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**Published version**

LUO, Quanshun, ROBINSON, Gary, PITTMAN, Manfred, HOWARTH, Martin, SIM, W.M., STALLEY, M.R., LEITNER, H., EBNER, R., CALISKANOGLU, D. and HOVSEPIAN, Papken (2005). Performance of nano-structured multilayer PVD coating TiAlN/VN in dry high speed milling of aerospace aluminium 7010-T7651. Surface and Coatings Technology, 200, 123-127.

# Performance of nano-structured multilayer PVD coating TiAlN/VN in dry high speed milling of aerospace aluminium 7010-T7651

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**Abstract:** A low-friction and wear resistant TiAlN/VN multilayer coating with TiAlN/VN bilayer thickness 3 nm has been grown by using the combined cathodic arc etching and unbalanced magnetron sputtering deposition on high speed steel tools for dry cutting of aluminium alloys. In this paper, in-lab and industrial high speed milling tests have been performed on an aerospace aluminium alloy 7010-T7651. The results show that the TiAlN/VN coated tools achieved lower cutting forces, lower metal surface roughness, and significantly longer tool lifetime by three times over the uncoated tools as a result of the low friction and eliminated tool-metal adhesion. Under the same conditions, a TiAlN based multicomponent coating TiAlCrYN also increased the tool lifetime by up to 100% despite the high cutting forces measured.

# 1 INTRODUCTION

Today, coolants are used in machining aluminium alloys. Dry (coolant-free) machining has been a strong demand not only for the environmental reason but also for the use and disposal of coolants which is even more expensive than the cost of cutting tools itself [1]. In dry machining of metals of good plasticity like aluminium, the strong tendency of built-up edge (BUE) formation should be considered to avoid high cutting force, poor surface finish and short tool lifetime [2]. It has been reported that carbon based coatings are able to increase tool performance in aluminium cutting [3–7]. This, however, was not reported in transition metal nitrides like TiN, TiAlN and CrN [1].

Amultilayer nitride coating TiAlN/VN consisting of nanoscale sub-layers TiAlN and VN has recently been developed to have super hardness values HK0.025 30–55 GPa [8–10]. In particular, its low friction coefficient (0.4–0.6) and low wear rate (~$10^{-17}$ $m^3$ $N^{-1}$ $m^{-3}$) in dry sliding tests are superior to other TiAlN- and TiN based coatings. This may imply good performance in dry machining of soft and ductile metals. In this paper, we report the results of trials in high speed milling aerospace aluminium alloy Al7010-T7651 using high speed steel (HSS) tools with PVD (physical vapour deposition) coatings. Outstanding performance of the TiAlN/VN coated tools has been compared to that of the uncoated HSS and a TiAlN-based multicomponent TiAlCrYN coating concerning the cutting force, work piece surface finish, flank wear and the tool-aluminium adhesion behaviour.

## 2. Experimental methods

### 2.1. Sample preparation

Endmill cutters of 25 mm in diameter and pre-polished coupons were manufactured from two powder-metallurgy steels, (A) C 2.0%, W 14.5%, Co 11%, V 5%, Cr 2.0%, Mo 2.5% and Fe in balance, HRC 68–70; and (B) C 1.64%, W 10.5%, Co 8%, V 5%, Cr 4.8%, Mo 2.0% and Fe in balance, HRC 65–67; and (C) a commercial cobalt-containing HSS Co8 (M42), HRC 65. Prior to the coating deposition, all the samples were cleaned in ultrasonically agitated aqueous alkali solutions and deionised water baths and dried in vacuum.

The TiAlN/VN and TiAlCrYN coatings were deposited by reactive unbalanced magnetron sputtering in a common Ar+N2 atmosphere controlled in total pressure mode ($\Delta p_{Ar}+\Delta p_{N2}$=constant), at temperature of 450 $^0$C and substrate bias voltage of -75V. An industrial scale fourcathode PVD coater (Hauzer HTC 1000-4) was used for the deposition. Prior to the multilayer coating deposition, a metal ion etching pre-treatment was applied in steered cathodic arc mode operating at high bias voltage ($U_b$= -1200V) to enhance the coating adhesion property [11]. 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 3.1±0.2 μm. Regime of the coating system and the deposition procedures have been described elsewhere [8,9].

### 2.2. Characterisation of PVD coatings

Coating thickness was determined by abrasive calowear testing followed by optical microscopic measurement. Coating hardness was measured using a Mitutoyo MVK-G1 Knoop hardness tester at indenting load 0.025 kg. The adhesion property was determined by scratch test in which the critical load Lc was quantified by optical observation of the scratch. The dry sliding friction and wear properties were investigated on a pin-on-disc tester using 6 mm in diameter $Al_2O_3$ ball, 5 N load, linear speed of 0.1 m· $s^{-1}$, 60,000– 200,000 laps (total sliding distance: ~10 km). The coatings and the tested tools were characterised using an analytical scanning electron microscope (Philips XL-40, 20 kV) and a transmission electron microscope (Philips CM20, 200 kV).

