



Surface finishing and tool wear in single point diamond turning of chemical vapour deposited tungsten carbide hard coatings

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ABSTRACT

Precision-engineered components which operate in demanding conditions often require the application of hard coatings such as tungsten carbide (WC) to improve their functional properties. Following the coating deposition process, a surface finishing or machining operation is often required to correct the sizing or achieve adherence to geometrical tolerancing and surface finish requirements. Single point diamond turning (SPDT) is a widely used ultraprecision machining technique for the fabrication of high-end engineering components made up of ductile materials, making it a desirable technique as a post-coating machining or finishing process. In this study the machinability of hard CVD W/WC coatings with a hardness of 1120 ± 15 HV and a thickness of 100 μm using SPDT was investigated. Here we report the results of axial and transverse turning using a cutting speed of 600 rpm and feed rates of 1 and 5 μm respectively. Experimental results show that an Ra of 0.2 μm is achieved with a diamond tool having a 0.5 mm nose radius. Significant tool wear was observed at the rake/flank edge of the diamond tool due to the coating's hardness. Surface and cross-sectional analysis of the samples' machined areas revealed presence of adhesive and abrasive wear. The occurrence of material pile-up due to tool loading on the surface of the coating was investigated through the indentation technique which demonstrated the occurrence of material deformation contributing to the overall surface roughness.

1. Introduction

The application of hard coatings on high-end precision engineering components is of principal importance to extend the working life of components which operate in demanding applications. Key applications which operate in high precision environments that benefit from hard coatings include forming tools, injection molding tooling, lenses for the space industry and aerospace components [1–7]. Amongst many existing hard coatings, chemical vapour deposited (CVD) W/WC coatings have superior mechanical properties due to their high hardness and wear resistance [8–10] and can be deposited with a thickness of 50 μm to 100 μm . This coating thickness provides high durability and load-bearing capacity, but may result in the coated parts losing their precise dimensional tolerancing. While CVD W/WC coatings could be deposited to practically any high-end engineering components, post deposition process specific machining and surface finishing techniques are required to provide size-correction and to meet tolerance and surface roughness specifications [11–13]. In this work, the use of single point diamond turning (SPDT) on CVD W/WC coatings is investigated due to

its presumed capability of providing a uniform machining operation on parts made of hard materials with specific profiles and achieving high levels of tolerances and surface finish [14–16].

The machining process of SPDT occurs at a single point, making the process more predictable when compared to more conventional techniques such as grinding which involve multiple abrasives operating in multiple directions [16]. Diamond turning machines are typically equipped with high precision features such as hydrostatic isolators and air bearings, which make the process highly controllable. This capability makes the process suitable to be used on engineering parts with defined profiles requiring a specific surface finish while retaining the original form of the part. To date the use of SPDT focuses predominantly on ductile materials (copper, aluminium, magnesium, tin, silver and gold), with its use on hard coatings being an area with limited experimental scrutiny. Scientific findings relating to the use of SPDT on hard coatings are thus far limited to conventional carbides such as WC-Co [17], SiC [18] and WC [5,16] coatings. In contrast to conventional cemented carbides, which are composed of carbides particles held together by soft metal binders with several voids, the CVD W/WC coatings used herein

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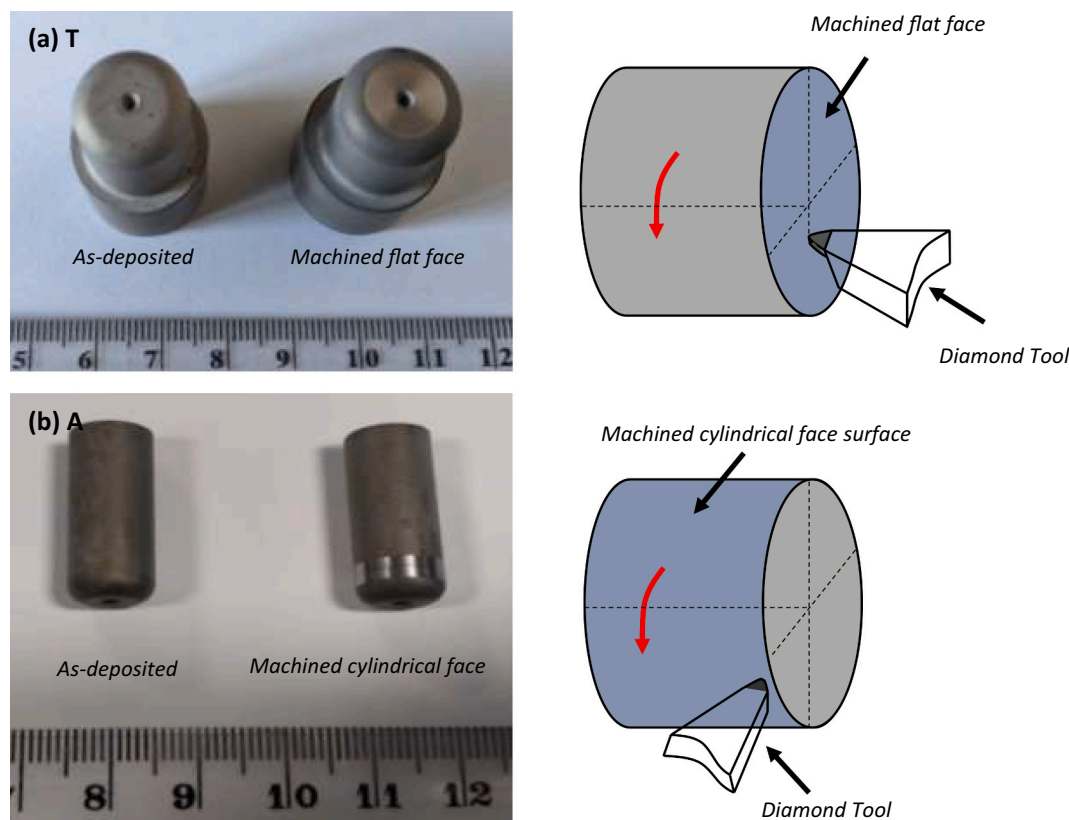


Fig. 1. Photographs of machined W/WC samples in the as-deposited and machined condition and corresponding schematic diagrams outlining the machining configuration of (a) sample T in the transverse direction and (b) sample A in the axial direction.

are predominantly composed of finely dispersed WC nanoparticles within voidless W metal matrix [12,13]. This property makes the CVD W/WC coatings significantly different than the more conventional WC coatings.

