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CHARACTERIZING (Ti,Al)N FILM COATING PRODUCED BY INVERTED CYLINDRICAL MAGNETRON SPUTTERING FOR METAL MACHINING APPLICATIONS

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Abstract. (Ti-Al)N coatings were deposited on Cobalt-cemented tungsten carbide (WC–Co) tool inserts by an unbalanced inverted cylindrical magnetron sputtering system (AC ICM-10). Cylindrical titanium and aluminum targets separated by a cylindrical metal with 80 mm height were used for the deposition. The targets were sputtered in an argon and nitrogen gases with constant flow rates and with a radio frequency power of 5 kW at 0.27 Pa of working pressure. The tool insert positioned at a distance of 185 mm from the upper end of the deposition chamber and at the same horizontal distance from the chamber walls. Thin film coating was characterized by X-Ray Diffraction, Scanning Electron Microscopy, and Energy Dispersive X-Ray Spectroscopy and confirmed to be of the Ti-Al-N type. Machining tests were carried out on a quenched-tempered steel (Cr4.2Mo4) using a lathe turning machine with different cutting speeds and feed rate and depth of cut were kept constant. Uncoated and coated carbide tool inserts were subjected to the same cutting conditions and the tool orientation were kept constant during all machining tests. Work piece surface roughness and the resulting cutting forces were measured and reported for each machining trial. Present results show that the X-ray diffraction showed the presence of a (200) NaCl crystal structure of the deposited films. The coated inserts exhibit lower wear rate and longer lifetime than those uncoated with high and low cutting speeds. Also, the coated inserts show significantly lower surface roughness than the uncoated.

1. INTRODUCTION

Increasing demands for high speed and high performance dry machining applications have brought new challenges for the quality of cutting tool materials. High performance dry machining generates severe cutting conditions associated with high temperature and stress within the cutting zone. In this application the use of advanced coated tools is critical to realizing the benefits of high performance machining. Traditional hard coatings, such as titanium- nitrides (Ti-N) single layer coatings, played an important role in the development stage of new-generation cutting tools in an attempt to improve the wear resistance of cutting and forming tools [1,2]. A major drawback of Ti-N, however, is its limited resistance to oxidation at high temperatures that can be reached during different cutting processes. For this reason, high-temperature chemical stability is a major prerequisite for hard coatings [3].

Recent improvements in the coatings of cutting tools have been achieved by the development of (Ti-

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Al) N coatings. (Ti-Al) N coatings exhibit good wear resistance, high oxidation resistance, high hardness at elevated temperatures, thermal and chemical stability, and low thermal conductivity [4-7]. An extremely important advantage of (Ti-Al) N coatings is that it possesses a high thermal stability due to the formation of a dense, highly adhesive, protective Al_2O_3 surface film on the (Ti-Al) N coating in the process of cutting. Such a film prevents diffusion of oxygen into the coating and thus reduces the diffusion wear, one of the major wear mechanisms in cutting tools [8]. For this reason (Ti-Al)N has become one of the best solutions as coating material for cutting tools, especially for dry and high speed cutting.

Most of (Ti-Al) N coatings have been investigated by PVD techniques such as cathodic arc vapor (plasma or arc ion plating) deposition, magnetron sputtering (or sputter ion plating) and combined magnetron and arc processes [9-21]. These PVD processes differ with respect to the type of evaporation of the metallic components and the plasma conditions employed during the deposition process. And afford the possibility of depositing hard, wear-resistant coatings on sharp-edged tools at significantly lower temperatures in the range of 300–500 °C.

Cylindrical magnetron sputtering technique has been employed to deposit various thin films coatings for over 20 years [22-24]. This technique offers advantages over other PVD processes such as: high deposition rates of electrical insulators without arcing [25,26], high coating efficiency, good target utilization, provide uniform coatings on relatively large single parts or multiple small parts without substrate rotation, it is possible to modularize and automate the coating operation, well-suited for coating non-planar inserts with complex shapes (i.e. drill bits, medical needles, manufacturing tools, and wires) and the combination of excellent material efficiency, good target utilization and lower target costs (arises from the ability to use rolled sheets that slip into place without bonding, thereby simplifying the fabrication) leads to significantly lower overall material costs.

