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ORIGINAL ARTICLE

Ultrasonic elliptical vibration texturing of the rake face of carbide cutting tools for adhesion reduction

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Abstract Carbide tools are widely used to cut high-strength and corrosion-resistant aluminum alloys. However, aluminum chips tend to adhere to the cutting edge and rake face, influencing machined surface quality and even leading to tool failure. This paper proposes an innovative application of the ultrasonic elliptical vibration texturing (UEVT) process with properly selected elliptical locus for generating superior microgrooves on the carbide tool's rake face using polycrystalline diamond (PCD) tools, in order to create a micropool-like lubrication effect at the chip-tool interface. Two microtextured carbide tools with a channel pitch of 400 and 200 μm and a depth of 12 μm were generated by UEVT. An experimental comparison between nontextured and UEVT tools in turning tubular aluminum alloy workpieces has demonstrated that microtextured tools with a pitch of 200 μm show a clear reduction in chip adhesion. The corresponding cutting performance is also improved due to the anti-adhesive property at the chip-tool interface. This work has demonstrated that ultrasonic elliptical vibration texturing has the potential for the mass production of microtextured tools for adhesion and friction reduction with high efficiency and accuracy.

Keywords Ultrasonic elliptical vibration texturing · Surface texture · PCD tool · Rake face · Carbide tool · Adhesion reduction

1 Introduction

Friction and wear are important surface phenomenon leading to adhesion on cutting tools, which are responsible for a large number of tool failures and replacements [1]. The use of diamond-like carbon coatings on cutting tools is a conventional approach to lower adhesion, but flood cutting fluid is required in practical use to avoid the adherence of the chips to the cutting edge [2].

In recent years, functionalization of tool surfaces by textures as a new surface engineering approach has attracted much attention because of the possibility of adhesion reduction and lubrication enhancement [3, 4]. Lei et al. firstly created microholes on the tool face to be filled with lubricant and demonstrated that friction and wear reduction at the chip-tool interface can be achieved [5]. Kawasegi et al. fabricated microtextured cutting tools with femtosecond laser interference to enable friction reduction on the tool surface and thus improving machinability [6]. Enomoto et al. developed a cutting tool with nanogrooves/microgrooves using femtosecond laser ablation to improve its anti-adhesive property and lubricity [7] while Xing et al. have also achieved self-lubrication effects of textured ceramic tools by applying laser texturing techniques [8].

Among the texturing techniques on cutting tool surfaces, laser machining is the most widely used method to fabricate microscale textures. Despite of being a mature and flexible processing technique, laser ablation is not suitable for mass production because of its high cost and long processing time. Moreover, it is still a challenge to accurately and efficiently

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generate microstructured textures on tool surfaces by laser processing [9]. Recently, few alternative microtexturing techniques were proposed. Obikawa et al. fabricated textures on tool surfaces through spattering, photolithography, and wet etching [10]. High-performance cutting was performed, but the texturing process was rather sophisticated for practical use. Koshy and Tovery applied sink electrical discharge machining (EDM) for rapid texturing of the rake face of a cutting tool with the intent of promoting lubrication at the chip-tool interface [11]. In spite of several advantages of the EDM process, it is not energy-efficient and is mainly applicable to conductive tool materials. In comparison, mechanical machining offers significant advantages for its capability to process a variety of work materials with accurate surface finish without requiring post-processing operations [12, 13].

In this paper, a newly developed ultrasonic elliptical vibration texturing (UEVT) system will be used and proposed for an innovative application of the UEVT process for microgrooving the rake face of carbide tools. The proposed process is a promising mechanical processing method for the fast generation of microstructures, especially on hard and brittle materials such as carbide materials [14]. To be specific, by utilizing two Langevin transducers excited by piezoelectric actuators, different elliptical loci will be generated at ultrasonic frequencies in accordance with suitable frequency/phase characteristics, to achieve superimposed cyclic vibrations of the cutting tool in the cutting and depth-of-cut directions. The resulting unique intrinsic cutting mechanism significantly reduces the thickness of cut, which makes texturing possible through ductile mode cutting of the hard carbide tool surface without brittle fracture at high nominal depths of cut [15]. It will be shown through a comprehensive experimental study on turning tubular aluminum alloy workpieces that the textured tools exhibit an adhesion reduction effect. The corresponding cutting performance related to the cutting force, friction coefficient, chip morphology, and cutting surface quality will also be evaluated.

2 Ultrasonic elliptical vibration texturing system

2.1 Design and modal analysis

The structural configuration of the newly developed UEVT system is shown in Fig. 1. In previous work, it was used for the fast generation of micro-dimples with different geometric characteristics [16]. In the context of the current paper, its use for the ductile cutting of microgrooves on carbide tool inserts will be explored. The system consists of two bolt-clamped Langvin transducers with an included angle of 60°. The base block provides a fixed node for the two transducers. The bolts connect the end mass and the flexure hinge under a certain preload force. Two pairs of piezoelectric transducers (PZT

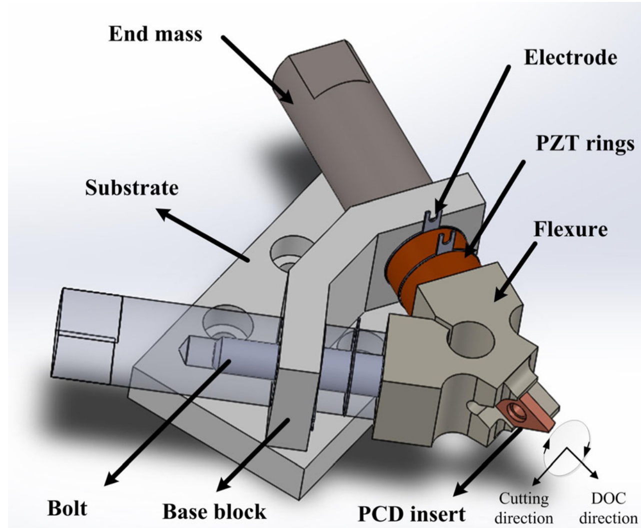


Fig. 1 The newly developed ultrasonic elliptical vibration texturing (UEVT) system

rings) are put in between the flexure and the base block, in order to excite resonant vibrations at the characteristic ultrasonic natural frequencies of the device.

When the transducers are properly designed, assembled, and adjusted, the two vibration modes occur approximately at the same resonant frequency and generate elliptical loci at the tip in the depth-of-cut (DOC) and cutting directions. Finite element analysis (FEA) was conducted to identify the system's resonant modes. From the simulation results, shown in Fig. 2, it can be seen that the resonant mode in the DOC direction occurs at 27.71 kHz, while in the cutting direction at 27.99 kHz. Therefore, at approximately these frequencies, ultrasonic elliptical vibration loci can be generated.

2.2 Ultrasonic elliptical locus generation

The resonant frequency and amplitude of the developed UEVT are actually determined by the mass distribution, the preload force between the PZT rings and flexure, and manufacturing and assembly imperfections. The system has complex vibration modes due to its complex geometry [17]; thus, a sine-sweep test was conducted to identify its resonant characteristics for generating proper ultrasonic elliptical locus.