The main considerations in exploring SPDT as a successful surface finishing technique include the capability of the process of improving the surface finish without adversely affecting the coating while being economically viable, where the tool integrity would be retained for a significant period of time. As outlined in our review study [11], the theoretical background on the machinability of W suggests that it is a non-turnable material. One of the criteria of turnable material is the acceptable level of tool wear that in terms of economic value is smaller than the overall value of the machined part. Therefore, materials with high melting temperatures and hardness, such as W, are typically classed as non-turnable [19]. Nonetheless, the limited experimental work reported in literature have motivated the study of the machinability of CVD W/WC coating. We report herein the machinability of hard CVD W/WC coatings using a single crystal diamond tool. The feasibility of the process was assessed with respect to the improvement in the surface topography of the coating and the level of tool wear following the machining process. The findings presented herein provide a basis for further development of post-deposition machining of hard coatings, which are of relevance to a wide range of precision engineering applications.

2. Materials and methods

A set of samples with a round geometry of 10 mm diameter $\times$ 20 mm length (Fig. SI 1b-c) were prepared from commercial 304 stainless steels. The samples had a 3 mm tapped hole at the back end of the samples to be used for fixturing during the coating deposition process and for mounting during the turning process. Subsequent to the coating

deposition, it was ensured that the back of the sample, from which the sample was fixtured, was free from overspray to make sure the sample was perfectly true to the rotating spindle. The samples had a small hole machined at the opposite side of the sample to serve as a centre.

A tungsten/tungsten carbide (W/WC) coating layer was deposited on the machined samples through chemical vapour deposition at a temperature of 500 °C by Hardide Coatings Ltd. (Bicester, Oxford-UK). The coating had a thickness of 100 μ m and a hardness of 1120 ± 15 HV. W/WC is composed of WC nanoparticles dispersed in a W metal matrix and crystallised from precursors gases atom-by-atom, forming a columnar microstructure. The coating is binderless and pore-free [8,11–13].

Diamond turning machining was carried out using a Moore Nanotech 350 UPL diamond turning lathe developed by Moore nanotech systems. The lathe has a two axis-machining system and uses an air bearing spindle through which the workpiece is attached and rotated. The spindle rotates at a speed range of 50 to 6000 rpm and has an angular accuracy of 0.0001° . The machine is typically used for SPDT and hard turning applications. Prior to the turning operation the workpiece was fixed onto a vacuum chuck and to the air-bearing spindle (Fig. SI 1a, b). The sample was clocked using an Induction probe (Mohr Millimar 1200 IC) to bring the diamond tool true with the rotating workpiece. The experiments were carried out at controlled room temperature conditions of $20 \pm 2^\circ\text{C}$ and relative humidity of $40 \pm 5\%$ to minimise the effects of thermal distortion and retain the highest tool accuracy. The lubrication between the diamond tool and the workpiece consisted of pressurised air and white spirit. The combination of these two media provided a cooling action.

A diamond tool (N0.50Mwg) with a -25° -rake angle, a clearance angle of 10° and a nose radius of 0.5 mm (Contour Fine Tooling Ltd) was used for all experiments carried out in this work (Fig. SI 2). New tools were used for each experiment where the tool condition was intact with no pre-existent wear which otherwise would have had an effect on the

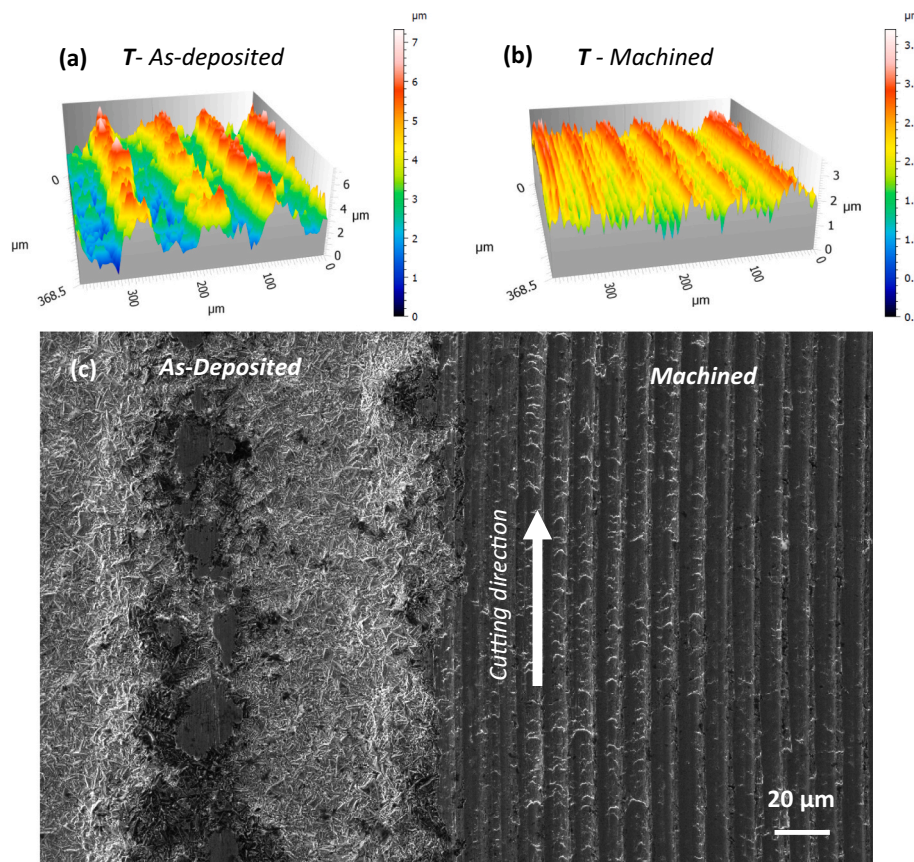


Fig. 2. White light interferometer 3D images of sample T in the (a) as-deposited and (b) machined condition and (c) SEM image showing the change in surface roughness from as-deposited to machined surface.

ultimate surface condition of the sample. In this work turning experiments were carried out using two configurations in the transverse (flat face) and axial (cylindrical face) directions. The schematic diagrams in Fig. 1 outline the tool configuration versus the workpiece in both cases.

A cutting speed of 600 rpm and feed rate of 10 rev/s was used for both transverse and axial turning. A depth of cut of 5 μm was used for transverse (T) turning on the flat face and a depth of cut of 1 μm was used on the cylindrical face. Here the sample turned in the transverse configuration is denoted as T, while that turned in the axial configuration is denoted as A.

Following the machining process the machined surfaces were evaluated for changes in surface roughness and surface morphology. The surface roughness was measured using a white light interferometer (Taylor Hobson CCI) with a 50 $\times$ objective lens and a sampling scale of 350 $\times$ 350 μm . The profilometer's software (Mountains Lab) enabled the generation of 3D micrographs exhibiting the changes in surface topography of the machined surfaces compared to the as-deposited condition. The surface morphology of as-deposited and machined coating surfaces was observed with a scanning electron microscope (SEM) (Tescan, Vega) using secondary electrons (SEM HV: 18 kV and Beam Intensity: 10). The nose of the diamond tools was also evaluated with the SEM to characterise the tool wear at the rake/flank edge. Elemental analysis by energy dispersive spectroscopy (EDS) was carried out to determine whether material transfer leading to adhesion wear had occurred during the turning operation.

