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Analysis of tool wear in ultrasonically assisted turning of β-Ti-15V-3Al-3Cr-3Sn alloy

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Abstract. An extremely high tool wear rate in the machining of titanium alloys (Ti alloys) is one of the major reasons limiting the use of conventional machining processes for the components made of these alloys. The machinability of a β-Ti-15V-3Al-3Cr-3Sn (Ti-15333) alloy can be significantly improved using an advanced machining technique known as *Ultrasonically Assisted Turning* (UAT). The key mechanism of tool wear associated with UAT of Ti-15333 alloy is still unknown. The present study begins to address this issue by examining wear behaviour of two different types of cutting inserts using UAT and Conventional Turning (CT) of Ti-15333 alloy. Tool wear was measured using 3D optical microscope and the composition of the Built-Up Edge (BUE) on the worn tools was analysed with scanning electron microscopy. A robust experimental methodology was developed, which provided repeatable and statistically reliable tool wear results. The KC5510 cutting inserts demonstrated better tool-life in UAT when compared to CP-500 inserts.

1. Introduction

In recent decades, machining of the alloys has been a subject of interest in the power-generation, chemical, aerospace, and biomedical industries. The poor machinability of Ti alloys using conventional machining processes is the main disadvantage due to titanium alloys high strength and lower thermal conductivity. A continuous and intensive contact between tool and a workpiece material can generate high cutting forces and temperature in the process zone during titanium alloys machining. This combined effect results in tool surface degradation, poor surface finish of the workpiece, and ultimately, tool failure. In softer materials, the effect of tool wear is less intensive because the contact pressure between the tool and workpiece does not exceed a few megapascals and temperature of the process zone is lower than that of hard-to-cut alloys; in hard-to-cut alloys, the temperature usually exceeds 800°C and contact pressure can go as high as $10^3 - 2 \times 10^3$ MPa [1]. In spite of the technological advancements in investigating tool wear in machining processes, it is still hard to fully understand the mechanism of tool wear in machining processes of metals due to the non-linear behaviour of the tool and strength of workpiece materials at elevated temperature, high strain/strain rate and the complex nature of tool-workpiece, and tool-chip contacts. A series of assumptions was used by various researchers to explain the physical nature of tool wear at different conditions, including diffusion, abrasion, adhesion, fracture, and crumbling [1,2]. In most cases, the immediate effect of tool wear can be

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found on the rake and flank faces of the cutting tool [3-5].

The advanced alloys that have more recently been introduced because of demand for high strength and resistance to corrosion present challenges with regard to their machinability with conventional machining processes. High levels of contact pressure and temperature of the process zone result in poor tool-life and surface finish [6]. The recommended cutting speeds and feed rates for finishing processes are in the range of 0.2-0.63 m/s and 0.15-0.2 mm/rev, respectively, for titanium alloys [7-9]. In order to overcome these problems, new cutting-tool materials were introduced to increase tool-life and quality of products [10], conventional and environmentally friendly coolants were used to remove an excess amount of heat generated at the tool workpiece interface [11], and new machining techniques were introduced to improve surface quality and tool-life in machining of hard-to-cut alloys [12-19].

A new machining technique was introduced to improve the machining of hard-to-cut materials called Ultrasonically Assisted Turning (UAT) [12,13,17,20-27]. UAT transforms a continuous cutting process into a transient one by superimposition of low-amplitude ultrasonic vibration on the movement of a cutting tool, resulting in an intermittent contact between it and a machined workpiece. This new technique has shown significant improvement in surface roughness and reduction in cutting forces in the machining of titanium- and nickel-based alloys. The same idea has also been extended to drilling process, e.g. for carbon-fiber-reinforced composite [28]. Most recently, Muhammad et al. [14,29] have introduced a new variant of UAT, called *Hot Ultrasonically Assisted Turning* (HUAT), which has shown a further reduction in cutting forces and improvement in surface roughness. However, no attempt has been made to investigate the tool-life for this new machining technique.

Hence, the current work presents results of an experimental study of tool wear analysis conducted using two types of cutting inserts (CP500 and KC5510) in conventional turning (CT and UAT). Both cutting inserts have PVD-coated with a ceramic layer of *(Ti-Al)N* over a primer layer of *TiN*, offering the highest resistance to wear [30], where the latter contains cobalt particles in the substrate materials which further enhance its toughness behaviour in intermittent cutting. Usually, the recommended tool for heat resistant alloys in CT processes is CP200. However, tough micro-grains in CP500 inserts make them a better choice than hard micro-grains in CP200 inserts in UAT.

2. Experimental procedures

2.1. Workpiece material

The workpiece used in this study was Ti-15333 alloy, which falls in the class of difficult-to-machine titanium alloys. A 50 mm-bar having a length of 300 mm, solution-treated and aged by annealing at 790°C for 30 minutes was selected for this study. The mechanical and thermal properties of the studied alloys are shown in Table 1.

