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Surface and Coatings Technology 146–147 (2001) 305–311

SURFACE & COATINGS TECHNOLOGY

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# Dry cutting performance of partially filtered arc deposited titanium aluminium nitride coatings with various metal nitride base coatings

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## Abstract

PVD titanium aluminium nitride coatings are known to improve the performance of cutting tools in aggressive machining applications, such as high-speed dry machining. This is generally acknowledged to be due to the fact that these coatings are able to maintain high hardness and resistance to oxidation at the elevated temperatures typically experienced in such metal cutting applications. In this investigation, the performance of single layer coatings of TiN and CrN, and double layer coatings of TiN/TiAlN and CrN/TiAlN were assessed on Co-HSS drills used to machine grey cast iron. It was found that the CrN coatings performed as well as the TiN coatings when drilling grey cast iron. In addition, the double layer coatings outperformed the single layer coatings with the CrN/TiAlN coatings having a 20% improvement in tool life compared with the TiN/TiAlN-coated drills. This result is particularly interesting since the Daimler–Benz indentation test suggested that the TiN/TiAlN had much lower adhesion than the CrN/TiAlN. These results are discussed in terms of an analysis of the physical and mechanical properties of the coatings but it highlights the need for meaningful measurement of critical coating properties which might relate to their performance in metal cutting. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Dry machining; Physical vapour deposition (PVD) coatings; Drill testing; Wear; Filtered arc deposition

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## 1. Introduction

Recent technological advances in physical vapour deposited (PVD) coatings for cutting tools are presenting manufacturers with an opportunity to reduce manufacturing costs and increase productivity [1]. Of particular interest to the automotive industry is the potential to improve the performance of cutting tools when machining grey cast iron, since this material continues to be the material of choice for cylinder block production in the popular car and truck markets. The lamellar structure of pearlite provides the strength and wear resistance required of cylinder blocks, and the network of flake graphite provides good machinability by generating planes of localised weakness that facilitate shear failure and result in short discontinuous chips [2]. Notwithstanding the good machinability of grey cast iron, cost reduction strategies within the automotive industry are looking for better tool life at higher cutting speeds and increased feed rates and to reduce, if not eliminate, the use of coolants in machining. Clearly, there is a need to explore the use of PVD coatings if one is to meet such goals. The aim of this study was to explore the performance benefits of standard single layer coatings and more novel double layer coatings when machining grey cast iron.

The superior machining performance of advanced surface coated cutting tools is determined by an ability to maintain high hardness and resistance to oxidation at elevated temperatures [3]. The more traditional PVD coatings such as TiN and TiCN have been shown to improve cutting tool performance in aggressive machining applications, but are restricted by their moderate high temperature oxidation resistance [4]. At temperatures as low as 550°C TiN forms a brittle oxide, $TiO_2$ (rutile), which is unable to sustain the high loads on

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PII: S0257-8972(01)01421-9

the cutting edge and renders cutting tool performance closer to that of uncoated cutting tools [5]. A more recent development in advanced surface coatings for cutting tools has been the introduction of aluminium to TiN coatings (TiAlN). With this addition the high temperature oxidation resistance increases to 925°C [6]. TiAlN has been effective at improving the high-temperature performance of cutting tools by forming a well-adhered stable passive double oxide layer, where the upper layer is Al rich and the lower layer is Ti rich [7,8]. This double oxide layer has been shown to reduce the rate of further oxidation by inhibiting oxygen diffusion to the underlying coating [6].

Despite these benefits, it has been shown that PVD process related factors that affect performance, for example, surface roughness and adhesion, are adversely affected by the addition of aluminium to TiN [9]. The increased roughness was shown to correspond to an increase in the size and number of macroparticles produced from the cathodic arc during evaporation, which in turn was shown to relate to the cathode melting temperature [10]. Also, Münz et al. [11] recently reported a reduction in surface roughness of sputtered TiAlN coatings that were deposited following metal ion etching from a highly ionised plasma generated from a single cathodic arc source. They compared various cathode materials as arc sources and showed that the size of macroparticles typically decreased with increasing melting temperature for all but the Cr target, which showed smaller macroparticles than targets of a similar melting temperature. They argued the reduced size of the Cr macroparticles may be partly attributed to the unusually high vapour pressure of Cr, which can cause sublimation of Cr particles during flight and after deposition [11]. The objectives of the present study were therefore to systematically quantify the effects of a range of metallic targets on the macroparticle content of metallic PVD deposited layers and to assess the effects of Ti and Cr metallic interlayers on the performance of partially filtered cathodic arc TiN, CrN and TiAlN coatings.

