TiAlN/VN superlattice structured PVD coatings: A new alternative in machining of aluminium alloys for aerospace and automotive components

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TiAlN/VN Superlattice Structured PVD Coatings: A New Alternative in Machining of Al Alloys for Aerospace and Automotive Components

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Abstract: A 3 μm thick superlattice structured TiAlN/VN coating has been deposited by the steered cathodic arc/unbalanced magnetron sputtering technique. The coating has been tested in dry high-speed milling of aluminium alloys Al7010-T7651 and AlSi9Cu1 and the performance compared to that of the diamond-like carbon (DLC) coated, TiAlCrYN coated and uncoated tools. In milling the Al7010-T7651 alloy, TiAlN/VN and DLC coated tools showed comparable performance, outperforming TiAlCrYN coated and uncoated tools by a factor of 2.3 and 3.5, respectively. In the case of milling AlSi9Cu1, the DLC coatings failed to produce any lifetime improvement, TiAlCrYN showed ~65% longer lifetime thus rendering TiAlN/VN as the best performing coating with 100% longer lifetime compared to that of the uncoated tools. The tests further showed that TiAlN/VN reduces the cutting forces and improves the surface finish. Scanning electron microscopy of the cutting edge carried out after the cutting tests showed that the TiAlN/VN coating significantly reduces metal transfer and built-up edge formation.

Key Words: PVD; Superlattice coatings; TiAlN/VN; Aluminium alloy cutting; Tool wear

1. Introduction

In automotive and aerospace industries, cutting aluminium alloys is a major manufacturing activity. Today, there is a worldwide demand for development of environmentally friendly and cost-effective cutting technologies including high-performance tool materials suitable for dry high-speed cutting [1–3]. In dry machining however, metals of good plasticity like aluminium always exhibit high friction and strong adhesive interaction with tool materials and therefore have a strong tendency of built-up edge (BUE) formation.

BUE has been known to be the main reason for high cutting force, poor surface finish and short tool lifetime. Other major tool failures include severe abrasive wear in cutting silicon-containing alloys and chipping wear in cutting high-strength alloys [2]. Therefore, aluminium cutting tools of good performance should possess low affinity to aluminium, low friction coefficient and high hardness. In the last two decades, many surface engineering materials fabricated by chemical or physical vapour deposition have been developed to improve tool performance in cutting "sticky" metal alloys. Among these developed materials, carbon-based coatings such as diamond and diamond-like-carbon (DLC) have shown the ability to significantly reduce the BUE formation and hence improve cutting performance [1-5]. On the other hand, transition metal nitride coatings like TiN, TiAlN and CrN were reported to show poor performance mainly due to the BUE formation [2,4,6].

In this paper, we report recent progress in the application of a low friction and highly wear resistant coating TiAlN/VN in dry high-speed milling of automotive and aerospace aluminium alloys. TiAlN/VN is a compositionally modulated nanoscale multilayer (superlattice) structured coating containing sequentially deposited sublayers of TiAlN and VN with bilayer spacing of 3 nm. The exceptionally low friction coefficient of 0.45, for a superhard ceramic coating ($HK_{0.025}$ 30–55 GPa) and low wear rate ($\sim 10^{-17}$ m^3 N^{-1} m^{-3}), have been reported elsewhere [7,8]. In the special case of dry utting of the "sticky" aluminium alloys, the low friction coefficient is expected to contribute for a good anti-BUE behaviour and chipping wear resistance, whereas the high hardness is expected to improve the resistance to abrasive wear. In a recent publication, we have reported the performance of TiAlN/VN coated tools in dry high-speed milling a silicon-free high-strength aerospace alloy Al7010-T7651 as compared to that of the uncoated and TiAlCrYN coated tools [9]. In this paper, the performance of the TiAlN/VN is compared to TiAlCrYN, a dedicated coating for dry high-speed milling [10], and DLC as a current market leader in this demanding application.

2. Experimental

2.1. Sample preparation

End mill cutters of 25 mm in diameter were manufactured from a powder-metallurgy high-speed steel (HSS) S290 (compositions C 2.0%, W 14.5%, Co 11%, V 5%, Cr 2.0%, Mo 2.5%, Fe in balance and hardness HRC 68–70) [11]. Prior to the coating deposition, all the samples were cleaned in an automated cleaning line comprising a range of ultrasonically agitated aqueous alkali solutions and deionised water baths and a vacuum drier.

An industrial scale four-cathode physical vapour deposition (PVD) coater (Hauzer HTC 1000-4) was used to deposit the TiAlN/VN and TiAlCrYN coatings in reactive unbalanced magnetron sputtering mode in a common $Ar+N_2$ atmosphere. The machine is equipped with two turbo molecular pumps operating at high pumping speed (S_p=2200 $l \cdot s^{-1}$) and a precise pressure monitoring Viscovac system, which allows reliable handling of the target poisoning effect by a simple control of the total pressure ($\Delta p_{Ar}+\Delta p_{N2}$=constant), during the reactive magnetron sputtering. The coatings have been deposited at temperature of 450 °C and substrate bias voltage of −75 V. Prior to the deposition, the surface was pre-treated by bombardment with V^+ metal ions produced from a steered cathodic arc discharge. The ions were accelerated towards the substrate by a high bias voltage (U_b=−1200 V) to achieve a low energy ion implantation, which leads to excellent coating adhesion [12]. To deposit the TiAlN/VN, two pairs of adjacent TiAl (50:50%) and V targets (99.8% pure) were used. The deposition of TiAlCrYN coatings employed one Cr (99.8%), two TiAl (50:50%) and one TiAlY (48:48:4%) targets. The deposition time was controlled to reach a coating thickness of 3±0.5 μm. Regime of the coating system and the deposition procedures have been described elsewhere [7,8].