The identification setup is shown in Fig. 3. In order to measure the locus, the vibrations in two directions are concurrently measured using two orthogonally arranged MicroSense capacitance sensors (model 5504, USA). The sensors have sub-nanometer resolution in a range of 100 μm and a 100-kHz bandwidth. Two harmonic excitation signals were generated by a National Instruments data acquisition card (PCIe-6361, USA) at a sampling frequency of 1.0 MHz. The output

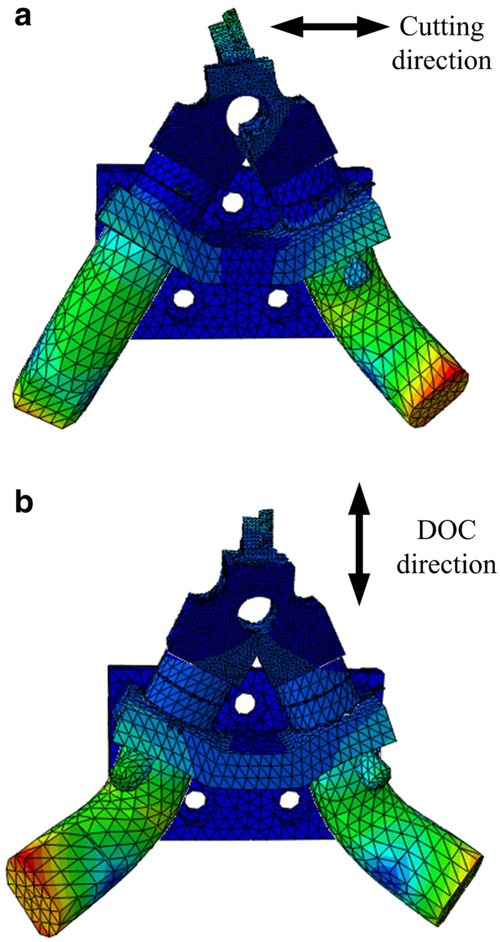


Fig. 2 Mode shapes in **a** cutting direction and **b** DOC direction

signals were then amplified by a piezo-amplifier (Trek PZD350, USA), with a bipolar output of 0 to ±350 V. Two sweep voltage signals (V_{pp}=700 V) with continuously increasing frequencies from 5 to 40 kHz were supplied to excite the PZT rings. The measured vibration displacements are also recorded by the data acquisition card at a 500-kHz sampling frequency.

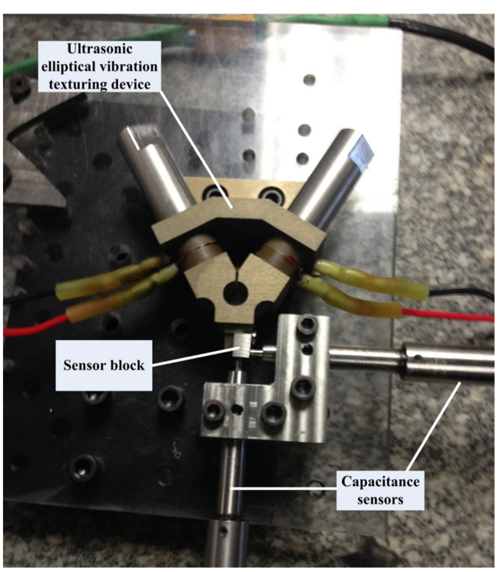


Fig. 3 Setup for identification of system response and elliptical locus measurement

By applying the fast Fourier transform (FFT) between the excitation signals and the vibration responses, the amplitude-frequency characteristics in the DOC and cutting directions are plotted in Fig. 4a, b, respectively. It can be seen that the ultrasonic resonances in the two directions simultaneously occur at 27.5 kHz which is very close to the previously presented FEM simulation result.

Clearly, several factors determine the two-directional vibrations that form the ellipse. According to the identified amplitude-frequency characteristics, different tool vibration amplitudes in the two directions would be obtained at different excitation frequencies. The other factor is the nature of the input excitation signals, namely the excitation amplitude and the corresponding input phase difference between the two sinusoidal excitation signals. They influence the vibration amplitudes and output phase difference which is defined as the phase difference between the two-directional generated sinusoidal vibrations; thus, various elliptical shapes can be obtained under different excitation conditions.

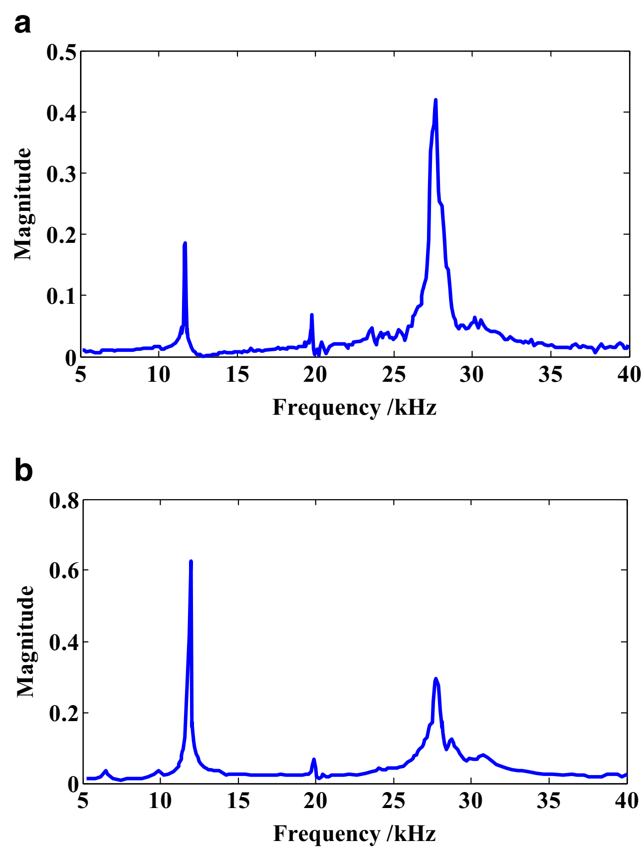


Fig. 4 Amplitude-frequency characteristics: **a** depth-of-cut direction and **b** cutting direction

During the experiments, the left and right PZT rings of the UEVT system were excited by sinusoidal voltages at the ultrasonic resonant frequency of the device at 27.5 kHz. When sinusoidal voltages of different amplitudes are applied to the left and right PZT rings, different elliptical shapes are generated, as shown in Fig. 5a. It can be observed that the amplitudes in the two directions decrease with the reduction of the applied voltages to the right PZT rings. Figure 5b shows that the formed ellipse becomes narrower with increased phase difference in the inputs from 60° to 180°.

At the resonant frequency of 27.5 kHz, although the vibration displacements peak at 10 μm, the ellipse is too narrow to conduct elliptical vibration texturing. The narrow ellipse is due to the low output phase difference between the generated two-directional sinusoidal vibrations. Ultimately, if the two vibrations are in-phase (0° of output phase difference), it becomes a straight line. Thus, it is essential to improve the output phase difference of generated vibrations to some extent.