To date, most of the published researches on the use of cylindrical magnetrons have been limited for coating fibers and wires, which is obviously an excellent application for the technology. However, the growing need for decorative and functional coatings on complex shapes has caused increased interest in cylindrical magnetron sputtering for these applications as well. In the current study an inverted cylindrical magnetron Isoflux ICM-10 sputtering system is used to investigate the possibility of producing single-layer (Ti-Al) N coatings for industrial applications. This system combines all the above features in addition to an unbalanced magnetic field design. This design enables the field lines to project from the target surface and converge toward the center of the system, consequently focusing the plasma. This arrangement produces extremely high ion and electron current densities near the target surface (five to twenty time's ion-current densities than those observed in conventional magnetron sputtering designs) promoting even higher deposition rates over normal ICM configurations. Nevertheless, the extension of the field lines to the center of the system increases the ion bombardment of the growing film. The magnetic field does not directly influence the ion motion, but ion flux follows that of electrons due to electrostatic attraction. Essentially, this will affect the arrangements and deposition of the

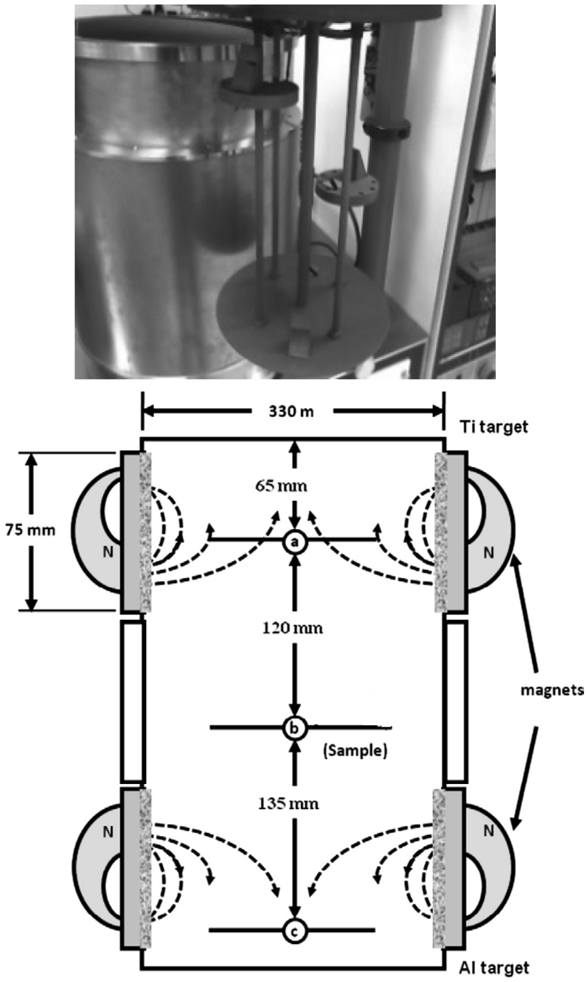

Fig. 1. Schematic illustration of the deposition chamber showing the substrate holder and relative position with respect to Al and Ti targets.

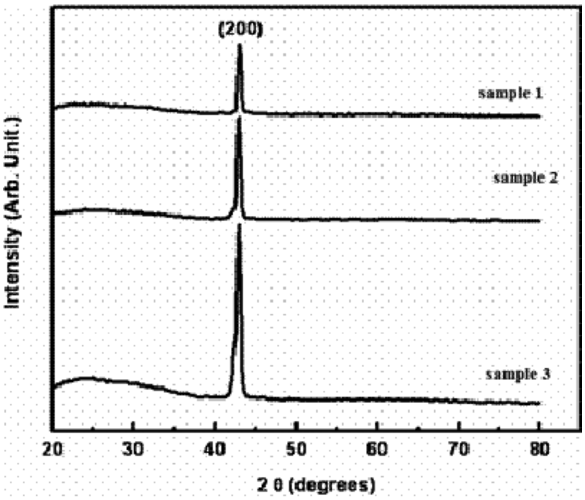

Fig. 2. XRD traces from three coated carbide tool inserts.

incoming material and influence the final crystal structure in the film. Alternatively, ion bombardment can also affect the film growth rate tremendously through re-sputtering and amorphization [27]. Some preferential features of the present system over currently used commercial systems are: 1) Hollow cathodes are desirable for applications involving larger, more complex substrates as metallic targets used have 450 mm diameter and 210 mm long, 2) It has an axial and radial deposition uniformities, 3) The Isoflux system is also easy to evacuate and use which mean lowering the overall cost of coated products.