W-based DLC coatings 3 μm thick have been deposited in a hybrid sputter-PVD and plasma enhanced chemical vapour deposition (PECVD) process. The process was performed in a machine with four unbalanced magnetron coils in a closed field configuration. After an argon-ion etching step, a combined metallic adhesion layer was produced by chromium sputtering and tungsten carbide sputtering. Finally, the a-C:H top coating was produced in a pure PECVD step, yielding a low friction top coating. Details for the deposition parameters are presented in [13].

2.2. Characterization of PVD coatings

A Mitutoyo MVK-G1 hardness tester was used to determine the Knoop hardness of the coating at an indentation load of 0.025 kg. The adhesion was evaluated by the critical load values Lc, measured in a scratch test using CSM Revetest equipment. Adhesion was also tested by indentation method using 6-grade evaluation scale with 1 as excellent and 6 as poor adhesion, as introduced by Dimelar-Bentz [14]. The coefficient of friction and wear properties were determined by a CSM pin-on-disc tribometer. The tests were carried out in a dry sliding conditions using Al2O3 ball counterpart being 6 mm in diameter, normal load 5 N, sliding speed 0.1 $m \cdot s^{-1}$ and total sliding durations 60,000 laps for the TiAlCrYN and 200,000 laps for the TiAlN/VN and DLC, respectively. Cross section microstructure of the TiAlN/VN coating was characterized using a transmission electron microscope (TEM, Philips CM20, 200 kV). The tested tools were analyzed using an analytical scanning electron microscope (SEM, Philips XL-40, 20 kV).

2.3. Milling test procedures

A high-speed milling machine MAZAK FJV-25 and a Marwin MPS horizontal machining centre were employed for milling tests in laboratory and in industrial conditions, respectively. Cutting parameters are listed in Table 1. In the laboratory tests, a computer-supported optical image analyser was used to define the progression of the cutting edge flank wear. The test was

Table 1 Parameters of milling tests

Spindle speed	24,000 rpm	Cutting depth	4 mm
Cutting speed	1884 $m \cdot min^{-1}$	Feed rate	0.165 mm·per tooth
Cutting width	In-lab tests: 2 mm, industrial tests: 25 mm (full-slot)		
Work pieces	Wrought Al7010-T7651: rectangular blocks with lengths of 485 mm (for in-lab tests) and 260 mm (for industrial tests); AlSi9Cu die-cast : 150–200 mm trapezoid-shape ingots		

regularly interrupted to measure the wear until reaching the pre-defined value of 0.23 mm, used as criteria for defining the tool lifetime. The cutting forces were measured by employing a Kistler 9265A2 dynamometer. The roughness parameters of rake surface before and after the tests were measured using a diamond-stylus Telysurf profilometer. In the industrial tests, the cutting forces were measured using a high frequency Kistler 9257B platform dynamometer. Furthermore, surface roughness (Ra) of machined parts was determined using portable Talysurf measurement equipment.

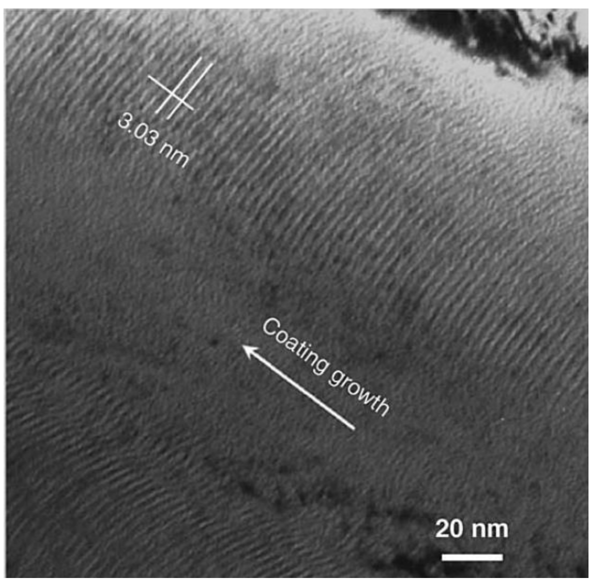

Fig. 1. Cross-section TEM micrograph showing nanoscale multilayer structure of the TiAlN/VN coating.