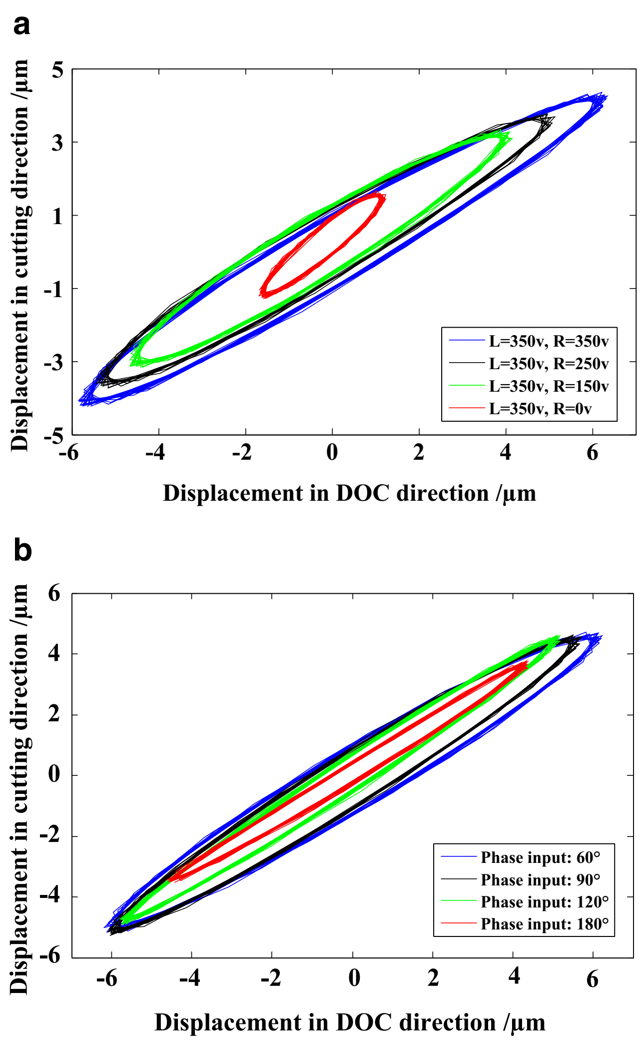


Fig. 5 Varied elliptical shapes **a** applying different voltages and **b** applying different phase inputs at 27.5 kHz

Through the identified phase-frequency characteristics around the resonant region from 27 to 29 kHz, as shown in Fig. 6, it is interesting to note that the output phase difference increases as the excitation frequency increases from 27.5 kHz, yet the generated amplitude in the two directions weakens. Therefore, by making a compromise between the lowered amplitude and increased output phase difference, the ultrasonic frequency of 28.35 kHz was selected and used to study variations in the elliptical loci as a function of the applied excitation voltages and phase inputs before applying the system in the UEVT process. At 28.35 kHz, with an input phase difference of 0°, sinusoidal excitation signals with amplitude of 350 V were applied to the left PZT rings, while different amplitudes ranging from 350 to 0 V were applied to the right PZT rings. The elliptical loci generated are shown in Fig. 7a, which indicate that the vibration amplitudes diminish as a function of the imbalance between the applied voltages, and that the formed ellipse also becomes narrower when different voltages are applied. The elliptical shape variation trend with the phase inputs is shown in Fig. 7b. When the phase input is 120°, the generated shape becomes a straight line and even distorted. Based on the above simulation analysis and experiments, it can be seen that various elliptical loci can be accurately generated under different conditions and, as shown below, implemented in ultrasonic elliptical vibration texturing operations.

2.3 Principle of operation

Figure 8 illustrates the basic principle of operation of the ultrasonic elliptical vibration texturing process. Based on the properly generated elliptical loci, combined with relatively low cutting speeds, overlapping ellipses are obtained that can be expressed as follows:

$$\begin{cases} x = a\cos(2\pi f t) - v_c t \\ y = b\cos(2\pi f t + \varphi) \end{cases} \tag{1}$$

where a and b are the vibration amplitudes in the two directions, f is the vibration frequency, v_c is the cutting speed, and φ

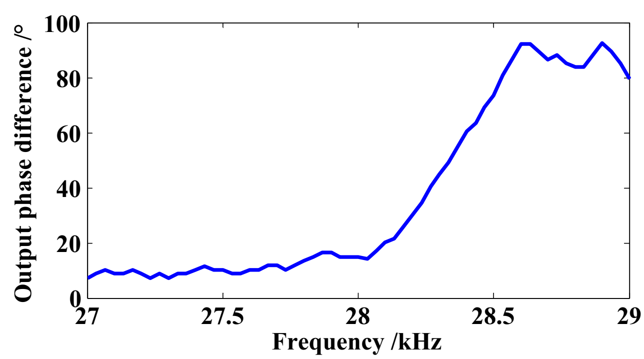


Fig. 6 Phase-frequency characteristics while applying different frequencies from 27 to 29 kHz

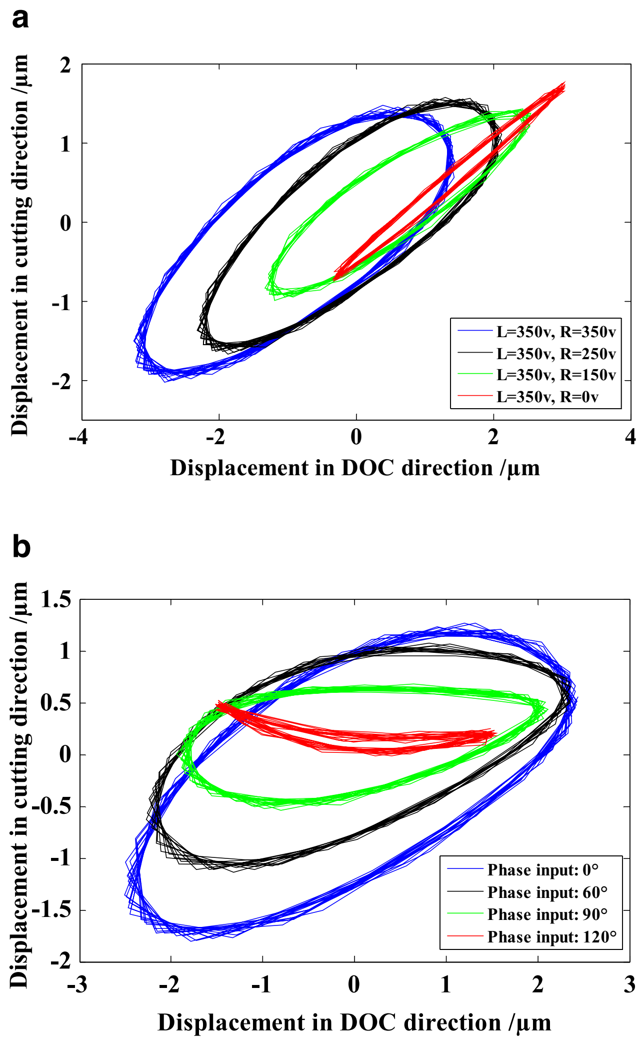


Fig. 7 Varied elliptical shapes by **a** applying different voltages and **b** applying different phase inputs at 28.35 kHz

