PAPER • OPEN ACCESS

Investigation on machining performance of TiB_2 and TiN coatings with modified cutting insert in AISI 1017 turning

To cite this article: Amirul Zainal *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **788** 012009

Investigation on machining performance of TiB_2 and TiN coatings with modified cutting insert in AISI 1017 turning

Amirul Zainal[1], Mohd Hafizu Zakaria[1] and Saiful Anwar Che Ghani[1,*]

[1] Human Engineering Group, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia

[*]Corresponding author:anwarcg@ump.edu.my

Abstract. In the last decades machining methods have witnessed an advancement in both cutting tools' geometry and hard coatings, sometimes in combination with Ti-based coating. In the present study, the machining performance of adhesion resistant Ti-based coating materials with modified cutting insert on tool wear was investigated in turning AISI 1017 carbon steel. TiB_2 and TiN hard coatings with similar layer thickness produced by physical vapor deposition (PVD) technique were considered as coating film for 1 mm thick tungsten carbide with Co binder cutting tools. The machining performance was evaluated mainly by surface roughness, cutting temperature and correlated in terms of tool wear. Through a set of experiments, modified cutting insert coated with TiB_2 exhibited about 24-33% improvement in tool wear compared to TiN coated insert. The results from this study show that TiB_2 coating can be used as coating material for cutting tool but further research on tribology and sustainability along with cutting dynamics study are prerequisites for commercial application of this coating material in the mainstream.

1. Introduction

Material processing of hard materials with (hardness range of 45–70 HRC) by means of material removal has always been difficult [1] and among the most popular tool materials employed to machine such materials are ceramic, mixed ceramic, cubic boron nitride (CBN) and polycrystalline boron nitride (PCBN) [2, 3]. Bobzin, Bagcivan, Ewering, Brugnara and Basturk [4] reported that among all the hard coatings used in machining difficult to cut materials, titanium based cutting tool is gaining popularity due to its enhanced frictional behaviour and economical nature. Moreover, this material has demonstrated good adhesion with carbide base in hard machining process [5] can further enhance the performance of these tools [6].

The high wear rate, deformation hardening, high chemical affinity between tool and workpiece material and a low thermal conductivity coefficient affects the tool negatively during the cutting process [7]. Elevated temperature that leads to excessive heat accumulated at the vicinity of cutting zone has been identified as the major factor contributing to rapid tool wear and bad surface finish of the work material [8, 9]. Therefore, top of the adverse effects tried to be solved in the last decades among researchers and industrialists is the effect of high temperature at the cutting zone while machining [10]. One of the potential solutions to reduce heat is by modifying the physical of the cutting insert to manage the temperature distribution at the tool-chip interface [11-13]. However, chemical reaction between the workpiece materials and tool materials cannot be explicitly solved by thermal management, thus for the reactive materials, researchers have come up with several suggestions. The most significant of these solutions is coating of the cutting tool [14].

Therefore, understanding of tool life relationship in the function of coating materials during machining is necessary for the design of cutting tools and the determination of cutting conditions and tool change strategies [15]. Metal refractory ceramic material Titanium Diboride (TiB_2) and Titanium Nitride (TiN) have been investigated by several studies because of its high hardness characteristics, high melting point, corrosion resistant properties and improved cutting adhesion wear mechanism [16, 17]. Vleugels and Van Der Biest [18] investigated interaction products and interaction mechanism by quantifying the tool workpiece reactivity in dry and high speed machining of steel using TiB_2, TiN, $TiC_{0.5}N_{0.5}$ composites tools. The experimental results indicate that TiN composites performed the best in the given machining conditions, whereas TiB_2 are not suitable composites for speed and dry machining of steel, because of the chemical dissolution of titanium diboride

The present paper is primarily concerned with investigating titanium based coating materials, namely TiB_2 and TiN deposited by physical vapor deposition (PVD) on carbide cutting tools and their machining performance in comparison with the machining using conventional uncoated tungsten carbide tool that is usually produced in 4 mm thickness. The combined strategies (reduced thickness and coating materials) are rarely considered in the literature particularly investigation by experiments despite the reported superior impact load behaviour possessed by the two Ti-based coating materials.

