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Introduction to Vibration-Assisted Machining Technology

1.1 Overview of Vibration-Assisted Machining Technology

1.1.1 Background

Precision components are increasingly in demand in various engineering fields such as microelectromechanical systems (MEMS), electro-optics, aerospace, automotive, biomedical engineering, and internet and communication technology (ICT) hardware. 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. However, because of their high hardness and usually low fracture toughness, the processing and fabrication of these hard-to-machine materials have always been challenging. Furthermore, the delicate heat treatment required and composite materials in aeronautic or aerospace alloys have caused similar difficulties for precision machining.

It has been reported that excessive tool wear and fracture damage are the main failure modes during the processing of such materials, leading to low surface quality and machining accuracy. Efforts to optimize a conventional machining process to achieve better cutting performance with these materials have never been stopped, and these optimizations include the cutting parameters, tool materials and geometry, and cutting cooling systems in the past decades [1–6]. Generally, harder materials or wear-resistant coatings are applied, and tool geometry is optimized to prevent tool cracking and to reduce wear on wearable positions such as the flank face [5, 7–10]. Cryogenic coolants are used in the machining process, and their input pressure has been optimized to achieve better cooling performance [2, 4, 11]. However, although cutting performance can be improved, the results are often still unsatisfactory.

Efforts to enhance machining performance have revealed that machining quality can be improved using the high-frequency vibration of the tool or workpiece. Vibration-assisted machining (VAM) was first introduced in the late 1950s and has been applied in various machining processes, including both traditional machining (turning, drilling, grinding, and more recently milling) and nontraditional machining (laser machining, electro-discharge machining, and electrochemical machining), and it is now widely used in the precision manufacturing of components made of various materials. VAM adds external energy to the

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conventional machining process and generate high-frequency, low-amplitude vibration in the tool or workpiece, through which a periodic separation between the uncut workpiece and the tool can be achieved. This can decrease the average machining forces and generate thinner chips, which in turn leads to high processing efficiency, longer tool life, better surface quality and form accuracy, and reduced burr generation [12–17]. Moreover, when hard and brittle materials such as titanium alloy, ceramic, and optical glass are involved, the cutting depth in the ductile regime cutting mode can be increased [18]. As a result, the cutting performance can be improved and unnecessary post-processing can be avoided, which allows the production of components with more complex shape features [14]. Nevertheless, there are still many opportunities for technological improvement, and ample scope exists for better scientific understanding and exploration.

VAM may be classified in two ways. The first classification is according to the dimensions in which vibration occurs: 1D, 2D, or 3D VAM. The other classification is based on the vibration frequency range, for example, in ultrasonic VAM and non-ultrasonic VAM. Ultrasonic VAM is the most common type of VAM. It works at a high vibration frequency (usually above 20 kHz), and a resonance vibration device maintains the desired vibration amplitude. Most of its applications are concentrated in the machining of hard and brittle materials because of the fact that high vibration frequency dramatically improves the cutting performance of difficult-to-machine materials. Meanwhile non-ultrasonic VAM uses a mechanical linkage to transmit power to make the device expand and contract, and this can obtain lower but variable vibration frequencies (usually less than 10 kHz). It is easier to achieve closed-loop control because of the low range of operating frequency, which makes it uniquely advantageous in applications such as the generation of textured surface.