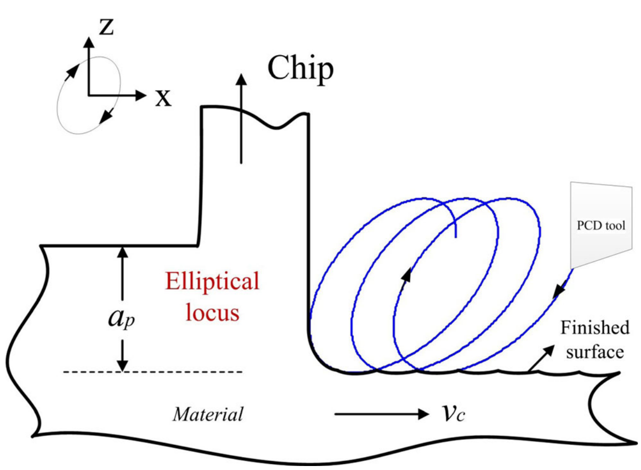


Fig. 8 Principle of operation of the ultrasonic elliptical vibration texturing process

is the phase difference between the generated sinusoidal vibrations $x(t)$ and $y(t)$.

Due to the largely overlapping elliptical loci, the actual depth of cut is significantly reduced with respect to the nominal depth of cut, which is beneficial to achieve ductile cutting of hard and brittle materials [14]. Therefore, it is also possible to utilize the ultrasonic elliptical vibration generation device for the texturing of the carbide tool rake face with the proposed UEVT system.

3 Experimental setup and texturing process

3.1 UEVT setup

The photograph of the experimental setup and its corresponding schematic block diagram are shown in Fig. 9. The UEVT system is installed on the *Y*-axis linear stage of a five-axis precision motion system (Aerotech, USA). The cutting and feed motions are achieved by the *X*- and *Z*-axes. A three-

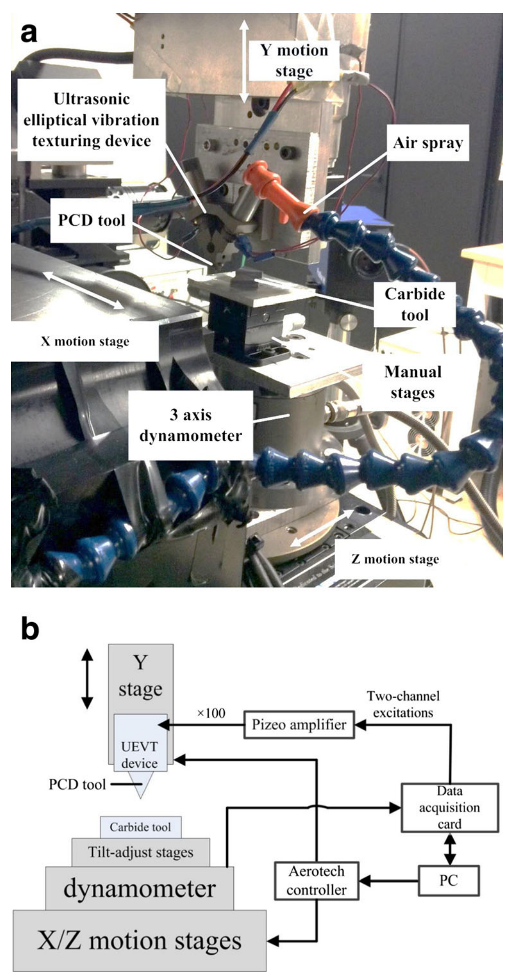
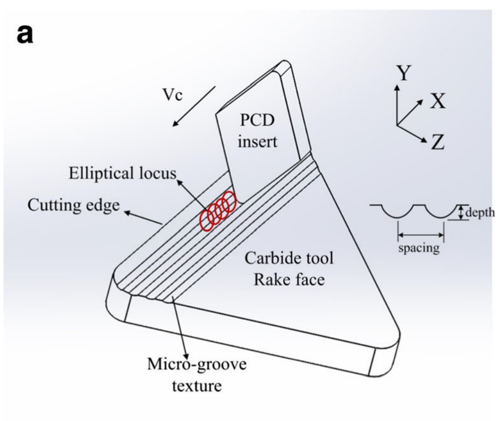


Fig. 9 **a** Photograph of the experimental setup for ultrasonic elliptical vibration texturing of carbide inserts using PCD tools; **b** schematic block diagram

axis Kistler dynamometer is used to measure the cutting forces when texturing the carbide tool inserts using polycrystalline diamond (PCD) tools. The force signals are sampled by the National Instrument data acquisition card. A two-degrees-of-freedom manual stage, mounted on the dynamometer platform, serves for horizontally adjusting the rake surface of the carbide inserts to be textured. Two-channel sinusoidal excitation voltages (±3.50 V) with a input phase difference of 0° at the ultrasonic resonant frequency of 28.35 kHz sourcing from the data acquisition card are amplified by the piezo-amplifier (×100). The amplified signals are supplied to excite the left and right PZT rings of the UEVT system to generate the proper ellipse. According to Sect. 2.2, the resultant vibration amplitudes in the DOC and cutting directions are 2 and 1.5 μm, with a phase difference of about 50° between the two directions. Compressed air is used to blow off the chip and cool the texturing process.

3.2 UEVT carbide tool texturing and the turning experiments

Figure 10a illustrates the UEVT process on the rake face of a triangular carbide tool insert (grade K68, Kennametal).



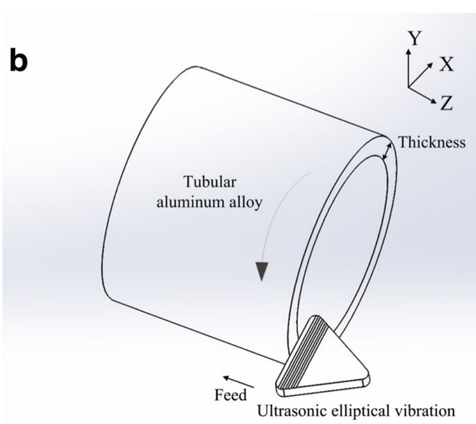


Fig. 10 **a** Illustration of the UEVT process on the rake face of a triangular carbide insert; **b** experimental setup for turning by UEVT carbide inserts

Compared with high speed steel (HSS) tools, carbide inserts have a higher hardness and wear resistance. PCD tools are expensive and unsuitable for use in subsequent turning operations due to the high depth of cut and feed rate used in this paper. More importantly, the traditional process of texturing the carbide tool is to use the laser machining, but the proposed ultrasonic texturing method offers greater advantages regarding accuracy and efficiency, especially for high hardness tools.