3. Results

3.1. Microstructure and mechanical properties of PVD coatings

The TiAlN/VN coating exhibits dense structure and well-defined TiAlN and VN multilayer architecture having a bilayer period 3.03 nm (Fig. 1). The arch-like multilayer fringes demonstrate a rough growth surface, which, however, results in lower residual stress (−3.2 GPa). More details of the TiAlN/VN microstructure characteristics can be found in Refs. [15,16]. Table 2 summarizes the properties of TiAlN/VN, TiAlCrYN and DLC coatings deposited on hardened HSS coupons ($HV_{0.05}$ 7.9 GPa), including multilayer period (λ), hardness HK0.025, adhesion properties, friction coefficient (μ) and wear coefficient (K_c). The coating thickness was controlled between 3.0 and

Table 2 Structural, mechanical and tribological properties of PVD and PACVD coatings

Coatings	λ (nm)	$HK_{0.025}$ (GPa)	L_c (N)	DB test grade	μ	K_c (10^{-17} m^3 N^{-1} m^{-1})
TiAlN/VN	3.03	33.5	46.8	1	0.43	2.3
TiAlCrYN	1.8	28.0	60.4	1	0.66	24.4
DLC	N/A	28.0	30.0	3–4	0.12	N/A

3.5 μm. As can be seen from this data, the TiAlN/VN coating exhibits higher hardness, lower friction and lower wear coefficients than these of the TiAlCrYN. Most significantly, the wear coefficient of TiAlN/VN is lower than that of the TiAlCrYN by a factor of ten. Both the TiAlN/VN and TiAlCrYN coatings exhibit strong adhesion property (L_c>45 N, grade 1 in DB test) owing to the Cr^+ or V^+ ion etching. The DLC coating deposited by PECVD also shows high hardness value of $HK_{0.025}$ 28 GPa and especially low friction coefficients (0.12). Moreover, the DLC coating exhibits significantly lower adhesion property than the TiAlN/VN and TiAlCrYN.

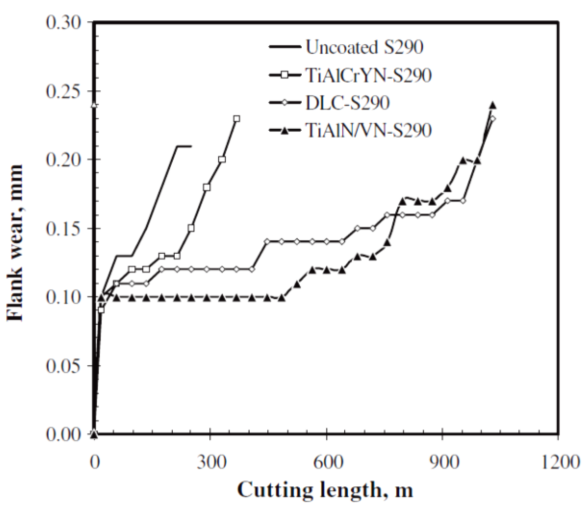

Fig. 2. Flank wear curves of coated and uncoated S290 HSS tools in milling aerospace aluminium alloy Al7010-T7651.

3.2. Tool performance in milling Al7010-T7651

Fig. 2 shows the flank wear of uncoated and coated HSS tools in dry milling Al7010-T7651 alloy. Compared to the fast flank wear of the uncoated tool, the three coated tools show a typical three-period flank wear curves but with different length of steady wear periods. The TiAlCrYN coated tool shows a short period of steady wear. Its overall cutting length is approximately 370 m, 46% longer than the uncoated tool. Both the DLC and TiAlN/VN coated tools show substantially longer periods of steady wear than the uncoated and TiAlCrYN coated tools. The ultimate cutting lengths for the DLC and TiAlN/VN coated tools are 1030 m, respectively, leading to increased tool life by 194% over the uncoated tool. The flank wear curve of the TiAlN/VN coated tool is below that of the DLC coated one in most of the testing period, indicating better wear resistance. Fig. 3 shows cutting force Fxy as measured in laboratory tests for several coated tools. The cutting force values for the TiAlN/VN and DLC coated tools are comparable but approximately 50% lower than

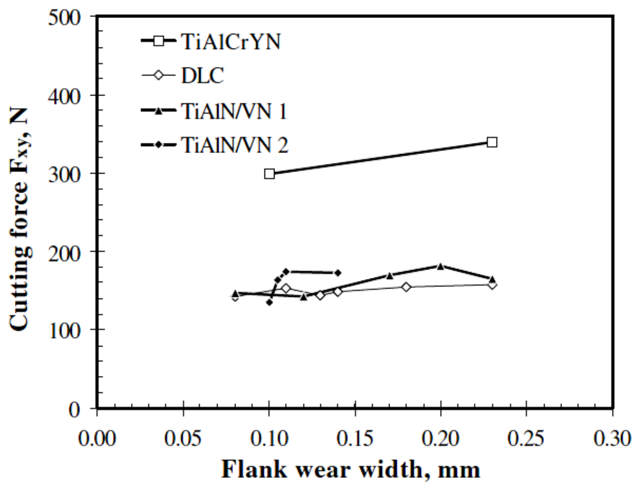

Fig. 3. Cutting force Fxy of varies coated S290 tools plotted against the increase of flank wear.