**Table 1** Parameters of milling tests

| Milling test | Cutting width (mm) | Feed rate (mm $tooth^{-1}$) | Coolant | Cutting length |
|---|---|---|---|---|
| In-Lab | 2 | 0.165 | Dry | (till 0.23 mm flank wear) |
| Industrial | 25 | 0.19 | Dry and wet | 14.56 m (0.26 m × 56 passes) |

**Other parameters:** Spindle speed 24,000 rpm, cutting speed 1,884 m $min^{-1}$, and cutting depth 4 mm.

### 2.3. Milling test procedures

Milling tests were run on an aerospace aluminium alloy 7010-T7651 by using a high-speed milling machine MAZAK FJV-25 in laboratory and using a Marwin MPS horizontal machining centre in industrial condition. Cutting parameters are listed in Table 1. In the laboratory tests, flank wear was measured on an optical image analyser by regularly interrupting the test until reaching pre-defined criteria of 0.23 mm, from which the tool lifetime was obtained. 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 carbon-stylus 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 a portable Talysurf measurement kit.

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

| Coatings | λ | T* | $HK_{0.025}$ | $L_c$ | μ | $K_c$ |
|---|---|---|---|---|---|---|
| | (nm) | | (GPa) | (N) | | $10^{-17}$ $m^3N^{-1}m^{-1}$ |
| TiAlN/VN | 3.0 | {110} | 33.5 | 46.8 | 0.43 | 2.3 |
| TiAlCrYN | 1.8 | {100} | 28.0 | 60.4 | 0.66 | 24.4 |

## 3. Results and discussions

### 3.1. Microstructure and mechanical properties of PVD coatings

Table 2 summarizes the properties of TiAlN/VN and TiAlCrYN coatings including multilayer period (λ), texture factor T*, hardness $HK_{0.025}$, critical scratch load $L_c$ (adhesion), friction coefficient (μ) and wear coefficient ($K_c$). The TiAlN/VN coating exhibits higher hardness and lower coefficients of friction and wear than the TiAlCrYN. In particular, the wear coefficient of TiAlN/VN is lower by 10 times than the TiAlCrYN. Both the coatings exhibit strong adhesion property ($L_c$ > 45N) as a result of the Cr or V ion etching. In Fig. 1, a bright field TEM micrograph shows the dense multilayer structure of the TiAlN/VN coatings. More details of the characterisations of TiAlN/VN coatings can be found in Refs. [9–11].

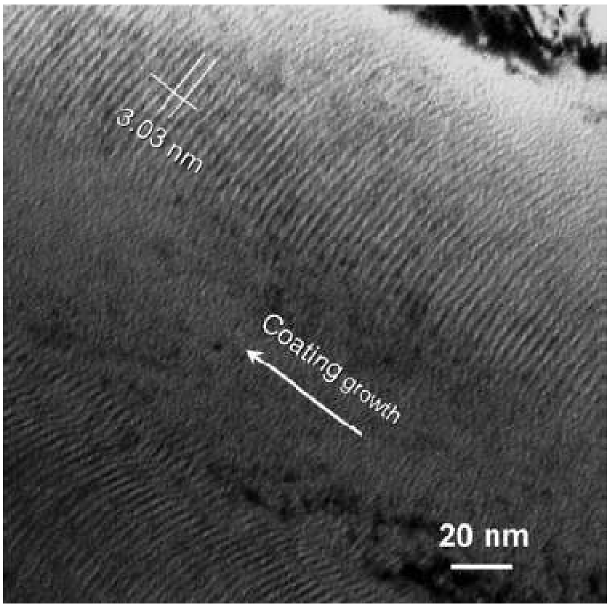


**Fig. 1.** Cross-section transmission electron micrograph showing nano-scale multilayer structure of the TiAlN/VN coating.