## 2. Experimental procedure

### *2.1. Coating deposition*

Coatings were deposited using a dual source filtered arc deposition system, comprising of two cathodic arc evaporation sources (58 mm diameter) that could be configured in either partial or full filtration modes. The partial filtration mode used a linear plasma duct (200 mm diameter) fitted between the cathode source and the coating chamber, which increased the separation between the cathode and substrate surface to 300 mm. The duct was fitted with solenoidal magnetic field coils (90–100 gauss) for focussing of the plasma flux. Further details regarding the chamber configuration are given in Martin et al. [12]. Prior to coating deposition, polished cobalt high speed steel (Co-HSS: M35) disks and 6.8-mm diameter split point twist drills were cleaned using a commercially operated water-based cleaning line. The substrates were then loaded into the coating chamber that was pumped down to a base pressure of $<2\times10^{-5}$ mbar. The substrates were then subjected to a 20-min ion etch at ambient temperatures using a hot anode, cold cathode ion source with a discharge voltage of 2.0 kV and a discharge current of 150 mA. The substrates were then heated to 350°C and subjected to a further 15-min ion etch. The surface topography and macroparticle content of metallic PVD coatings were compared for a range of metallic cathode targets, namely: Ti; TiAl (50 at.% Ti, 50 at.% Al); Cr and V. Following these experiments, Ti and Cr targets were used to deposit Me/MeN coatings with deposition times of 2 min for the Me interlayer and then 30 min for the respective MeN base coatings. The TiAlN coatings were double layer coatings comprising a metallic interlayer that was deposited for 2 min followed by a MeN base coating (30 min) and TiAlN top coating (30 min). An arc current of 100 A, bias voltage of $-150$ V and nitrogen pressure of $6–8\times10^{-3}$ mbar were used for the deposition of all coatings in the present study.

### *2.2. Evaluation of coating properties*

The following quantitative and qualitative techniques were used to evaluate the coatings deposited on polished Co-HSS disks:

- *Arithmetic mean surface roughness* ($R_a$) of uncoated and coated disks was measured using a Rank Taylor Hobson Talysurf 10 profilometer (Cut-off length: 0.25 mm).
- *Substrate-coating adhesion* of MeN and MeN/TiAlN coatings was characterised using the Daimler–Benz indentation test (500 N load) [13].
- *Surface topography* was observed using optical and scanning electron microscopy (SEM), which also enabled a measurement of macroparticle characteristics: size; shape; and distribution.
- *Coating thickness* was measured by fracture metallography of coating cross-sections obtained by brittle fracture of coated Co-HSS substrates (30-mm diameter polished coupons) cooled to liquid nitrogen temperatures.
- *The composition* of the coating surface and of macroparticles was analysed using energy-dispersive X-ray spectroscopy (EDS).
- *Coating hardness and elastic modulus* were measured using nano-indentation (UMIS 2000 device with loads varying from 5 to 50 nm. Indent penetration was between 50 and 160 nm).
- *Substrate hardness* was measured using a Vickers hardness tester (30 kg load).

### 2.3. Drill testing

One method for evaluating the performance of twist drills is the measurement of outer corner flank wear. This technique has been shown in previous work [9] to be particularly relevant to commercial manufacturing practice where the extent of drill wear is indicative of the need for tool change of drills used in production. In the present investigation, this method was used to evaluate uncoated and partially filtered PVD-coated drill performance when drilling a workpiece of as-cast automotive grade grey cast iron (refer to Table 1 for the workpiece and twist drill compositions). Blind holes were drilled without cutting fluid to a depth of 20.4 mm (3× diameter) in purpose-cast ingots (500×290×50 mm) at a cutting speed of 30 m/min and a feed rate of 0.22 mm/rev. The wear lands generated at the outer corners of the drills were measured periodically using a microscope at a magnification of ×25 and the drills were deemed to have failed when the outer corner wear lands exceeded 0.5 mm.