2. Methodology

2.1. Experimental setup

This study with the aim to investigate the tool life with single turning tool was conducted in accordance with ISO 3685 [19]; the work piece material was cylindrical bars AISI 1017 carbon steel of 50 mm in diameter and 150 mm in length. The nominal composition (wt. %) of AISI1017 is given as C: 0.15; Mn: 0.3; P: 0.04; S: 0.04; and Fe: remainder. The properties of an AISI 1017 are low hardenability and tensile carbon steel which could offer high machinability, high strength, and high ductility. AISI 1017 is a good machinability material, hence wear mechanisms can be limited to adhesion only. The mechanical properties of the tested material are shown in table 1.

Table 1. Mechanical properties of AISI 1017.

Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Hardness (HB)
405	190	116

2.2. Experimental setup

Indexable turning tungsten carbide (WC) inserts with no chip breaker and 6% cobalt binder were used on Computer Numerical Control (CNC) lathe HAAS SL40 machine tool. The experimental setup on a machine tool is presented in figure 1, and the insert image shows the position of the tool and the portable microscope for measuring progressive wear. Customized reduced thick inserts, similar to ISO designation CNMN 120108, were coated with TiN and TiB2 using Physical Vapor Deposition (PVD) technique. The tool holder used in the test has ISO designation of VBMT 160408.

A fine wire thermocouple k-type is implanted inside the insert support and beneath the tool insert at a distance of 1 mm from the cutting edge to monitor the tool temperature changes in machining AISI 1017 with uncoated WC insert as well as with TiN and TiB2 coated carbide inserts as shown in figure 2. The insert support with thickness of 4 mm has been modified to accommodate the channel for routing the fine wire thermocouple of 0.2 mm wire diameter to the data acquisition system for cutting temperature monitoring and data storing. The sampling rate for temperature acquisition is 3 S/s.

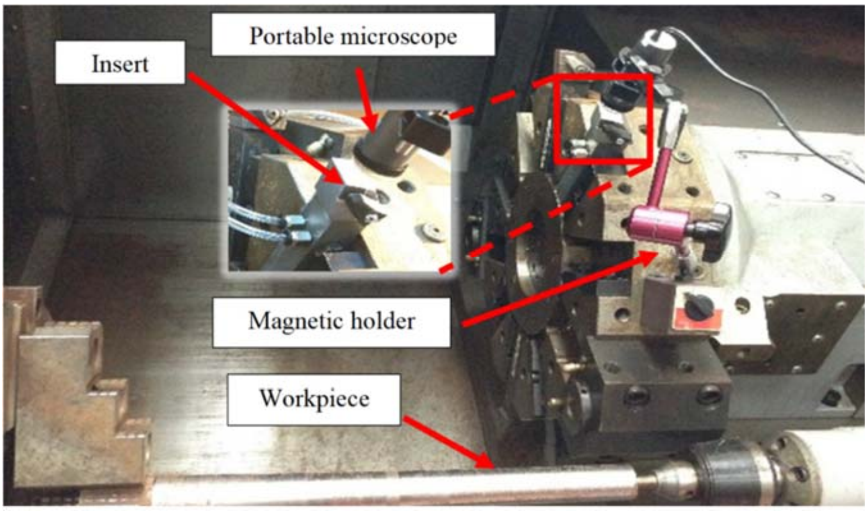


Figure 1. Experimental setup.