1.1.2 History and Development of Vibration-Assisted Machining

The history of vibration technology in VAM can be traced back to the 1940s. During the period of World War II, the high demand for the electrically controlled four-way spool valves mainly used in the control of aircraft and gunnery circuits stimulated the development of servo valve technology [19]. Because of their wide frequency response and high flow capacity, electrohydraulic vibrators were successfully developed and applied in VAM in the 1960s with positive effects in enhanced processing quality and efficiency [20]. With the further development of technology, electromagnetic vibrators featuring higher accuracy and a wide range of frequency and amplitude generation were developed based on electromagnetic technology, and these were successfully applied to various VAM processes [21]. The need for complex hydraulic lines was eliminated, and greater tolerance for the application environment was allowed, which also leads to smaller devices. As a result, a transmission line or connecting body can be attached to the vibrator to achieve a wide range of vibration frequencies and amplitude adjustments [22]. In the 1980s, the maturity of piezoelectric transducer (PZT) piezoelectric ceramic technology had brought a new choice for the vibrator. A piezoelectric ceramic stack could be sandwiched under compressive strain between metal plates, and this has advantages including compactness, high precision and resolution, high frequency response, and large output force [23]. Various shapes of piezoelectric ceramic elements can be used to make different types of vibration actuators, which indicate that the limitations of traditional vibrators were overcome and the application of VAM technology for precision machining was broadened. In addition, it helped in the development of multidimensional VAM equipment. Elliptical VAM has received extensive attention since it was first proposed in the 1990s. Although this process has many advantages compared to its 1D counterpart in terms of reductions in cutting force and prolongation of tool life, it requires higher performance in the vibrator, producing a more accurate tool tip trajectory [24–28]. Piezoelectric actuators with high sensitivity can fulfill the requirements of vibration devices and promote the development of elliptical VAM technology.

1.2 Vibration-Assisted Machining Process

This section briefly introduces commonly used VAM processes, including milling, drilling, turning, grinding, and polishing. Different vibration device layouts are required to implement these vibration-assisted processes and to achieve advantages over the corresponding conventional machining processes.

1.2.1 Vibration-Assisted Milling

Milling is one of the most common machining processes and is capable of fabricating parts with complex 3D geometry. However, uncontrollable vibration problems during the cutting process are quite serious and can affect processing stability, especially in the micro-milling process, leading to excessive tolerance, increased surface roughness, and higher cost. Vibration-assisted milling is a processing method that combines the external excitation of periodic vibrations with the relative motion of the milling tool or workpiece to obtain better cutting performance. In addition to the same advantages as other VAM processes, complex surface microstructures can also be obtained because of the combination of a unique tool path and external vibration. Currently, the application of vibration-assisted milling mainly focuses on the one-dimensional direction. The vibration may be applied in the feed direction, cross-feed direction, or axial direction, and tool rotational vibrations may also be applied [14]. Little research has been carried out on 2D vibration-assisted milling because of the difficulty of developing two-dimensional vibration platforms (motion coupling and control difficulty), and the vibration mode of these 2D vibration devices mainly involves elliptical vibration and longitudinal torsional vibration.

1.2.2 Vibration-Assisted Drilling

Problems such as large axial forces and poor surface quality are found in the process of drilling the hard and brittle materials. Vibration-assisted drilling technology combines the VAM mechanism with the traditional drilling process, and this can achieve more efficient drilling, especially for small bore diameters and deep holes. Compared with conventional drilling, the interaction between the tool and the workpiece is changed, and the drilling tool edge cutting conditions are improved. Vibration-assisted drilling has found applications in the high-efficiency and high-quality machining of various parts with difficult-to-machine holes [29]. Its main merits are as follows:

(1) *Reductions in drilling power and drilling torque*. The vibration changes the interaction between the drill tool and the workpiece, and the cutting process changes from continuous cutting to intermittent cutting, leading to lower tool axial force. In addition, the friction factor between the tool and the workpiece/chips is reduced because of the pulse torque formed by the vibration. As a result, drilling torque is reduced [30, 31].
(2) *Improvement in chip breaking and removal performance*. The chip breaking mechanism is quite different when vibration is added. Fragmented chips can be obtained under certain vibration and machining parameters. Chip removal performance is much better compared with the continuous chips produced in conventional drilling [32].
(3) *Improvement in the surface quality of the walls of the drilled holes*. In the vibration-assisted drilling process, the reciprocal pressing action of the cutting edge on the inner hole surface is beneficial in reducing surface roughness. Moreover, the improved chip breaking performance also leads to smoother chip removal, which reduces the scratching of the drilled hole surface by chips and the surface roughness [33, 34].
(4) *Improvement in tool life*. The intermittent cutting improves the drilling tool's cooling conditions, leading to lower cutting temperature and relieving the built-up edge and tool chipping effects. As a result, longer tool life can be obtained [35, 36].