## 3. Results and discussion

### 3.1. Metallic coatings

Polished Co-HSS coupons were coated with a number of thin metallic coatings in order to assess their macroparticle characteristics. This, in effect, simulated the deposition of a metallic interlayer, which is standard practice in the deposition of PVD compound coatings. The arithmetic mean surface roughness results for the respective metallic coatings were plotted as a function of cathode melting temperature (Fig. 1). The surface roughness of the respective metallic coatings increased in order from vanadium (8%) to chromium (29%), titanium (173%) and titanium–aluminium (50:50) (330%). Prior research into the number and size of macroparticles as a function of cathode target melting temperature has shown this relationship to be approximately linear for the majority of target materials [10,11]. One exception is chromium, which, as a result of its high vapour pressure, can sublimate under sufficiently high vacuum causing a reduction in macroparticle size [11]. The results from the present study show a strong linear relationship between the measured roughness and cathode melting temperature for all target materials investigated. Of particular interest was the fact that there exists an upper limit for the cathode melting temperature, above which no further improvement in roughness can be achieved due to the intrinsic roughness of polished Co-HSS substrates.

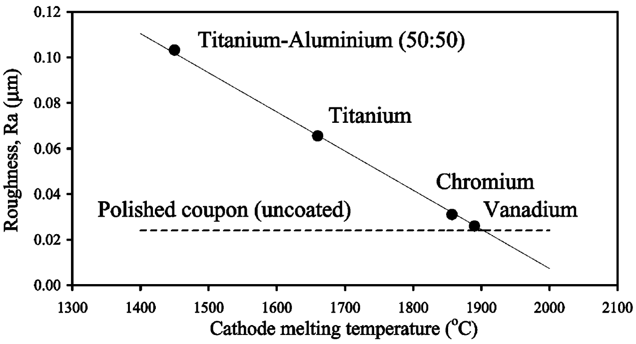

Fig. 1. Comparison of the surface roughness ($R_a$) of various metallic interlayers as a function of cathode target melting temperature (°C).

### 3.2. Partially filtered cathodic arc coatings

#### 3.2.1. Coating thickness

SEM fractography of sectioned Co-HSS coupons revealed a dense but columnar grain structure for TiN and CrN single layer coatings with thicknesses of 2.4 μm for TiN and 1.6 μm for CrN. In the case of TiN/TiAlN coatings the SEM cross-section (Fig. 2a) reveals a two-layer coating consisting of a base layer of TiN (2.4 μm thickness) upon which the TiAlN top-layer was deposited (0.5 μm thickness). Likewise, the CrN/TiAlN cross-section (Fig. 2b) reveals a two-layer coating consisting of a base layer of CrN (1.6 μm thickness) and TiAlN top layer (0.5 μm thickness). The linear duct filter configuration used throughout these investigations gave deposition rates of 4.8 μm/h for the TiN coatings, 3.2 μm/h for the CrN coatings and 1.0 μm/h for the TiAlN coatings.

Table 1
Nominal workpiece and substrate compositions

| Cast iron workpiece | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Element | C | Si | Mn | Cr | Cu | Sn | S | Ti | Fe |
| wt.% | 3.25 | 1.95 | 0.7 | 0.3 | 0.55 | 0.025 | 0.025 | 0.04 | rem. |
| Co-HSS substrate | | | | | | | | | |
| (M35) | | | | | | | | | |
| Element | C | Cr | Mo | V | W | Co | Mn | Si | Fe |
| wt.% | 0.92 | 4.15 | 5.00 | 1.80 | 6.25 | 4.75 | 0.30 | 0.28 | rem. |