The elliptical vibration cutting insert used for texturing the carbide inserts is a commercial PCD insert with a 100-μm nose radius from Sumitomo (Grad DA1000). The rake and clearance angles are 0° and 7°, respectively. The cutting speed (v_c) for texturing is set to be 1 mm/s. Actually, tens of times higher speed can be applied to further reduce the texturing time during cutting carbide using PCD insert [14]. The parallel microgrooved textures generated are located near the cutting edge of the carbide tool insert. Two spacing distances of 200 and 400 μm are chosen to form two textures with different densities.

Figure 10b shows the experimental setup for turning using the UEVT carbide tool. The tubular aluminum alloy workpiece with a wall thickness of 2 mm is fixed on the spindle, and the textured carbide tool is on the slide carriage of the machine. In the turning experiments, cutting oil, biodegradable, #44220, was continuously supplied to the carbide tool's rake face. The turning speed was set to 375 rev/min, and the feed rate f in the Z direction was set to 0.04 mm/rev.

During the turning experiments, the cutting force is monitored by the three-axis Kistler dynamometer. The textured rake face after the UEVT process and the inspection of adhesion after turning the tubular aluminum alloy workpieces, as well as the turned surface quality, were measured by a variable focus optical microscope (Alicona, Austria).

4 Results and discussion

4.1 Ultrasonic elliptical vibration textured rake face

The texturing of the carbide tool insert using the PCD tool is investigated first with and without the developed ultrasonic elliptical vibration texturing system, as shown in the 2D images of Fig. 11. It can be clearly seen that the surface quality at the bottom of the non-UEVT microgrooves is seriously degraded and cracked, while distinctly smooth and consistent bottom surfaces without any burrs and crack are perfectly obtained by the UEVT process at the same cutting speed.

Figure 12a shows the corresponding 3D images of the textured microgrooves obtained by the conventional cutting method. The textured depth of the microgrooves is distinctly increased along with significantly improved

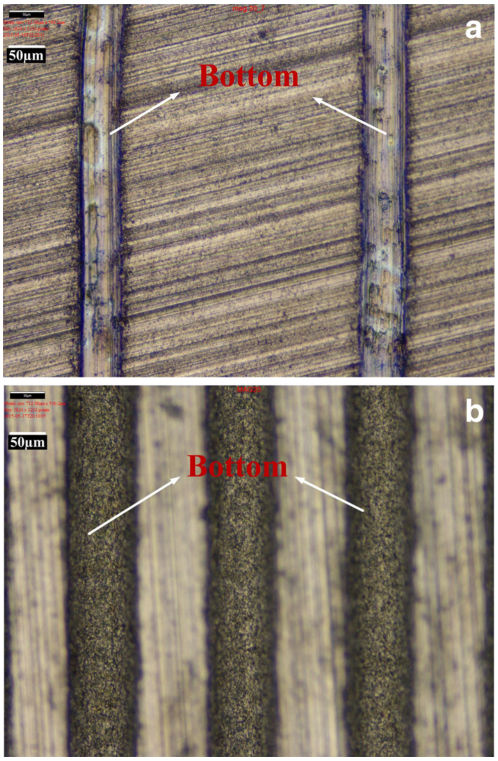


Fig. 11 2D image of **a** conventional mechanical cutting result and **b** UEVT texturing result

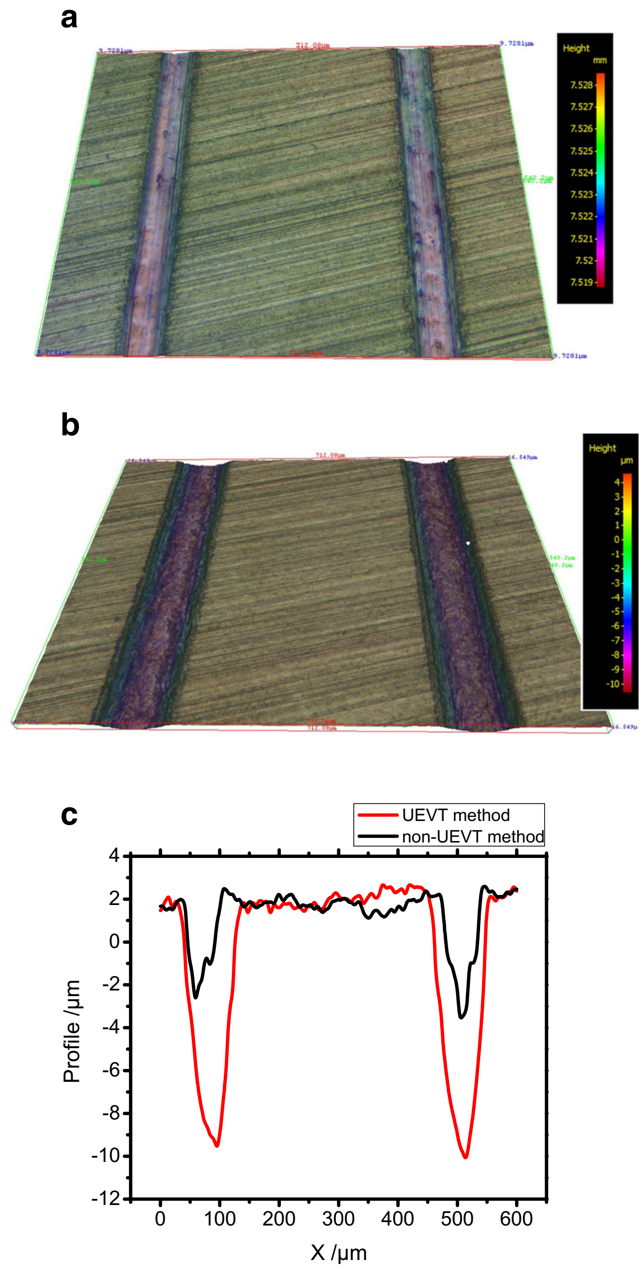


Fig. 12 3D images of the textured microgrooves **a** with conventional cutting method, **b** UEVT texturing, and **c** profile comparison

texture quality by applying the UEVT process, as shown in Fig. 12b. Randomly selected profiles are shown in Fig. 12c. With the non-UEVT process, severely distorted microgrooves are generated because brittle fracture occurs and the depth is only about 5 μm. .If the depth of a groove is very low, it is not big enough to store a sufficient amount of lubricants to reduce the friction force [8]. Besides, fractured and non-uniform grooves with stored lubricant may affect the stable chip flow. On the contrary, ductile texturing of smooth and accurate microgrooves with depths of up to 12 μm can be obtained by using the developed UEVT system. This is due to the largely overlapped elliptical vibration cycles which significantly reduce the thickness of the chip and thus improve cutting performance. Although the ductile texturing may be maintained through conventional cutting method by decreasing the depth of cut to a critical value which is normally below 1 μm for carbide materials [15], it means more than ten repeated grooving is needed to finish one-line grooving. As a result, it will considerably decrease the efficiency and cannot guarantee the profile accuracy either.