Table 3 Measurements of cutting forces, metal surface finish roughness and tool surface roughness changes in industrial milling tests on aerospace aluminium alloy Al7010-T7651

	HSS	TiAlCrYN	DLC	TiAlN/VN
Cutting forces F_x and F_y in dry cutting test (N)				
F_x	1075	1000	889	870
F_y	460	410	417	417
Cutting forces F_x and F_y in wet cutting test (N)				
F_x	1125	1170	972	T920
F_y	540	540	567	511
Roughness (Ra) of tool rake surface (µm)				
New tool	0.492	0.327	0.084	0.099
Tested tool	0.558	0.382	0.082	0.101
Surface roughness (Ra) of machined part (µm)				
Dry cutting	1.24	0.72	0.83	0.78
Wet cutting	1.27	0.78	1.03	0.80

that of the TiAlCrYN. The low cutting forces of the TiAlN/VN and DLC coatings have been confirmed in the industrial tests too (Table 3). Table 3 also indicates that the TiAlN/VN and DLC coatings have significantly reduced the tool surface roughness and achieved lower surface finish roughness of the machined parts. The beneficial effect of the low friction TiAlN/VN and DLC coatings can also be seen in wet cutting processes. In contrast, the high-friction coating TiAlCrYN shows cutting force F_x being comparable to that of the uncoated tools.

3.3. Tool performance in milling AlSi9Cu1 alloy

In the dry milling tests using die cast ingots of AlSi9Cu1 alloy, it was difficult to produce a flank wear curve similar to those (Fig. 2) obtained in milling of Al7010-T7651 rectangular blocks because of the irregular (trapezoid) shape in the AlSi9Cu1 ingots. Instead, two lifetime parameters, the total volume of metal removal and the real cutting time, were worked out after each test. Fig. 4 displays the real cutting time of differently coated tools when reaching the criteria of 0.23 mm flank wear. The TiAlN/VN coated tool shows the longest cutting time, an increase by 100% of tool lifetime of uncoated S290 HSS tool. The TiAlN/VN coating is suggested to have the best wear

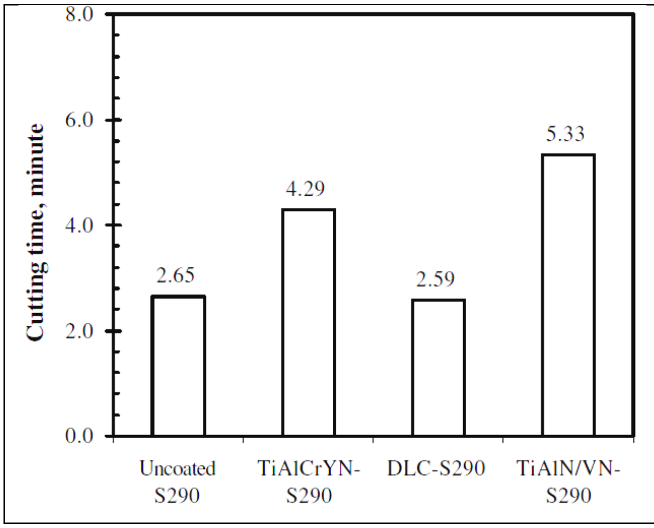

Fig. 4. Lifetime of coated and uncoated S290 tools in milling die cast aluminium alloy AlSi9Cu1.

resistance in such high abrasive cutting environment. In contrast, the TiAlCrYN coated tool has shown only an increase of the lifetime by 62%. The DLC coated tool does not show any improvement in cutting time.

3.4. SEM observation of BUE formation and tool wear

SEM observations were conducted on each tool after its lifetime cutting test. Special attention was paid on tool wear and on the adhesive interaction between tool surface and aluminium, such as BUE and metal transfer. In Fig. 5, selected SEM back-scattered electron micrographs show the BUE and metal transfer behaviour of uncoated and coated S290 HSS tools after dry milling Al7010 alloy. The uncoated tool (Fig. 5a) exhibits transferred metal on the flank surface over a width up to 0.2 mm. The transferred metal exhibits a significantly rougher surface than the original tool surface as a result of self-mating contact to the bulk metal surface. Along the cutting edge, a uniform BUE layer can be seen. The TiAlCrYN coated tool shows similar severity of metal transfer as compared to the uncoated tool (Fig. 5b). However, a clean cutting edge was remained, i.e. free from BUE formation.

The TiAlCrYN coating provided a good protection to the flank surface up to the cutting edge with no evidence of coating spallation or crack. Fig. 5c and d show that both the DLC coated and TiAlN/VN coated tools kept a clean flank surface with very little metal transfer. No BUE formation was observed. The DLC coated flank edge exhibits non-uniform wear (Fig. 5c) as a result of spalling failure of the coating. The TiAlN/VN coating (Fig. 5d) shows only progressive sliding wear without any crack or spallation.

Fig. 6 presents typical high-magnification SEM secondary electron images showing the wear of the uncoated and coated tools in dry milling the Al7010 alloy. In Fig. 6a, the uncoated tool shows typical sliding of a multiphase structure, i.e. preferential wear of the ferrous matrix leading to the presence of carbide particles on the worn surface. In Fig. 6b, the cutting edge along the flank side is still fully covered by the TiAlCrYN coating, indicating good wear protection. For the DLC coated tool, Fig. 6c, the early occurrence of coating spallation resulted in exposed steel

