Ceramics International 44 (2018) 4142–4153

Contents lists available at ScienceDirect

Ceramics International

journal homepage: www.elsevier.com/locate/ceramint

Suppression of diamond tool wear in machining of tungsten carbide by combining ultrasonic vibration and electrochemical processing

Xinquan Zhang[a], Rui Huang[a], Kui Liu[a], A.Senthil Kumar[b], Hui Deng[c,*]

[a] *Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, 637662, Singapore*
[b] *National University of Singapore, 10 Kent Ridge Crescent, 119260, Singapore*
[c] *Department of Mechanical and Energy Engineering, Southern University of Science and Technology, No. 1088, Xueyuan Road, Shenzhen, Guangdong 518055, China*

ARTICLE INFO

Keywords:
Hybrid machining
Tungsten carbide
Ultrasonic vibration
Electrochemical processing
Diamond turning

ABSTRACT

As an important ceramic material, tungsten carbide (WC) is utilized as the typical mold in precision glass molding, which has replaced conventional grinding and polishing to provide a highly replicative process for mass manufacturing of optical glass components. Ultra-precision grinding, which is time consuming and has low reproducibility, is the only method to machine such WC molds to high profile accuracy. Although diamond turning is the most widely used machining method for fabrication of optical molds made of metals, diamond turning of WC is still considered challenging due to fast abrasive wear of the diamond tool caused by high brittleness and hardness of WC. Ultrasonic vibration cutting has been proven to be helpful in realizing ductile-mode machining of brittle materials, but its tool life is still not long enough to be utilized in practical diamond turning of optical WC molds. In the current study, a hybrid method is proposed to combine electrochemical processing of WC workpiece surface into the diamond turning process. Cutting tests on WC using poly-crystalline diamond tools were conducted to evaluate its effect on improvement of tool wear and surface quality. Validation cutting tests using single crystal diamond tools has proven that the proposed hybrid method is able to significantly reduce the diamond tool wear and improve the surface quality of machined ultra-fine grain WC workpiece compared to ultrasonic vibration cutting without electrochemical processing.

1. Introduction

Tungsten carbide (WC) is an important ceramic material in various industry fields, because it well combines various advanced properties like high hardness, high toughness, high strength and wear resistance into one alloy. In particular, WC is an irreplaceable mold material in precision glass molding due to its low coefficient of thermal expansion and high thermal stability at elevated temperature. Precision glass molding allows mass production of high-precision aspheric optical glass lenses, which has various superior optical, mechanical and chemical properties compared to conventional polymer lenses, such as higher temperature resistance, stronger chemical resistance to acid and organic solutions, higher refractive index, scratch resistance and reusability. As reported by Dambon et al. [1], most of the molds and inserts used in precision molding of low-T_g glasses are made of WC, and its optical profile with sub-micron accuracy has to be machined using ultra-precision grinding technology with several rounds of profile error compensation. Due to such low-reproducibility and time-consuming grinding process, the mold cost contributes as a major portion in precision glass molding, resulting into the high unit price of molded glass lenses and limited industry application. Furthermore, the limitation of size and geometry of grinding wheels has also strongly restricted complex optical features to be precision machined on WC and hence impose constrain on the manufacturable types of molded glass optics.

As a mature technology, ultra-precision diamond turning has already been widely used in machining of metal optical molds, reflectors, plastic optical lenses and other optics-related components [2]. Compared to ultra-precision grinding, diamond turning utilizes defined tool geometry to directly generate the continuous surface profile on substrate surface using programmed tool path, without the relatively complicated and delicate wheel truing, dressing and centering processes as summarized and reported by Brinksmeier et al. [3]. Moreover, diamond tool has more flexibility in terms of size and geometry than grinding wheel, making diamond cutting a more versatile technology to generate complex and sophisticated optical profiles than grinding. Unfortunately, due to the high hardness and brittleness of WC, conventional diamond turning of WC is infeasible due to the fast excessive diamond tool wear and chipping on the cutting edge as well as subsurface brittle facture generated on the workpiece caused by brittle-mode cutting. Researchers are continuing putting effort to explore new

---

[*] Corresponding author.
E-mail address: dengh@sustc.edu.cn (H. Deng).

https://doi.org/10.1016/j.ceramint.2017.11.215
Received 20 September 2017; Received in revised form 12 November 2017; Accepted 29 November 2017

methods to enable direct diamond cutting of WC using diamond tools. For example, Marius et al. has observed that the critical depth of cut for ductile-brittle mode transition can be shifted when cutting fluids with different pH values are applied in diamond cutting of binderless WC [4,5]. Okada et al. has found that applying ultra-small feed rates in direct milling of WC with a diamond-coated carbide end mill could significantly improve the tool's wear resistance as well as the cutting performance [6].

Since more than two decades ago, ultrasonic vibration cutting (UVC) has been successfully applied in ultra-precision diamond turning process, in order to machine non-diamond-turnable metals (e.g. stainless steel reported by Moriwaki et al. [7], tungsten alloy reported by Suzuki et al. [8], etc.) and brittle ceramic materials (e.g. silicon reported by Zhang et al. [9], WC reported by Zhang et al. [10], etc.). UVC of WC was firstly reported by Suzuki et al. [11] to investigate the surface quality of micro grooving of WC with different amplitude and cutting speed applying ultrasonic elliptical vibration cutting. Later, Nath et al. has conducted a few studies on machinability of WC with the assistance of 2D UVC (i.e. ultrasonic elliptical vibration) cutting using polycrystalline diamond (PCD) tools [12,13], and concluded that ductile-mode machining of WC can be achieved using UVC with carefully selected cutting speed and vibration amplitude. Then, Zhang et al. has also conducted a comprehensive study on the wear rate of single crystal diamond (SCD) tools and surface integrity in 2D UVC of different types of tungsten carbide, and suggested a few appropriate conditions for machining of WC [10]. However, it has been found that the flank tool wear of SCD tools used in ultrasonic vibration cutting of WC is still significantly large (4 µm) even for a short cutting distance (4 m), and hence cannot be practically applied in diamond turning of a typical optical lens mold with a diameter 8 mm, which usually requires a cutting distance of at least 30 m or above. This fact has indicated the necessity of further studies to suppress the diamond tool wear in UVC of WC.

In recent years, Harano et al. from Sumitomo Electric Industries has developed a new type of PCD tool, which is named as nano-polycrystalline diamond (NPD) [14]. NPD is claimed to have comparable edge sharpness with SCD, but higher wear resistance than SCD due to its special isotropic mechanical properties. They has found that diamond tool flank wear can be improved by around 30% using NPD tools in ultra-precision cutting of WC compared to SCD tools. But it has not studied that if NPD tool will still perform similarly better than SCD tool in terms of tool wear suppression in UVC of WC.

Electrochemical processing has already been integrated into conventional machining processes in order to enhance their performance, particularly in grinding and polishing of brittle materials, like electrolytic in-process dressing of grinding wheel reported by Ohmori and Nakagawa [15] and in-situ surface oxidation of hard brittle material [16]. Deng et al. has integrated electrochemical processing into mechanical polishing process to enhance the material removal rate in polishing of silicon carbide (SiC). Silicon oxide (SiO_2), which has a lower surface hardness compared to SiC, is formed during the electrochemical process and hence improve the polishing performance. But electrochemical processing has not been combined into ultraprecision diamond turning of hard brittle ceramics, like tungsten carbide. It is necessary to investigate the effect of integrated electrochemical process on UVC of tungsten carbide, to evaluate its capability on improving cutting performance and suppressing diamond tool wear.

The objective of this study is to combine ultrasonic vibration cutting and electrochemical process to realize ductile-mode machining of ultra-fine grain tungsten carbide with minimized diamond tool wear. To achieve this, firstly 4 grooving tests with different vibration amplitudes in thrust directions are conducted to evaluate ductile-mode cutting performance under these cutting conditions. Then, PCD tools are used to conduct a series of face turning tests of WC with different combination of vibration amplitude, nose radius and spindle speed to determine the appropriate cutting conditions for the smallest diamond tool wear. With the determined cutting conditions applied, SCD and NPD tools are utilized in face turning of WC with the assistance of ultrasonic vibration to compared their tool wear conditions with respective to increasing cutting distances. Electrochemical processing is applied to modify the surface properties of WC surface to enhance its ductility and suppress its brittleness. PCD tools are firstly utilized to study the effect of processing duration on machining performance in face turning of WC in terms of tool wear and surface roughness. Then, SCD tools are eventually used to validate the performance of this hybrid machining method combining ultrasonic vibration and electrochemical process on suppressing diamond tool wear and improving the surface quality of machined WC. Compared to ultrasonic vibration cutting without electrochemical processing, diamond tool wear (VB) of less than 6 µm (≈ 40% reduction) has been achieved for a cutting distance of 40 m, and an areal surface roughness (S_a) of 23 nm (≈ 50% improvement) were obtained on the diamond cut WC surface.