As shown in Figure 1.1, according to the direction of vibration, vibration-assisted drilling can be divided into axial, torsional, and axial–torsional composite vibration drilling. The vibration direction in axial vibration drilling is consistent with the direction of the drilling tool axis, while in torsional vibration drilling, it is consistent with the direction of the drilling tool's rotation. Axial torsional composite vibration drilling combines the previous two types.

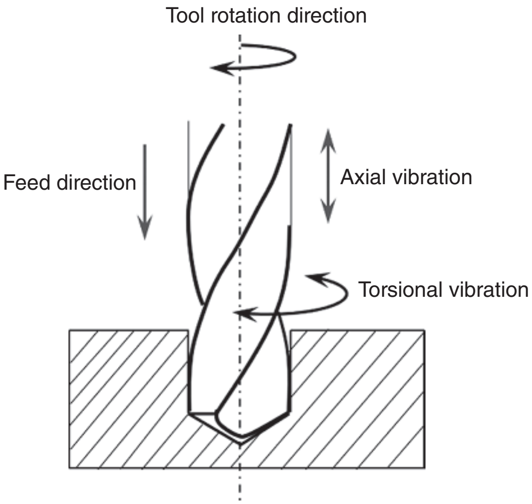

Figure 1.1 Schematic of vibration-assisted drilling.

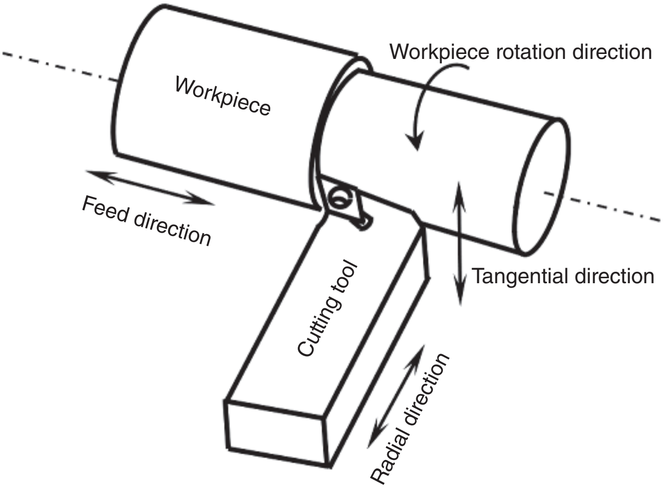

Figure 1.2 Schematic of vibration-assisted turning.

1.2.3 Vibration-Assisted Turning

Turning is a widely used machining method because of its high processing quality, metal removal rate, and productivity and efficient equipment utilization. However, drawbacks such as large cutting forces, difficulties in chip removal, and serious tool wear can cause serious processing problems, such as low machined quality and efficiency and high cost. Vibration-assisted turning provides a new method for the efficient and high-quality machining of difficult materials. As shown in Figure 1.2, vibration is applied to the turning tool mainly in the radial, tangential, and feed directions. Multidimensional vibration-assisted turning is generally referred as elliptical vibration-assisted turning, where two of the above three vibration directions are chosen and applied to the turning tool. One-dimensional vibration-assisted turning represents a large proportion of methods of vibration-assisted turning proposed so far. Most apply vibration in the feed direction, and experimental results have proven that this has a significant influence in reducing cutting forces, cutting temperature, and improving the quality of processing. Currently, only a few studies have applied vibration in the other directions, and the effects and cutting mechanisms of involved in material processing need further research.

1.2.4 Vibration-Assisted Grinding

Compared with other machining processes, grinding is increasingly used in the field of ultraprecision/precision machining because of its better machining accuracy and surface roughness. However, processing material with grinding wheels is a complex and stochastic process, where the ground surface may become damaged and low wheel life is caused by the high grinding forces and high surface cutting temperature (as the grinding wheel instantaneous temperature can reach 1000 °C). Vibration-assisted grinding process applies vibration to the grinding wheel or workpiece during the grinding so as to improve the material removal performance. The vibration can be applied in the tangential, radial, or