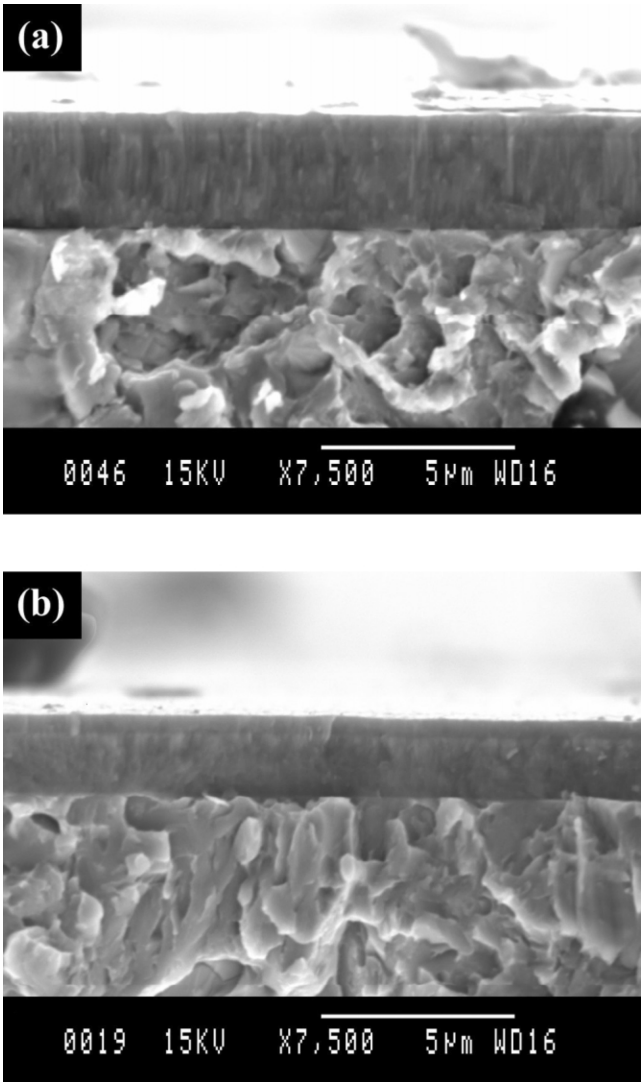

Fig. 2. SEM micrographs of fractured cross-sections of: (a) TiN/TiAlN showing a double layer coating consisting of a TiN base coating (2.4 μm) and TiAlN top coating (0.5 μm); and (b) CrN/TiAlN showing a double layer coating consisting of a CrN base coating (1.6 μm) and TiAlN top coating (0.5 μm).

### *3.2.2. Arithmetic mean surface roughness, $R_a$*

The results of arithmetic mean surface roughness tests on uncoated and coated Co-HSS coupons are reported in Table 2, which shows an increase in roughness for the Ti-based coatings, compared with the Cr-based coatings. The large number of Ti macroparticles that accumulate on the substrate during deposition of the Ti interlayer can explain the increased roughness of Ti-based coatings. The macroparticles of Ti are either retained in the subsequent nitride coating as solid growth defects or they are expelled during the latter stages of the coating process to form dish-like growth defects resembling pits in the coating surface (Fig. 3a). The present study of metallic interlayers deposited from a partially filtered cathodic arc source revealed that chromium, with a melting temperature of 1857°C, approached the upper limit for the practicable cathode target melting temperature, above which only slight improvement in roughness could be achieved due to the intrinsic roughness of polished Co-HSS (Fig. 1). The chromium interlayer, which contained an inconsequential number of macroparticles, gave rise to smooth nitride coatings owing to a lack of potential sites from which growth defects could initiate. The subsequent CrN and CrN/TiAlN coatings had very few macroparticles and a low number of pitting defects (Fig. 3b), which resulted in only minor increases in the roughness of polished Co-HSS coupons. The increased roughness of CrN/TiAlN over CrN can be attributed to the presence of a small number of TiAl macroparticles generated during deposition of the TiAlN top layer rather than from an increase in the extent of pitting,