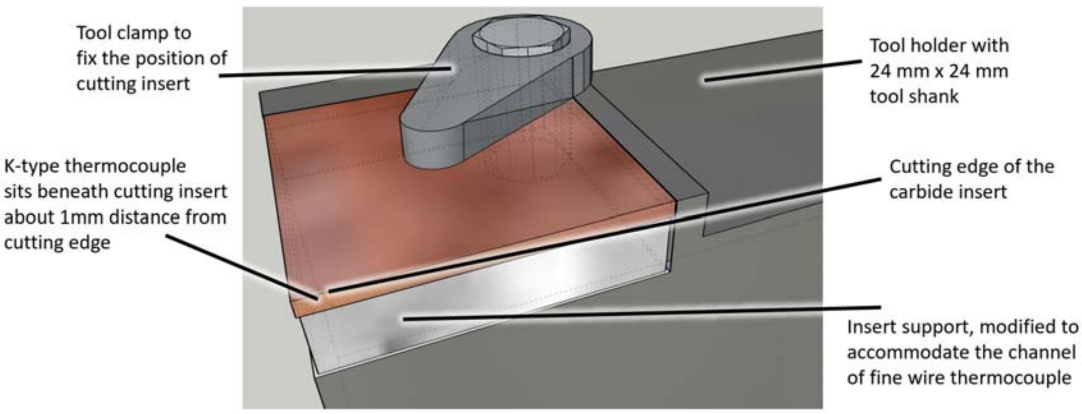


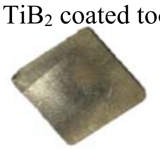
Figure 2. Cutting tool configuration equipped with k-type thermocouple and modified insert support.

2.3. Cutting trials
Continuous dry turning test trials on AISI 1017 carbon steel bar were performed with fixed cutting conditions according to the cutting tool manufacturers' recommendations. The machine tool used a continuous variable spindle speed that is useful during the machining of bars with different diameters at the same cutting speed. The experimental conditions are shown in table 2. In order to clearly evaluate the performance difference and wear progress of the cemented carbide inserts in terms of tool wear, the cutting process was periodically stopped and the amount of flank wear and notch wear formed on the inserts were measured using a digital portable microscope as depicted in the insert image of figure 1.

2.4. Flank wear and surface roughness measurement
The average and maximum flank wear lands, were measured by using a Dino-Lite optical microscope with a magnification ranging from 50 to 220 times. Wear images of the inserts were taken using the TM3030PLUS HITACHI SEM device. The International Standards Organisation (ISO 3685) [20]

outlines the standard method for performing tool life testing with single cutting tool. Surface roughness measurement was performed using surface roughness profiler MarSurf-PS1 based on ISO 4287 where the values were measured with a cut-of length of 5.6 mm. Ten dimensional values were measured at random point.

Table 2. Experimental conditions.

Description	Details		
Machine tool	HAAS CNC SL40		
Workpiece material (chemical compositions)	C:0.15; Mn:0.3; P:0.04; S:0.04; and Fe:remainder		
Cutting tool	Uncoated tool  Insert thickness: 4 mm	TiN coated tool  Insert thickness: 1 mm Coating thickness: 2.5 μm	TiB_2 coated tool  Insert thickness: 1 mm Coating thickness: 2.5 μm
Tool holder	VBMT 160408		
Cutting method	Orthogonal cutting		
Cutting condition	Dry		
Cutting speed (Vc)	100 m/min		
Feed rate (f)	0.2 mm/rev		
Depth of cut (a_p)	0.4 mm		

3. Results and discussion

After the performance of multi-pass cutting trials, the samples were inspected by portable microscope, scanning electron microscopy (SEM), as well as by surface profiler, microphotographs of the progressive wear and wear mechanisms being made, as well as the surface roughness produced, respectively. The real time temperature reading was acquired online during machining for about 20 s per cutting path. Figure 3 depicts the time recorded for the second pass of each cutting insert. The top left corner illustrates a machined workpiece with second pass is circled in blue. Every cutting insert consists of three pieces for improving the accuracy, and during this steady state cutting process all insert types show agreement to each other with TiB2 coated has the least fluctuation with standard deviation of about 2.7 ºC. The highest temperature recorded was by uncoated tool (481.88 ºC), followed by TiN coated tool (449.76 ºC) and the lowest maximum tool temperature recorded was by TiB2 coated tool (333.74 ºC).