2. Principle of ultrasonic vibration cutting

In the UVC process, the tool vibrates harmonically along the x-axis

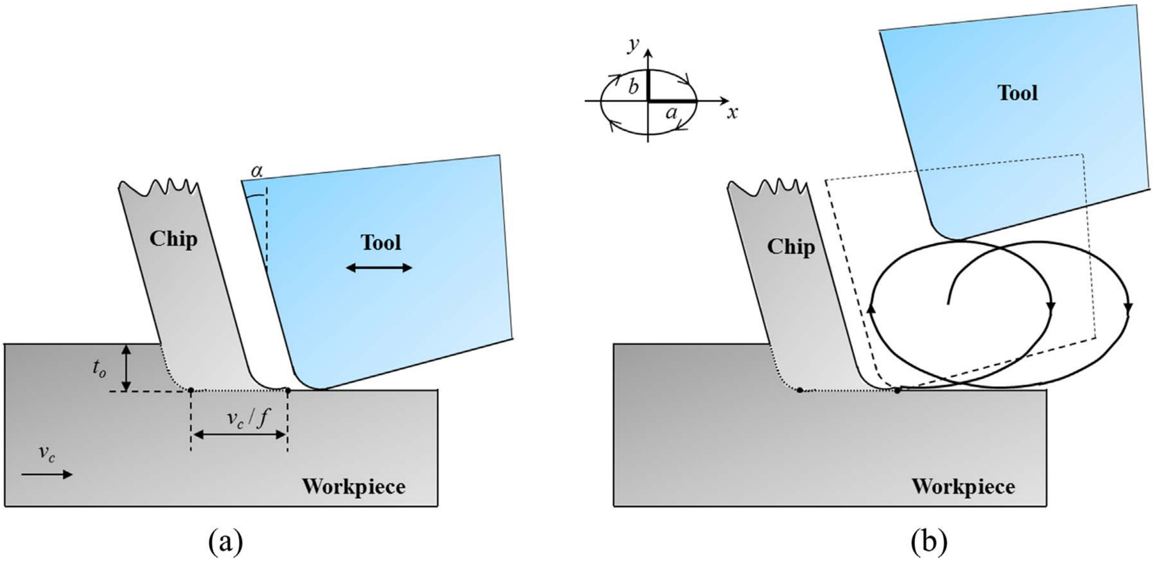


Fig. 1. Schematic illustration for the (a) 1D (a) and (b) 2D ultrasonic vibration cutting process.

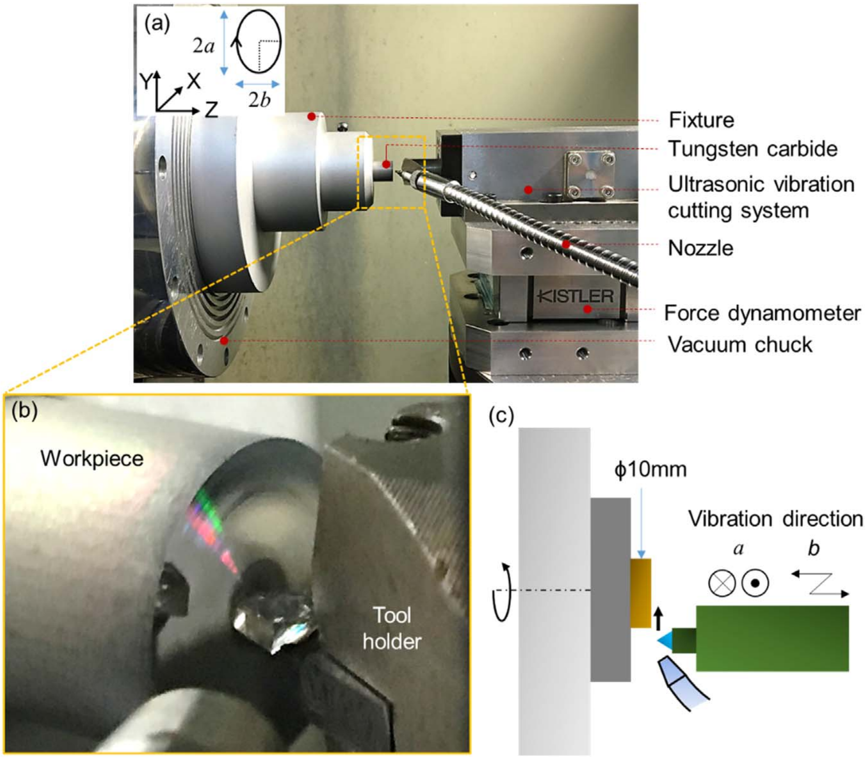


Fig. 2. (a) Physical experimental setup for face turning and grooving tests, (b) close-up view the SCD tool and WC workpiece, (c) schematic view of the UVC test.

and y-axis at a frequency f, and the workpiece is fed against the tool with a nominal cutting speed of v_c. Fig. 1 shows a schematic view of the 1D and 2D UVC process. The tool position relative to the workpiece can be given in the following equation:

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

where a is the cutting directional vibration amplitude, b is the thrust directional vibration amplitude, t is the time, and ϕ is the phase shift and is given 90° in this study. 1D UVC can be considered as a special 2D UVC when there is no vertical vibration (i.e. $b = 0$).

Brehl and Dow has summarized that speed ratio is considered as one of the most essential parameters in UVC [17], and tool rake face will separate from the uncut work material (i.e. intermittent cutting occurs) if its value is less than 1. It is defined as the ratio of the nominal cutting speed to the maximum vibration speed:

$$R_s = v_c/2\pi af \tag{2}$$

In UVC of brittle materials, it has already been reported by Suzuki et al. that reduced speed ratio will improve the performance for ductile-mode machining of brittle materials [11], and Zhang et al. [9] has developed an analytical model to predict the increment of critical undeformed chip thickness for reduced nominal cutting speed. However, Zhang et al. [10] has found that diamond tool wear after 2D ultrasonic vibration planing has a strong correlation with cumulative cutting distance, implying that reduced speed ratio or cutting speed can increase the diamond tool wear instead. Moreover, although researchers has generally concluded that smaller thrust directional amplitude will lead to improved cutting performance in terms of surface quality in 2D UVC of WC, as reported by Nath et al. [18] and Suzuki et al. [11], the performance of 1D UVC and 2D UVC in terms of surface quality and tool wear condition has not been carefully compared. As an optical mold for precision glass molding usually has its end aspheric surface with optical profile, face turning should be applied to precisely evaluate the machining performance for different vibration and cutting conditions.

3. Identification of cutting conditions

In this section, the machining performance of different combination of cutting and vibration parameters (including thrust directional vibration amplitude, spindle rotation speed and tool nose radius) are evaluated through a series of grooving and face turning tests using both SCD and PCD tools, in terms of diamond tool flank wear and machined surface quality, and the most appreciate cutting conditions are identified for later machining tests.

3.1. Experimental setup

The machining tests are performed on a 5-axis ultra-precision CNC machining system (*Moore Nanotech 350FG*), which has a 1 nm programming resolution for all the 3 linear axes. The ultrasonic vibration cutting system enables the installed tool to vibrate along the cutting direction (a) and the thrust direction (b) at a frequency of 38.87 kHz, and the peak to zero vibration amplitudes are adjustable ranging from 0 to 2 µm. Fresh diamond tools are installed and tightly locked at the tool holder located at the end of the ultrasonic horn. Tool centering with respective to the air spindle is conducted for each diamond tool before their cutting tests using a small brass workpiece. Dry air without mist is blown to the cutting zone to take away the heat generated and blow away the chips for all the tests.

Fig. 2 shows the experimental setup for face turning ang grooving tests. The workpiece utilized in this study is made of ultra-fine (0.5 µm grain size) tungsten carbide grain bound with 12% cobalt. The HV and HRA hardness values given by the supplier are 17.3 GPa and 92.5, respectively. The WC workpiece is in a cylindrical rod shape and locked in a fixture, which is then held on vacuum chuck of the machining system. Before the machining tests are conducted, the end face of the WC rod is pre-trimmed to obtain a flat surface with its flatness less than 0.4 µm. (Fig. 2).