The objectives of this study were to investigate the possibility of producing single-layer Ti-Al-N coatings prepared by the inverted cylindrical magnetron sputtering method for cutting tools and the cutting performance of a (Ti-Al)N coated Cobalt-cemented tungsten carbide (WC–Co) tool inserts (substrates) for finish turning carbon steel. In addition, comparison between uncoated and coated inserts was performed.

2. EXPERIMENTAL DETAILS

2.1. Coating deposition

(Ti-Al)N coatings were deposited on Cobalt-cemented tungsten carbide (WC–Co) tool inserts by AC unbalanced ICM sputtering system manufactured by Isoflux TM-10. Fig. 1 shows a schematic diagram of the deposition chamber used in this work. Aluminum and titanium targets with 330 mm and 318 mm inner and outer diameters respectively, and 80 mm height were used for the deposition. The targets have a cylindrical metal spacer between them with the same dimensions as the targets (a dummy target). The inserts were pre-cleaned using high-purity water and acetone then dried by an air gun and positioned at a distance of 185 mm from the upper end of the deposition chamber and at the same horizontal distance from the chamber walls. This configuration would eliminate any unbalance in the amount of each target material deposited due to gravitational effects and ensure that both Al and Ti are deposited in an even manner. A shutter was used to start and end the film deposition inside the chamber. The shutter and fixtures were pre-cleaned by sand blasting to get rid of all leftover materials from the previous depositions. The experimental procedures for the deposition were as follows: The deposition chamber was vacuumed to 0.8×10^{-6} Pa and argon was introduced to the chamber at a rate of 150 slandered cubic centimeters (sccm). The radio frequency (RF) power of 1 kW was applied to each cathode (target) using a PEII-5000 supply unit (40 kHz, maximum power 5 kW, maximum voltage 600 V). The chamber pressure was then stabilized at 0.27 Pa. For the deposition process, RF power was maintained at 5 kW for each target while argon and nitrogen were used as the sputter and reactive gases, with flow rates of 75 and 40 sccm, respectively. The insert temperature during deposition was around 450 °C. The crystalline structure of the coatings was studied by using X-ray diffraction (XRD), diffractometer type Phillips PW 1830, with a 0.1° step size and a speed of 1.0 s/step. To measure coating thickness a scratch was made on the surface of the film and then a Sloan Dek Tak 3030 profilometer was used. Film thickness range of 1 – 1.8 μm was obtained.

2.2. Machining test

The coated and uncoated inserts were tested in finish turning on quenched-tempered Cr4.2Mo4 steel (DIN 1.7225 / SAE 4140). The tests employed dry turning, where laminating coolants from the cutting operation is expected to result in an increase in the amount of heat, creating a potential for premature tool wear. Two values were employed for cutting speed of 150 and 300 m/min, while feed rate and depth of cut were kept constant at 0.1 mm rev^{-1} and 0.5 mm, respectively. The tests were run for a total cutting-path-length of 315 m as a control factor. These conditions are representative of typical cutting conditions used in finish turning [28–31]. Tool