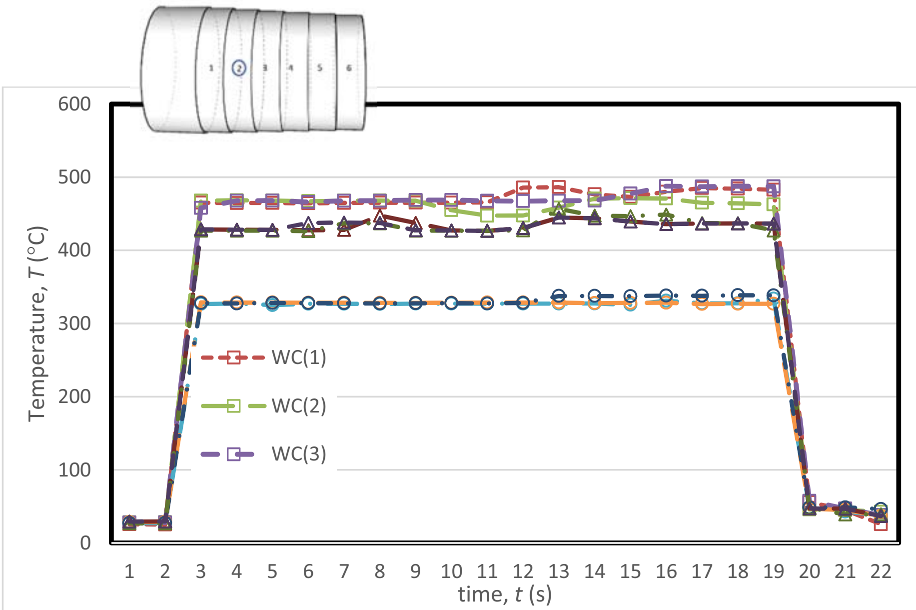
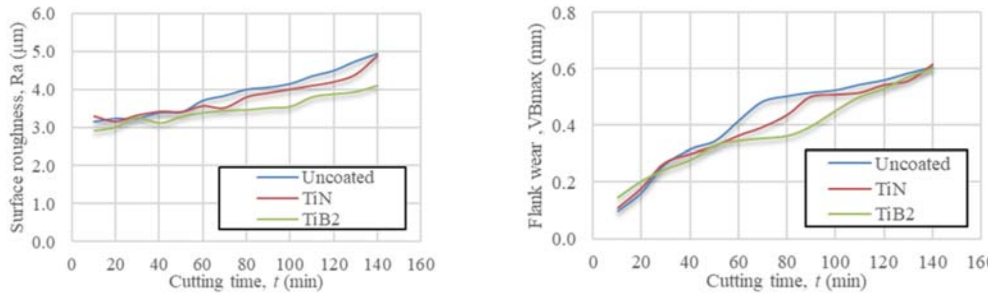


Figure 3. The tool temperature reading for the second cutting path of each cutting insert.