3.2. Grooving test

To compare the cutting performance of 1D UVC and 2D UVC in

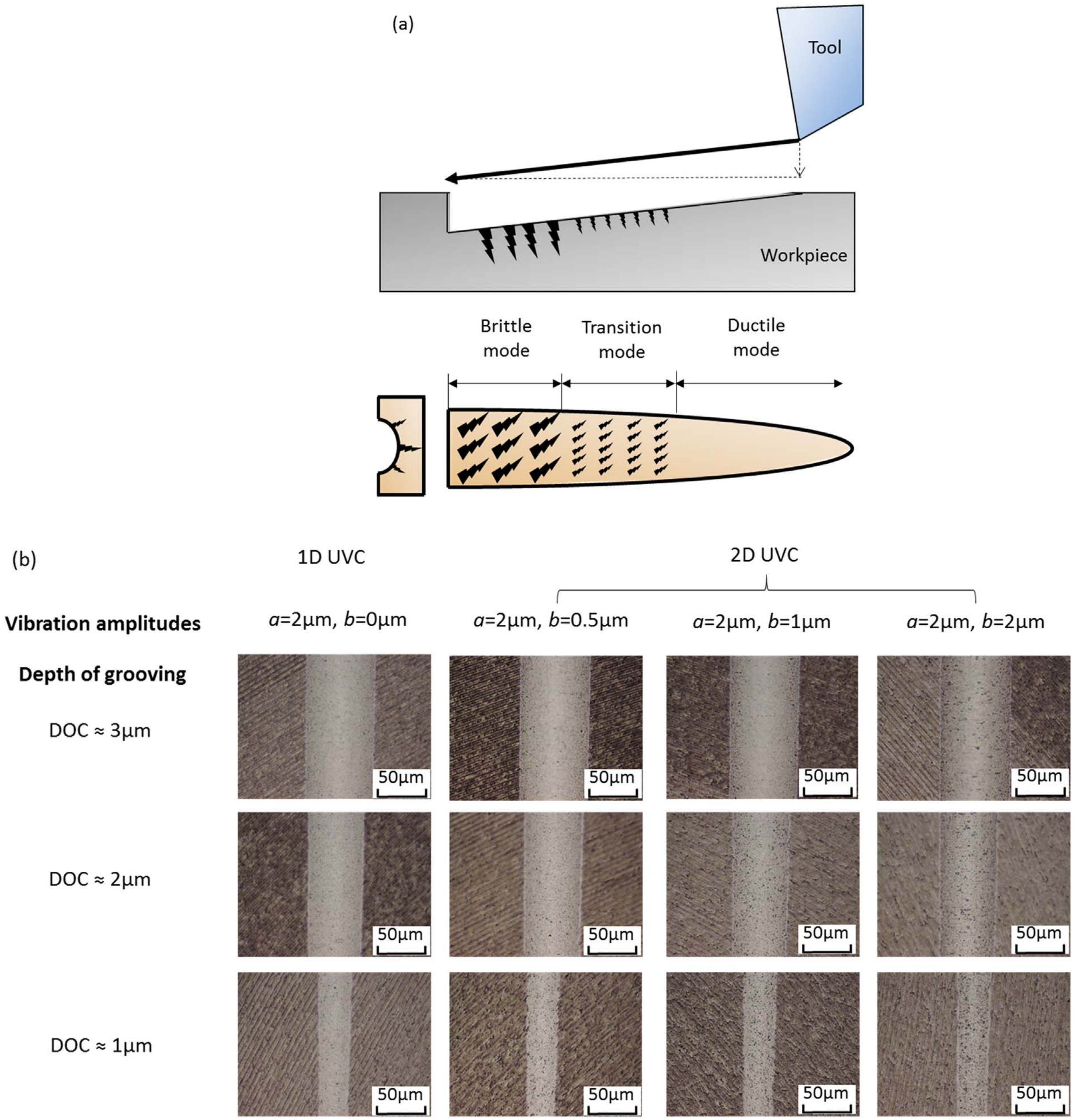


Fig. 3. (a) Schematic section view of the ultrasonic vibration grooving test on WC workpiece, (b) microscopic images of machined grooves at different DOCs.

terms of surface quality and generation of brittle fracture, 4 grooving tests are conducted on the WC workpiece using a SCD tool with 0.2 mm nose radius, −30° rake angle and 10° clearance angle, as shown in Fig. 3(a). A nominal cutting speed of 1200 mm/min is applied in the tests, and the calculated speed ratio (R_s) is 0.041, which is significantly smaller than the maximum speed ratio derived by Nath et al. [18]. After performing the groove tests, microscopic pictures of the machined grooves are taken and shown in Fig. 3(b), with respective to different grooving depths.

From Fig. 3(b), for the grooves machined by 2D UVC, it can be observed that less brittle fracture is observed with the reduction of thrust directional vibration amplitude (*b*) at all grooving depths, which precisely matches the phenomenon observed by Suzuki et al. [11] and Zhang et al. [10]. In particular, it can also be found from these pictures that, when the thrust directional vibration amplitude is reduced to zero (i.e. 1D UVC), minimum brittle fracture is observed on the bottom surface of grooves, for all conditions with either small or large grooving depth. The phenomenon of increased brittle fracture at 2D UVC of WC could be caused by the punching impact induced by the micro elliptical digging motion of the diamond tool. As Shamoto et al. [19] and Zhang et al. [20] has already theoretically proven that 2D UVC will lead to a much smaller shear plane angle due to the reversed friction between tool and chip, a smaller partial pneumatic pressure applied on the tool-workpiece contact zone in 2D UVC is expected, which will in turn weaken the ductile-mode machining capability of ultrasonic vibration cutting.

To confirm the effect of thrust direction vibration amplitude on the suppression of brittle fraction in cutting of brittle materials, the same experimental set up is utilized to conduct grooving tests on single crystal silicon with higher brittleness using another single crystal diamond tool with 0.6 mm nose radius. From the results shown in Fig. 4, it can be proven that 1D UVC does perform better than 2D UVC in suppressing fracture generation on the machined brittle workpiece surface, and lower thrust directional vibration amplitude leads to better ductile-

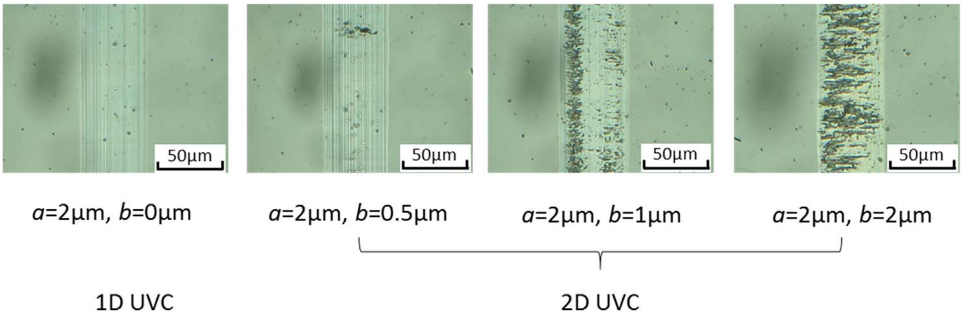


Fig. 4. Microscopic images of ultrasonic vibration cut grooves on silicon at different thrust directional amplitudes.

Table 1

Conditions for the face turning tests on WC with ultrasonic vibration.

Experiment No.	Vibration amplitudes, μm		Spindle speed at OD, RPM	Nose radius, mm
	a	*b*		
I	2	0.5	40	0.2
II	2	0.5	20	0.2
III	2	0	20	0.2
IV	2	0.5	20	0.4
V	2	0	20	0.4

mode cutting.

3.3. Identification of UVC parameters

After evaluating the surface quality of machined grooves with different vibration parameters, it is also necessary to evaluate the diamond tool wear conditions in UVC of WC workpiece with different combination of vibration and cutting conditions. In this study, a series of face turning experiments are conducted using PCD tools with a depth of cut of 4 μm and a feed rate of 2.5 μm per revolution, and total cutting distance is calculated to be approximately 31 m. The PCD tools used in this study have a 0° rake angle, an 11 °clearance angle and a grade number of DA150. Table 1 lists the selected machining parameters utilized in this study. Considering the sensitivity of nominal cutting speed on the cutting performance in UVC, constant surface speed is applied in all the face turning tests in this study, and the spindle rotation speed at the outer diameter (OD, ϕ10 mm) is shown in the table. For example, the nominal cutting speed for 20 revolution per minute (RPM) at OD is 314 mm/min, and the spindle rotation rate will increase accordingly when the diamond tool approaches to the workpiece center and its relative radial position decreases. Fig. 5 shows the rake and flank tool wear conditions captured using a microscope as well as the values of flank wear (VB) for these 5 cutting tests.