2.2. Cutting tools

Two types of inserts were used for machining of Ti-15333 alloy and their specification is given in Table 2.

Insert CP-500 is suitable for intermittent cutting as it has a tough micro-grain structure, and the coating technique provides a multiphase coating consisting of a ceramic layer of titanium-aluminium nitride on a layer of titanium nitride. The use of aluminium as a coating material results in an oxide-layer formation, increasing the insert's ability to withstand high cutting temperatures, which are encountered when machining workpieces with low thermal conductivity, e.g. Ti-based alloys. The tool geometry is shown in Figure 1.

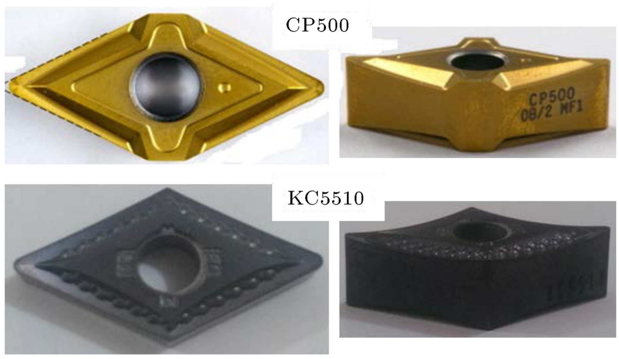

Figure 1. Geometry of inserts.

Table 1. Properties of Ti-15333.

Workpiece material	Ti-15333
Workpiece diameter, D (mm)	50
Producer	GfE Metalle and Materialien GmbH
Heat treatment	Solution-treated and aged
Young's modulus, E (GPa), at room temperature	87
Density, ρ (kg/m^3)	4900
Thermal conductivity, k (W/km)	8.08
Ultimate tensile strength, σ_{u1} (MPa)	1200

Table 2. Specification of cutting inserts.

Specification	Insert 1	Insert 2
Manufacturer	SECO	KENNAMETAL
Tool part number	DNMG 150608 MF1 CP-500	DNMG 150608 KC-5510
Insert material	Micro-grained tungsten carbide	Fine-grained tungsten carbide 6% cobalt substrate
Coating material	Conventional PVD (Ti, Al)N-TiN	Advanced PVD TiAlN
Tool-nose radius, r_c (mm)	0.8	0.8
Nose angle (°)	55	55
Cutting-edge radius (μm)	25	25
Rake angle	14°6′	14°6′
Chamfer angle (°)	0	0

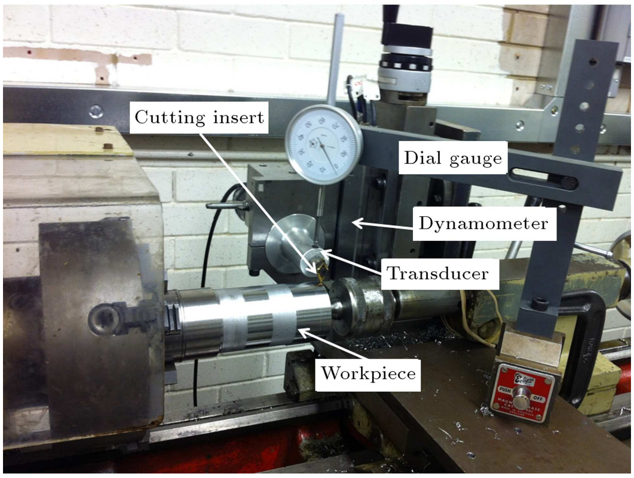

Figure 2. Experimental setup for CT and UAT.

Insert KC5510 is an advanced PVD TiAlN-coated fine-grained tungsten carbide grade. It is specifically engineered for machining of high-temperature Ti-alloys. The fine-grained tungsten carbide 6%-cobalt substrate has excellent toughness and deformation resistance while the advanced PVD coating allows double speeds for metal cutting when compared to those for conventional PVD-coated cutting tools.

2.3. Cutting conditions

Both CT and UAT experiments were performed on a Harrison 300 universal lathe machine using a setup shown in Figure 2. The workpiece was clamped in a four-jaw spindle chuck and a dial-gauge was used to achieve accurate depth of cut in all the experiments. Constant feed rate, $f = 100$ μm/rev, and depth of cut, $a_p = 300$ μm, were used in experimentation. Vibration with a frequency of 20 kHz and amplitude of 10 μm was applied to the cutting inserts in the cutting direction in the UAT regime. The same setup with ultrasonic switched off was used for conventional machining. Two cutting speeds, 10 m/min and 30 m/min, were used in the dry-turning experiments. The test matrix used for tool wear analysis is presented in Table 3.