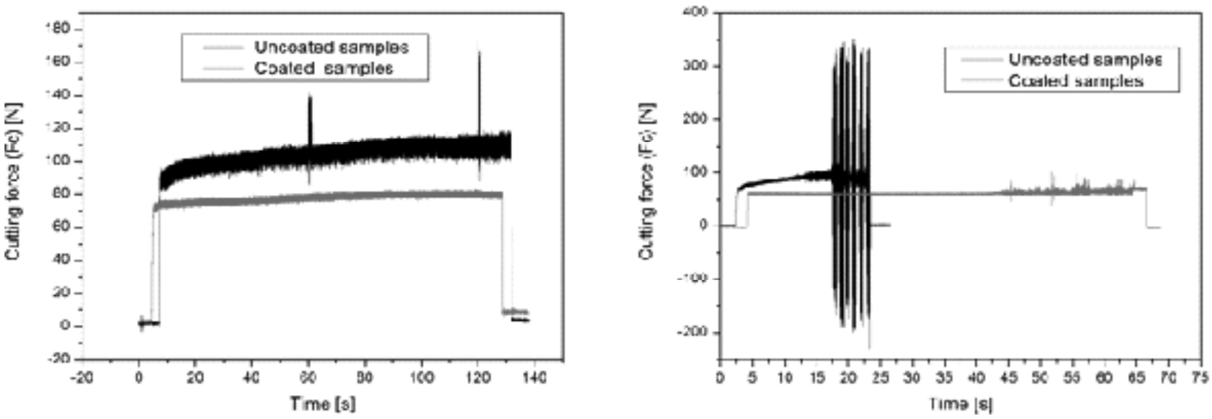

Fig. 3. Cutting force experienced during machining trials using (a) cutting speed of 150 m/min and (b) 300 m/min.

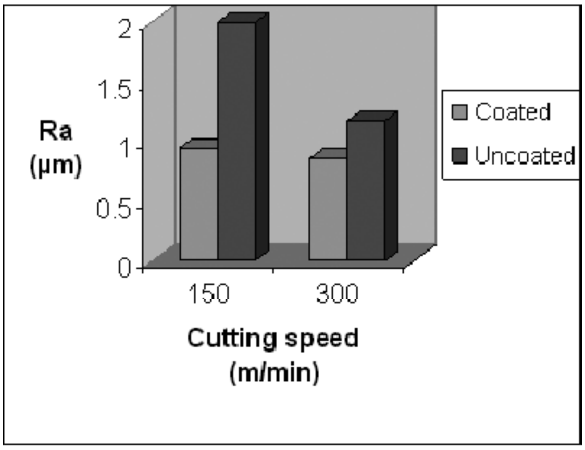

Fig. 4. Surface roughness values (R_a) for the different cutting conditions using coated and uncoated tool inserts.

wear, flank and crater, was monitored and quantified using a tool maker microscope. The wear pattern of the film was observed by scanning electron microscopy (SEM) type FEI Strata 235 DB. The surface roughness, in terms of R_a, of machined surfaces was measured at the same intervals, as for tool wear, using a portable stylus type profilometer (manufacture by Mahr Co.).

3. RESULTS AND DISCUSSION

3.1. Crystal structure

Fig. 2 shows the XRD profiles of the (Ti- Al)N films. All films were characterized as (NaCl-type) structures, with a (200) preferred orientation at a 2θ value of 43°. The high energy titanium and aluminum atoms in the films favors the high energy plane of the (200) orientation. In this case the titanium atoms that sputter away from the upper target react with nitrogen in the ion flux and the rising aluminum atoms from the lower target and deposit on the substrate forming the (Ti,Al)N compound; also ions are dragged to the growing films by the cycling electrons in the magnetic field. The collision impact results in energy transfer to the deposited atoms, resulting in growing planes with higher surface energy, i.e. (200). The results obtained in this study are consistent with previous findings [24,28] and indicate that the resulting thin-film coating to be (Ti-Al)N.

3.2. Cutting performance

The cutting forces experienced during machining with both coated and uncoated carbide inserts as a function of the time(tool life) for cutting speeds of 150 and 300 m min^{-1} are shown in Figs. 3a and 3b, respectively. Fig. 3a indicates that machining conditions at low cutting speeds are within the working range for both coated and uncoated inserts, whereas boarder levels of cutting forces are clearly experienced during machining with the uncoated carbide tool inserts. It is also evident from this figure that the cutting forces are quite constant for coated tool inserts, while there is a continuous gradual increase in cutting forces coupled with the appreciable amounts of tool vibration, evidenced by the larger bands, for the uncoated tool inserts. Fig. 3b clearly indicates that only coated tool inserts were able to perform satisfactorily under high-speed cutting conditions. Inability of uncoated tool inserts to perform satisfactorily under such conditions is indicated by the limited tool life (less than 30% of full cutting path). At this stage large vibration levels were observed, evidenced by the large perturbations in cut-