3. Results

The effect of SPDT on cylindrical and flat faces can be visually observed in Fig. 1a–b. The images of the samples in the as-deposited and machined conditions show a distinctive change from a matte grey

texture to a reflective surface. Note that a 5 μm depth of cut was used on sample T while a depth of cut of 1 μm was used on sample A. Machining of samples T gave better results due to a larger depth of cut being used and therefore bigger penetration into the coating surface, allowing for a better and quicker machining turnaround. Cylindrical machining was found to be more challenging due to machining with a smaller depth of cut and due to variation in the concentricity of the sample. Low concentricity was due to the coating thickness variation arising during the deposition process, necessitating several turning passes to clear a small area.

The 3D surface profile micrograph of the as-deposited flat surface shows a periodic surface morphology with a rippled texture, where the surface peaks are approximately 100 μm apart and 4 μm deep (Fig. 2a). These surface features are essentially a replication of the substrate's machining marks which are conformally covered by the CVD coating during deposition. Note that the substrates were CNC-cut and machined prior to the W/WC coatings deposition to produce as highly concentric parts as possible, with high accuracy. The as-deposited flat surface is also characterised by randomly distributed coating growths (nodular growths) (Fig. 3a) with a height of a few microns (2–3 μm) forming an uneven surface. The SPDT flat surface is characterised by clear feed marks with symmetrical V-grooves with 4 μm deep valleys and peaks spaced 10 μm apart (Fig. 2b). The SEM image of the flat surface, machined with a 5 μm depth-of-cut shows a clear effect of SPDT on the coating morphology (Fig. 2c), with formations of micro-scratches, adhesive wear and micro-cracking formed along the cutting direction.

Compared to the as-deposited condition (Fig. 3a), the cylindrically machined sample A (Fig. 3b), is characterised by a uniform machining texture with evenly spaced grooves. SEM observations of the machined surface (Fig. 3c) show that the machined area has shallower machining grooves due to the shallow depth-of-cut used (1 μm). Consequently,

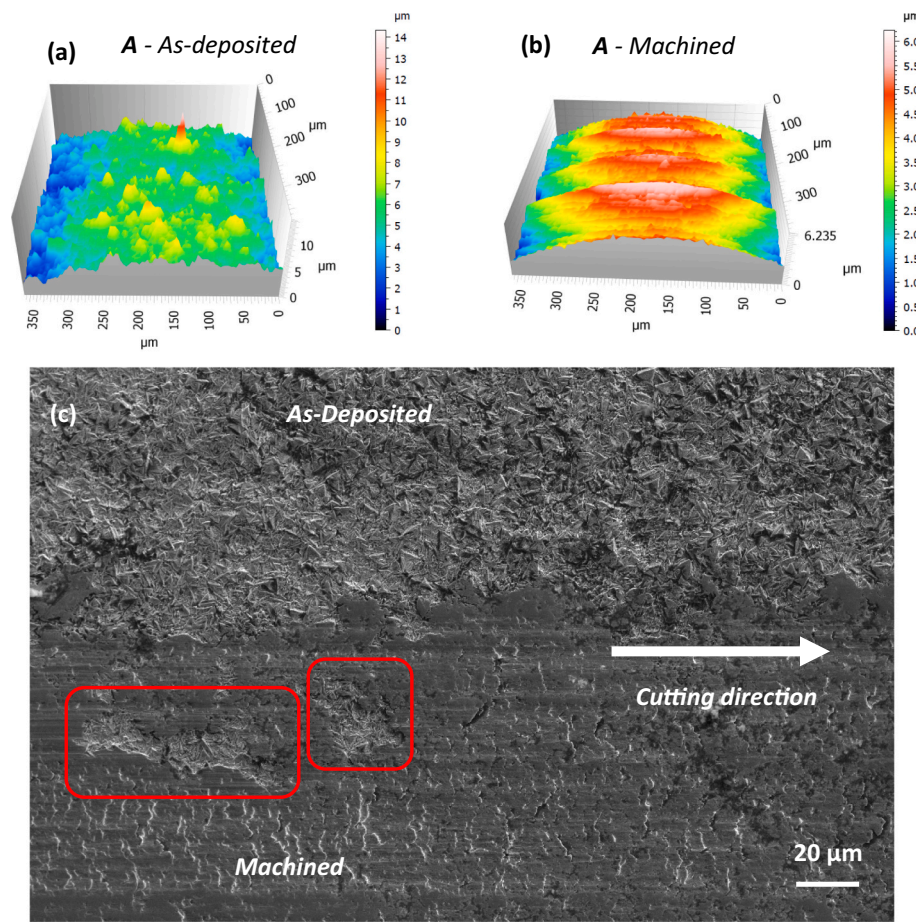


Fig. 3. White light interferometer 3D images of (a) as-deposited and (b) machined cylindrical faced samples and (c) SEM image showing the change in surface roughness from as-deposited to machined surface. The areas in red boxes indicate patches of coating retained in the as-deposited condition within the machined area.

some areas in the machined areas were retained in the as-deposited condition. Adhesive wear was still predominantly observed, with patches of material becoming slightly lifted along the cutting direction.

Fig. 4a-b show the cross-sections of samples T and A in the machined areas. Both surfaces exhibit rippled textures which correspond to the machining marks induced by the diamond tool nose. The surface of sample T (Fig. 4a) shows a fragmented thin layer that consists of chunks of W material becoming detached from the surface, forming loose abrasive media (Fig. SI 3). These observations corroborate the observation made from the SEM surface topography image in Fig. 2c. The surface of sample A which was machined with a 1 μm depth of cut shows insignificant material deformation (Fig. 4b), owing to the smaller depth of cut which was used (1 μm) and consequently shallower cut. The low depth of cut combined with high coating hardness suggests that rubbing (Fig. 8c) was occurring rather than cutting during the SPDT operation.

The surface roughness was used as an indicator of the surface quality of the machined surface. The average surface roughness Ra was measured across the machining marks in both the as-deposited and machined surfaces (Table 1). Both T and A samples exhibit an average decrease in Ra of 0.18 μm after machining. In contrast, the change in maximum profile peak height (Rp) and maximum profile valley depth (Rv) for sample T showed a larger change when compared to sample A. The average Rp and Rv for sample T decreased by 0.84 μm and 0.63 μm respectively, while those for sample A decreased by 0.61 μm and 0.33 μm respectively suggesting that the larger the depth-of-cut the bigger the improvement in Rp and Rv.