The related texturing forces for microgrooving are also investigated. It can be concluded from Figs. 12 and 13 that besides the distinctively improved textured microgroove quality and the considerable increase in ductile cutting depth, the cutting force in the cutting direction is lowered by about 70 %. Moreover, the comparatively fluctuating cutting forces with the non-UEVT method indicate a potentially unstable texturing process due to brittle fracture and burr generation which lead to degraded surface quality.

Figure 14 gives a photo of the textured carbide tool with parallel microgrooves on its rake face obtained by using the developed UEVT system. Figure 15 shows the 3D images of the textured carbide tool's rake face with different pitches, 400 and 200 μm, respectively. Compared to traditional laser ablation, accuracy is greatly improved because the ablation procedure cannot be well controlled and seriously deforms the

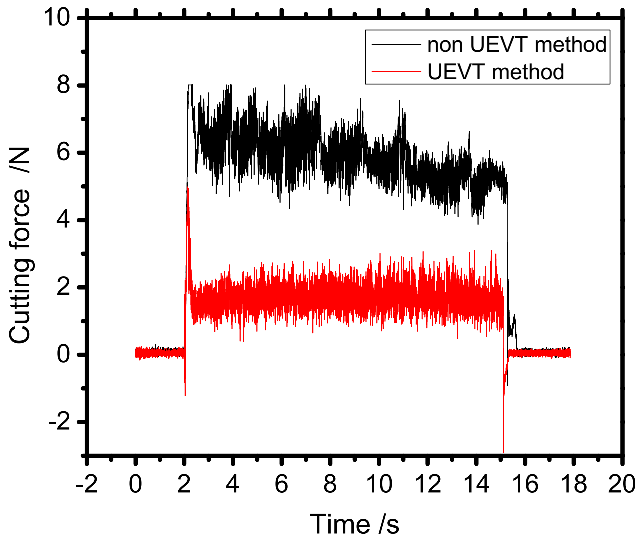


Fig. 13 Cutting forces by non-UEVT method and UEVT method

adjacent surfaces due to the introduced heat [18]. Moreover, if applying the commonly used picosecond lasers to texture the same size and profile of the microgroove on the carbide tool rake face, multiple passes are essential. The process is time consuming and is more than 60 times longer than using the UEVT method [19]. On the contrary, the UVET process only takes several minutes to finish the rake face texturing of a carbide tool insert and guarantees texture accuracy, having thereby a great potential in industrial applications for improvement of energy efficiency and mass production of microtextured cutting tools.

4.2 Textured rake face adhesion inspection

Three types of carbide tools were evaluated: (1) non-UEVT carbide tool, (2) UEVT carbide tool with

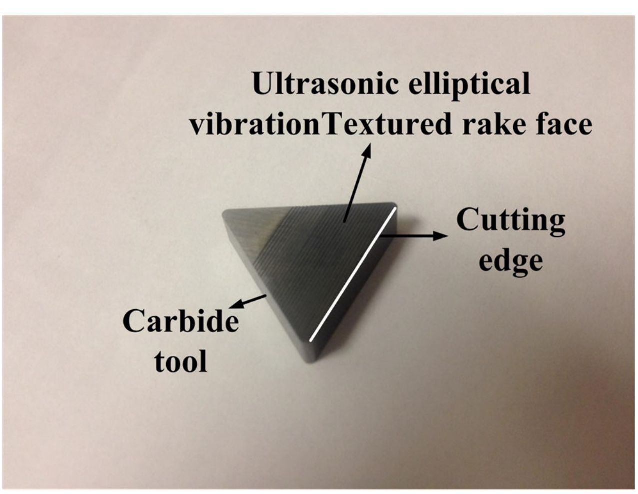


Fig. 14 Photo of textured carbide insert with parallel microgrooves on its rake face

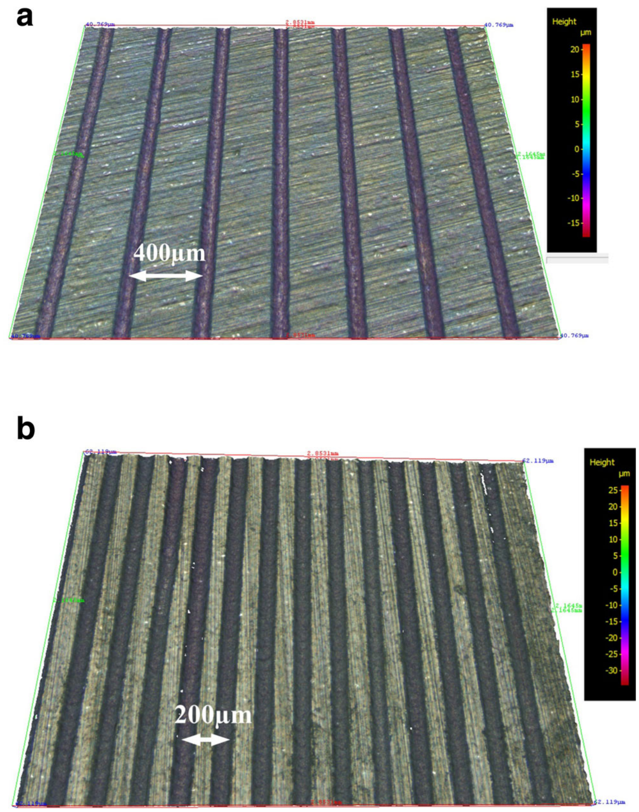


Fig. 15 3D image of the rake face of the textured carbide insert with a pitch of **a** 400 μm and **b** 200 μm

400 μm pitch microgrooves, (3) and UEVT carbide tool with 200 μm pitch microgrooves. Turning performance was analyzed after cutting for 20 m. Figure 16 shows the observed rake face of the three carbide tools. For the non-UEVT carbide tool, the aluminum chips readily adhere to the cutting edge and the rake face. It can be seen that a substantial amount of chip builds up on the rake face. This phenomenon will lead to the increase in cutting forces and cutting surface roughness, and even tool breakage [7]. On the contrary, for the UEVT carbide tools, the chip buildup is significantly reduced, indicating that the textures fabricated by the ultrasonic elliptical vibration process have a distinct anti-adhesive influence. This is particularly true for the UEVT carbide tools with a groove pitch of 200 μm. The reasons may be described as follows. The accurately generated microgrooves with a more than 10-μm depth are working as micropools where the cutting fluid is contained and provides a lubrication effect for the chip flow. In this case, the lubricant can be squeezed by the flowing chips to form a smooth and thin film so that direct tool-chip contact can be further reduced [5]. Therefore, a clear decrease in chip adhesion on the rake face of UEVT tools can be can be seen.