There are three main stages in the formation of flank wear during machining with WC–Co inserts, namely, initial phase, stable wear rate phase, and final phase. In the initial wear stage for fresh tool, small contact area (at tool-chip interface) and high contact pressure at the sharp cutting edge resulted in a high wear rate. As cutting progresses and due to the relative motion between the tool and workpiece, various wear modes become active and the tool starts deteriorate. The progressive wear at initial stage for machining AISI1017 with different cutting tools can be clearly observed in the first 25 minutes of the cutting time in figure 2. After the initial stage, the wear gradually increases into a stable wear stage, normally at this cutting stage the machining output such as surface roughness, cutting force and cutting temperature can easily be predictable [13, 20]. Normally, end of the useful tool life ends sometime in this stage. The tool life criteria of a used cutting tool in single point turning operation according to the standard ISO 3685 (1993) can be defined differently [21]. Among the possible tool life criteria are the land width of flank wear V_B or the crater depth in the rake face. For this investigation the maximum land width of flank wear V_{Bmax} is considered to determine the end of tool life. Based on these criteria, the end of tool life recorded for uncoated tool is 58 minutes, with correlated average arithmetic surface roughness, Ra of 3.2 µm, the end of tool life for TiN coated is 71 min, with correlated roughness average, Ra of 3.4 µm and the end of tool life and Ra for TiB_2 are 93 min and 3.2 µm, respectively. The progressive surface roughness is shown in figure 4(a) and progressive wear is shown in figure 4(b). After the end of tool life, at the final stage, the flank wears increases drastically due to the increase in cutting force and cutting temperature as a result of worn cutting edge which finally leads to the failure.

Figure 5 depicts the relationship between the tool life and the correlated surface roughness average, Ra. In general both Ti-based coating materials can improve the tool life of carbide inserts in machining AISI1017, but highest improvement of more than 60 % extended tool life can be achieved when using TiB_2 PVD coating. It is also demonstrated that TiB_2 can produce good surface finish for longer period of time, compared to uncoated and TiN coated tools. Since tool life and mechanics of chip formation are highly influenced by cutting temperature, further investigation with temperature monitoring system is required [22].



(a) (b)

Figure 4. Progressive surface roughness and progressive wear for machining with different tools.

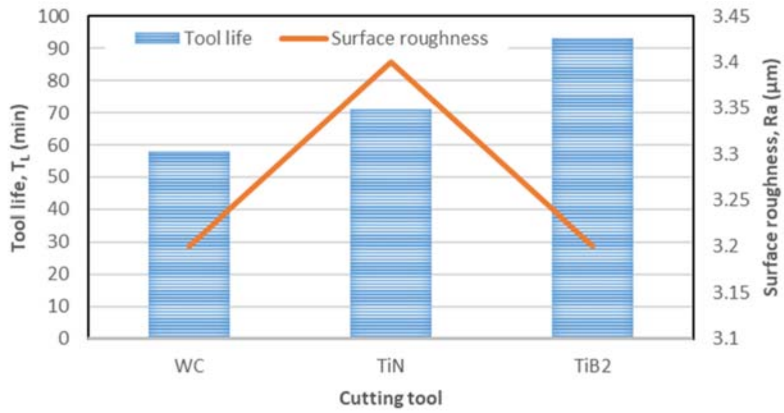
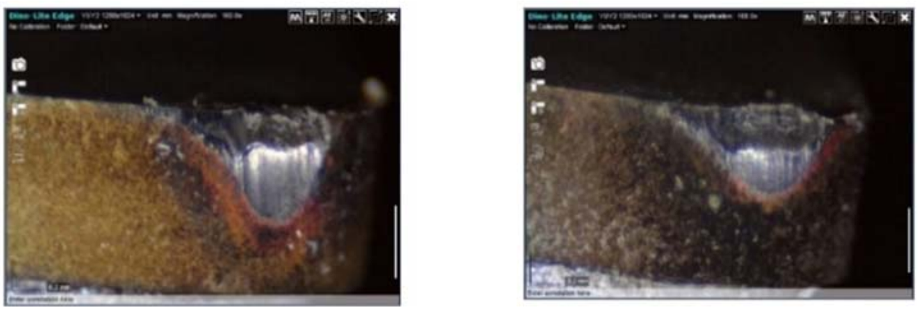


Figure 5. Tool life and surface roughness correlation for uncoated tool (WC) and Ti-based coated tools.