4. Discussion

The interaction of the diamond tool against the workpiece during the SPDT operation is characterised by four main modes of wear which include abrasive, adhesive, diffusive and oxidation wear [20]. SEM observations of the machined surfaces with a 5 μm and 1 μm depth of cut confirm that adhesive and abrasive wear were the main wear mechanisms manifested during the turning operation. Fig. 5a-b shows a high magnification image of the surface morphology of the turned W/WC coating on sample T, with clear evidence of adhesive and abrasive wear. Adhesive wear is generated by sliding of two bodies against each other subjected to a high sliding force. In this case the stationary diamond tool with a hardness exceeding 2000 HV is sliding against a rotating W/WC coating with a hardness of ~1100 HV. During the relative motion, the surface asperities of the coating are subjected to a shear stress causing them to brake and become detached from the surface of the coating but remain present (Fig. 5a). This gives rise to three-body particles, where upon further turning the detached abrasive media become entrapped between the tool and the workpiece causing abrasive wear (Fig. 5b) [21,22]. Note that the removal of these asperities of the coating by SPDT process results in a smooth and uniform surface (Fig. SI 4).

The presence of loose abrasive media gives rise to the formation of scratch marks formed on the surface of the machined surface (Fig. 6a-b). The shear wear occurring on the surface of the machined surface contributes to the formation of a step-like texture manifested as an exfoliated surface (Fig. 6a), also observed in the cross-section of the machined area (Fig. 4a). This is particularly visible on samples machined with a 1 μm depth of cut where rubbing wear is the predominant tool-workpiece interaction. Formation of micro-cracks (Fig. 6a) are also widely

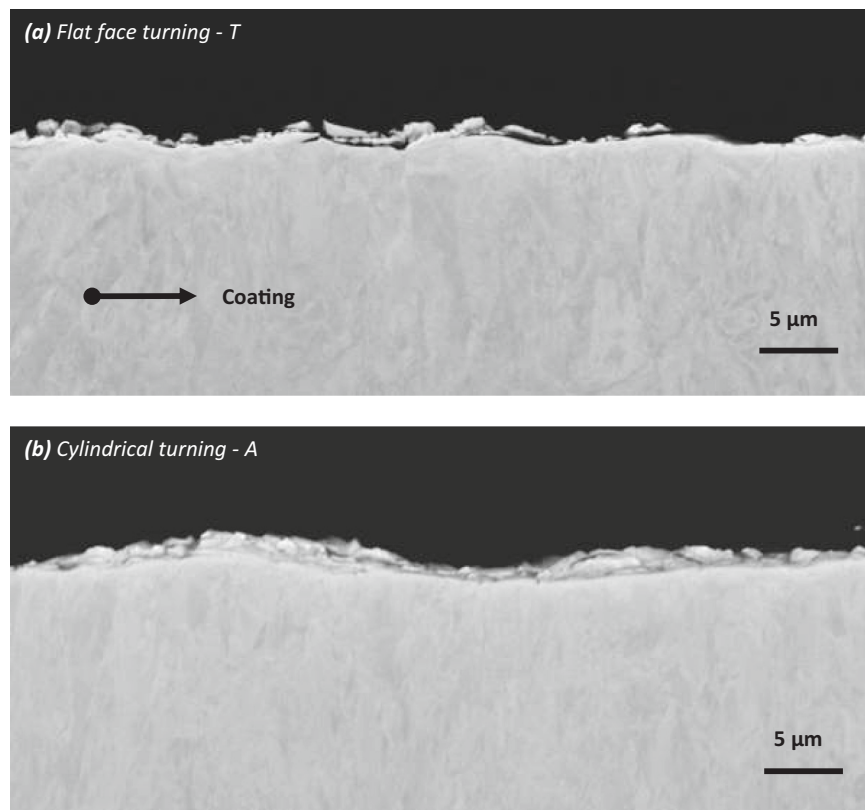


Fig. 4. SEM cross-sectional view in the machined areas of (a) sample T machined in the transverse direction and (b) sample A machined in the axial direction.

Table 1

Surface roughness parameters of as-deposited and machined surfaces. Here the surface roughness results are shown as mean $\pm$ standard deviation values.

Roughness Parameter	Flat-face turning/ Transverse – T (5 μ m depth-of-cut)		Cylindrical turning/Axial – A (1 μ m depth-of-cut)	
	As-deposited	Machined	As-deposited	Machined
Ra (μ m)	0.39 $\pm$ 0.02	0.21 $\pm$ 0.07	0.40 $\pm$ 0.16	0.22 $\pm$ 0.03
Rp (μ m)	1.48 $\pm$ 0.05	0.64 $\pm$ 0.08	1.36 $\pm$ 0.53	0.75 $\pm$ 0.10
Rv (μ m)	1.31 $\pm$ 0.28	0.68 $\pm$ 0.21	1.22 $\pm$ 0.37	0.89 $\pm$ 0.14

observed on the machined surface, suggesting that plastic deformation of the coating is occurring. Cross-sectional analysis of the machined areas show that the affected surface layer is very thin, $<1 \mu\text{m}$ (Fig. 4).

Due to the high hardness of the W/WC coatings studied in this work (~ 1100 HV) diamond tools with a negative rake angle of 25° were used (Fig. 7a). Negative rake angle tools are typically used for turning hard materials such as silicon and germanium to maintain a ductile machining regime [18,23,24]. Despite this, significant tool damage was still developed on the diamond tool nose when machining was carried out in both the axial and transverse directions. Immediate observation of the rake/flank tool edge with an optical microscope, following the machining operation (Fig. SI 5) revealed an observable level of damage where the tool nose was flattened and roughened. Tool wear is typically quantified in terms of the flank wear length which is the tapered area developed between the rake and flank edges. The larger the tapered area, the bigger the contact surface area between the diamond tool and the workpiece ultimately having a bearing on the machining quality.

Prior to the SPDT operation the diamond tool has a perfectly defined,

sharp edge free from any damage (Fig. 7a-b). Observation of the tool tip using SEM (Fig. 7c-d), following SPDT shows that the detached coating fragments are transferred to the tool, giving rise to metal-on-metal wear. Elemental analysis by EDS shows that the worn material consists of tungsten debris and carbon arising from the worn diamond tool (Fig. SI 6). The wear debris adhered to the tool tip may also be transferred back to the workpiece surface causing them to be broken into finer particles due to the repeated motion and loading which occurs during the machining process [21]. Further analysis of the diamond tool nose shows that the rake/flank edge is significantly worn. Comparison of the tool condition before (Fig. 7b) and after (Fig. 7c-d) machining shows that the sharp edge of the rake/flank is transformed into a tapered edge.