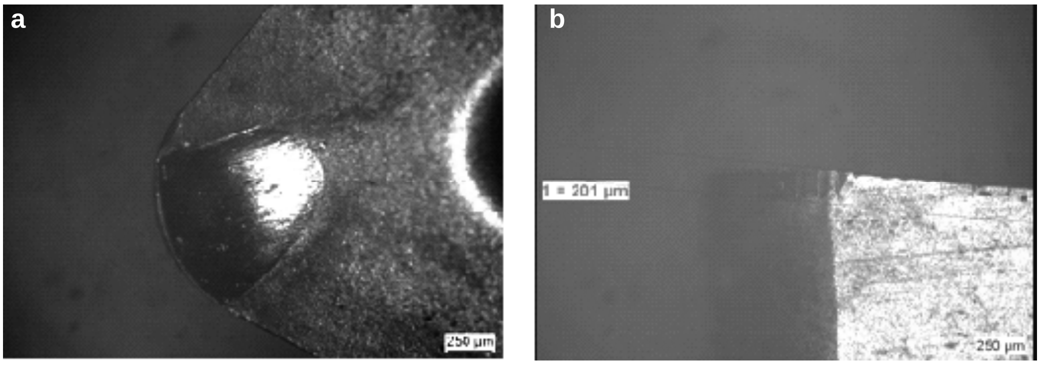

Fig. 5. Optical images of uncoated carbide tool insert showing flank wear after machining at 300 m/min, (a) top view and (b) side view.

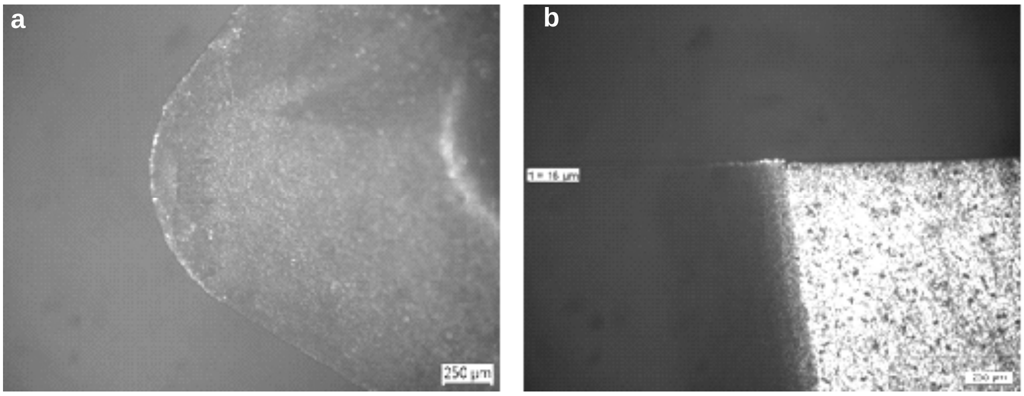

Fig. 6. Optical images of (Ti,Al)N-coated carbide tool insert showing flank wear after machining at 300 m/min, (a) top view and (b) side view.

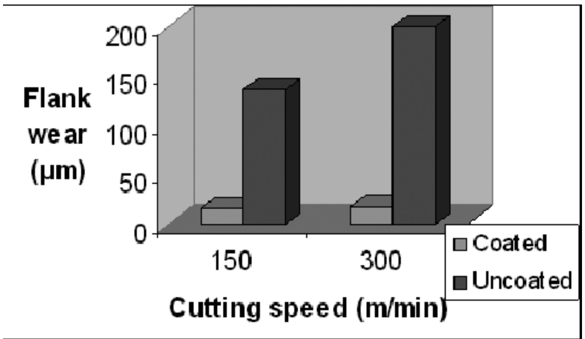

Fig. 7. Tool life (in terms of flank wear) vs. cutting speed for coated and uncoated carbide tool inserts.

ting force, and machining trials have to be terminated at that point for the uncoated tool inserts.

3.3. Surface roughness

The cutting force patterns noted for the two types of tool inserts would necessarily have an impact on the resulting machined surface quality as well as tool life and wear rate. The quality of machined surface, in terms of surface roughness values (R_a), for the different cutting speeds and tool inserts is shown in Fig. 4. It is obvious from this figure that machining with coated tool inserts resulted in a much smoother surface, indicated by the low R_a values, for both low and high machining speeds (R_a approximately 1 μm) compared to machining with uncoated tool inserts (R_a approximately 2 μm). These results would also be expected from cutting force patterns noted for this combination of tool insert-cutting speeds. Also as Fig. 3 shows the cutting force levels and the associated vibration patterns are expected to result in different heating modes and local temperature maxima. This in turn would affect tool life in terms of the type and rate of wear experienced.