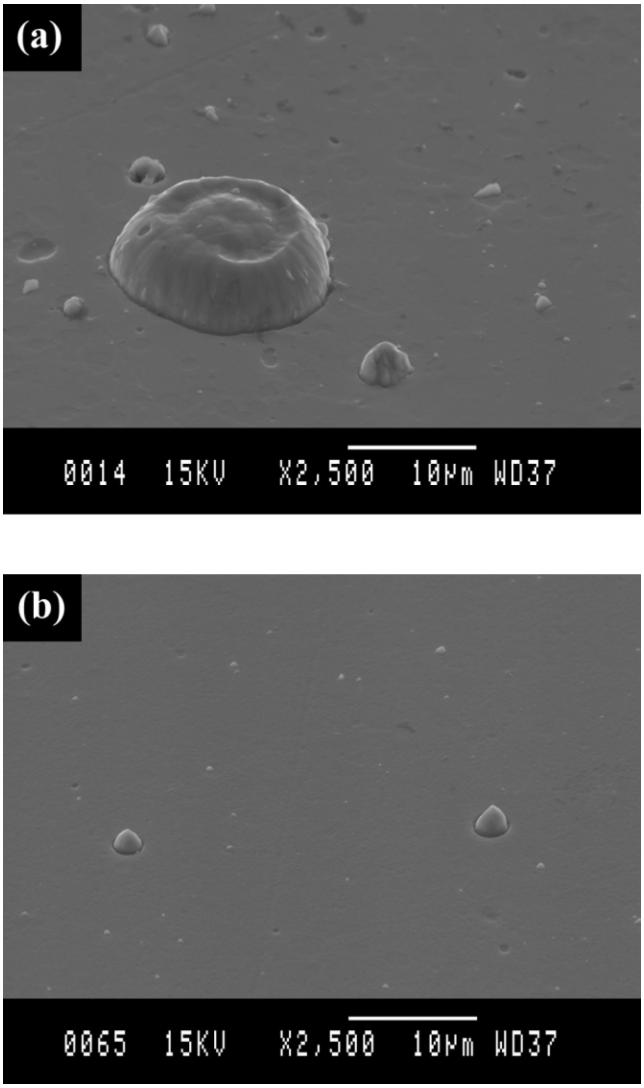

Fig. 3. SEM micrographs showing the surface topography of: (a) TiN/TiAlN; and (b) CrN/TiAlN coatings.

Table 2
Mechanical properties of partially filtered cathodic arc coatings

| | Metallic interlayer | Coating thickness (μm) | Roughness[a] ($R_a$) ($10^{-3}$ μm) | Maximum macroparticle diameter (μm) | Number of macroparticles per area ($10^3$ mm$^2$) | Adhesion (VDI rating) | Hardness (GPa) | Elastic modulus (GPa) |
|---|---|---|---|---|---|---|---|---|
| TiN | Ti | 2.4 | 16.6 | 6 | 10 | 3 | 29.9 | 541.7 |
| TiN/TiAlN[b] | Ti | 2.9 | 17.8 | 25 | 14 | 6 | 30.7 | 564.8 |
| CrN | Cr | 1.6 | 7.6 | 3 | 5 | 1 | 22.8 | 400.3 |
| CrN/TiAlN[b] | Cr | 2.1 | 7.9 | 2 | 8 | 1 | 28.2 | 394.3 |

[a] Roughness of polished Co-HSS coupons prior to coating was $7.4\times10^{-3}$ μm.
[b] Thickness of top-layer TiAlN was 0.5 μm.

which remained consistently low for both CrN and CrN/TiAlN.

### 3.2.3. Coating adhesion

Recently published results of adhesion tests of partially filtered cathodic arc coatings [9] indicated poor adhesion for TiN/TiAlN coatings with delamination occurring between the TiN base coating and Co-HSS substrate. According to the Daimler–Benz adhesion characterisation scale the TiN/TiAlN coatings deposited in this investigation again ranked poorly (Fig. 4a), with a score of 6 (lowest quality ranking). In the present study, the adhesion of MeN/TiAlN coatings was improved by replacing the Ti metallic interlayer and TiN base coating with a Cr metallic interlayer and CrN base coating. The results of Rockwell C indentation tests on partially filtered CrN/TiAlN coatings (see Fig. 4b), showed a well-adhered coating with a Daimler–Benz adhesion quality ranking of 1. Outside the indentation, cracking was observed within a radial boundary no greater than 85 μm from the indent circumference.

### 3.2.4. Nano-indentation hardness and elastic modulus, E

The values of hardness and elastic modulus of the partially filtered coatings (Table 2) were measured using nano-indentation with loads ranging between 5 and 50 mN. The elastic modulus of double layered MeN/TiAlN coatings can be influenced by the modulus of the MeN base coating. However, this observation appears not to hold for the hardness of TiAlN top layers, with TiN/TiAlN and CrN/TiAlN coatings having similar hardness (TiN/TiAlN: 30.7 GPa; CrN/TiAlN: 28.2 GPa) despite variability in the base coating hardness (TiN: 29.9 GPa; CrN: 22.8 GPa).