Micrographs of flank wear lands occurred on uncoated and TiB_2 coated tools in figure 6(a) and figure 6(b) revealed that abrasion wear and adhesion wear dominated the mechanisms of material loss at the tool edge of uncoated tool, whilst notch wear due to mechanical impact influenced the wear of coated tool. Adhesive interlocking is clearly visible as a result of interaction of iron from the workpiece and the tool material when investigated by a Scanning Electron Microscope (SEM) as shown in figure 7.



(a) (b)

Figure 6. Flank wear observed after 100 min cutting time for (a) uncoated tool and (b) TiB_2 coated tool.

Significantly, the functions of the coating layer could lower the intensity of heat flow from frictional heat sources, blocking adhesion processes between the iron element in the workpiece and the tool materials [23]. Verification with energy disperse x-ray (EDX) yielded the lower content of iron observed on the flank face of coated tool compared to uncoated tool and the same observations were published by Brieseck, Bohn and Lengauer [24]. Nonetheless, these results agreed that the coated tool also worn during turning but by comparing with the results of uncoated inserts, the Ti-based coating materials can effectively protect the substrate from chemical-induced wear [25].

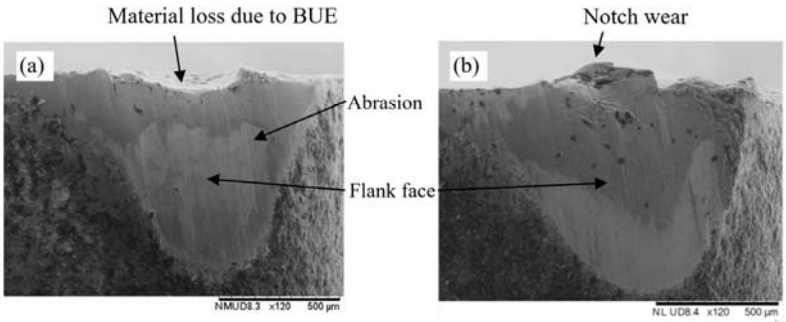


Figure 7. SEM images of tools for wear mechanism study at their end of tool life for (a) uncoated tool and (b) TiB_2 coated tool.

Meanwhile, it observed in figure 8. The progressive tool temperature shows drastic increase for the trends by uncoated carbide tool and TiN coated tools. These phenomena mainly correlate with the condition of cutting tool edge, which for the uncoated the flank wear exceeded the tool life limit at 60 minutes and for the TiN tool life ends at 71 minutes. A slight delay in temperature response is due to limitation of thermocouple working principle that it is too dependent on the physics of heat propagation in the solid media as reported by Li, Tao, Huang and Yin [26].

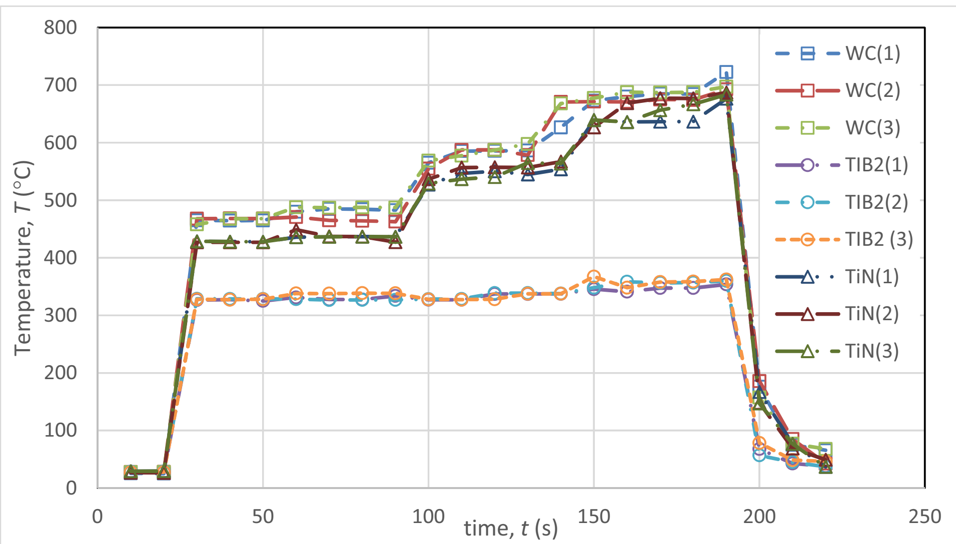


Figure 8. The progress tool temperatures for different cutting insert coating materials for the whole cutting processes.