From Fig. 5, by comparing experiment II and III as well as IV and V, it can be confirmed that 1D UVC performs better than 2D UVC in terms of flank tool wear rate for both nose radius, corresponding with the result obtained in the grooving tests as illustrated above. Moreover, by comparing experiment II and IV as well as III and V, it can also be concluded that, under the same vibration and cutting conditions, a large nose radius will lead to a reduced tool flank wear. This result is caused by the reduced maximum undeformed chip thickness (t_{max}) with

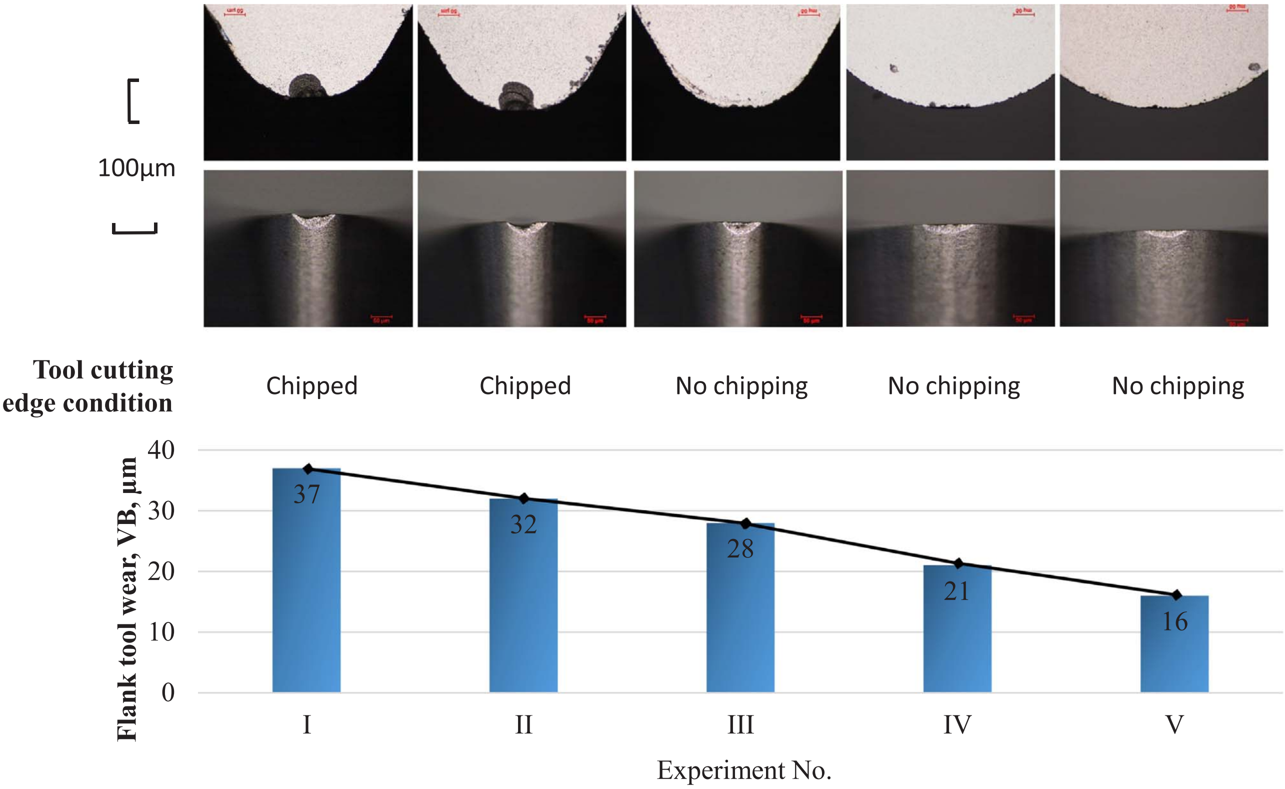


Fig. 5. PCD tool fracture and wear conditions for the 5 face turning tests (31 m cutting distance) with different cutting conditions.

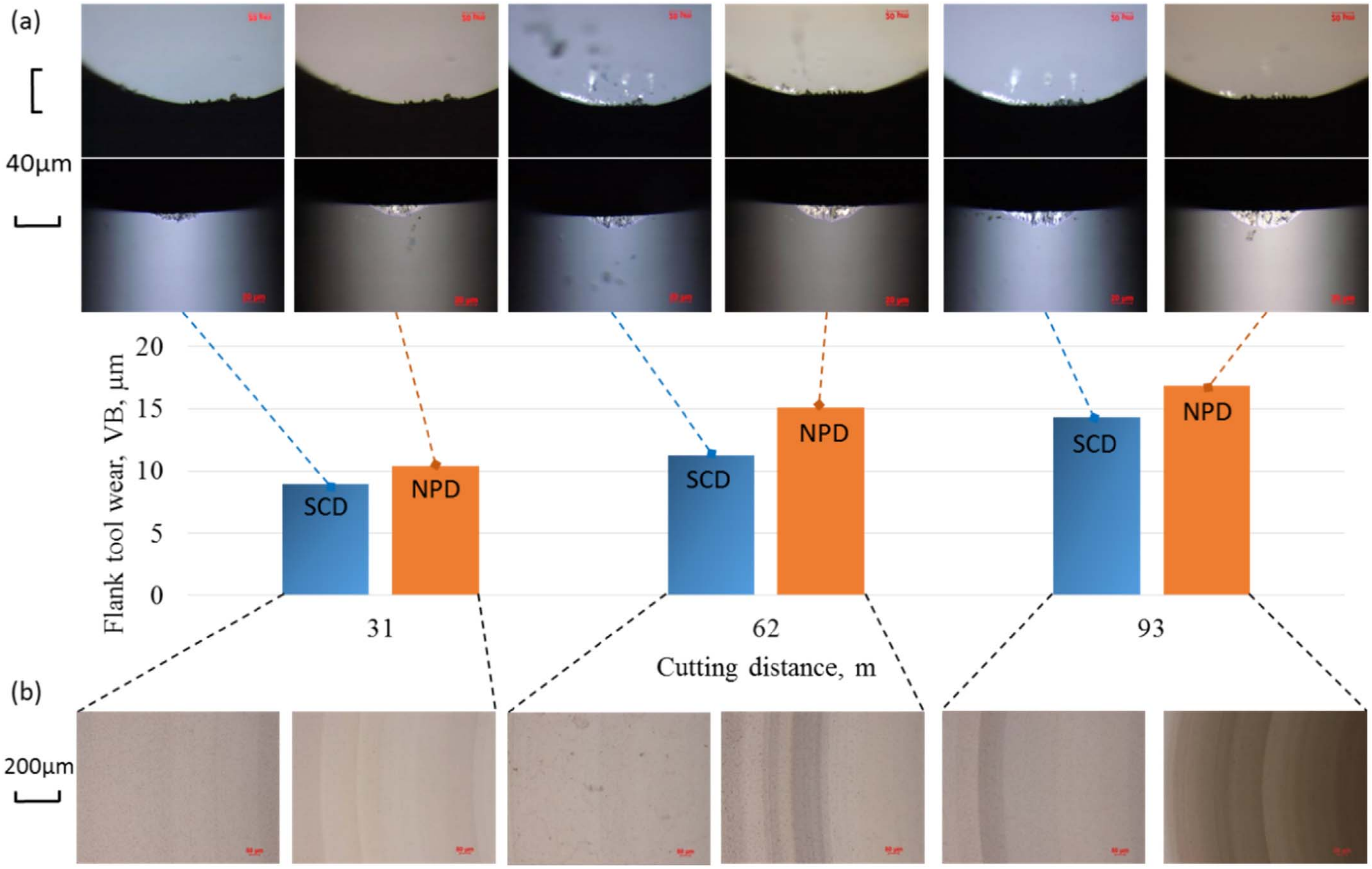


Fig. 6. (a) Diamond tool wear conditions against the increment of cutting distance, (b) machined WC workpiece surface taken by microscope.