### 3.2.5. Cutting tool performance

The results of drill tests on uncoated and coated Co-HSS twist drills are shown in Fig. 5. The failure criterion for the drills was a critical sized flank wear land at the outer corners of the drills. It is evident that the single layer coatings have, as one would expect, outperformed the uncoated drills by a factor of approximately 1.5 times. This result for the single layer coatings was achieved despite the thinner CrN coating having lower hardness (22.8 GPa) than the TiN coating (29.9 GPa). In the case of the double layer coatings a further improvement in tool life over single layered PVD coatings was observed, that is 0.5 μm TiAlN on top of

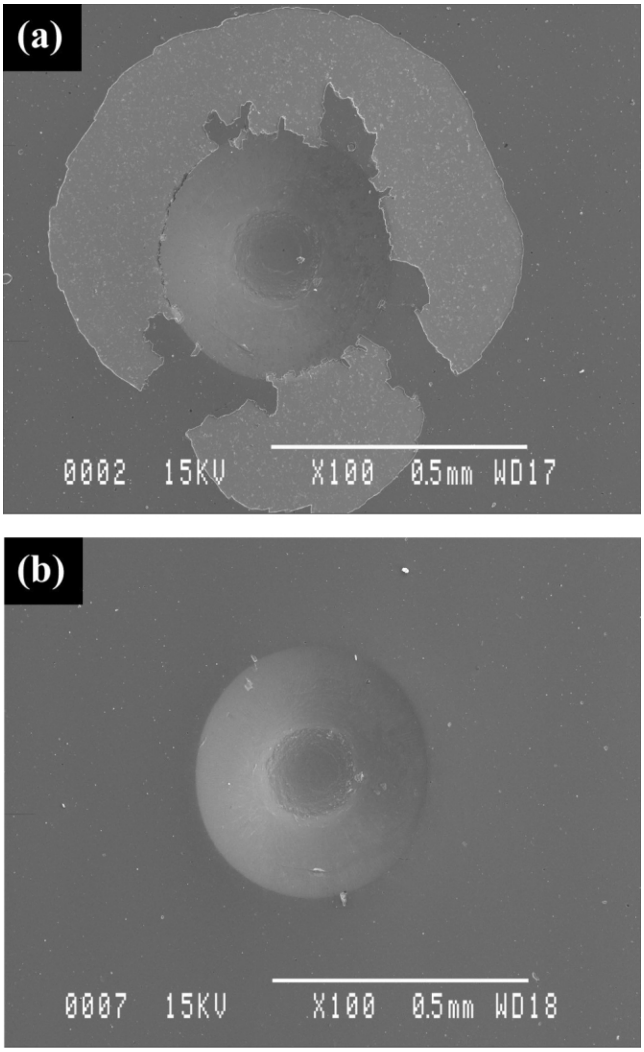

Fig. 4. SEM micrographs of Rockwell ‘C’ indentations in Co-HSS coupons showing bulk delamination in the TiN/TiAlN coating (a), in contrast with the excellent adhesion of CrN/TiAlN (b).