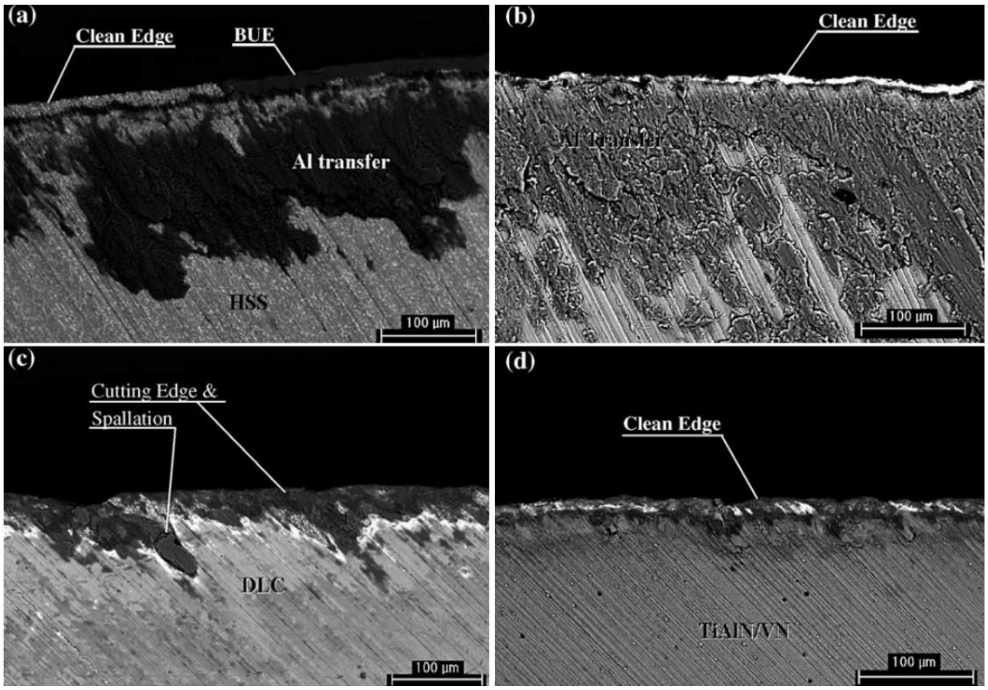

Fig. 5. SEM back-scattered electron images showing the BUE and metal transfer behaviour of lifetime-tested tools after dry cutting Al7010-7651 alloy. (a) Uncoated S290 tool, cutting time 36 min; (b) TiAlCrYN coated tool, cutting time 49 min; (c) DLC coated tool, cutting time 157 min; (d) TiAlN/VN coated tool, cutting time 162 min.

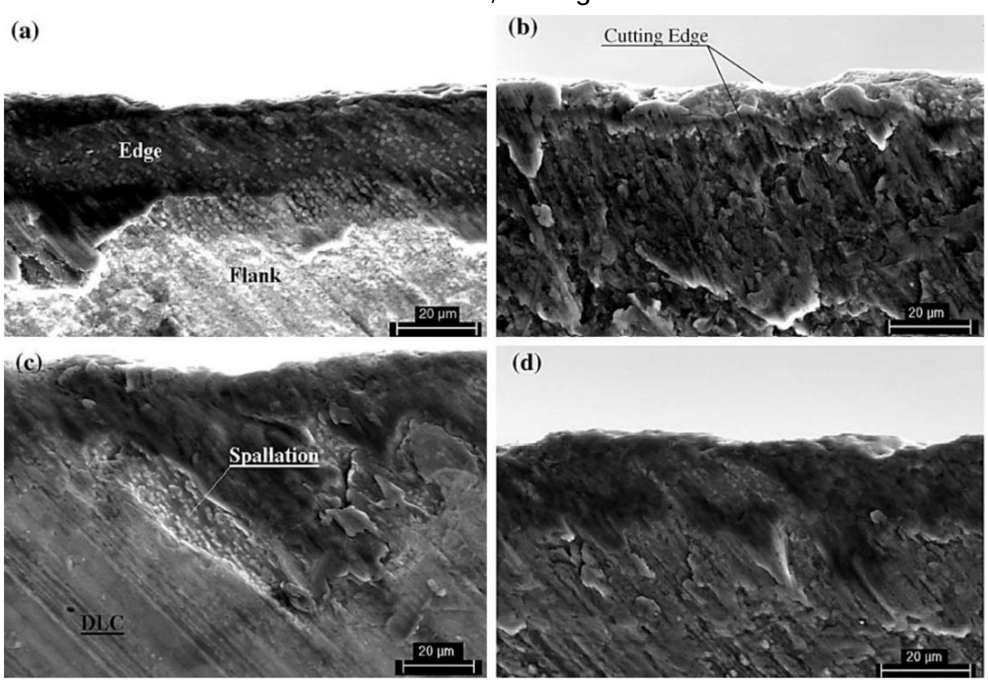

Fig. 6. SEM secondary electron images showing sliding wear in cutting edges after dry cutting Al7010-7651 alloy. (a) Uncoated HSS tool, cutting time 36 min; (b) TiAlCrYN coated tool, cutting time 49 min; (c) DLC coated tool, cutting time 157 min; (d) TiAlN/VN coated tool, cutting time 162 min.

