaki H, Yoshino K (2005) Development of 3 DOF ultrasonic vibration tool for elliptical vibration cutting of sculptured surfaces. CIRP Ann Manuf Technol 54(1):321–324

41. Ko JH, Tan SW (2013) Chatter marks reduction in meso-scale milling through ultrasonic vibration assistance parallel to tooling's axis. Int J Precis Eng Manuf 14(1):17–22

42. Razfar MR, Sarvi P, Zarchi MMA (2011) Experimental investigation of the surface roughness in ultrasonic-assisted milling. Proc Inst Mech Eng B J Eng Manuf 225(9):1615–1620

43. Zarchi A, Mohammad M, Razfar MR, Abdullah A (2012) Investigation of the effect of cutting speed and vibration amplitude on cutting forces in ultrasonic-assisted milling. Proc Inst Mech Eng B J Eng Manuf 226(7):1185–1191

44. Ostasevicius V et al (2013) Study of vibration milling for improving surface finish of difficult-to-cut materials. J Mech Eng 59(6):351

45. Shen X-H et al (2011) A study of surface roughness variation in ultrasonic vibration-assisted milling. Int J Adv Manuf Technol 58(5–8):553–561

46. Zahedi SA, Roy A, Silberschmidt VV (2013) Vibration-assisted machining of single crystal. J Phys Conf Ser 451:012038

47. Xing D, Zhang J, Shen X, Zhao Y, Wang T (2013) Tribological properties of ultrasonic vibration assisted milling aluminium alloy surfaces. Procedia CIRP 6:539–544

48. Zhang C et al (2013) Rotary ultrasonic machining of optical K9 glass using compressed air as coolant: a feasibility study. Proc Inst Mech Eng B J Eng Manuf 228(4):504–514

49. Wang PC. 2014 Research on devices in ultrasonic longitudinal-torsional vibration helical milling [D]. Harbin Institute of Technology School of Mechatronics Engineering Master Theses

50. Zhang J, Sun B (2006) Design and analysis of 2-DOF nanopositioning stage based on dual flexure hinges. China Acad J Elect Publ House 5(28)

51. Jin X, Xie B (2015) Experimental study on surface generation in vibration-assisted micro-milling of glass[J]. Int J Adv Manuf Technol 81(1–4):507–512

52. Li G. 2012 Non-resonant vibration auxiliary table development and study on micro-milling technology experiment[D]. Harbin institute of technology

53. Chern GL, Chang YC (2006) Using two-dimensional vibration cutting for micro-milling[J]. Int J Mach Tools Manuf 46(6):659–666

54. Wanqun Chen, Dehong Huo, Lu Zheng, et al. 2017 Design, analysis and testing a high bandwidth XY stage for vibration-assisted milling, Proceedings of the 17th euspen International Conference, Hannove, Germany

55. E. Uhlmann, I. Perfilov, D. Oberschmid. 2015 Two-axis vibration system for targeted influencing of micro-milling. euspen's 15th International Conference & Exhibition, Leuven, Belgium

56. Moriwaki T, Shamoto E, Song YC, Kohda S (2004) Development of a elliptical vibration milling machine. CIRP Ann Manuf Technol 53(1):341–344

57. Shen XH, Zhang JH, Li H, Wang JJ, Wang XC (2012) Ultrasonic vibration-assisted milling of aluminum alloy[J]. Int J Adv Manuf Technol 63(1–4):41–49

58. Ding H, Chen SH, Cheng K (2011) Dynamic surface generation modeling of two-dimensional vibration-assisted micro-end-milling. Int J Adv Manuf Technol 53:1075–1079

59. Lian H, Guo Z, Huang Z, Tang Y, Song J (2013) Experimental research of Al6061 on ultrasonic vibration assisted micro-milling[J]. Procedia CIRP 6:561–564

60. Hsu C, Huang C, Wu C (2007) Milling of MAR-M247 nickel-based superalloy with high temperature and ultrasonic aiding. Int J Adv Manuf Technol 34(9–10):857–866

61. Zarchi MA, Razfar M, Abdullah A (2013) Influence of ultrasonic vibrations on side milling of AISI 420 stainless steel. Int J Adv Manuf Technol 66(1–4):83–89

62. Janghorbanian J, Razfar MR, Zarchi MMA (2013) Effect of cutting speed on tool life in ultrasonic-assisted milling process. Proc Inst Mech Eng B J Eng Manuf 227(8):1157–1164

63. Feucht F, Ketelaer J, Wolff A, Mori M, Fujishima M (2014) Latest machining technologies of hard-to-cut materials by ultrasonic machine tool[J]. Procedia CIRP 14:148–152

64. Hettiarachchi, Nandita, et al. Development of a circular vibration milling attachment and its application to machining of hardened steel. Int J Manuf Res 1.3 (2006): 300–313

65. Ding H, Ibrahim R, Cheng K, Chen S-J (2010) Experimental study on machinability improvement of hardened tool steel using two-dimensional vibration-assisted micro-end-milling. Int J Mach Tools Manuf 50(12):1115–1118

66. Ibrahim, Rasidi. 2010 Vibration assisted machining: modelling, simulation, optimization, control and applications. Diss. Brunel University School of Engineering and Design PhD Theses

67. Ostasevicius V, Gaidys R, Dauksevicius R et al (2013) Study of vibration milling for improving surface finish of difficult-to-cut materials[J]. Stroj Vestnik J Mech Eng 59(6):351–357