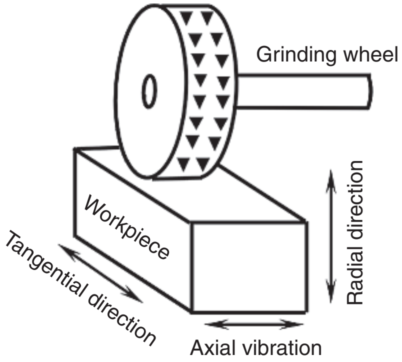

Figure 1.3 Schematic of vibration-assisted grinding.

axial direction along the grinding wheel, as is shown in Figure 1.3. Vibration-assisted grinding in the tangential and radial directions is similar to intermittent grinding, and tool–workpiece separation can be obtained during the machining process. Although vibration-assisted grinding in the axial direction involves a continuous grinding process, the machining process is quite different in conventional grinding and features separation, impact and reciprocating ironing characteristics, and lubrication effects, which can reduce grinding wheel blockage, cutting forces, workpiece residual stress, and machined surface burn. As a result, better processing performance and longer tool life can be obtained. In addition, it can also effectively reduce the chipping of hard and brittle workpiece materials and surface or subsurface cracking as well as machined surface quality [37–39]. Although similar to the mechanism of other VAM processes, the randomness of the size, shape, and distribution of abrasive grains on the grinding wheel surface and the complexity of the grinding motion bring great challenges to the study of the mechanisms involved in the vibration-assisted grinding.

1.2.5 Vibration-Assisted Polishing

At present, various miniature optical lenses are generally fabricated by precision injection molding with silicon carbide or tungsten carbides molds, and these molds usually require polishing to achieve optical grade surface quality. However, small mold sizes and increasingly high precision requirements make the polishing process challenging. In the conventional polishing process, the high-speed rotation of soft polishing tools such as wool, rubber, and asphalt polishing heads are often used to process the workpiece surface. However, when the surface has complex curved shapes and a small curvature radius, the complicated polishing mechanism and uncontrollable polishing forces severely limit the processing results. Vibration-assisted polishing can overcome some of the shortcomings in conventional polishing. Using this method, the polishing head does not need to be rotated at such high speeds, which helps in ensuring constant polishing force during the polishing process, which can also be used for smaller size molds. Current research shows that vibration-assisted polishing can improve the surface roughness of the polished workpiece and the surface accuracy while achieving high polishing efficiency [40–42].

1.2.6 Other Vibration-Assisted Machining Processes

With the advantages of VAM gradually being demonstrated, more machining processes are being added to the VAM family. Two examples of the newly developed VAM processes are vibration-assisted boring and vibration-assisted electrical discharge machining. In order to solve the difficult machining problem of complex deep hole parts with high length-to-diameter ratios (>20) such as aeroengine fuel nozzles, vibration-assisted boring has been developed. Compared with the conventional boring process, the tool can be prevented from colliding with the machined surface during the separation stage, the plastic critical cutting depth of the brittle material is increased, and cutting edge cracking and cutting tool flank face reverse bulges are avoided [43, 44]. Its separation and reversal characteristics can greatly reduce the radial thrust force and effectively improve the absolute stability of the cutting stiffness. As a result, the machined surface quality is improved and cutting flutter can be suppressed. Vibration-assisted electrical discharge machining has also been successfully applied in processing micro-hole parts made of hard and brittle materials [45–47]. In conventional electrical discharge machining, the discharge gap between the tool and the workpiece is usually only a few micrometers to several tens of micrometers and easily causes the deterioration due to the slag discharge effect and local concentration of processing debris, causing abnormal discharges and reducing processing efficiency. Compared with the process, vibration-assisted electrical discharge machining has better processing efficiency, and the results show that the slag removal effect is ameliorated and electrode wear reduced.