As discussed previously, loose abrasive media was generated by adhesive wear. Material transfer which is stuck to the diamond tool tip is also found to contribute to the formation of abrasive wear. The parallel abrasive marks shown in Fig. SI 7 correspond to the microgrooves formed at the nose of the diamond tool during machining using a depth of cut of $5 \mu\text{m}$ (Fig. 7c). The integrity of the cutting tool, particularly the nose and sharpness of the rake/flank edge changes with machining time from shearing to ploughing to rubbing (Fig. 8). In its original condition, when the tool has a sharp cutting edge, plastic deformation causes shearing of the workpiece material. As the tool starts to become worn and blunt, material is still removed from the surface of the workpiece, in a less uniform manner through a ploughing action. As the tool is completely worn, the interaction between the tool and the workpiece occurs through rubbing, where negligible workpiece material is removed. The degradation of the tool tip increases the contact surface area, consequently increasing the frictional contact and the tool tip temperature. In this work the length of the worn area for both the transverse and axial surfaces was $\sim 30 \mu\text{m}$. The main difference between the two was that for T with $5 \mu\text{m}$ depth of cut, several microgrooves parallel to the direction of cutting were formed. In contrast, the worn area achieved in A with a $1 \mu\text{m}$ depth of cut is polished with an absence of obvious microgrooves. This behaviour confirms that rubbing, rather

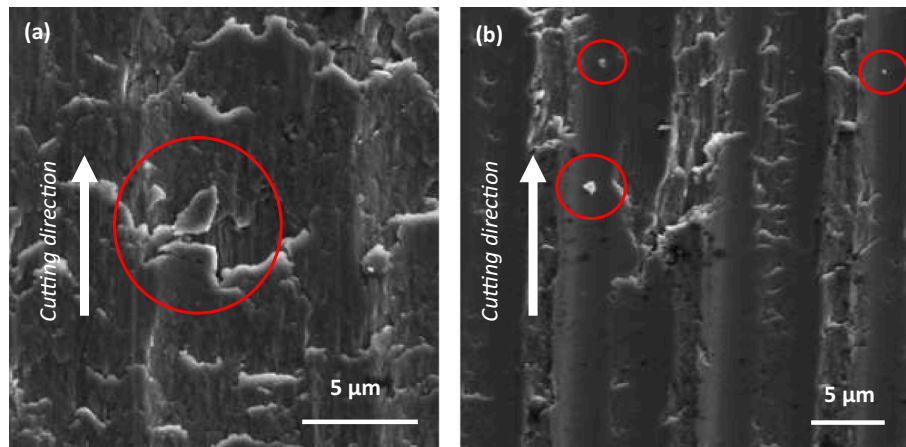


Fig. 5. SEM images of (a) chunks of W/WC coating being sheared-off and (b) loose W/WC debris retained on the surface of the machined surface following SPDT of sample T with a 5 μm depth-of-cut.

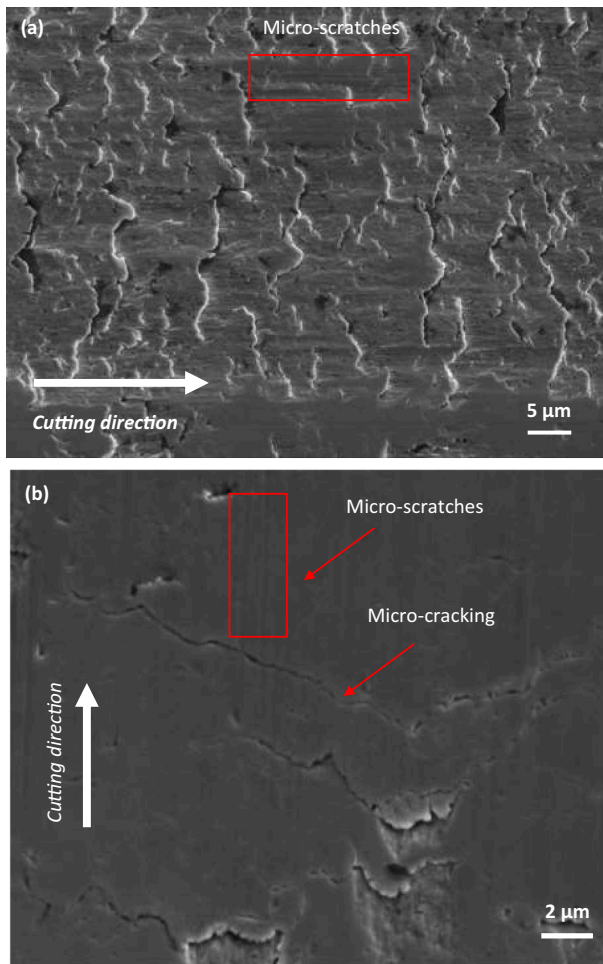


Fig. 6. SEM images showing (a) material exfoliation due to adhesive wear and micro-scratches due to abrasive wear and (b) micro-cracking on sample A machined with a 1 μm depth-of-cut.

than cutting was occurring during the SPDT operation.

The schematic diagram in Fig. 9a shows the ideal profile which is theoretically formed when the diamond tool cuts through the material, provided that the cutting tool is intact, with a sharp rake/flank edge. The peak to valley depth is dependent on the tool geometry, particularly the

nose radius. The integrity of the diamond tool is thus of paramount importance as its profile is replicated on the surface of the coating where any defects in the tool tip would cause a non-uniform cut. The true profile of the machined surface is also a reflection of the material swelling and recovery which occurs at the trailing edge of the diamond tool. This is a result of the high pressure which impinges on the surface of the material by the diamond tool which causes plastic deformation of the surface, contributing to a secondary surface roughness component [25]. Fig. 9b outlines the effect of surface swelling (orange profile) generated by the cutting forces and the subsequent effect of material recovery (blue profile) when compared to the ideal surface profile produced by the tool nose radius (grey profile) [26].

The swelling and recovery behaviour observed on the turned W/WC coatings motivates us to study the spring back behaviour of W/WC coatings through an indentation technique. This technique was adapted from scratch tests where a Berkovich indenter is used to determine the material swelling as a result of the indentation, ultimately impacting the overall surface roughness of the machined surface. In theory indentation is similar to single point machining where the applied forces cause the material to flow towards the sides of the indenter or the machining too tip, in the case of SPDT (Fig. SI 8a). The depth of the deformed material is dependent on the hardness of the material and the loading [25,27]. Here a similar technique was employed using a Vickers indenter instead of a Berkovich indenter.