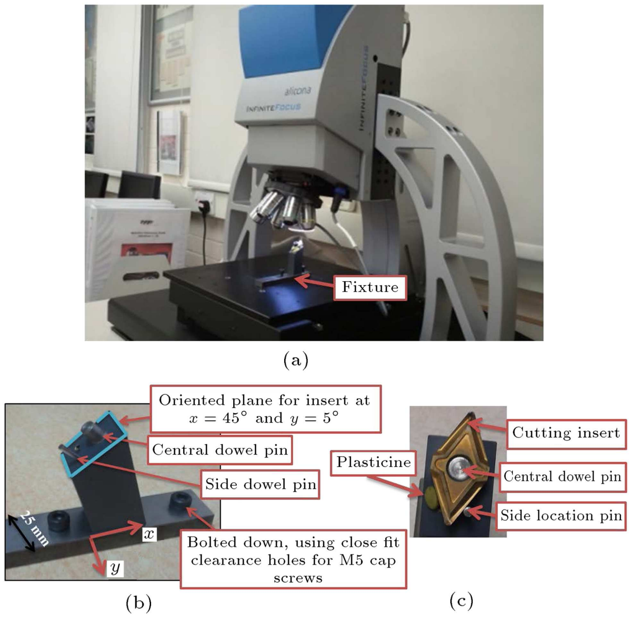

Figure 3. (a) Alicona infinite-focus system used for tool wear analysis. (b) Special insert fixture. (c) Cutting insert placed on oriented plane of fixture.

2.4. Tool-wear measurement

In this study, a 3D optical measurement system; infinite-focus by Alicona, was used for tool wear analysis (Figure 3(a)). A special tool fixture was designed to ensure accurate positioning of the cutting insert at various stages of its life in experimentation (Figure 3(b)). The orientation of the plane of the fixture (Figure 3(c)) was achieved through a series of trials, carried out on the Alicona infinite-focus system to get a good-quality scan of the inserts. A 5X objective of the system was used because of its large field of view compared to a 10X objective, and it was found that it was fully capable to cope with the wear-prone region even when the wear progress occurred along the flank face of the cutting edge. A stepwise procedure was used to carry out tool wear analysis in both CT and UAT. Initially, the analysed cutting inserts were given an ultrasonic bath to remove unwanted solid, semi-solid,

Table 3. Test matrix for tool wear analysis.

Cutting insert no. (insert part name)	Edge no.	Process	Machining time t_m (s)	Cutting conditions			
				Cutting speed (m/min)	Depth of cut (μm)	Feed (μm/rev)	Coolant
1 (SECO grade CP500)	1	CT	100; 300; 500; 700	10	300	100	None (dry process)
	2	CT	100; 300; 500; 700	30			
	3	UAT	100; 300; 500; 700	10			
	4	UAT	100; 300; 500; 700	30			
2 (KENLOC grade KC5510)	1	CT	100; 300; 500; 700	10			
	2	CT	100; 300; 500; 700	30			
	3	UAT	100; 300; 500; 700	10			
	4	UAT	100; 300; 500; 700	30			

or liquid contaminants, which could include metallic and non-metallic debris, chips, dirt particles, or other elements from the surface of the insert. A cleaning procedure with pressurized air was used to ensure removal of any dirt particles to get more accurate scan of the cutting insert.

The Alicona machine software has an in-built feature known as *difference measurement*, which is dedicated to volume measurement. This feature was used to calculate the amount of volume reduction for the cutting inserts after machining by comparing a scan of the virgin sample (a reference scan) with that for the used insert. All experiments for CT and UAT were carried out on the in-house state-of-the-art experimental setup available at Loughborough University, UK. Additional details about the experimental setup can be found elsewhere [12,21]. The experiments were repeated three times for each cutting condition. The spread in data was huge as one of tested KC5510 inserts at both cutting speeds does not fail due to BUE formation. However, the rest of the data was reasonably in good shape and the results were repeatable in both CT and UAT.

3. Tool wear results

Evolution of the average tool wear rate for both cutting inserts (grades CP500 and KC5510) in CT, when machining Ti-15333, is shown in Figure 4. The machining distance (in m) on the axis of abscissas is the distance travelled by the cutting insert, which was calculated from the cutting speed and the cutting period that the insert worked for; whereas, the average tool wear rate on the ordinate was then calculated from the experimental data obtained with the Alicona system, using the following equation:

$$\text{Average tool wear rate} = \frac{\Delta V}{t_m}. \qquad (1)$$

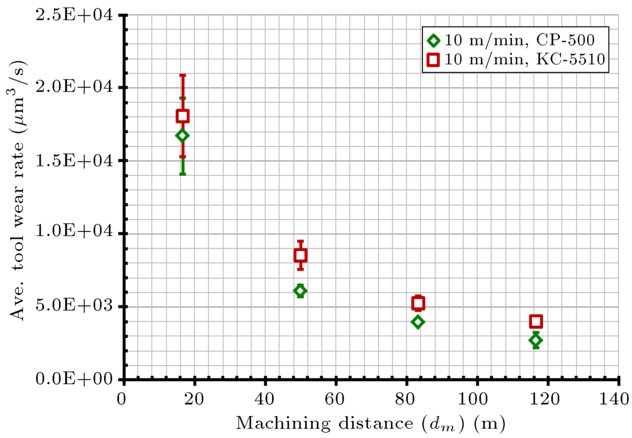

Figure 4. Comparison of tool wear for both inserts at cutting speed of 10 m/min in CT.