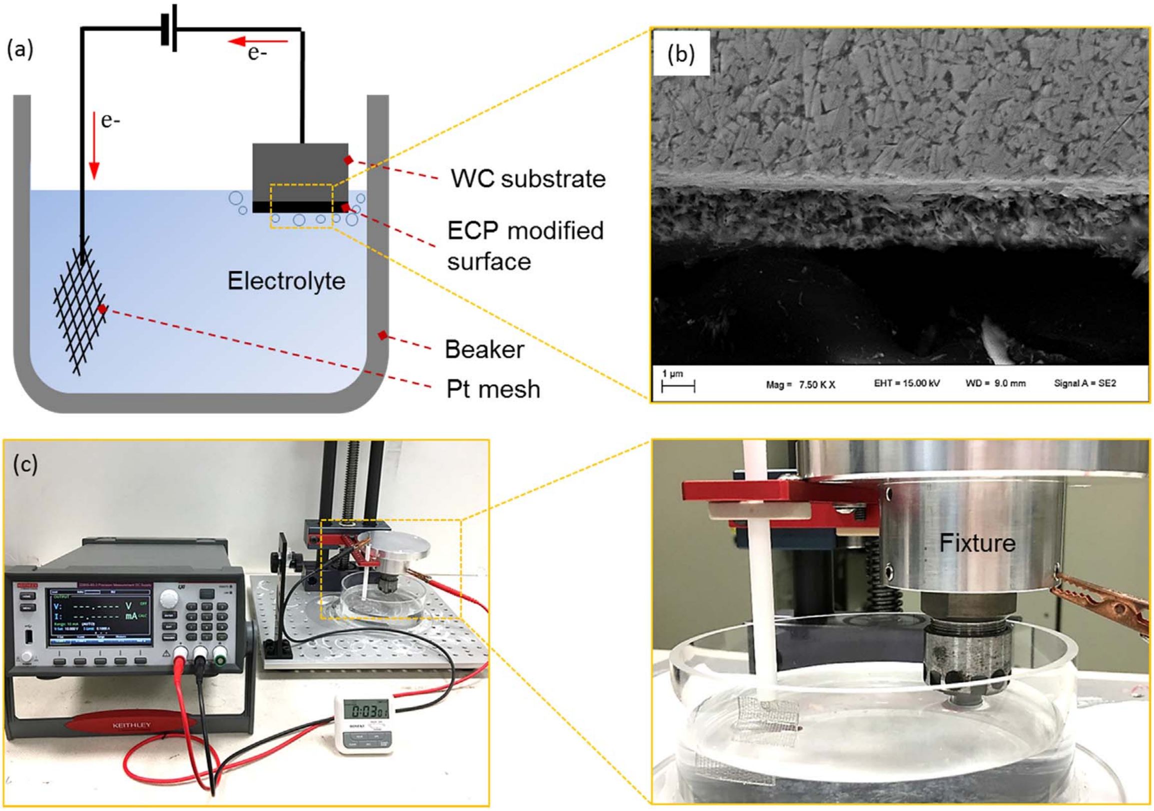
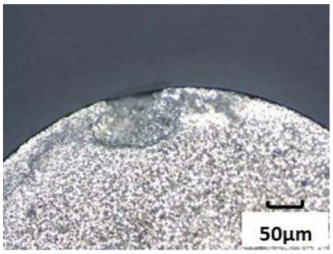
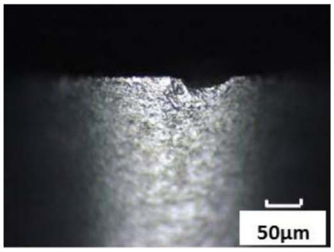
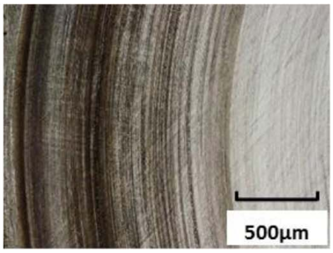
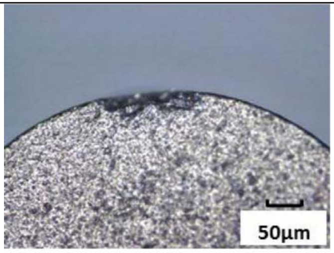
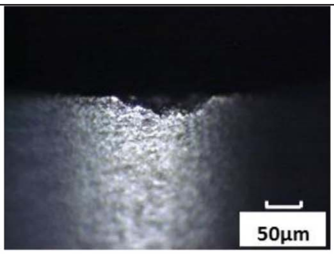
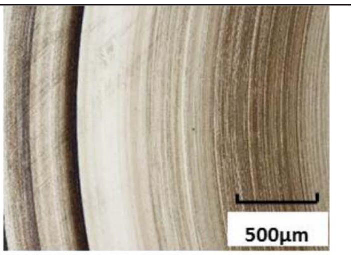
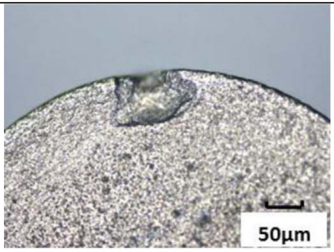
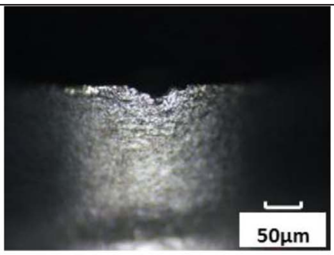
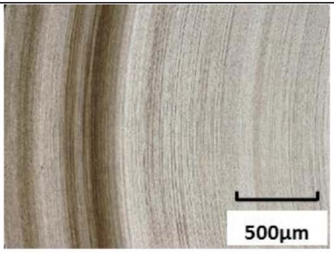
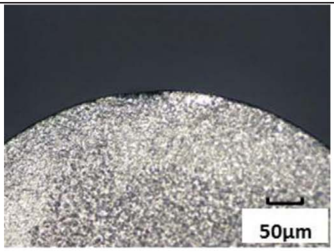
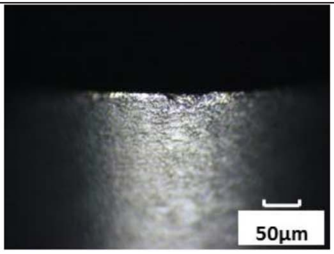
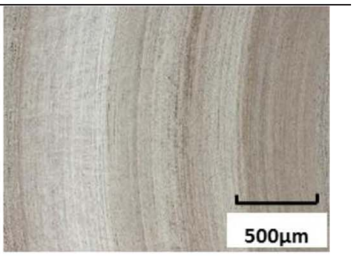
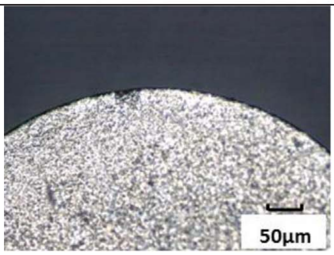
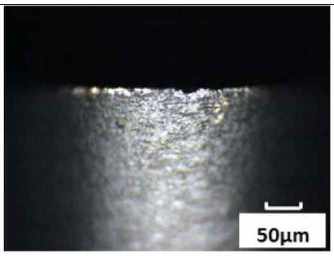
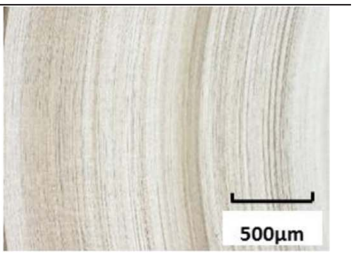


Fig. 7. (a) Schematic illustration of electrochemical processing, (b) SEM picture of the cross section surface of ECP treated WC insert, (c) physical view of the ECP system with WC workpiece installed.

Table 2
Experimental results of ECP time in UVC of WC using PCD tools.

ECP duration (mins)	Tool wear conditions		Machined surface
	Rake face	Flank face	Microscopic images
0			
0.5			
1			
2			
4			

a larger tool nose radius, and machining of brittle materials is usually very sensitive to this parameter, as reported by Yan et al. [21]. By comparing experiment I and II, we can find that reduced nominal cutting speed or spindle rotation speed will lead to a smaller tool flank wear, which seems not complying the findings obtained from 2D UVC of WC (reduced nominal cutting speed lead to increased tool flank wear) by Zhang et al. Further studies should be conducted in future to confirm the effect of nominal cutting speed on the diamond tool wear rate in UVC of WC.

3.4. Identification of diamond type (SCD vs NPD)

Although nano-polycrystalline diamond has already been introduced by researchers several years ago to eliminate the anisotropy effect of single crystal diamond for better tool wear resistance in ordinary diamond turning of brittle materials, like WC. Its cutting performance in terms of tool wear rate improvement in UVC has not been studied until now. In this study, to identify the type of diamond tool to be used in UVC of WC, a SCD and a NPD tool are utilized in 1D UVC (i.e.

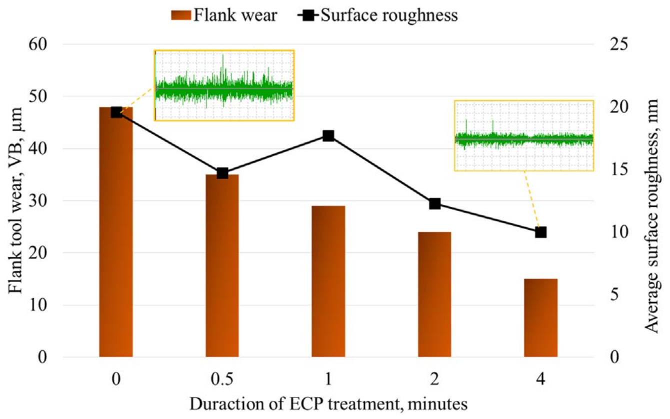


Fig. 8. Effect of ECP treatment duration on tool wear and surface roughness (R_a, cut-off length $\lambda_c = 0.08$ mm).

Table 3
Cutting conditions for diamond turning of tungsten carbide workpiece.

Cutting parameters	Values
Feed rate, f_r (µm/rev)	2
Depth of cut, A_p (µm)	7
Spindle rotation rate at OD, N (RPM)	20
Nominal cutting speed (constant), v_c (mm/min)	6.28
Workpiece diameter (mm)	10
Total cutting distance (m)	40
Cutting directional vibration amplitude, a (µm)	2
Thrust directional vibration amplitude, b (µm)	0
Coolant condition	Dry air
Cutting tool	
Tool material	Single-crystal diamond
Nose radius (mm)	0.5
Rake angle (deg.)	−30

$b = 0$) of WC to compare their tool wear condition. The same WC workpiece, nominal cutting speed (20RPM at OD), feed rate (2.5 µm/rev) and depth of cut (4 µm) with the above test using PCD tools are applied in this face turning test, and the diamond tool used here has a nose radius of 0.2 mm and a −30° rake angle.

It can be observed from Fig. 6(a) that the flank wear of NPD tool is always not smaller than SCD tool with increasing cutting distances, which means that NPD does not perform better than SCD in UVC of WC material, not like the ordinary diamond turning process. No catastrophic chipping on the cutting edge has been observed from both types of diamond tools, meaning that abrasive tool wear dominates the tool wear mechanism in UVC of WC. The same trend on surface quality of machined WC workpiece can be observed from the microscopic images in Fig. 6(b), and more obvious feed marks are found on machined workpiece using the NPD tool for all the 3 cutting distances.