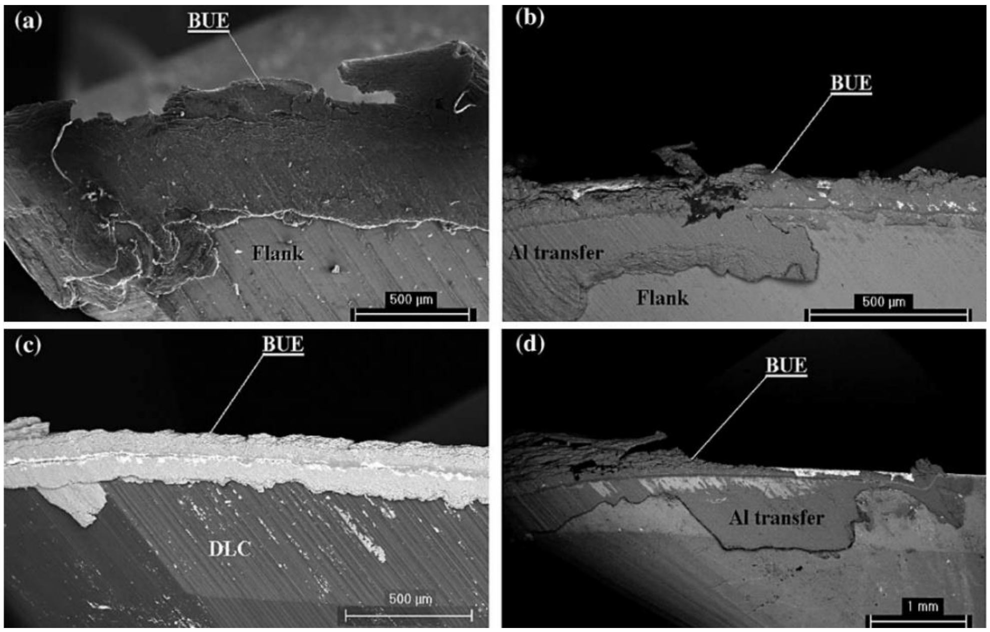

Fig. 7. SEM back-scattered electron images showing the BUE and metal transfer behaviour of lifetime-tested tools after dry cutting AlSi9Cu1 alloy. (a) Uncoated HSS tool, cutting time 2.7 min; (b) TiAlCrYN coated tool, cutting time 4.3 min; (c) DLC coated tool, cutting time 2.6 min; (d) TiAlN/VN coated tool, cutting time 5.3 min.

substrate and metal transfer. The cutting edge of the TiAlN/VN coated tool (Fig. 6d) was still fully protected by the coating, without any adhesion failure, suggestive of good wear resistance under such cutting environment.

The SEM back-scattered electron images in Fig. 7 show strong adhesive interaction between cutting edge and the soft alloy AlSi9Cu1. In Fig. 7a, the uncoated S290 HSS tool is almost fully covered by BUE and transferred aluminium, indicating poor cutting behaviour. The three coated tools have also accumulated limited amount of transferred metal, seeing Fig. 7b for TiAlCrYN, Fig. 7c for DLC and Fig. 7d for TiAlN/ VN, respectively. Despite that, the amount of metal transfer was significantly restricted. In each case, the outline of cutting edge can be easily recognized, suggestive of effective cutting operation of the coated tools. For the TiAlCrYN coated tool (Fig. 7b), the flank surface metal transfer became less and discontinuous. Al transfer on the DLC coated tool flank is within a band of approximately 0.2 mm width whereas the rest flank surface remained clean (Fig. 7c). The best result of transferred metal and BUE reduction was obtained in the TiAlN/VN coated tool (Fig. 7d) where considerable flank and cutting edge areas are free from metal deposit. The high-magnification secondary electron images in Fig. 8 illustrate typical abrasive wear of both the uncoated and coated tools in cutting the AlSi9Cu1 alloy. The uncoated S290 HSS cutting edge shows severe abrasive grooves (Fig. 8a), in which the abrasive grooves were interrupted by the presence of carbide articles. Fig. 8b is a SEM micrograph taken at the cutting edge of TiAlCrYN coated tool, in which the exposed HSS substrate is full of abrasive grooves and transferred aluminium. In the lower part of the image, a slightly dark contrast band