ΔV is the average volume reduction in the cutting insert and t_m is the total machining time. A lower average tool wear rate in CP-500 cutting insert was observed when compared to that for insert KC5510, resulting in a better tool-life in turning of Ti-15333. Moreover, it can be noticed that for both inserts, the average tool wear rate in the initial distance-travelled interval 16 m to 50 m and in the two subsequent intervals (i.e., 50 m to 83 m and 83 m to 116 m) attenuated so that it had the lowest magnitude in the last interval. This is an expected phenomenon, since the wear rate under constant load and velocity condition is high during an initial unsteady state and lower in the later, steady-state regime. Similarly, adhesion of material at the tool edge in CT of Ti-15333 also reduced the tool wear rate for both inserts, particularly in CP500. The ultrafine micro-grain structure of KC5510 insert, compared to the micro-grain size of CP500 inserts [31,32], give better tool strength of KC5510 inser; however, more BUE formation tendency in CP500 inserts improve its tool-life in CT whereas the coarse grain size of the workpiece material is the same

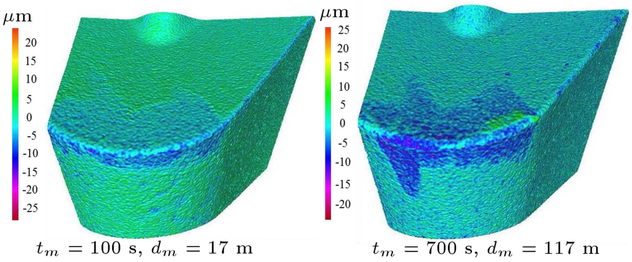

Figure 5. Progression of tool wear in KC5510 at cutting speed of 10 m/min in CT.

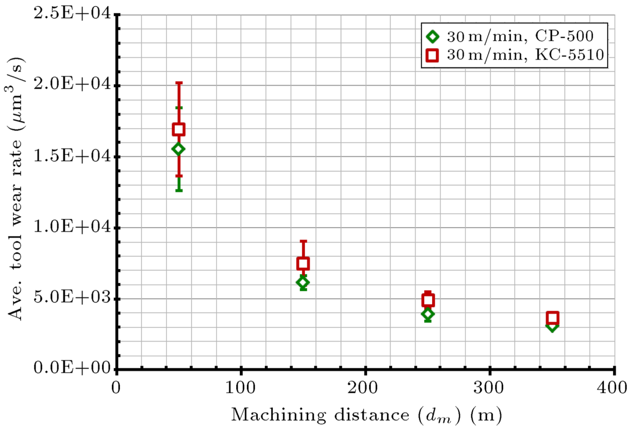

Figure 6. Comparison of tool wear for both inserts in CT at cutting speed of 30 m/min.

for both inserts [21]. In addition to that, no phase transformation in a machined surface was observed. The difference in the wear rate at the stable state was not significant since only minor removal of coating material with no chipping or crater wear was found on the tools (see Figure 5). However, the tool wear can be significantly higher when the coating is removed [4].

The development of average tool wear rate at a higher cutting speed, 30 m/min, is shown in Figure 6 for both inserts: CP500 and KC5510. The observations depicted for 30 m/min are rather similar to those discussed for a lower speed above. These include the facts that CP500 insert had a lower wear rate and the difference in the wear rate between both inserts was not significant, since only the coating was affected and there was no physical damage to the insert. However, observations during machining tests demonstrated formation of unstable Built-Up Edge (BUE) for both lower and higher cutting speeds, which was due to adhesion of the workpiece material to the rake face of the insert (adhesive wear mechanism). This shows the chemical affinity between materials of the inserts and the workpiece. The BUE for CP500 insert after machining for 500s at 30 m/min is shown in Figure 7. The height of the added material was 72 μm and was calculated using smartscope FLASH 200 system [33].

Transition to vibro-impact machining in the UAT

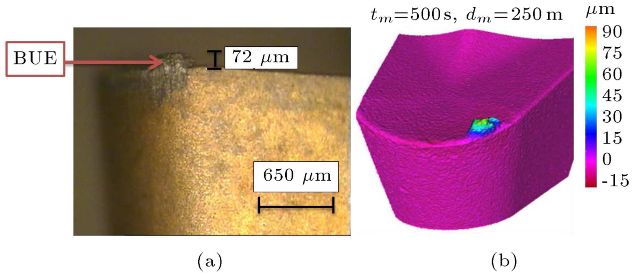

Figure 7. (a) BUE of CP500 insert at t_m = 500 s and V = 30 m/min: image obtained with Smartscope FLASH 200 system. (b) Data obtained with Alicona infinite-focus system.