1.3 Applications and Benefits of Vibration-Assisted Machining

1.3.1 Ductile Mode Cutting of Brittle Materials

When the cutting depth is less than a certain critical value (the critical cutting depth) in the processing of brittle materials, the cutting process will be transformed from brittle cutting mode into ductile cutting mode. This removes the workpiece materials by plastic flow instead of brittle fractures, leading to a crack-free surface. In ductile cutting mode, the critical cutting depth can be defined as the cutting depth at which a crack appears on the machined surface. If the undeformed chip thickness is less than the critical cutting depth, brittle cutting can be reduced in conventional cutting and a better surface finish can be obtained. However, in the actual processing of brittle materials, their critical cutting depth is usually in the range of microns or submicron, which reduces the processing efficiency and increases the manufacturing time. VAM is an effective method used to increase the critical cutting depth in ductile cutting mode and to improve the economics and feasibility of the processing of brittle materials. It has been reported that smaller cutting forces can reduce microcrack propagation on the surface of the brittle parts and can increase the critical cutting depth for brittle materials under ductile cutting mode. In addition, a large enough plastic yielding force, but not large enough to cause material rupturing, is also a necessary condition for the ductile cutting of brittle workpieces. Therefore, it is feasible to increase the brittle materials critical cutting depth within a reasonable stress range by using VAM [48–50].

1.3.2 Cutting Force Reduction

A large number of cutting experiments and finite element analysis show that under the same cutting conditions, the average cutting force of VAM is significantly lower than in the traditional cutting process, and the cutting force in 2D VAM process is less than that in 1D. Although the instantaneous peak cutting force of 1D VAM is close to the steady-state cutting force in conventional machining, a lower average cutting force can be obtained because of the periodic contact between the tool and workpiece during cutting [51–53]. In 2D VAM process, the shape of chips and the interaction between them and the tool rake face are quite different from 1D VAM because of the elliptical cutting tool trajectory, which leads to lower average cutting force and reduced instantaneous peak cutting force. The cutting force reduction is manifested in the following ways:

(1) The chip thickness in the 2D VAM can be reduced because of the continuous overlapping of elliptical tool paths. As a result, the cutting forces in different directions can be reduced.
(2) Under certain conditions such as circular or narrowly elliptical tool paths, the cutting tool moves faster than the chip flow speed, causing reverse friction between the tool and the workpiece, and the back cutting force can be reduced or even reversed.
(3) The periodic contact between the cutting tool and workpiece improves the lubrication conditions during the cutting process and facilitates the dissipation of heat from the tool, resulting in a reduction in cutting force.

1.3.3 Burr Suppression

Burr formation, similar to chip generation, is a common and undesirable phenomenon in the machining process and is one of the most important criteria in the evaluation of the machined surface. VAM can effectively suppress burr formation during processing, and some researchers have proposed that burr height can be reduced up to 80% compared with conventional machining [54–56]. Figure 1.4 shows examples of burr reduction in VAM. Almost no burrs can be found on the machined surface. This phenomenon is mainly due to the reduced cutting force, which leads to lower transient compressive stress and yield stress in the cutting deformation area. In addition, unique tool trajectories (such as elliptical trajectories) can result in discrete small pieces of chips. As a result, burr formation can be suppressed.

1.3.4 Tool Life Extension

Machining processes are inherently involved in tool wear, which is usually evaluated in terms of average cutting force, machined surface roughness, and cumulative cutting length. It has an important impact on surface quality and machining costs. VAM can effectively

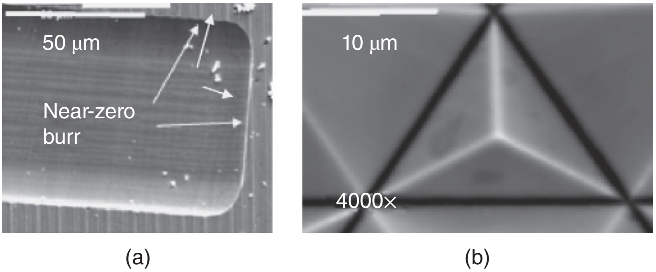

Figure 1.4 SEM images of burr-free structures made using 2D VAM. Single-crystal diamond tool in hard-plated copper. (a) Microchannel, 1.5 μm deep, and (b) a 8 μm tall regular trihedron made using a dead-sharp tool with a 70° nose angle. Source: Brehl and Dow [14]. © 2008, Elsevier.