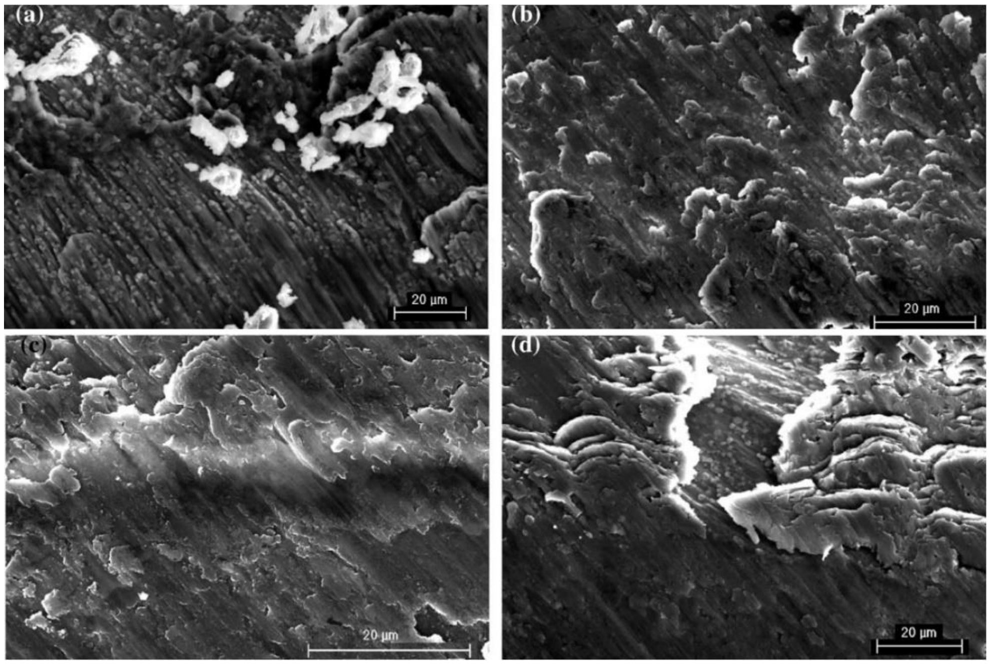

Fig. 8. SEM secondary electron images showing abrasive wear failure in cutting edges after dry cutting AlSi9Cu1 alloy. (a) Uncoated HSS tool, cutting time 2.7 min; (b) TiAlCrYN coated tool, cutting time 4.3 min; (c) DLC coated tool, cutting time 2.6 min; (d) TiAlN/VN coated tool, cutting time 5.3 min.

indicates the real sliding contact region of the TiAlCrYN coated flank where abrasive grooves are less pronounced than the exposed cutting edge area. In Fig. 8c, a dark band locates horizontally in the middle of the image indicating abrasive wear of the DLC coating. The worn DLC region has been identified in Fig. 7c (the associated lowmagnification back-scattered electron image) by its brighter contrast owing to its high tungsten (heavy element) content. The straight abrasive grooves imply low resistance of the DLC coating against the highly abrasive wear. Fig. 8d is a secondary electron image taken at the cutting edge of TiAlN/VN coated tool. The upper part of the image shows the cutting edge area where the exposed HSS substrate is partly covered with BUE of severely deformed aluminium. The lower part shows the TiAlN/ VN protected flank side being free from coating failure except the marginal sliding grooves.

4. Discussion

The nanostructured multilayer TiAlN/VN coating has delivered outstanding performance in cutting both wrought alloy Al7010-T7651 and highly abrasive die cast alloy AlSi9Cu1. The excellent tribological behaviour of the TiAlN/ VN coated tools was demonstrated by the

significantly reduced adhesion of the sticky aluminium alloys to the tool surface, which has been evidenced either by the clean and BUE-free cutting edge in cutting the high-strength aluminium alloy Al7010 (Fig. 5d) or by the reduced BUE formation and metal transfer in cutting the soft cast aluminium alloy AlSi9Cu1 (Fig. 7d). The TiAlN/VN coating has also been approved to possess strong sliding wear resistance not only in cutting the wrought alloy Al7010-T7651 (Figs. 2 and 6d) but also in cutting the silicon-containing alloy AlSi9Cu1 (Figs. 4 and 8d). Obviously, the good adhesion property achieved by the metal-ion etching pre-treatment had also played an important role in preventing any possible cohesive or adhesive failure of the coating as the SEM observations (Figs. 6d and 8d) demonstrate well protected flank edges. For the sliding wear of the TiAlN/VN, we assume that the low coefficient of friction leads to lower cutting forces and improved metal surface finish (Table 3 and Fig. 3), whereas the low wear coefficient results in low flank wear and long tool lifetime (Figs. 2 and 4). The incorporation of V in the coating formula, reduces the temperature for the onset of the oxidation of the TiAlN/VN coating to the range between 500 and 600 °C [17,18] and promotes the formation of low melting-point V2O5 and AlVO4 oxides. The V-containing oxides act as good solid lubricants in dry sliding contact [19,20]
and therefore effectively reduce the friction coefficient (Table 2). SEM observations conducted in this work suggest that the TiAlN/VN coating helps eliminate the severity of BUE formation and metal transfer. On the other hand, nanolayered superlattice nitrides are known to show superhardness and higher wear resistance than that of the monolithically grown hard coatings [21,22].

The currently observed metal-tool interaction (i.e. transferred metal and BUE in Figs. 5a and 7a) and severe sliding abrasive wear (Figs. 6a and 8a) for the uncoated HSS tools are consistent to previous reports [2]. The TiAlCrYN coated tool shows significant increase in tool life in cutting AlSi9Cu1 (Fig. 4) indicating its high resistance against abrasive wear. It is also indicated that good adhesion property of the TiAlCrYN and TiAlN/VN coatings achieved by metal ion etching pre-treatment has also contributed to the wear resistance by avoiding adhesive coating failure. However, similar to other transition metal nitrides such as TiN, CrN, TiCN and TiAlN, high friction coefficient is the major drawback of the TiAlCrYN coating. It resulted in high cutting forces (Fig. 3 and Table 3) and remarkable metal transfer (Fig. 5b).

The DLC coated tools demonstrate the capability of achieving low cutting forces (Fig. 3 and Table 3), good surface finish and long tool life in cutting high-strength aluminium alloy Al7010-T7651 (Fig. 2). This is partly attributed to its low tendency of aluminium adhesion as evidenced in Fig. 5c, which is consistent exactly to other carbon-based materials [1–5]. However, further improvement in tool life in cutting the wrought alloy is restricted as SEM observation has revealed spalling failure in the DLC coating (Figs. 5c and 6c), which is believed to be related to the low adhesion property as reported in Table 2. The cutting tests reported also suggest that the DLC coated tool does not increase the tool life in cutting aluminium-silicon alloy (Fig. 4). The tool failed due to fast abrasive wear (Fig. 8c).