3.4. Wear behavior

The wear of inserts was investigated for each set of cutting conditions after each machining trial. A top view (rake face) and a side view (flank face) of the uncoated and coated tool inserts after machining under high speed cutting conditions are shown in Figs. 5 and 6, respectively. As shown from Figs. 5b and 6b flank wear rates (indicated by the measured amounts of wear), were very different. While the amounts of wear for the coated inserts were mea-

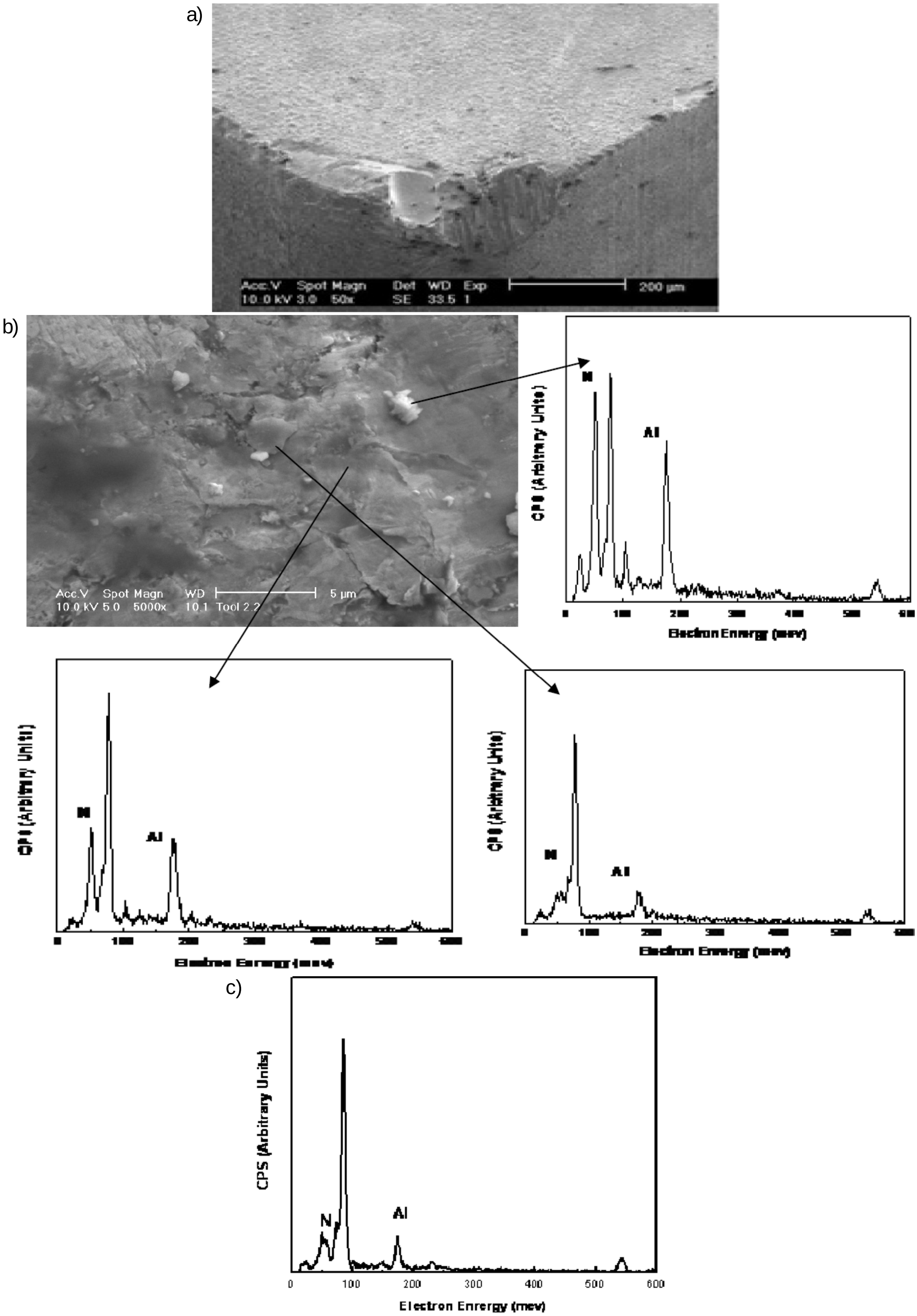

Fig. 8. SEM images of coated tool inserts after machining at 300 m/min, (a) early stages of wear at flank surface, (b) micro abrasion at high-speed dry cutting and the corresponding EDX spectrum from a large (Ti,Al)N droplets and (c) initiation of micro-fatigue cracks at large (Ti,Al)N droplets and corresponding EDX spectra.