68. Aspinwall DK, Kasuga Y, Mantle AL (2001) The use of ultrasonic machining for the production of holes in γ-TiAl. Proc ISEM XIII: 925–937

69. Jin X, Xie B (2015) Experimental study on surface generation in vibration-assisted micro-milling of glass[J]. Int J Adv Manuf Technol 81(1–6):507–512

70. Teti R (2002) Machining of composite materials. Ann CIRP 51(2): 611–634

71. Alam K, Mitrofanov AV, Silberschmidt VV (2011) Experimental investigations of forces and torque in conventional and ultrasonically-assisted drilling of cortical bone. Med Eng Phys 33(2):234–239

72. Uhlmann E, Protz F, Stawiszynski B, Heidler S (2017) Ultrasonic assisted milling of reinforced plastics. Procedia CIRP 66:164–168

73. M'Saoubi R et al (2015) High performance cutting of advanced aerospace alloys and composite materials. CIRP Ann Manuf Technol 64(2):557–580

74. Li, Zhang Dong, (2014) et al. Study of carbon/carbon composite material surface morphology on ultrasonic vibration assisted milling. Key Engineering Materials. Vol. 579. Trans tech publications

75. Ishida T, Noma K, Kakinuma Y, Aoyama T, Hamada S, Ogawa H, Higaino T (2014) Helical milling of carbon fiber reinforced plastics using ultrasonic vibration and liquid nitrogen[J]. Procedia CIRP 24: 13–18

76. Bachrathy, Daniel, Jokin Munoa, and Gabor Stepan. Experimental validation of appropriate axial immersions for helical mills. Int J Adv Manuf Technol 84.5–8 (2016): 1295–1302

77. http://phys.org/news/2011-09-vibration-assisted-milling-higher-quality-surfaces.html

78. Kim J, Choi H (1998) Characteristics of chip generation by ultrasonic vibration cutting with extremely low cutting velocity. Int J Adv Manuf Technol 14:2–6

79. Ko JH, Shaw KC, Chua HK, Lin RM (2011) Cusp error reduction under high speed micro/meso-scale milling with ultrasonic vibration assistance[J]. Int J Precis Eng Manuf 12(1):15–20

80. Chern GL, Liang JM (2007) Study on boring and drilling with vibration cutting[J]. Int J Mach Tools Manuf 47(1):133–140

81. Zhang C, Zhang J, Feng P (2013) Mathematical model for cutting force in rotary ultrasonic face milling of brittle materials[J]. Int J Adv Manuf Technol 69(1–4):161–170

82. Nath C, Rahman M (2008) Effect of machining parameters in ultrasonic vibration cutting. Int J Mach Tools Mf 48:965–974

83. Ding H, Chen SJ, Ibrahim R, Cheng K (2011) Investigation of the size effect on burr formation in two-dimensional vibration-assisted micro end milling[J]. Proc Inst Mech Eng B J Eng Manuf 225(11): 2032–2039

84. Tsai MY, Chang CT, Ho JK (2016) The machining of hard mold steel by ultrasonic assisted end milling. Appl Sci 611(6):373

85. Maurotto A, Wickramarachchi CT (2016) Experimental investigations on effects of frequency in ultrasonically-assisted end-milling of AISI 316L: a feasibility study. Ultrasonics 65:113–120

86. Patil, Sandip, Suhas Joshi, and Asim Tewari. Microstructural analysis of ultrasonic vibration assisted turning of Ti alloy Ti-6Al-4V. Proceedings of the 8th International Conference on MicroManufacturing

87. Brehl DE et al (2007) Machining forces for elliptical vibration-assisted machining. ASPE Proc, Vib Assist Mach Technol 71:76

88. Poudel, Anju.2015 Investigation on the chatter vibration and surface texture in vibration assisted micro-milling process. Diss. Oklahoma State University

89. Janghorbanian J, Razfar MR, Zarchi MMA (2013) Effect of cutting speed on tool life in ultrasonic-assisted milling process[J]. Proc Inst Mech Eng B J Eng Manuf 227(8):1157–1164

90. Churi NJ, Pei ZJ, Treadwell C (2007) Wheel wear mechanisms in rotary ultrasonic machining of titanium[C]//ASME 2007 International Mechanical Engineering Congress and Exposition. Am Soc Mech Eng:399–407

91. Pei ZJ, Ferreira PM (1999) An experimental investigation of rotary ultrasonic face milling[J]. Int J Mach Tools Manuf 39(8):1327–1344

92. Ohnishi O et al (2008) Effect of ultrasonic vibration on micro grooving. Mem Fac Eng, Kyushu Univ 681:1–9

93. Gong H, Fang FZ, Hu XT (2010) Kinematic view of tool life in rotary ultrasonic side milling of hard and brittle materials[J]. Int J Mach Tools Manuf 50(3):303–307

94. Lucas M, MacBeath A, McCulloch E et al (2006) A finite element model for ultrasonic cutting. Ultrasonics 44:503–509

95. Tao G et al (2017) Feed-direction ultrasonic vibration− assisted milling surface texture formation. Mater Manuf Process 32(2):193–198

96. Dongliang Xing.2012 Study on tribological properties of ultrasonic vibration assisted milling surfaces, Diss. Shandong University