4. Conclusion

This paper presents the impact of Ti-based coating materials, namely TiN and TiB2 on the wear of cutting tools in comparison with conventional uncoated tool. The results clearly indicate that Ti-based coating materials lead to extended tool life of 22 – 60 % than nominally achieved using uncoated carbide tool and both Ti-based coating materials influence quite differently on the behavior of BUE formation and generated surface evolution over the multi pass straight turning cutting length. In machining AISI1017 in dry condition, TiB2 is the most suitable since it produce the longest tool life and longest period of good surface finish quality at the lowest tool temperature.

Acknowledgment

The authors gratefully acknowledge the financial support supported by the Malaysian Ministry of Higher Education for Fundamental Research Grants (RDU160015) and Research Acculturation Collaborative Effort (RDU151313), and Universiti Malaysia Pahang (www.ump.edu.my) under grants PGRS160385 and RDU150338. The authors also thank the research team from Automotive Engineering Centre (EAC) and Green Research and Advanced Materials Lab, who provided insight and expertise that greatly assisted in the present research work.

References

[1] Ding H, Ibrahim R, Cheng K and Chen S-J 2010 Experimental study on machinability improvement of hardened tool steel using two dimensional vibration-assisted micro-end-milling *International Journal of Machine Tools and Manufacture* **50** 1115-8
[2] Santecchia E, Hamouda A M S, Musharavati F, Zalnezhad E, Cabibbo M and Spigarelli S 2015 Wear resistance investigation of titanium nitride-based coatings *Ceramics International* **41** 10349-79
[3] Ding W, Linke B, Zhu Y, Li Z, Fu Y, Su H and Xu J 2017 Review on monolayer CBN superabrasive wheels for grinding metallic materials *Chinese Journal of Aeronautics* **30** 109-34
[4] Bobzin K, Bagcivan N, Ewering M, Brugnara R H and Basturk S 2014 Comparison of (Ti,Al)N and (Ti,Al)N/γ-Al2O3 coatings regarding tribological behavior and machining performance *Surface and Coatings Technology* **257** 58-62
[5] Kalss W, Reiter A, Derflinger V, Gey C and Endrino J L 2006 Modern coatings in high performance cutting applications *International Journal of Refractory Metals and Hard Materials* **24** 399-404
[6] Siow P C, A. Ghani J, Ghazali M J, Jaafar T R, Selamat M A and Che Haron C H 2013 Characterization of TiCN and TiCN/ZrN coatings for cutting tool application *Ceramics International* **39** 1293-8
[7] Bordin A, Bruschi S and Ghiotti A 2014 The Effect of Cutting Speed and Feed Rate on the Surface Integrity in Dry Turning of CoCrMo Alloy *Procedia CIRP* **13** 219-24
[8] Ghani S A C, Cheng K and Minton T 2013 Back chip temperature in environmentally conscious turning with conventional and internally cooled cutting tools *Journal of Mechanical Engineering and Sciences* **4** 356-72
[9] Ferri C, Minton T, Bin Che Ghani S and Cheng K 2014 Efficiency in contamination-free machining using microfluidic structures *CIRP Journal of Manufacturing Science and Technology* **7** 97-105
[10] Sartori S, Ghiotti A and Bruschi S 2017 Hybrid lubricating/cooling strategies to reduce the tool wear in finishing turning of difficult-to-cut alloys *Wear* **376-377** 107-14
[11] Bleicher F, Pollak C, Brier J and Siller A 2016 Reduction of built-up edge formation in machining Al- and cast iron hybrid components by internal cooling of cutting inserts *CIRP Annals* **65** 97-100
[12] Minton T, Ghani S, Sammler F, Bateman R, Fürstmann P and Roeder M 2013 Temperature of internally-cooled diamond-coated tools for dry-cutting titanium *International Journal of*