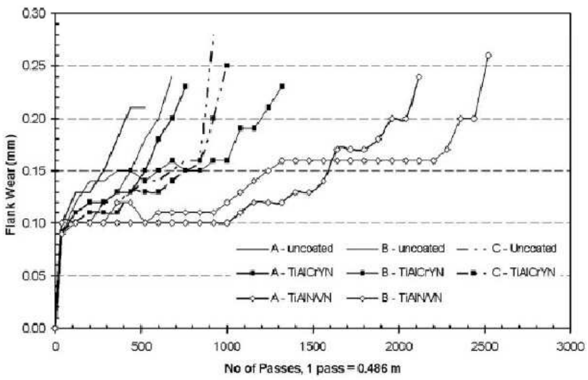


**Fig. 2.** Flank wear of coated and uncoated HSS tools plotted against cutting length in milling Al7010 alloy.

### 3.2. The cutting performance of uncoated HSS tools

Fig. 2 shows the flank wear width of coated and uncoated cutters plotted against cutting distance, in which the three steel grades are marked A, B and C (seeing previous description). Most of the tested tools exhibited a typical 3-period curve, i.e. fast initial wear, steady wear, and accelerated wear until reaching the criteria of 0.23 mm flank wear. All the three uncoated cutters tested showed short lifetime as compared to the PVD coated ones. Among the three cutters tested, two (marked B and C) failed due to chipping wear (not shown here) whereas the one marked A due to progressive increase of flank wear width. SEM observations of the tested cutters showed extensive transfer of work piece material on the flank surface and cutting edge, i.e. the formation of BUE. Even in the wet cutting tests, aluminium transfer was found on each uncoated cutters tested although the amount was significantly less than the dry-tested cutters. An example is given in Fig. 3 in which the dark contrasted area indicates considerable amount of aluminium transfer. The observations of aluminium transfer, BUE and chipping failures were consistent to literatures [1,2]. Table 3 shows that, in both the in-lab and industrial tests, the uncoated cutters exhibited high cutting forces and resulted in poor metal surface finish. In addition, the current tests show that dry milling process exhibits lower cutting forces and lower metal surface roughness than the wet cutting process.

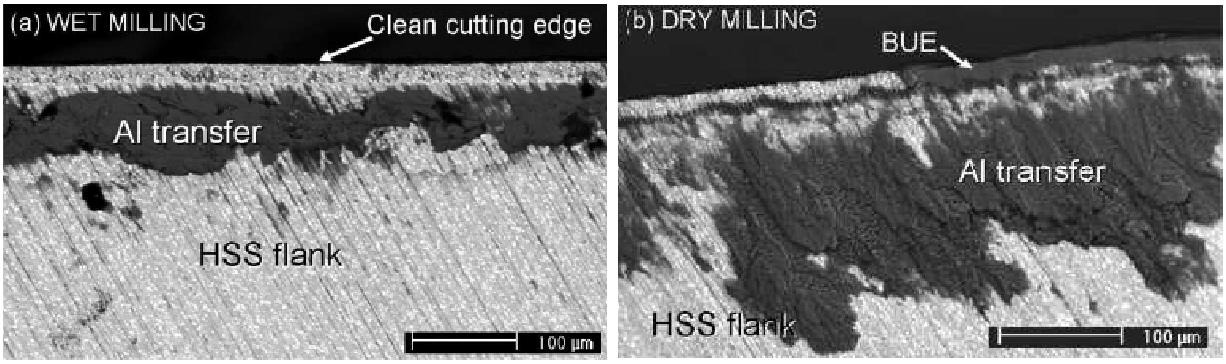


**Fig. 3.** SEM micrographs of uncoated steel flank after (a) wet cutting and (b) dry cutting tests.

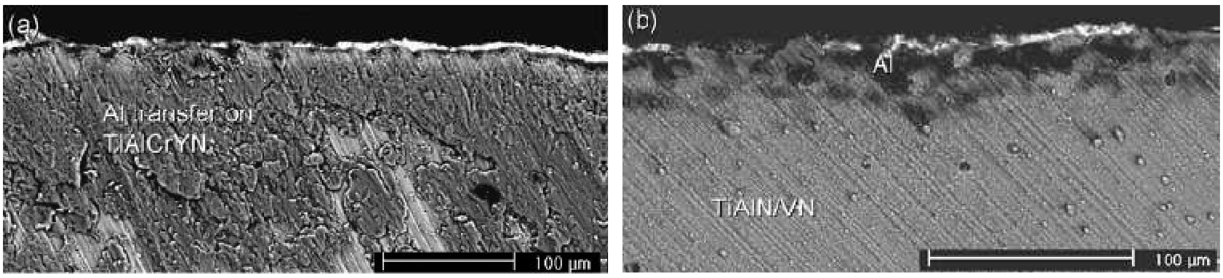


**Fig. 4.** SEM micrographs of coated tool flank after dry cutting. (a) TiAlCrYN coated; and (b) TiAlN/VN coated.

**Table 3** Results of in-lab and industrial milling tests

| | HSS | TiAlCrYN | TiAlN/VN |
|---|---|---|---|
| *In-lab test tool life [min] and increment against uncoated tool [%]* | | | |
| On Steel A | 36 | 49 [+36%] | 142 [+294%] |
| On Steel B | 43 | 85 [+98%] | 179 [+316%] |
| On Steel C | 59 | 63 [+7%] | – |
| *Roughness ($R_a$) of tool rake surface [μm]* | | | |
| New tool | 0.492 | 0.327 | 0.099 |
| In-lab tested tool | 0.558 | 0.382 | 0.101 |
| *In-lab test cutting force $F_{xy}$ [N]* | | | |
| New tool | – | 300 | 147 |
| Used tool | – | 339 | 166 |
| *Industrial test cutting force $F_x$ [N]* | | | |
| Dry cutting | 1075 | 1000 | 870 |
| Wet cutting | 1125 | 1170 | 920 |
| *Surface roughness ($R_a$) of machined part [μm]* | | | |
| Dry cutting | 1.24 | 0.72 | 0.78 |
| Wet cutting | 1.27 | 0.78 | 0.80 |