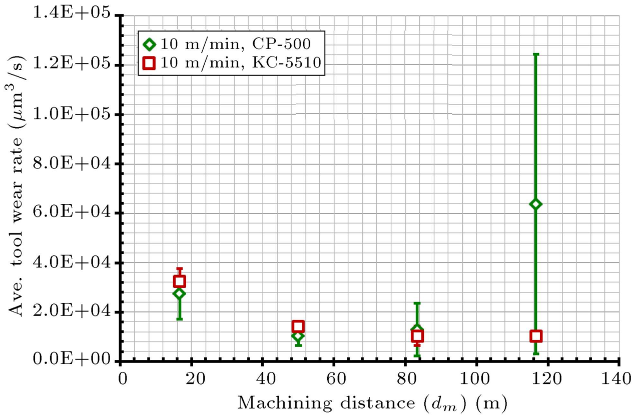

Figure 8. Comparison of tool wear in both inserts in UAT at cutting speed of 10 m/min.

regime, as expected, affected the character of the tool wear evolution. The development of the average tool wear rate with machined length, when machining Ti-15333 using this regime at the lower cutting speed of 10 m/min, is shown in Figure 8 for both insert types. Generally, the levels of average tool wear rate for insert CP500 were lower than those for KC5510 for the initial distance travelled by the insert up to approximately 50 m; this difference was small. However, when CP500 insert was worked for higher distances, beyond 60 m, its wear rate increased drastically by a factor of more than 6 times between the travelled distances 83 m and 116 m. This is due to the fact that two of the three CP500 inserts used underwent catastrophic failures as shown in Figure 9. The main reasons for the higher tool wear rate in CP500 inserts are the lack of BUE formation in UAT compared to KC5510 inserts, oxidation of WC tools, and their grain size which is coarser than KC5510 [31,32]. The cobalt content added to KC5510 insert refines its grain size compared to CP500 inserts and gives it more strength and toughness.

For CP500 insert, the catastrophic failure in the form of plastic deformation was linked to the substrate composition of the CP500 insert, which caused significantly lower impact resistance than that of insert

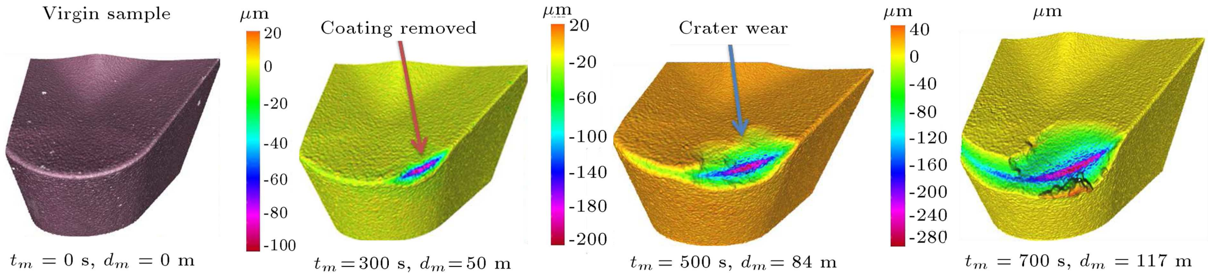

Figure 9. Wear progress to catastrophic failure in CP-500 cutting inserts in UAT at cutting speed of 10 m/min.