4. Development of hybrid machining technology

4.1. Electrochemical processing of WC

Although ultrasonic vibration has already been proven effective in suppressing the diamond tool wear and realizing ductile-mode cutting in machining of hard brittle WC, but the tool wear is still not small enough to be utilized in diamond turning of typical WC molds for precision glass molding application. Besides the high brittleness of WC, another major contribution factor causing the high wearing rate of diamond in cutting of WC is its close hardness value to diamond, resulting into fast abrasive tool wear due to the sliding friction between the diamond and carbide grain.

In order to lower the micro hardness of WC workpiece and hence reduce the abrasive tool wear rate of diamond, electrochemical processing (ECP) is utilized to soften the top layer of WC workpiece by partially changing its chemical composition, as shown in Fig. 7(a) and (b). A field emission scanning electron microscope (FE-SEM), *Zeiss ULTRA plus*, is utilized in this study to take the pictures of WC workpiece and SCD tools for analysis. The accelerating voltage for observing the workpiece using SEM is 10–15 kV, while a much lower voltage, 3 kV, is applied in observing diamond tools to prevent overcharging. A customized ECP device is designed in this study, as shown in Fig. 7(c), to conduct surface modification before the WC workpiece is face turned with assistance of ultrasonic vibration using diamond tools. The electrolyte used in ECP in this study is NaOH solution with 0.5% weight percentage, and constant current mode (0.5 A) with varying electric voltage is applied. After ECP, the substrate is rinsed in water and dried by air gun. Then, the workpiece is installed on the vacuum chuck of the air spindle for the UVC test.

4.2. Evaluation using PCD tools

After development of ECP methodology for surface treatment of WC workpiece, it is necessary to evaluate its performance in suppressing the diamond tool wear in UVC of WC workpiece with respect to processing duration. Hence, a series of cutting tests using PCD tools with 0.4 mm nose radius and 0° rake angle are conducted on WC workpiece which is

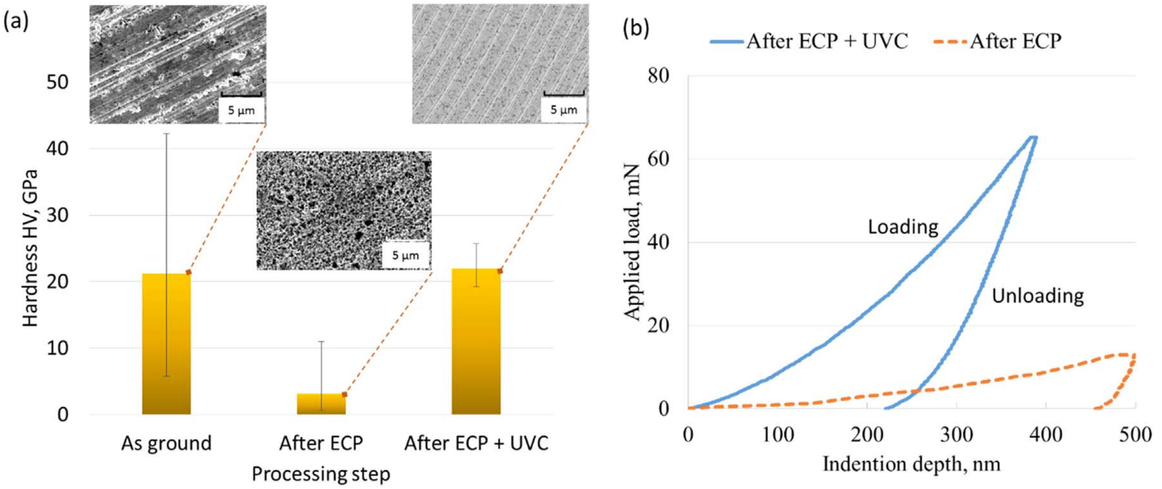


Fig. 9. (a) Surface hardness of WC workpiece at three conditions: as ground, after ECP (3 min) and after ECP + UVC; (b) applied load against the indentation depth.

treated with different ECP time under the same experimental conditions. The same WC workpiece is utilized, and 1D UVC is applied on this face turning test. A spindle speed of 20RPM at OD, a feed rate of 2 µm/rev and a depth of cut of 7 µm are utilized, with the total cutting distance for each test calculated as 40 m.

Table 2 and Fig. 8 shows the results of tool wear conditions and surface finish for these machining tests. The average surface roughness (R_a) of machined workpiece is measured using a stylus profilometer and a stylus tip of 2 µm radius. It can be clearly observed that the flank wear of PCD tool and the surface roughness value gradually decrease with the increment of ECP treatment time. In particular, for the cutting tests on WC workpiece with ECP time less than 2 min, significant chipping has been observed on the rake face of the PCD tools, and microscopic images also show very uneven surface and wide circular feed marks which could be caused by the turning motion of the cracked cutting edges. The reduced tool wear with increased treatment time shall be caused by the increased ductility and reduced brittleness of the top surface of WC workpiece, which hence can enhance the performance of ductile-mode machining in UVC by reducing the impact force between cutting edge and workpiece.

5. Validation using SCD tools

After evaluating the effect of ECP time on the flank wear conditions of PCD tools using UVC, it is necessary to utilize SCD tool to validate the performance of ECP in the tool wear suppression, because SCD tool usually has much better contour accuracy and edge sharpness which are essential for achieving the desired profile accuracy of machined optical molds. 1D UVC is applied in the face turning test on the same WC workpiece as above. The conditions for cutting, vibration and tool geometry are listed in Table 3. Two cutting tests are conducted in order to evaluate the effect of ECP, namely, comparison between direct UVC without ECP and UVC after 3 min ECP.

For the hybrid cutting test combining ECP and UVC, its surface hardness before and after the UVC are evaluated using a nano-indentation system, and the results are shown in Fig. 9. From Fig. 9, it can be observed that the surface hardness is significantly reduced after ECP compared to the pre-ground surface. After the subsequent UVC on the ECP treated WC surface, the surface hardness returns to the normal level, because the relatively softer layer generated by ECP has been removed during the cutting process. It can also be observed that the distribution range of measured surface hardness (30 points) after UVC is much smaller compared to the WC surface as ground, demonstrating that ultrasonic vibration-assisted cutting may lead to more uniform material removal compared to the abrasive process.

To analyze the surface chemical composition after the ECP and the subsequent UVC process, *ESCALAB 205Xi* X-ray photoelectron spectroscopy (XPS) microprobe from *Thermo Scientific* is used to analyze the workpiece surface, and the results are shown in Fig. 10(a) and (b) respectively. Al-Kα radiation is used in the XPS analysis with a spot size of 900 µm and 30 times of scanning for selected elements. From Fig. 10(a), it can be observed that, besides WC, WO_3 is also formulated according to the intensity distribution against the binding energy. As reported by Parreira et al. [22] and Maillé et al. [23], WO_3 usually has a relatively lower surface hardness. For example, the hardness of pure WO_3 thin film deposited via RF sputtering has been measured to be around 4 GPa [23], which is very close to the measured average hardness (3.16 GPa) of WC workpiece after ECP in this study. Due to the varying mixture rate of WO_3 and WC as well as varying porosity condition at different indentation positions, the measured surface hardness of WC workpiece after ECP can range from 0.7 to 10.9 GPa. It can also be observed from Fig. 10(b) that that only WC is left after the subsequent UVC process on the ECP treated WC surface, meaning that generation of WO_3 in ECP only happens on the top thin layer of contact surface between the WC workpiece and electrolyte, and does not penetrate into the deeper substrate of WC. Similar phenomenon can also be found on the disappearing of CoO after UVC is conducted on the ECP treated workpiece. Based on the XPS analysis results, the following chemical equations can be used to illustrate the change of composition during the ECP:

$$WC + 10OH \rightarrow WO_3 + 5H_2O + CO_2\uparrow \quad (3)$$

$$Co + 2OH \rightarrow CoO + H_2O \quad (4)$$

The diamond tools after the machining test are evaluated using an optical microscope and an SEM, and their pictures are shown in Fig. 11(a) and (b) respectively. It can be clearly observed that ECP treatment will significantly reduce the wear of SCD tools used in UVC of WC workpiece. The flank wear, VB, has been reduced from 11.2 to 5.8 µm, demonstrating that ECP is able to successfully suppress the diamond tool wear in UVC of WC workpiece. It should be caused by the reduced brittleness and hardness of the ECP treated superficial layer, which is resulted from the partial transition from WC to WO_3 on the WC surface.