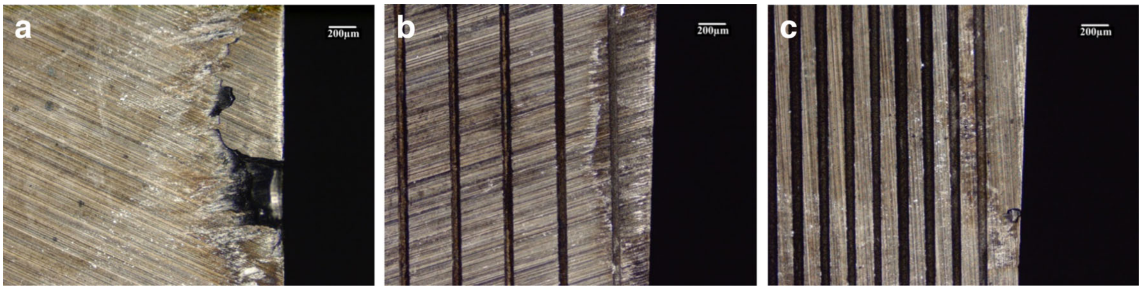


Fig. 16 Rake face adhesion observation of **a** non-UEVT insert, **b** UEVT insert with a pitch of 400 μm, and **c** UEVT insert with a pitch of 200 μm

4.3 Cutting force monitoring

The cutting force components including the principal force in the Y direction and the tangential force in the X direction were recorded during the turning process of the tubular aluminum alloy workpieces. As shown in Fig. 17a, the cutting forces are lowered for the UEVT tools. Compared with non-UEVT tool, the reduction percentage in the mean tangential force for the UEVT tool (400 μm pitch) is found to be 7.5 %, while the principal force does not have a considerable drop. However, for the UEVT tool (200 μm pitch), the recorded principal and tangential forces are reduced up to 7.1 and 17.1 %, respectively. The decrease in cutting force is attributed to the reduced friction force and anti-adhesion of buildup at tool-chip interfaces due to the micropool lubrication effect. The results also indicate that the ultrasonic elliptical vibration textured micro-grooves on the rake face contribute to a much more significant reduction in the tangential force than in the principal force. This is especially true for the UEVT tool with the 200 μm pitch microgrooves. It is because the tool-chip interfaces provide a stable lubrication effect for the UEVT tools and reduce the friction force in the tangential direction.

The friction coefficients for three kinds of tools at the tool-chip interfaces can be calculated according to the following formula [20]:

$$\mu = \tan(\beta) = tan\left(\lambda + arctan\left(F_t/F_p\right)\right) \qquad (2)$$

where β is the friction angle, γ is the UEVT carbide tool rake angle, F_t is the tangential force, and F_p is the principal force.

Although the principal force for the UEVT tool (400 μm pitch) is not clearly reduced, the much more lowered tangential force leads to the reduction of the friction coefficient and of the friction angle as well, as shown in Fig. 17b. The two friction parameters are further decreased for the UEVT tool (200 μm pitch) down to 0.786 and 38.1°, respectively.

The cutting force dynamics corresponding to the obtained results are also investigated by the FFT of the cutting forces for the three kinds of tools, as shown in Fig. 18. The frequency spectra are shown in the right column. It can be seen that the main frequency components of 6.39 Hz corresponds to the spindle speed of 383 r/min, which is also in accord with the set spindle speed of 375 r/min during the experiment. The related amplitude at this frequency represents the force variation during the turning process of the tubular aluminum workpiece. Interestingly, besides the reduction of the average cutting force for UEVT tools, the force variations are also lowered. The reduction percentages for the UEVT tool (400 μm pitch) and UEVT tool (200 μm pitch) are 12 % and 10 %, respectively. This is reasonable since the textures

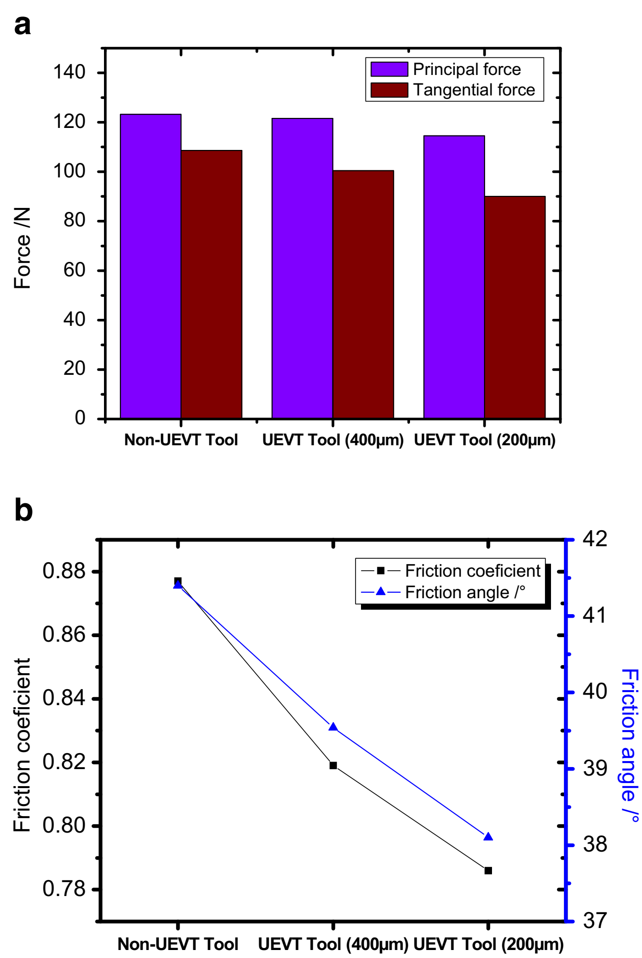


Fig. 17 **a** Cutting forces for three types of carbide inserts; **b** corresponding friction coefficients and friction angles