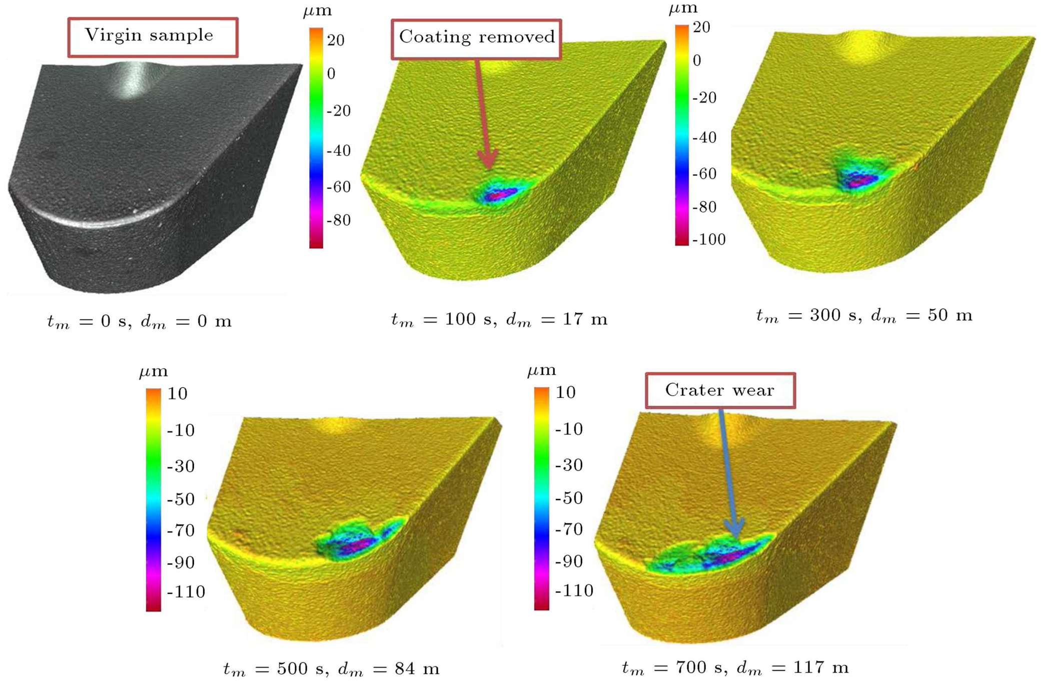

Figure 10. Wear progress of insert KC-5510 in UAT at cutting speed of 10 m/min.

KC5510 [34]. This phenomenon can be explained by considering wear progress with the worked time. It was observed that the Ti(AlN)-TiN coating was removed at 300 s of the worked time. The reason for the quick removal is the brittleness of the thin layer of aluminium oxide. Since, the insert was developed for conventional machining operations and was not designed to withstand multiple micro-impacts characteristic to UAT. When it lost its structural integrity, high temperature in the process zone resulted in a swift removal of the coating from the cutting inserts. Once the coating failed, the substrate of the inserts was exposed to high cutting forces and excessive temperature leading to fast tool failure. As a result, a crater and flank wear were observed along the cutting edge as shown in Figure 9.

In contrast, for KC5510 cutting inserts, it was observed that the average wear rate attenuated by nearly 2×10^4 μm^3/sec at distance 50 m compared to that at 16 m and, additionally, by nearly 2×10^2 μm^3/sec at a distance of 83 m. This is beneficial, since it results in a longer tool-life. This extremely positive tool wear behaviour of KC5510 insert, as compared to that of CP500, can be explained by its substrate composition [34]. Similarly, the BUE formation in UAT of KC5510 was frequently observed when compared to CP500 which added life to these types of inserts at higher speeds in turning of Ti alloys. The wear development in the KC5510 cutting insert is shown in Figure 10. Crater wear was mainly responsible for the failure (90 μm [35]) of KC5510 cutting inserts in UAT of Ti-15333.

Comparing the wear progress in two studied inserts, a significant difference was observed in UAT. Though the coating was eventually removed from both inserts, the substrate of insert KC5510 demonstrated significantly greater resistance to localized plastic deformation as well as resistance to failure once the physical damage began [34,36].

The discussed tool wear evolution in CP500 exacerbated at a higher cutting speed of 30 m/min as shown in Figure 11. It was observed that for KC5510 insert,

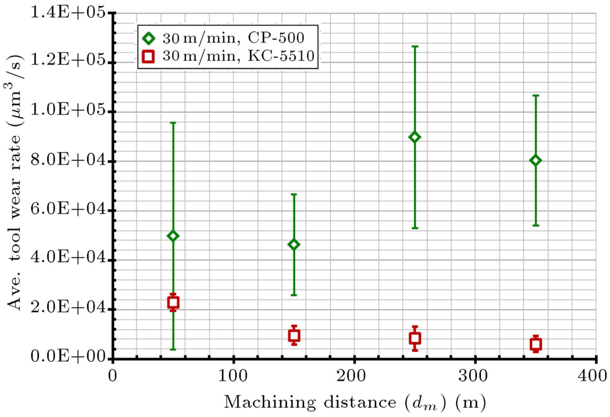

Figure 11. Comparison of tool wear in both inserts in UAT at cutting speed of 30 m/min.

the average wear rate was significantly lower than that observed for CP500 inserts; it attenuated gradually with increase in the distance travelled by the insert. It is a very positive result implying that KC5510 could enable higher cutting speeds in machining Ti-15333, increasing productivity by achieving higher material removal rate (it was shown [21,37] that UAT resulted in a large force reduction and improvement of surface finish in these tests). In contrast, the tool wear in CP500 inserts was characterised by a rapid increase in the wear rate, more than an order of magnitude higher than that for KC5510 for the same travelled distance of 250 m.

The CP550 inserts at a cutting speed of 30 m/min demonstrated increased chipping and flaking, and eventually catastrophic fracture of the insert occurred. This is depicted in Figure 12 for one of the CP500 inserts, which was worked for 100 s, 300 s, and 500 s. The average wear rate for CP500 was higher at 30 m/min due to higher cutting temperature and thermal as well as mechanical stresses at high.