improve cutting tool life, especially in the processing of hard materials. Unlike the irregular wear caused by traditional machining tools, the tool wear in VAM is smooth and inclined. At lower spindle speeds, due to the lower cutting temperatures, the dominant wear mechanism is abrasive wear. Because of the mechanical and impact contact between the workpiece and tool flank surface in VAM, tool life is less than that in the conventional process. At higher cutting speeds, temperature-activated wear mechanisms occur, such as diffusion, chemical wear, and thermal wear. On the other hand, because of the intermittent separation of the workpiece and tool, the temperature in the cutting zone in VAM is lower than that in conventional process, which tends to increase the tool life. Another reason for reducing the temperature in VAM is the change in friction coefficient from semi-static to dynamic, which results in a reduced friction coefficient in the process and a change in the chip formation mechanism. As the 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 machining process decreases, and the cutting forces in VAM and conventional milling processes become closer to each other. A detailed analysis on how VAM enhances tool life is provided in Chapter 5.

1.3.5 Machining Accuracy and Surface Quality Improvement

Compared with the conventional machining process, VAM can greatly improve the machining accuracy and surface quality, and the improvements vary depending on the tool and workpiece materials, vibration conditions (vibration amplitude, vibration frequency, and vibration dimensions), tool parameters, and processing parameters such as feed rate, spindle speed, and cutting depth. If the processing parameters are unchanged, the surface roughness in 1D and 2D VAM can be reduced by approximately 40% and 85%, respectively [14]. There are many reasons for this. On the one hand, lower cutting forces can enhance the stability of the cutting process, which reduces tool run-out in the cutting depth direction and generates smaller chips. On the other hand, VAM can reduce cutting tool wear and effectively avoid damage caused to the machined surface by worn tools. The tool's self-excited vibration is replaced with regular sine or cos vibration, which reduces the residual height of the unremoved material. As a result, a better machined surface quality can be obtained.

1.3.6 Surface Texture Generation

Engineered textured surfaces have the characteristics of regular textural structures and high aspect ratio, enabling the component surface to serve specific functions such as reducing adhesion friction, improving lubricity, increasing wear resistance, changing hydrophilic performance, and enhancing optical properties. Etching methods are commonly used to produce high precision surface microstructures, but these are costly and time-consuming. As a more flexible method, it has been proven that VAM in either a single direction or two directions can form certain surface textures depending on the cutting edge geometry and kinematics. Currently, the proposed surface textures mainly include a squamous, micro-dimple pattern and micro-convex pattern types, and their size ranges from a few microns to tens of microns, as shown in Figure 1.5. There is an emerging trend to obtain certain surface performance using VAM. For example, the size of the surface texture features can be controlled by changing the vibration and processing parameters, leading to variable surface wettability (Figure 1.5) [12]. The process can also be used to create microchannels for the microfluidic control of the fluid flow, to name a few. A detailed analysis on how VAM produces surface texture is provided in Chapter 8.

1.4 Future Trend of Vibration-Assisted Machining

With the development of processing technology, the application of VAM is becoming increasingly widespread, and research into VAM is becoming more and more intensive, mainly in the following main aspects:

(1) *Development and adoption of new tool materials*. The proportion of difficult-to-machine materials in modern products is increasing, as well as a higher processing quality of these parts. In order to achieve better cutting performance, in addition to the optimization of tool geometry parameters, more attention has been focused on the development and application of tool materials in VAM, and main research focus is on natural and synthetic diamond and ultrafine grained carbide materials.

(2) *Ultra-high-frequency vibration-assisted machining*. Ultra-high-frequency VAM will continue to be a research focus in VAM in the future. Recent research indicates that the possibility of grinding wheel ablation can be effectively reduced by adding high-frequency vibration, which also improves the grinding wheel's life and the surface quality of the workpiece. In recent years, research into ultra-high-frequency vibration equipment has made it possible to reach a maximum vibration frequency of 100 kHz, and at the same time, its processing performance for brittle and hard materials has also been significantly improved.