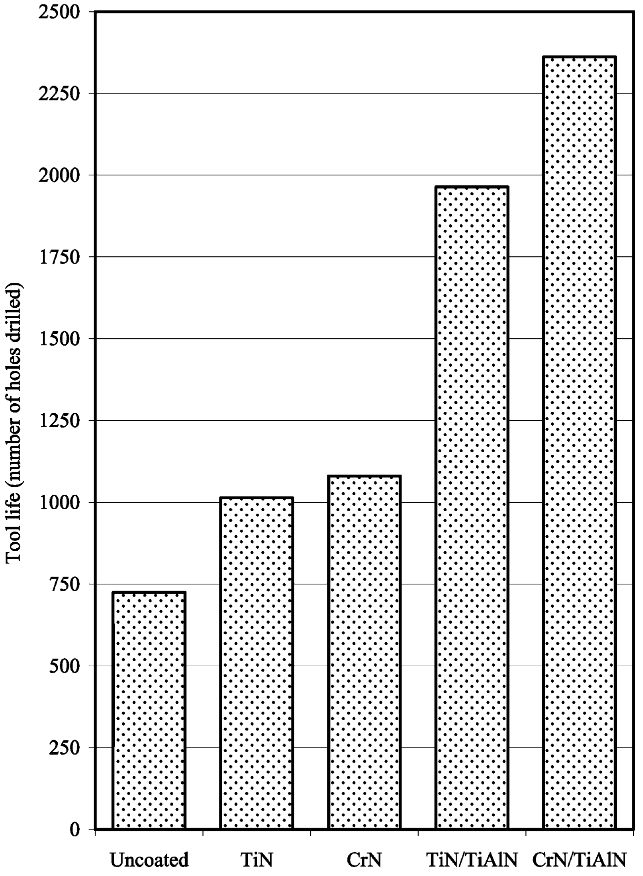

Fig. 5. Comparison of drill life between uncoated and TiN, CrN, TiN/TiAlN and CrN/TiAlN coated 6.8-mm diameter Co-HSS (M35) spilt point twist drills when dry drilling grey cast iron.

TiN increased the tool life relative to uncoated drills by 2.7 times and on CrN by 3.3 times.

The results for TiN and TiN/TiAlN-coated drills are in line with prior research in dry drilling using coated Co-HSS twist drills, which identified increased tool life for dual layered TiN/TiAlN-coated drills. The increased performance was achieved despite the apparent reduced coating adhesion and increased surface roughness of the TiN/TiAlN coatings [9]. The latter deficiencies in coating properties were addressed in the present study, which sought to improve coating adhesion and surface roughness with the intent to further improve cutting tool performance of MeN/TiAlN-coated twist drills.

By replacing the TiN base coating with CrN the adhesion of MeN/TiAlN coatings, as measured using the Daimler–Benz adhesion test, increased from the lowest adhesion quality ranking of 6 (TiN/TiAlN, see Fig. 4a) to the highest ranking of 1 (CrN/TiAlN, see Fig. 4b). Despite the significant improvement in coating adhesion as measured by the Daimler–Benz test, the results of drill tests improved only by a factor of 1.2 times. This raises important questions regarding the suitability of the Daimler–Benz adhesion test for assessing adhesion and/or the significance of adhesion in the performance of cutting tools in aggressive machining applications such as dry and high-speed machining of grey cast iron.

Another significant result was that the roughness of CrN/TiAlN was significantly lower than that of TiN/TiAlN. Investigations on the wear mechanisms of coated drills showed that the improvement in surface roughness of CrN/TiAlN coatings contributed to a reduction in workpiece pick-up on the cutting edges and outer margins of the drills. In contrast, the high surface roughness of TiN/TiAlN coatings resulted in extensive pick-up of work material on the drills. From the present drill test results it would appear that the 20% improvement in drill life between TiN/TiAlN and CrN/TiAlN is a result of the improvement in surface roughness of CrN/TiAlN rather than the improvement in adhesion, as assessed by the Daimler–Benz test.

## 4. Conclusion

In the present investigation, the performance of Co-HSS twist drills with single layer TiN and CrN coatings and double layer TiN/TiAlN and CrN/TiAlN coatings were assessed when machining grey cast iron. In the case of the single layer coatings, the life of drills was increased by a factor of 1.4 times for TiN and 1.5 times for CrN. The drill test results of the single layer coatings were unexpectedly close given the significantly lower coating adhesion of TiN compared with CrN. In the case of double-layered coatings, a further improvement in tool life over single layered PVD coatings was observed. The TiAlN top coatings increased the life of uncoated drills by 2.7 times when deposited on TiN and by 3.3 times when deposited on CrN. The increased cutting tool performance may be partly attributed to the vastly superior surface finish of CrN/TiAlN, which resulted in significantly less pick-up of work material on the cutting edges and outer corners of the drills. Another significant result was the observed reduction in elastic modulus of CrN/TiAlN (394.3 GPa) compared with TiN/TiAlN (564.8 GPa). The elastic modulus of PVD coatings has been shown to be indicative of the residual coating stress, which, in light of the present drill tests, appears to affect the performance of coated cutting tools in high speed machining of grey cast iron.

## Acknowledgements

The authors wish to thank the Ford Motor Company of Australia for its support of the ongoing research and to thank Surface Technology Coatings and Sutton Tools for providing surface coatings and test facilities.

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