Heavy chipping was already observed when the insert was worked for 100 s (see Figure 13), and the wear manifested itself as rake-face wear initially, due to high temperature and stress at the insert-chip contact on the rake face. Also, it can be seen that the protruding material was observed, most probably the chip/workpiece material welded onto the rake face. To confirm the presence of an external workpiece material on the insert, an analysis has been done on the BUE using Scanning Electronic Microscopy (SEM) (see more below). In the insert worked for 300 s and 500 s, crater wear and catastrophic fracture are the dominant features in tool failure. Some of the prominent wear mechanisms observed for CP500 insert at high cutting speed were abrasive wear (as chipping occurred), thermal mechanisms (high cutting temperature at high speed), attrition (removal of grains of tool material by the adherent chip), and adhesive wear (at tool-chip interface).

The formation of BUE in UAT of Ti-15333 using KC5510 cutting inserts is an unstable process, which results in a decrease in the average tool wear rate of KC5510 cutting inserts at higher cutting speeds. In most cases, the BUE was welded to the rake face of the cutting inserts as shown in Figure 13.

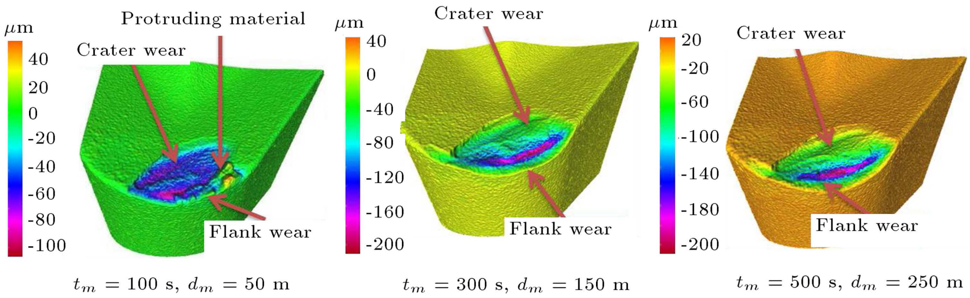

Figure 12. Wear progress of insert CP-500 at cutting speed of 30 m/min in UAT.

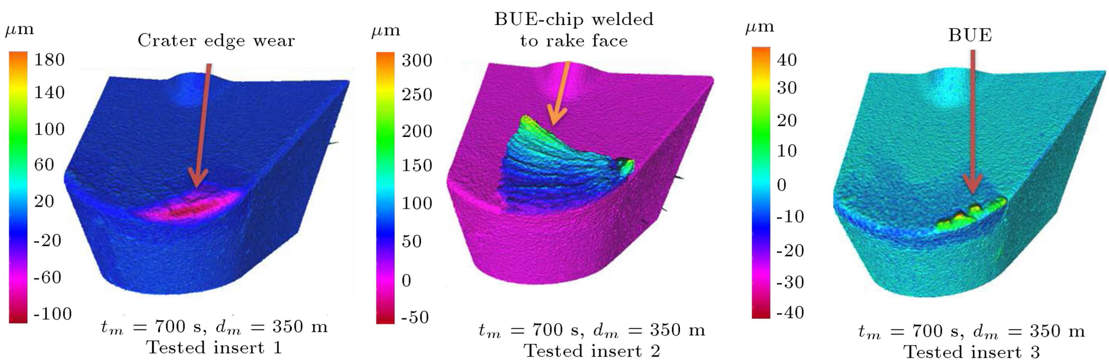

Figure 13. Wear progress of insert KC-5510 at cutting speed of at 30 m/min in UAT.