(3) *Precision/ultraprecision application*. It has been reported that the dimensional and geometric accuracy and wear resistance as well as corrosion resistance of the workpiece can be improved dramatically when low-frequency vibration is applied. However, only high-frequency VAM, such as ultrasonic VAM, can currently achieve a precision machining process. For example, a surface roughness of Ra 0.02–0.04 μm can be obtained by vibration-assisted honing, and surface quality improves by an order of magnitude in the ultrasonic vibration extrusion process compared to conventional

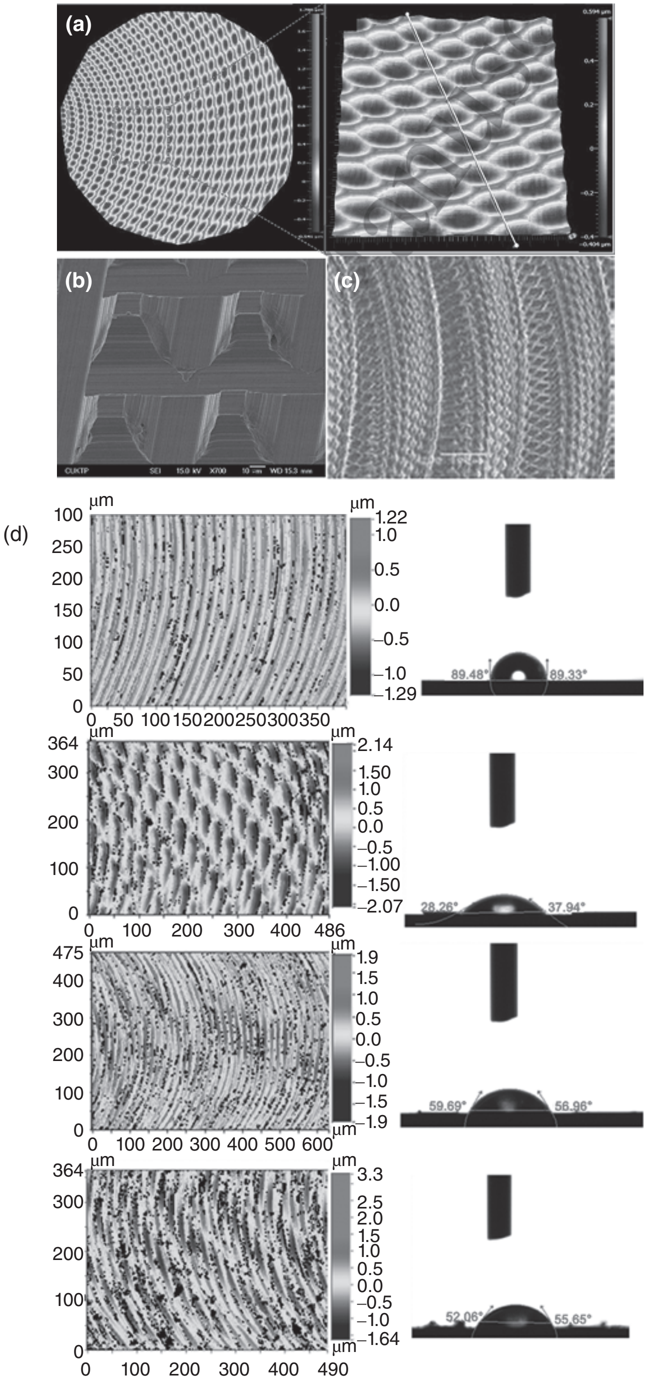

Figure 1.5 Surface texture produced by vibration-assisted machining: (a) micro-dimple patterns. Source: Lin et al. [57]. © 2017, IOP Publishing Ltd, (b) micro-convex patterns. Source: Kim and Loh [58]. © 2010, Springer Nature, (c) squamous patterns. Source: Tao et al. [59]. © 2017, Taylor & Francis Group, and (d) surface wettability variation with different surface textures. Source: Chen et al. [12].

extrusion. Ultrasonic vibration machining can not only guarantee the quality of ultraprecision machining but also allows for higher cutting rates, leading to higher productivity.

(4) *In-depth study of vibration-assisted machining mechanism*. Although the cutting mechanism of VAM has been investigated by several researchers, it is still not fully understood. Current and future research on VAM will focus on several areas, including the effect of the separation and non-separation of the workpiece and cutting tool on chip formation, mechanical analysis of the interaction between the cutting tool and workpiece, microscopic studies, and mathematical descriptions of VAM mechanisms, to name a few.

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