### 3.3. The cutting performance of TiAlCrYN and TiAlN/VN uncoated tools

In Fig. 2, the TiAlCrYN and TiAlN/VN coated cutters show lower wear rate and longer lifetime than those uncoated. The TiAlN/VN coated cutters exhibit the lowest flank wear rate with cutting length over 1250 m (0.486 m in each cutting pass), leading to increased tool life by 294% and 316% respectively over the uncoated cutters. The TiAlN/VN coated tools also show significantly lower surface roughness than the uncoated and TiAlCrYN coated tools both before and after the cutting tests, Table 3. In particular, low surface roughness of the tested ones indicates reduced BUE tendency. The cutting forces measured on the TiAlN/VN coated tools account for only approximately 50% of the TiAlCrYN coated ones. In the full-slot industrial cutting test, the TiAlN/VN coated tools exhibited the lowest cutting forces and significantly reduced metal surface roughness. The TiAlCrYN coating also resulted in good surface finish comparable to the TiAlN/VN where the cutting forces remained similar to the uncoated tools.

Fig. 4 shows the flank wear and aluminium transfer behaviour of TiAlCrYN and TiAlN/VN coated tools. Both the coatings provided good wear protection to the cutting edge without any cracking, coating spalling or chipping wear. We believe that the good wear resistance was also attributed to the enhanced adhesion property as a result of the metal ion etching pre-treatment [11]. This enabled to keep a sharp cutting edge leading to long tool life. Moreover, both the coatings helped to keep a clean cutting edge free from any BUE. However, the TiAlCrYN and TiAlN/VN show remarkably different severity of aluminium transfer. The TiAlCrYN coated flank was covered with substantial amount of aluminium (Fig. 4a), similar to the uncoated cutters, Fig. 3. This behaviour was comparable to the previously reported TiN, CrN and TiAlN [1] and was probably attributed to its high friction coefficient. The severe metal transfer has led to high cutting forces and limited tool lifetime. In contrast, only a little amount of aluminiumtransfer was found on the TiAlN/VN coated surface, Fig. 4b. The evidences of little metal transfer, low cutting force, good surface finish and considerably extended tool lifetime suggest the TiAlN/VN coating as a good candidate in dry cutting soft aluminium alloy. The good performance of the TiAlN/VN coating is attributed to its substantially lower dry sliding friction coefficient. It has been recently found that dry sliding of the TiAlN/VN coating leads to the formation of an amorphous tribo-film of lubricious Ti–Al–V–O oxide [12,13]. The lubricious tribo-film helps avoid severe mechanical wear of the multilayer nitride such as delamination and spallation which were usually observed in other high-friction nitride coatings [14], and thus results in tribo-oxidation dominated mild wear. The current results confirm that the low friction coefficient also favours low tendency of toolmetal adhesion which, together with the super-hardness and superior wear resistance, promises excellent performance in cutting aluminium.

## 4. Conclusions

In high speed milling of aluminium alloy 7010-T7651 both in industrial and laboratorial conditions, the removal of coolant leads to slightly lower cutting forces and lower surface roughness of machined parts. However, it resulted in BUE formation and substantial amount of soft metal transfer to the tool surface, which caused chipping wear and short lifetime of uncoated steel tools. The TiAlN/VN and TiAlCrYN coatings grown by combined cathodic arc and UBM sputtering process have avoided the BUE formation and significantly improved the surface finish of machined parts. The best performance was obtained in the nanomultilayer structured and low-friction coating TiAlN/VN by showing significantly reduced cutting forces, eliminated aluminium adhesion and over four times tool lifetime as compared to the uncoated tool steels.

## Acknowledgements

The research was sponsored by The European Commissions through the research project '*Revolutionary New Steels, Coated and Designed for Cutting Tools to Machine Aluminium and Titanium alloys*' (No. GRD1-2001-40514). The authors wish to thank all the partners participating in this project: Hauzer Techno Coating BV (The Netherlands), Hydra-Clarkson International (UK), Emuge Franken (Germany), Centro Ricerche Fiat (Italy), and Eltro (GB) Ltd. (UK). Bodycote PVD Coatings Centre (Sheffield, UK) is acknowledged for providing PVD support.

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