A series of 500 g indentations were produced on the surface of a sample which was prepared to a mirror finish to eliminate any surface features which would interfere with the measurement of the depth of the swollen material. White light interferometry was employed to measure the height of the deformed material in comparison to the polished baseline (Fig. SI 8b). Interferometry micrographs revealed the material deformation along the indentation edges (Fig. 10a). The average depth measured across the deformed material as outlined in Fig. 10b was 265 ± 50 nm (Fig. 10c). The material pile-up demonstrated with a Vickers indenter can be observed to form practically in the 3D interferometry images of the turned surfaces, where continuous peaks to the edge of the machining groove are formed (Fig. 2b and Fig. 3b). The generation of a continuous ridge of piled-up material along the machining track in SPDT will therefore have a similar effect, where the induced plastic-flow roughness component is added to the overall surface roughness of the machined surface.

The presence of unpaired d-shell electrons in W subshell gives the material a bcc crystal structure with superior mechanical properties (Fig. SI 9) [19]. Such properties, including high hardness and high melting temperature, can cause the covalent bonds in the diamond lattice of the tools to break and lead to excessive tool wear. Tungsten is a carbide-forming metal which can react with carbon from the diamond

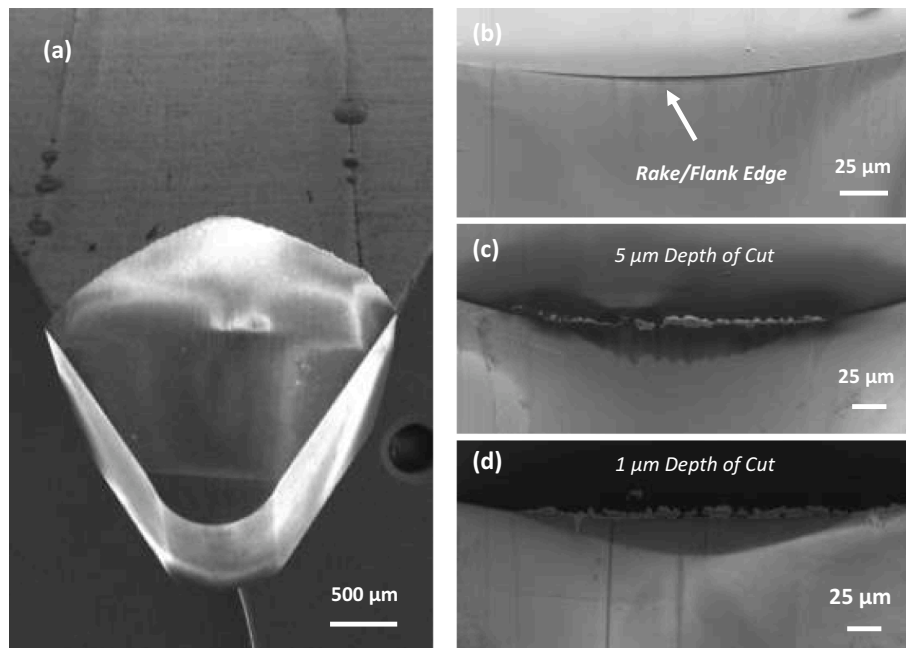


Fig. 7. (a) SEM image of the diamond tool with a rake angle of -25° and flank angle of 10° used for machining W/WC coatings, (b) high magnification SEM image showing the rake/flank edge of the diamond tool in the original condition, worn diamond tool edge after machining using a (c) 5 μm and (d) 1 μm depth of cut.

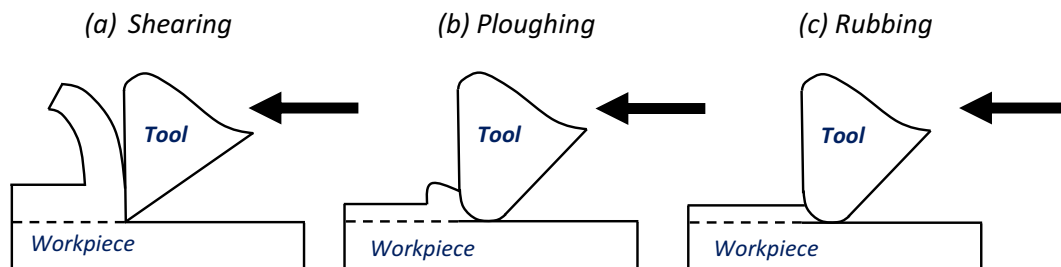


Fig. 8. Effect of tool integrity on tool-workpiece interaction. (a) sharp tool edge resulting in a shearing action, (b) blunt tool nose resulting in a ploughing action and (c) worn tool nose resulting in a rubbing action (Arrows indicating machining direction).

surface under elevated temperatures. This might be an additional factor contributing to the diamond tool cutting edge degradation, as the tool tip surface area increases significantly due to friction with the W/WC coating surface [28]. From a commercial feasibility standpoint, the use of diamond turning as a machining or surface finishing technique on W/WC coatings and other hard materials is dependent on the associated tool costs in relation to the value of the components. As shown in this work, SPDT of W/WC has resulted in the development of high tool wear for a relatively small machined area of 0.6 cm^2 and 0.8 cm^2 for samples T and A respectively. The response of the W/WC coating to SPDT resulted in the development of wear characteristics which affect the overall surface integrity of the coating making the process undeliverable when it comes to surface finishing or machining selection [19]. For this reason, CVD W/WC coatings can be considered as a non-turnable material.

5. Conclusion

The impact on the surface finishing and integrity of CVD W/WC coatings surface finished through SPDT has been investigated. In this work it has been demonstrated that an ultimate R_a of $0.2\text{ }\mu\text{m}$ can be achieved on both cylindrical and axially turned samples from an initial R_a of $0.4\text{ }\mu\text{m}$, irrespective of the depth of cut which was used. Surface and cross-sectional analysis had shown that adhesive wear and abrasive

wear were the main wear mechanisms observed on the machined W/WC surface. Cross-sectional analysis corroborated the observations at the surface of both transverse and axially machined areas. The diamond tools used for both axial and transverse turning suffered significant wear after machining small coated area of $<1\text{ cm}^2$, causing the rake/flank edge to become tapered. EDS analysis confirmed that material transfer on the diamond tool occurred, suggesting metal-on-metal wear occurred during the SPDT operation. Despite the process being capable of improving the surface roughness of CVD W/WC coatings, the high hardness of the coating and its effect on the excessive tool wear makes the process economically unviable to be utilised in practical applications. These findings should be considered in the selection and further development of post-deposition machining of hard coatings for the benefit of many precision engineering applications.

CRediT authorship contribution statement

Christian Micallef conceived and planned the experiments in discussion with Adrianus Indrat Aria and Yuri Zhuk.

Christian Micallef carried out the testing and material characterisation at Cranfield University and Hardide coatings.

Christian Micallef carried out the interpretation of results in discussion with Adrianus Indrat Aria and Yuri Zhuk.