Machine Tools and Manufacture **75** 27-35
[13] Jeffries N P and Zerkle R D 1970 Thermal analysis of an internally-cooled metal-cutting tool *International Journal of Machine Tool Design and Research* **10** 381-99
[14] Bertolini R, Bruschi S, Ghiotti A, Pezzato L and Dabalà M 2017 Influence of the machining cooling strategies on the dental tribocorrosion behaviour of wrought and additive manufactured Ti6Al4V *Biotribology* **11** 60-8
[15] Bruschi S, Bertolini R and Ghiotti A 2017 Coupling machining and heat treatment to enhance the wear behaviour of an Additive Manufactured Ti6Al4V titanium alloy *Tribology International* **116** 58-68
[16] Konca E, Cheng Y T, Weiner A M, Dasch J M, Erdemir A and Alpas A T 2005 Transfer of 319 Al alloy to titanium diboride and titanium nitride based (TiAlN, TiCN, TiN) coatings: effects of sliding speed, temperature and environment *Surface and Coatings Technology* **200** 2260-70
[17] Czettl C, Thurner J and Schleinkofer U 2018 Knowledge based coating design of CVD TiN-TiBN-TiB2 architecture *International Journal of Refractory Metals and Hard Materials* **71** 330-4
[18] Vleugels J and Van Der Biest O 1999 Chemical wear mechanisms of innovative ceramic cutting tools in the machining of steel *Wear* **225-229** 285-94
[19] Bruschi S, Bertolini R, Bordin A, Medea F and Ghiotti A 2016 Influence of the machining parameters and cooling strategies on the wear behavior of wrought and additive manufactured Ti6Al4V for biomedical applications *Tribology International* **102** 133-42
[20] Kara F, Aslantaş K and Çiçek A 2016 Prediction of cutting temperature in orthogonal machining of AISI 316L using artificial neural network *Applied Soft Computing* **38** 64-74
[21] Kümmel J, Braun D, Gibmeier J, Schneider J, Greiner C, Schulze V and Wanner A 2015 Study on micro texturing of uncoated cemented carbide cutting tools for wear improvement and built-up edge stabilisation *Journal of Materials Processing Technology* **215** 62-70
[22] Jiang F, Liu Z, Wan Y and Shi Z 2013 Analytical modeling and experimental investigation of tool and workpiece temperatures for interrupted cutting 1045 steel by inverse heat conduction method *Journal of Materials Processing Technology* **213** 887-94
[23] Vereschaka A A, Grigoriev S N, Sitnikov N N, Oganyan G V and Batako A 2017 Working efficiency of cutting tools with multilayer nano-structured Ti-TiCN-(Ti,Al)CN and Ti-TiCN-(Ti,Al,Cr)CN coatings: Analysis of cutting properties, wear mechanism and diffusion processes *Surface and Coatings Technology* **332** 198-213
[24] Brieseck M, Bohn M and Lengauer W 2010 Diffusion and solubility of Cr in WC *Journal of Alloys and Compounds* **489** 408-14
[25] Liu , Ma C, Tu G and Long Y 2016 Cutting performance and wear mechanism of Sialon ceramic cutting inserts with TiCN coating *Surface and Coatings Technology* **307** 146-50
[26] Li J, Tao B, Huang S and Yin Z 2018 Built-in thin film thermocouples in surface textures of cemented carbide tools for cutting temperature measurement *Sensors and Actuators A: Physical* **279** 663-70