Fig. 12(a), (b) and (c) show the results of machined workpiece surface measured using white light interferometer (*ContourGT-K, Bruker*), microscope and digital camera, respectively. Vertical scanning interferometry (VSI) mode and 50× objective lens are utilized when taking pictures using the interferometer. The measured areal surface roughness (S_a) with ECP is much lower than the surface machined without ECP. From Fig. 12(b), it can be observed that no micro defects are found on the machined surface with ECP than without ECP,

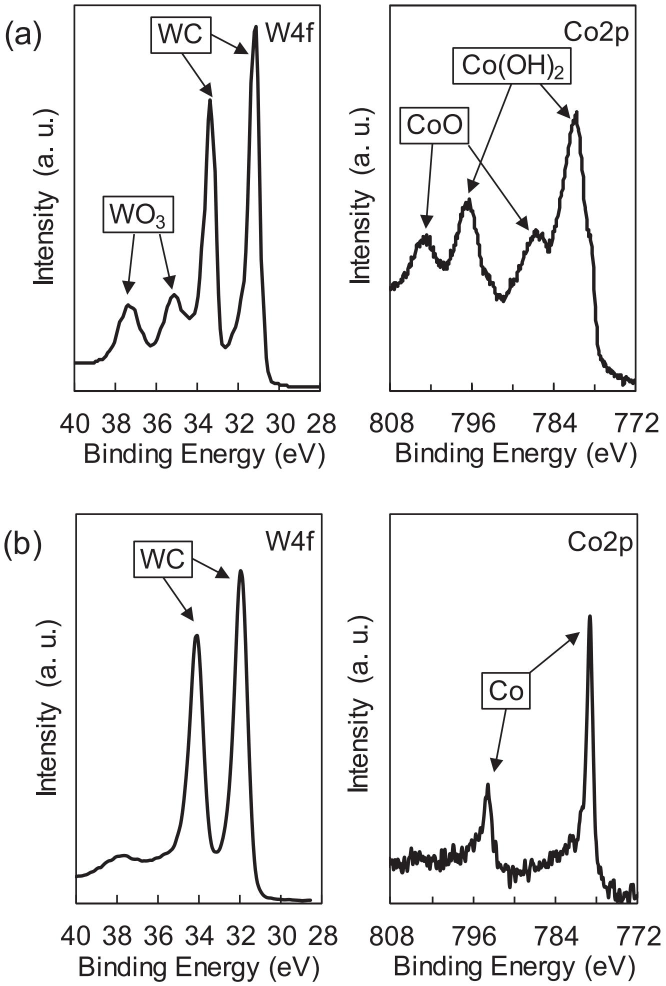


Fig. 10. XPS analysis for the workpiece surfaces (a) after ECP treatment but before UVC, and (b) after sequential ECP and UVC.

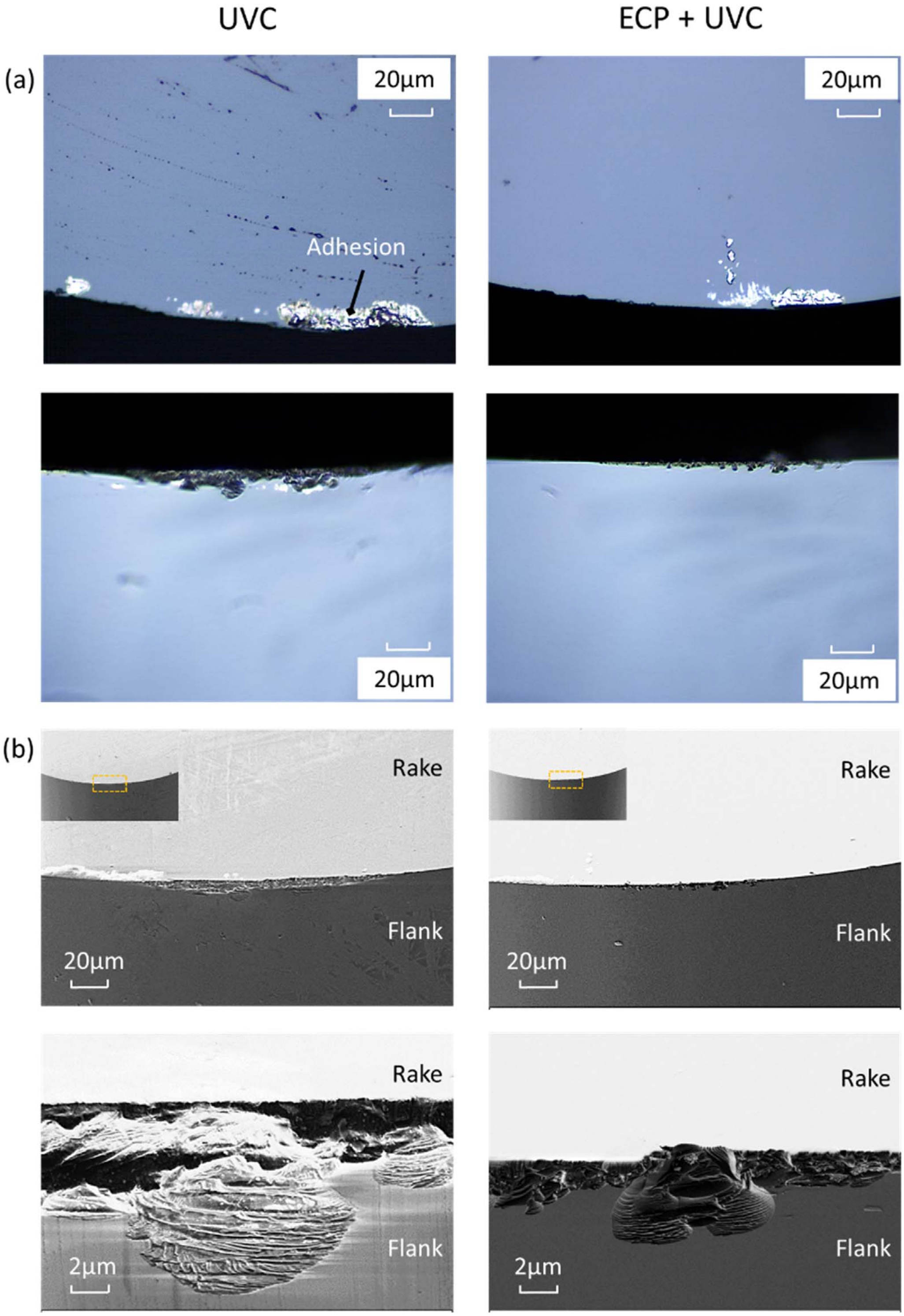


Fig. 11. Comparison of tool wear conditions after ultrasonic vibration-assisted face turning of WC workpiece with and without ECP treatment.

demonstrating that ductile-mode machining has been realized by the developed technology with sequential ECP and UVC and the identified appreciate cutting conditions. During the ductile-mode machining condition, brittle materials can be removed in a ductile fracture mode, accompanied by mainly plastic deformation around the cutting zone. It will lead to better surface finish and less tool wear, and the machined surface usually has much less micro defects because there is minimum micro crack initiation and propagation into the workpiece substrate material at such ductile fracture mode. When ECP is applied, near mirror surface finish has been achieved with better optical quality on the ultra-fine grain WC workpiece, as shown in Fig. 12(c).

6. Conclusions

In this study, a hybrid machining technology combining ultrasonic vibration cutting and electrochemical processing is proposed to suppress the diamond tool wear in cutting of tungsten carbide. The appropriate machining conditions are identified first, including cutting and vibration parameters as well as the suitable type of diamond. The proposed hybrid machining method is evaluated in terms of ECP duration using poly-crystalline diamond tools, and then thoroughly validated using single crystal diamond tools. The following conclusions are drawn from this study:

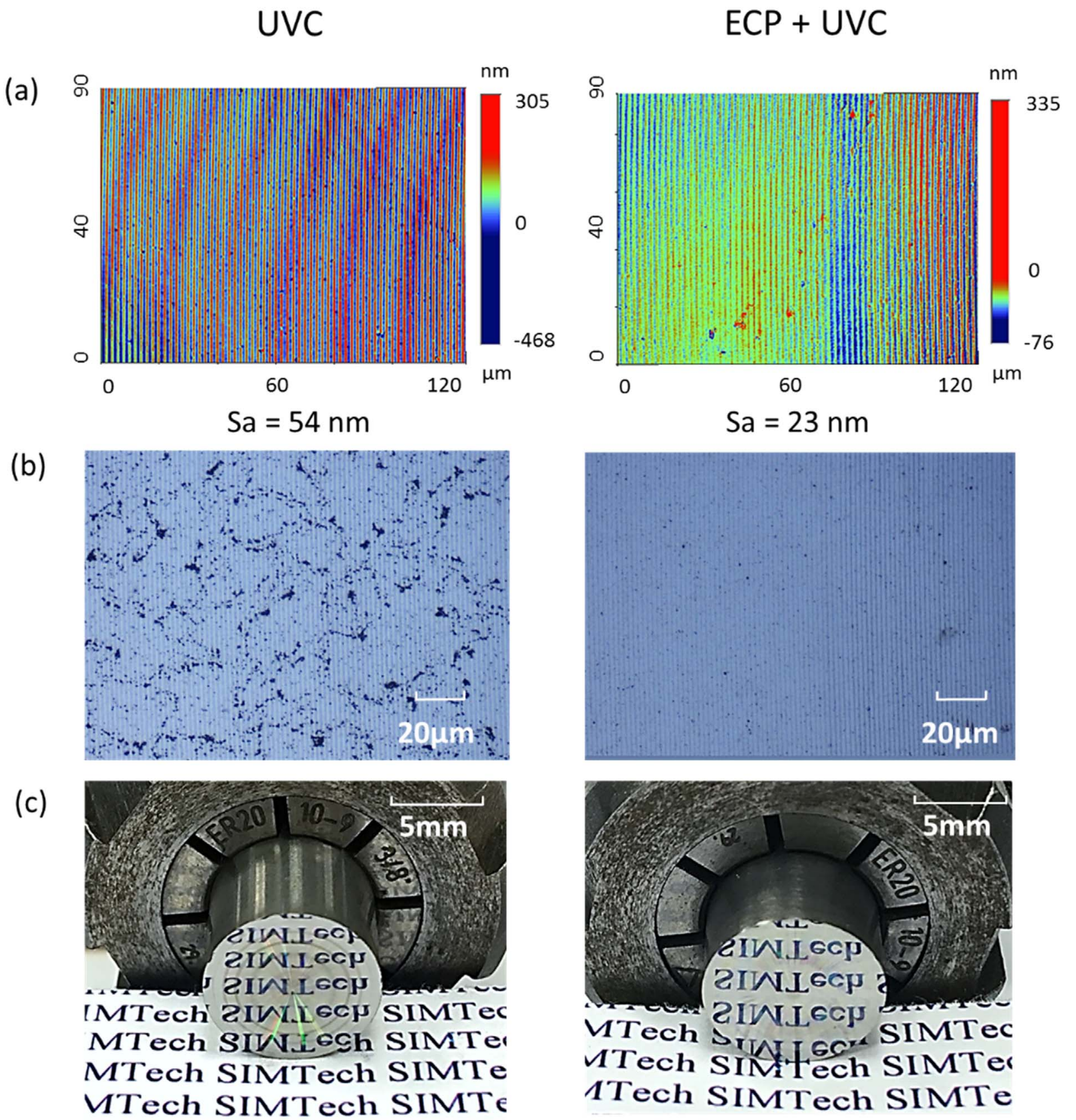


Fig. 12. Comparison of face turned workpiece after UVC of WC with and without ECP.

1. Lower thrust directional amplitude in 2D UVC will lead to less brittle fracture generated on machined brittle surface of WC, and 1D UVC with no thrust directional vibration leads to minimum brittle fracture and less diamond tool wear.
2. Increased tool nose radius and reduced nominal cutting speed in UVC will lead to less diamond tool wear and suppress the catastrophic crack of cutting edges in face turning of WC.
3. Nano-polycrystalline diamond with isotropic mechanical properties does not perform better than single crystal diamond as the tool material in terms of tool flank wear in 1D UVC of WC.
4. With the increase of the treatment duration of ECP for the uncut surface of WC workpiece, the PCD tool wear decreases and the machined surface quality is increased.
5. Surface hardness of WC workpiece decreases after ECP due to its partial conversion to WO_3 with lower hardness and less brittleness, which is mixed with WC grain and supersede the original superficial layer of pure WC.
6. Less tool wear and better surface quality can be achieved using the proposed hybrid machining method compared to direct UVC using SCD tools, and a tool flank wear of less than 6 μm and damage-free near-mirror surface finish are eventually obtained for ultra-precision machining of ultra-fine grain WC for 40 m cutting distance.

References

[1] O. Dambon, F. Wang, F. Klocke, G. Pongs, B. Bresseler, Y. Chen, A.Y. Yi, Efficient mold manufacturing for precision glass molding, J. Vac. Sci. Technol. B: Microelectron. Nanometer Struct. Process. Meas. Phenom. 27 (3) (2009) 1445–1449.

[2] F.Z. Fang, X.D. Zhang, A. Weckenmann, G.X. Zhang, C. Evans, Manufacturing and measurement of freeform optics, CIRP Ann. 62 (2) (2013) 823–846.

[3] E. Brinksmeier, Y. Mutlugünes, F. Klocke, J.C. Aurich, P. Shore, H. Ohmori, Ultra-precision grinding, CIRP Ann. 59 (2) (2010) 652–671.

[4] M. Doetz, O. Dambon, F. Klocke, O. Fähnle, Influence of coolant on ductile mode processing of binderless nanocrystalline tungsten carbide through ultraprecision diamond turning, in: SPIE Optical Engineering + Applications, International Society for Optics and Photonics, 2015, pp. 95750R-95750R-95757.

[5] M. Doetz, O. Dambon, F. Klocke, O. Faehnle, Chemical influence of different pH-values on ductile mode processing through ultra-precision diamond turning, in: Proceedings of the Third European Seminar on Precision Optics Manufacturing, Vol. 10009, International Society for Optics and Photonics, 2016, pp. 1000905.

[6] M. Okada, A. Yoshida, T. Furumoto, H. Watanabe, N. Asakawa, M. Otsu, Mechanisms and characteristics of direct cutting of tungsten carbide using a diamond-coated carbide end mill, Int. J. Adv. Manuf. Technol. 86 (5–8) (2016) 1827–1839.

[7] T. Moriwaki, E. Shamoto, Ultraprecision diamond turning of stainless steel by applying ultrasonic vibration, CIRP Ann. 40 (1) (1991) 559–562.

[8] N. Suzuki, M. Haritani, J. Yang, R. Hino, E. Shamoto, Elliptical vibration cutting of tungsten alloy molds for optical glass parts, CIRP Ann. 56 (1) (2007) 127–130.

[9] X. Zhang, M. Arif, K. Liu, A.S. Kumar, M. Rahman, A model to predict the critical undeformed chip thickness in vibration-assisted machining of brittle materials, Int. J. Mach. Tools Manuf. 69 (0) (2013) 57–66.

[10] J. Zhang, N. Suzuki, Y. Wang, E. Shamoto, Fundamental investigation of ultra-precision ductile machining of tungsten carbide by applying elliptical vibration cutting with single crystal diamond, J. Mater. Process. Technol. 214 (11) (2014) 2644–2659.

[11] N. Suzuki, S. Masuda, M. Haritani, E. Shamoto, Ultraprecision micromachining of brittle materials by applying ultrasonic elliptical vibration cutting, In: International Symposium on Micro-NanoMechatronics and Human Science, Nagoya, Japan, 2004, pp. 133– 138.

[12] C. Nath, M. Rahman, K.S. Neo, Machinability study of tungsten carbide using PCD tools under ultrasonic elliptical vibration cutting, Int. J. Mach. Tools Manuf. 49 (14) (2009) 1089–1095.

[13] C. Nath, M. Rahman, K.S. Neo, A study on the effect of tool nose radius in ultrasonic elliptical vibration cutting of tungsten carbide, J. Mater. Process. Technol. 209 (17) (2009) 5830–5836.

[14] K. Harano, T. Satoh, H. Sumiya, Cutting performance of nano-polycrystalline diamond, Diam. Relat. Mater. 24 (2012) 78–82.

[15] H. Ohmori, T. Nakagawa, Mirror surface grinding of silicon wafers with electrolytic in-process dressing, CIRP Ann. 39 (1) (1990) 329–332.

[16] H. Deng, K. Hosoya, Y. Imanishi, K. Endo, K. Yamamura, Electro-chemical mechanical polishing of single-crystal SiC using CeO2 slurry, Electrochem. Commun. 52 (2015) 5–8.

[17] D.E. Brehl, T.A. Dow, Review of vibration-assisted machining, Precis. Eng. 32 (3) (2008) 153–172.

[18] C. Nath, M. Rahman, K.S. Neo, Modeling of the effect of machining parameters on maximum thickness of cut in ultrasonic elliptical vibration cutting, ASME J. Manuf. Sci. Eng 133 (2011) 011007.

[19] E. Shamoto, N. Suzuki, R. Hino, Analysis of 3D elliptical vibration cutting with thin shear plane model, CIRP Ann. 57 (1) (2008) 57–60.

[20] X. Zhang, A. Senthil Kumar, M. Rahman, C. Nath, K. Liu, An analytical force model for orthogonal elliptical vibration cutting technique, J. Manuf. Process. 14 (3) (2012) 378–387.

[21] J. Yan, Z. Zhang, T. Kuriyagawa, Mechanism for material removal in diamond turning of reaction-bonded silicon carbide, Int. J. Mach. Tools Manuf. 49 (5) (2009) 366–374.

[22] N.M.G. Parreira, N.J.M. Carvalho, A. Cavaleiro, Synthesis, structural and mechanical characterization of sputtered tungsten oxide coatings, Thin Solid Films 510 (1) (2006) 191–196.

[23] L. Maillé, C. Sant, P. Aubert, P. Garnier, Morphological and mechanical properties study of [WO 3/W] n nanoscale multilayers, Thin Solid Films 479 (1) (2005) 201–206.