The first draft of the manuscript was written by Christian Micallef

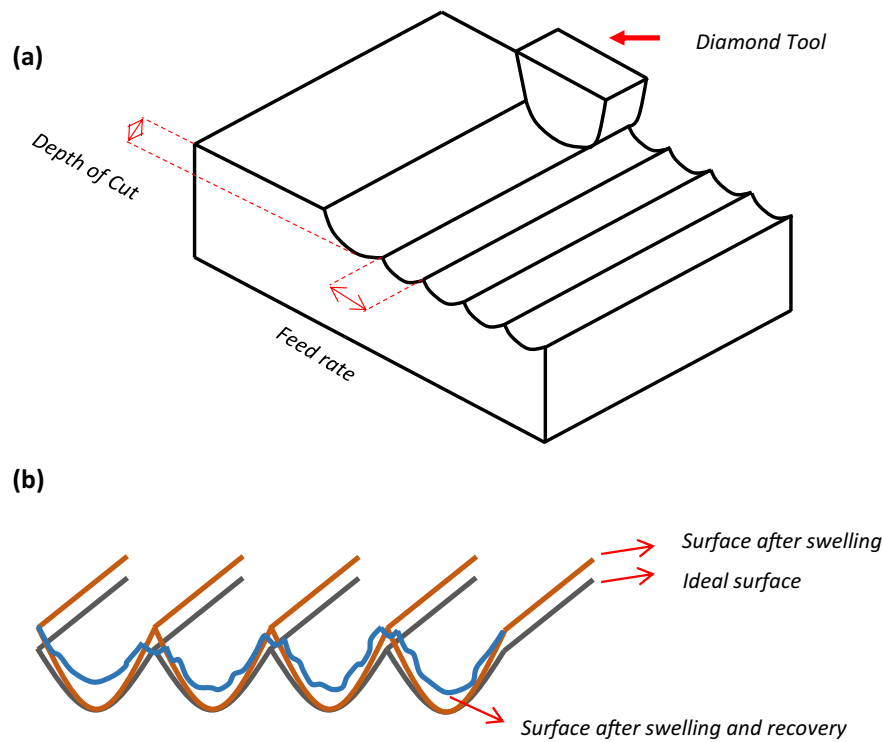


Fig. 9. Schematic model of (a) the theoretical impact of the tool nose radius on the surface topography of the workpiece and (b) effect of material swelling and recovery following diamond turning.

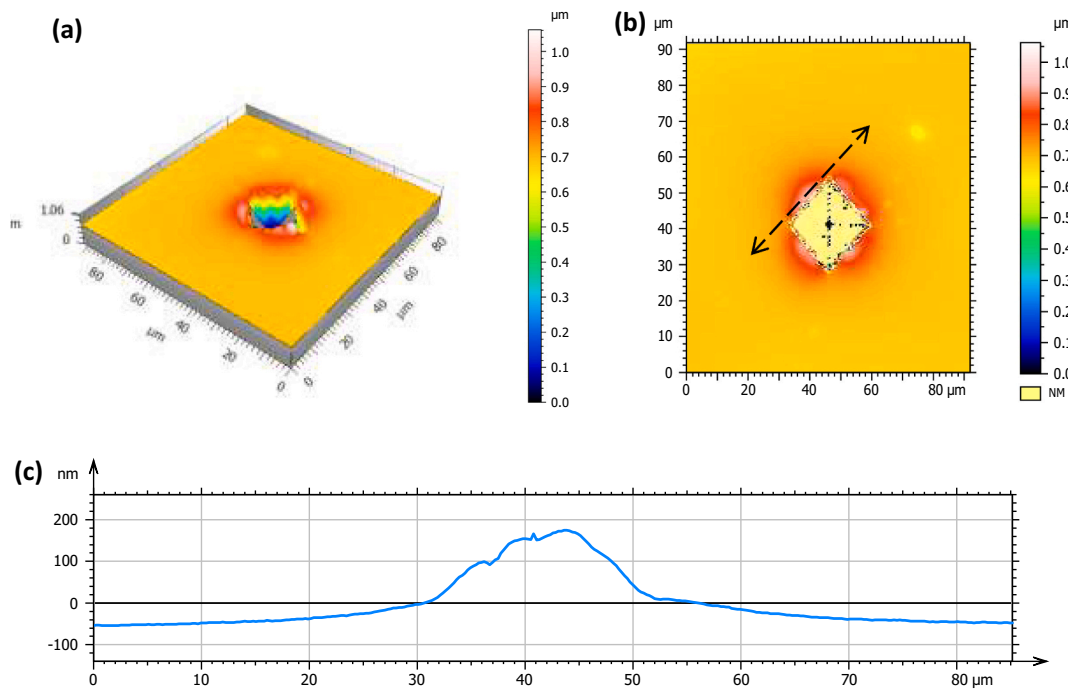


Fig. 10. (a) 3D image of a Vickers hardness indent using 500 g load on the surface of W/WC coating, (b) 2D image of the indent showing the line scan at which the depth of material deformation was measured and (c) graph showing the depth of material pile-up across the deformed material.

with support from Adrianus Indrat Aria and Yuri Zhuk.

Adrianus Indrat Aria and Yuri Zhuk provided the supervision throughout the course of conducting this research work and preparation of the presented manuscript.

All authors reviewed the results and approved the final version of the manuscript.

Declaration of competing interest

We declare that the submitted article has not been submitted in any other journal and is not under consideration for publication elsewhere. We also declare that two of the authors, Christian Micallef and Yuri Zhuk, are both directly employed by Hardide Coatings plc.

Data availability

Data underlying this study can be accessed through the Cranfield University repository (CORD) at <https://doi.org/10.17862/cranfield.rd.20931634.v1>. Data are available under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.surfcoat.2022.128864>.