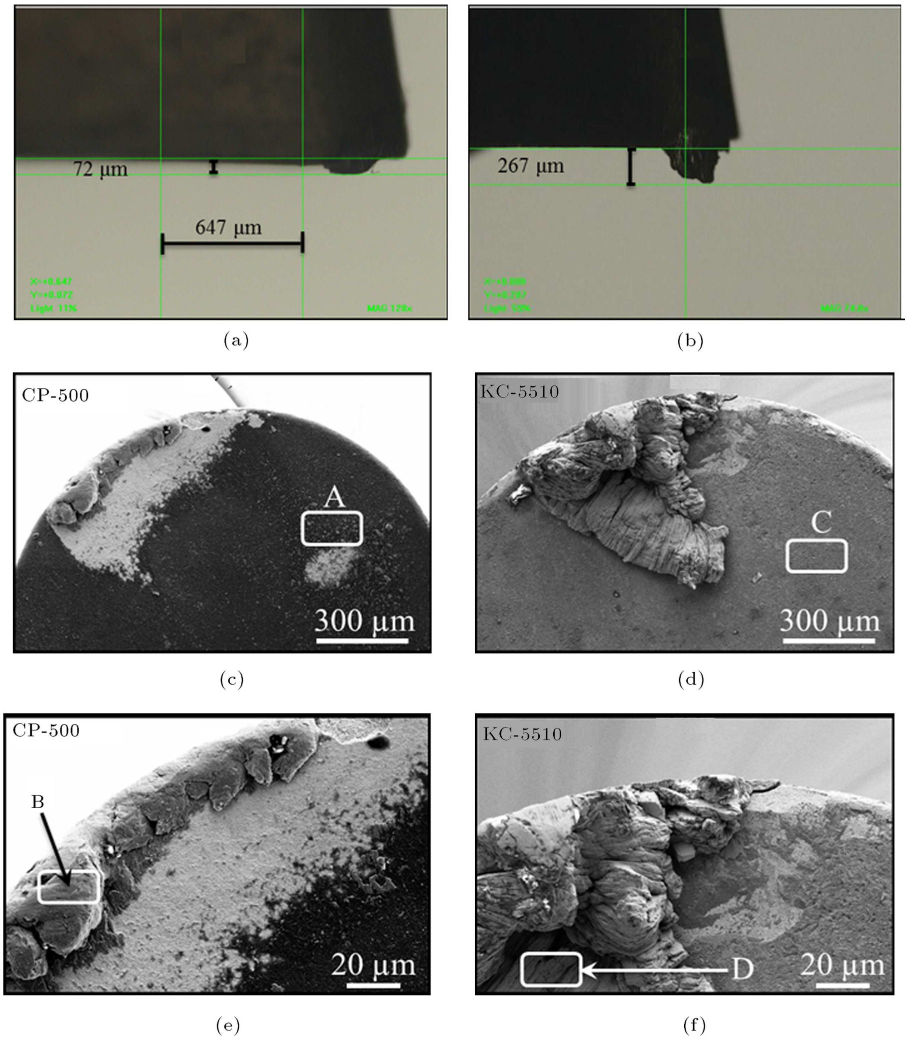

Figure 14. SEM micrographs depicting BUE formed on inserts CP500 ((a), (c), and (e)) and KC5510 ((b), (d), and (f)).

Table 4. Insert specifications and cutting conditions: analysed for BUE.

Insert type	**CP500**	**KC5510**
Machining process	CT	UAT
Cutting speed (m/min)	30	10
Worked time (s)	500	500
Feed rate (mm/rev)	0.1	0.1

4. SEM analysis of BUE formation

The formation of BUE was observed in both CT and UAT processes, and was unpredictable since it formed randomly during the experiments at both high (30 m/min) and low (10 m/min) cutting speeds. Two inserts, one for each machining process, were selected and used for SEM analysis (see Table 4).

The protruding height of BUE and magnified images of their surface profiles for both inserts are shown in Figure 14. Comparing Figure 14(a) and 14(b), it was observed that insert KC5510's BUE protrudes more by about 195 μm compared to that for CP500. Moreover, it can be stated that along the rake face, transferred material is present in the form of highly deformed attached chunks for both inserts. This is a typical feature of adhesive wear, which occurs due to bonding or micro welding at surface asperities of contacting bodies, i.e. chip and insert. The high levels of cutting temperature and stresses at the tool-chip interface assisted this process. Further analysis was carried out to investigate the composition of the material added to the rake face of the tool in the form of BUE. Therefore, Energy-Dispersive X-ray (EDX) spectroscopy was carried out in the selected regions (marked A, B, C, and D) as shown in Figure 14.

The spectra results show the elemental weights (wt.%) present in the selected regions. Considering Table 5, elements Ti, Al, and N are present in larger elemental weights with minor traces of other elements. This is expected as both inserts have an outer coating of TiAlN for improved hot hardness and wear resistance. Table 6 shows that the BUE on both inserts had

Table 5. EDX results of inserts CP500 and KC5510 (wt%).

Elements	Ti	N	Al	V
Region A, CP500	61.8	19.9	17.3	0.7
Region C, KC5510	46	15.7	30.1	0.8

Table 6. EDX results of BUE for inserts CP500 and KC5510 (wt%).

Elements	Ti	V	Sn	Al	Cr	Fe	W
Region B, CP500	75.7	14.9	3.3	3	2.5	0.3	0.2
Region D, KC5510	75.4	15.8	2.6	2.3	2.1	0.4	0.2

significantly increased amount of Ti, about 75% by weight, and elements Sn, Cr, and V in noticeable fractions. This confirmed that BUE was composed of transferred workpiece material - Ti15333.

5. Conclusions

The main conclusions of this work are:

- The prominent wear mechanism for CP500 and KC5510 cutting inserts in UAT at 10 m/min and 30 m/min was attrition wear where the particles were pulled out from the substrate;
- A catastrophic tool failure was observed in both tools once the tool coating was removed in UAT. However, the level of wear was significantly higher in CP500 cutting insert than in KC5510;
- The experimental results demonstrated that KC5510 cutting insert exhibited lower tool wear levels at 30 m/min when compared to 10 m/min, indicating its potential for improved material removal rate in UAT;
- In UAT, CP500 cutting insert showed poor wear resistance and readily experienced catastrophic failure at both cutting speeds;
- The average tool wear rate was higher for UAT than for CT for both inserts, though KC5510 demonstrated a performance not much worse than in conventional turning. Obviously, both types of cutting inserts were designed for conventional machining processes and their brittle coatings performed poorly in a vibro-impact regime of UAT. This finding supports a need for the design of tools, specially aimed at UAT.

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