5. Conclusions

(1) Using the combined cathodic arc and unbalanced magnetron sputtering techniques, a nanostructured multilayer (superlattice) coating TiAlN/VN has been grown as a dedicated protective coating for cutting tools to be used in aluminium alloy cutting.

(2) Lubricant-free high-speed milling trials were performed on two examples aluminium alloys, an aerospace wrought alloy Al7010-T7651 and a cast alloy AlSi9Cu1. In the tests, the TiAlN/VN coated highspeed steel tools outperformed all the other candidate tools by showing increased tool lifetimes by factors of 3.5 and 1 in cutting Al7010-T7651 and AlSi9Cu1, respectively, as compared to the uncoated S290 tools. The TiAlN/VN coated tools also showed significantly reduced cutting forces, eliminated formation of built-up edge and material transfer, and reduced surface finish roughness of machined parts.

(3) A TiAlN based multicomponent nitride coating TiAlCrYN and a DLC coating have also been evaluated under the same cutting conditions to compare to the uncoated S290 tools. The TiAlCrYN coating also showed improved wear resistance leading to limited increase of tool lifetimes, although it brought about higher cutting forces than the TiAlN/VN and DLC coated tools due to more pronounced metal transfer.

(4) The DLC coated tools exhibited a tool lifetime longer than the uncoated tool by a factor of 3.4, clean cutting edge and low cutting forces in cutting Al7010-T7651. In cutting the highly abrasive alloy AlSi9Cu1, however, the DLC coating showed no improvement in tool lifetime as compared to the uncoated S290 steel.

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References

[1] C.H. Shen, Surf. Coat. Technol. 86–87 (1996) 672.
[2] M. Lahres, P. Müller-Hummel, O. Doerfel, Surf. Coat. Technol. 91 (1997) 116.
[3] J.D. Kim, Y.H. Kang, Int. J. Mach. Tools Manuf. 37 (1997) 1155.
[4] M. Nouari, G. List, F. Girot, D. Coupard, Wear 255 (2003) 1359.
[5] H. Fukui, J. Okida, N. Omori, H. Moriguchi, K. Tsuda, Surf. Coat. Technol. 187 (2004) 70.
[6] G.E. D'Errico, E. Guglielmi, G. Rutelli, J. Mater. Process. Technol. 92–93 (1999) 251.
[7] W.-D. Münz, L.A. Donohue, P.Eh. Hovsepian, Surf. Coat. Technol. 125 (2000) 269.
[8] P.Eh. Hovsepian, D.B. Lewis, W.-D. Münz, Surf. Coat. Technol. 133–134 (2000) 166.

[9] Q. Luo, G. Robinson, M. Pittman, M. Howarth, W.-M. Sim, M.R. Stalley, H. Leitner, R. Ebner, D. Caliskanoglu, P. Eh. Hovsepian, Surf. Coat. Technol. 200 (2005) 123.

[10] M.I. Lembke, D.B. Lewis,W.D. Munz, J.M. Titchmarsh, Surf. Eng. 17 (2) (2001) 153.

[11] H. Leitner, R. Ebner, B. Major, G. Pockl, Z. Met.Kd. 90 (1999) 8.

[12] C. Schönjahn, L.A. Donohue,W.-D. Münz, R.D. Twesten, I. Petrov, J. Vac. Sci. Technol. 18 (2000) 1718.

[13] C. Strondl, N.M. Carvalho, J.T.M. De Hosson, G.J. van der Kolk, Surf. Coat. Technol. 162 (2003) 288.

[14] Verein Deutscher Ingenirure, Richtlinie 3198, (1992), Dusseldorf, Germany.

[15] H. Meidia, A.G. Cullis, C. Schonjahn,W.-D. Münz, J.M. Rodenburg, Surf. Coat. Technol. 151 (2002) 209.

[16] Q. Luo, D.B. Lewis, P.Eh. Hovsepian, W.-D. Münz, J. Mater. Res. 19 (2004) 1093.

[17] D.B. Lewis, S. Creasey, Z. Zhou, J.J. Forsyth, A.P. Ehiasarian, P.Eh. Hovsepian, Q. Luo, W.M. Rainforth, W.-D. Münz, Surf. Coat. Technol. 177–178 (2004) 252.

[18] P.H. Mayrhofer, P.Eh. Hovsepian, W.D. Mitterer, Surf. Coat. Technol. 177–178 (2004) 341.

[19] C.P. Constable, J. Yarwood, P. Hovsepian, L.A. Donohue, D.B. Lewis, W.-D. Münz, J. Vac. Sci. Technol., A, Vac. Surf. Films 18 (2000) 1681.

[20] A. Erdemir, Tribol. Lett. 8 (2000) 97.

[21] Q. Luo, W.M. Rainforth, W.-D. Münz, Scr. Mater. 45 (2001) 399.

[22] Q. Luo, W.M. Rainforth, W.-D. Münz, Wear 225–229 (1999) 74.