References

- [1] Tianfeng Zhou, T.K. Jiwang Yan, Size effects on transferability and mold change of glass molding press for microgrooves, *Adv. Mater. Res.* 497 (2012) 235–239, <https://doi.org/10.4028/www.scientific.net/AMR.497.235>.
- [2] W. Bai, A. Bisht, A. Roy, S. Suwas, R. Sun, V.V. Silberschmidt, Effect of hybrid machining on structural integrity of aerospace-grade materials, *Procedia CIRP* 77 (2018) 163–166, <https://doi.org/10.1016/j.procir.2018.08.266>.
- [3] E. Brinksmeier, J. Osmer, Precision mould making - from macro to micro, *Key Eng. Mater.* 447 (448) (2010) 1–8, <https://doi.org/10.4028/www.scientific.net/KEM.447-448.1>.
- [4] A. Sharma, D. Datta, R. Balasubramaniam, Prediction of tool wear constants for diamond turn machining of CuBe, *J. Micromanufacturing* 4 (2021) 18–26, <https://doi.org/10.1177/2516598420930992>.
- [5] 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 (2009) 5830–5836, <https://doi.org/10.1016/j.jmatprotec.2009.06.013>.
- [6] L. Zou, Y. Huang, M. Zhou, G. Xiao, Thermochemical wear of single crystal diamond catalyzed by ferrous materials at elevated temperature, *Crystals* 7 (2017) 1–10, <https://doi.org/10.3390/cryst7040116>.
- [7] S. Goel, The current understanding on the diamond machining of silicon carbide, *J. Phys. D: Appl. Phys.* 47 (2014), 243001, <https://doi.org/10.1088/0022-3727/47/24/243001>.
- [8] C. Micallef, Y.N. Zhuk, R.J.K. Wood, Gallling resistance of nanostructured CVD tungsten/tungsten carbide coatings, *Surf. Topogr. Metrol. Prop.* 7 (2019) 25004, <https://doi.org/10.1088/2051-672X/ab1535>.
- [9] Y.N. Zhuk, Hardide™: advanced nano-structured CVD coating, *Int. J. Microstruct. Mater. Prop.* 2 (2007) 90–98, <https://doi.org/10.1504/IJMMP.2007.012942>.
- [10] Y.N. Zhuk, Thick nano-structured CVD coating HARDIDE as enabler for engineering systems in extreme wear and erosion conditions, in: *Mater. Sci. Technol. Conf. Exhib. MS T'07 - "Exploring Struct. Process. Appl. Across Mult. Mater. Syst* 3, 2007, pp. 1970–1981.
- [11] C. Micallef, Y. Zhuk, A.I. Aria, Recent progress in precision machining and surface finishing of tungsten carbide hard composite coatings, *Coatings* 10 (2020) 1–36, <https://doi.org/10.3390/coatings10080731>.
- [12] C. Micallef, C.-W. Chiu, Y. Zhuk, A.I. Aria, Rapid surface finishing of chemical vapour deposited tungsten carbide hard coatings by electropolishing, *Surf. Coat. Technol.* 428 (2021), 127900, <https://doi.org/10.1016/j.surfcoat.2021.127900>.
- [13] C. Micallef, K. Walton, Y. Zhuk, A.I. Aria, Surface finishing and residual stress improvement of chemical vapour deposited tungsten carbide hard coatings by vibratory polishing, *Surf. Coat. Technol.* 439 (2022), 128447, <https://doi.org/10.1016/j.surfcoat.2022.128447>.
- [14] B. Bulla, F. Klocke, O. Dambon, Analysis on ductile mode processing of binderless, nano crystalline tungsten carbide through ultra precision diamond turning, *J. Mater. Process. Technol.* 212 (2012) 1022–1029, <https://doi.org/10.1016/j.jmatprotec.2011.12.010>.
- [15] J. Yan, Z. Zhang, T. Kuriyagawa, Mechanism for material removal in diamond turning of reaction-bonded silicon carbide, *Int. J. Mach. Tools Manuf.* 49 (2009) 366–374, <https://doi.org/10.1016/j.ijmachtools.2008.12.007>.
- [16] M.J. Kim, J.K. Lee, Y. Hwang, D.H. Cha, H.J. Kim, J.H. Kim, Experimental study of the diamond turning characteristics of tungsten carbide (Co 0.5%) when using a chamfered diamond bite, *J. Korean Phys. Soc.* 61 (2012) 1390–1394, <https://doi.org/10.3938/jkps.61.1390>.
- [17] F.A. Almeida, F.J. Oliveira, M. Sousa, A.J.S. Fernandes, J. Sacramento, R.F. Silva, Machining hardmetal with CVD diamond direct coated ceramic tools: effect of tool edge geometry, *Diam. Relat. Mater.* 14 (2005) 651–656, <https://doi.org/10.1016/j.diamond.2004.09.002>.
- [18] Z. Zhang, J. Yan, T. Kuriyagawa, Study on tool wear characteristics in diamond turning of reaction-bonded silicon carbide, *Int. J. Adv. Manuf. Technol.* 57 (2011) 117–125, <https://doi.org/10.1007/s00170-011-3289-3>.
- [19] E. Paul, C.J. Evans, A. Mangamelli, M.L. McGlaulin, R.S. Polvani, Chemical aspects of tool wear in single point diamond turning, *Precis. Eng.* 18 (1996) 4–19, [https://doi.org/10.1016/0141-6359\(95\)00019-4](https://doi.org/10.1016/0141-6359(95)00019-4).
- [20] X. Wang, J. Zhao, Y. Gan, X. Tang, S. Gai, X. Sun, Cutting performance and wear mechanisms of the graphene-reinforced Al₂O₃-WC-TiC composite ceramic tool in turning hardened 40Cr steel, *Ceram. Int.* (2022) 1–11, <https://doi.org/10.1016/j.ceramint.2022.01.251>.
- [21] C. Zhang, Understanding the wear and tribological properties of ceramic matrix composites, in: *Advances in Ceramic Matrix Composites*, Woodhead Publishing Limited, Beijing, 2014, pp. 312–339. ISBN 9780857091208.
- [22] S. Affatato, D. Brando, Introduction to wear phenomena of orthopaedic implants, in: S. Affatato (Ed.), *Wear of Orthopaedic Implants and Artificial Joints*, Woodhead Publishing Limited, 2013, pp. 3–26.
- [23] R. Balasubramaniam, R.V. Sarepaka, S. Subbiah, *Diamond Turn Machining Theory and Practice*, 1st ed., CRC Press Taylor & Francis Group, Kanpur, 2017. ISBN 9781138748323.
- [24] I. Durazo-Cardenas, P. Shore, X. Luo, T. Jacklin, S.A. Impey, A. Cox, 3D characterisation of tool wear whilst diamond turning silicon, *Wear* 262 (2007) 340–349, <https://doi.org/10.1016/j.wear.2006.05.022>.
- [25] K. Liu, S.N. Melkote, Effect of plastic side flow on surface roughness in micro-turning process, *Int. J. Mach. Tools Manuf.* 46 (2006) 1778–1785, <https://doi.org/10.1016/j.ijmachtools.2005.11.014>.
- [26] M.C. Kong, W.B. Lee, C.F. Cheung, S. To, in: *A Study of Materials Swelling and Recovery in Single-point Diamond Turning of Ductile Materials* 180, 2006, pp. 210–215, <https://doi.org/10.1016/j.jmatprotec.2006.06.006>.
- [27] V. Jardret, H. Zahouani, J.L. Loubet, T.G.M. Understanding and quantification of elastic and plastic deformation during a scratch test, *Wear* 218 (1998) 8–14.
- [28] A.V. Ukhina, A.A. Yusuf, D.V. Dudina, E.N. Galashov, B.B. Bokhonov, Surface modification of synthetic diamond with tungsten, in: *Proceedings of the Proceedings - 2016 11th International Forum on Strategic Technology, IFOST 2016, IEEE*, 2017, pp. 95–98.



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