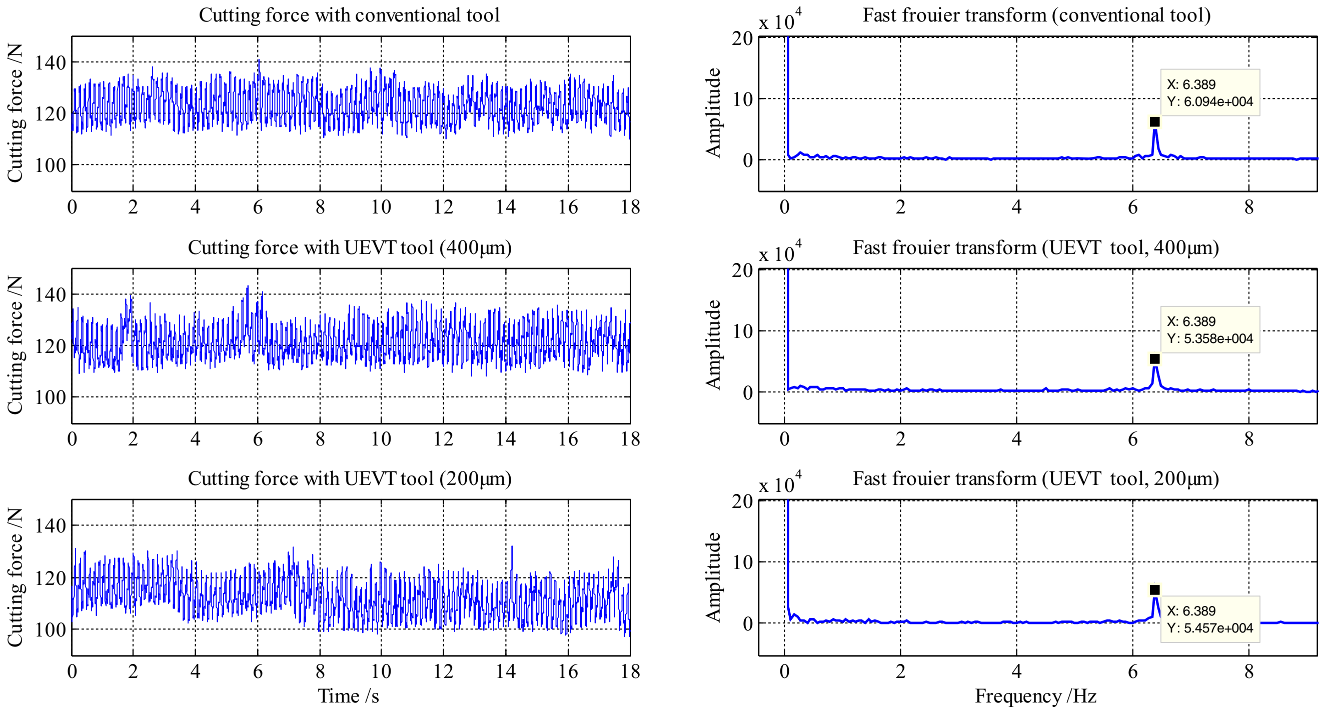


Fig. 18 Cutting force dynamic analysis for three types of carbide inserts

functioning as micropool provide a lubrication film to reduce the friction force and stabilize the cutting force.

4.4 Chip and surface observation

The chip morphology for the three cases is compared in Fig. 19. Continuous chips are observed for the non-UEVT tool, whereas segmented chips are produced by the UEVT tools. This behavior may again be related to the evidence that the micropools promote the coiling of chips [8]. The UEVT tool with smaller pitch tends to curl and fracture the chips, as shown in Fig. 19c. The fracture of chips is also a contributing factor to improved cutting surface quality, because long continuous chips can easily influence the finished surface.

The surface quality turned by three types of tools is also investigated, as shown in Fig. 20. The surface roughness (*Ra* value) is the average of values obtained by five sampling lengths in different regions. With non-UEVT tool, the chip buildup and its adhesion on the cutting edge results in high surface roughness value with relatively large deviation. Due to the anti-adhesion property of UEVT tools and reduced cutting forces, the corresponding surface quality is also improved.

To sum up, the orthogonal machining of aluminum alloy was implemented in this paper to verify the applicability and investigate the cutting performance with textured carbide tool by the proposed UEVT method. Textured tools with other methods have been tried to apply in oblique machining [6, 8]. It is also feasible to apply the ultrasonic elliptical vibration texturing into oblique machining, by adjusting the position and the orientation relationship between UEVT textures and cutting edge.

5 Conclusions

This paper reports on a new application of the ultrasonic elliptical vibration texturing process to generate parallel microgrooves on the rake face of carbide tool inserts with

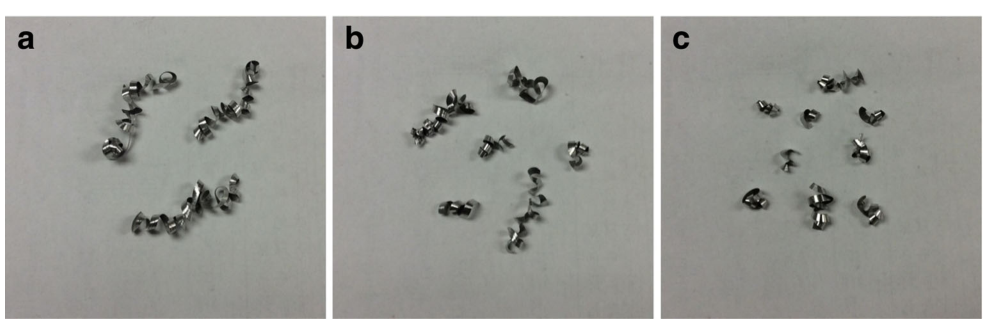


Fig. 19 Chip morphology for **a** non-UEVT insert, **b** UEVT insert with a pitch of 400 μm, and **c** UEVT insert with a pitch of 200 μm

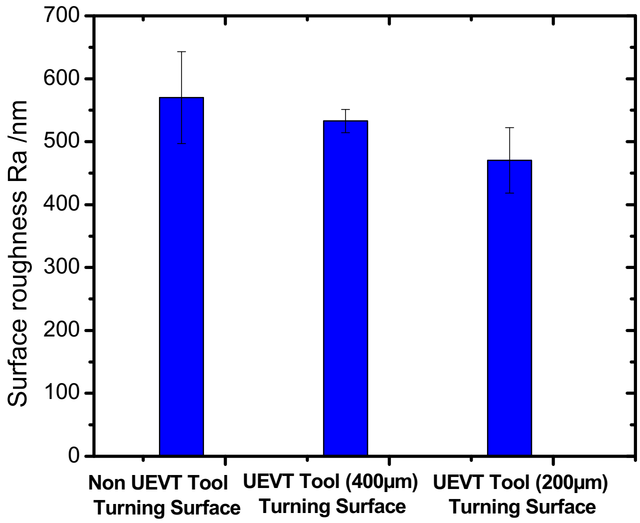


Fig. 20 Turned surface roughness using three types of carbide inserts

a newly developed UEVT system using a PCD tool. Unlike the traditional mechanical cutting method, the elliptical vibration locus is essential for texturing hard and brittle carbide cutting tools. Therefore, different elliptical loci controlled by the applied voltages and phase inputs are first studied for this kind of transducers. With properly selected elliptical locus according to the simulation analysis and identified amplitude/phase-frequency characteristics, the proposed UEVT process is confirmed to be able to accurately texture considerably smoother and deeper microgrooves than the traditional grooving process. Compared to the commonly used laser machining method for texturing tools, the efficiency of the UEVT process is drastically improved, which brings a great potential in industrial applications for mass production of microtextured cutting tools.

Parallel microgrooves with different pitches on the carbide tool rake face were textured by the UEVT process. Compared with the non-UEVT carbide tool, they were tested by turning tubular aluminum alloy workpieces and exhibited significantly improved anti-adhesive properties. The UEVT tool with a 200 μm pitch was found to lead to a reduction of 17.1 % in the tangential cutting force with a smaller variation and friction coefficient, as well as an improvement in the machined surface quality. The idea of ultrasonic elliptical vibration texturing traditional tools using harder PCD tools may also find applications on accurately and efficiently texturing other drilling or milling tools for adhesion reduction as well as performance improvement.

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