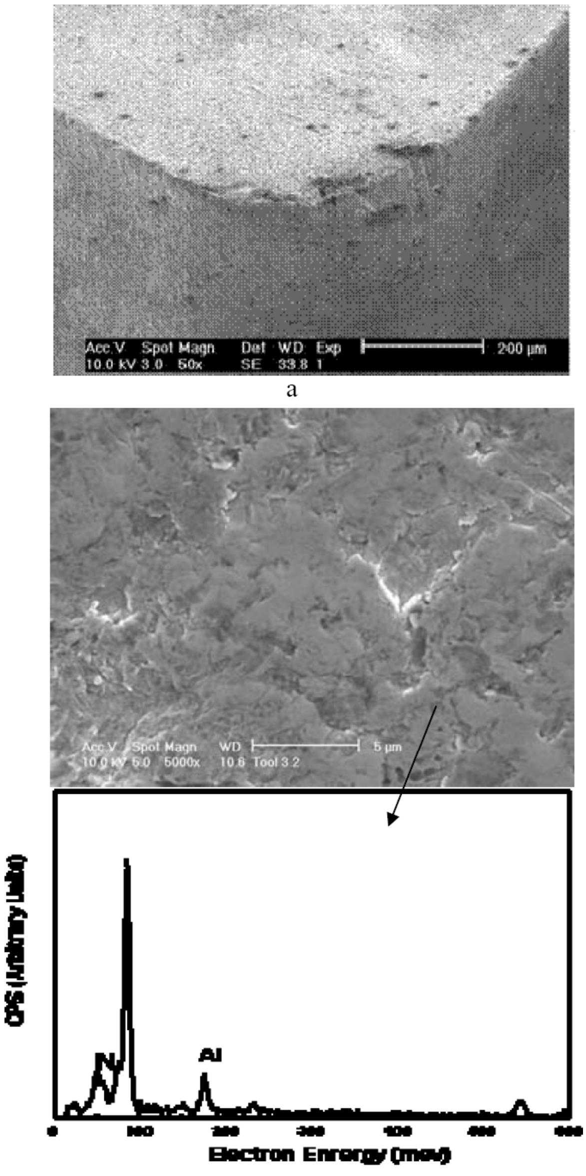

Fig. 9. SEM images of flank side of coated tool inserts after machining at 150 m/min. (a) edge chipping and sliding wear and (b) micro-fatigue cracking and micro-abrasion at a large (Ti,Al)N droplet and its corresponding EDX spectrum.

sured to be in the range of 16-18 μm, the corresponding levels for the uncoated inserts were found to fall in the range of 136-201 μm. Fig. 7 represent graphically the variation of the flank wear as a function of the cutting speeds for uncoated and coated inserts. As the figure shows the coated insert reduce the rise in flank wear for both cutting speeds, as compared to uncoated insert.

SEM examinations enabled the coating surface to be analyzed and revealed that various micro-wear mechanisms were active at different cutting speeds (Figs. 8 and 9). Fig. 8a shows the flank surface of a coated cutting insert after machining at 300 m min^{-1} at early stages of wear. As figure shows, the sliding wear is noticed to have taken place and is evidence by the formation of grooves parallel to the metal flow direction. Fig. 8b shows micro-abrasion indicated by microgrooves parallel to contact direction where (Ti, Al) N droplets (annotated by the arrow) worn out and wear take away at different rates by metal flow. Gu et al. [31] have reported similar observations on (Ti, Al) N-coated milling inserts. Fig. 8c is another view taken at the largest depth of cut and reveals the presence of micro-fatigue cracks. Interestingly, crack initiation started from the biggest (Ti, Al) N micro-droplets (annotated by arrows). This could be explained by the presence of severe dynamic impact and high normal stresses developed at high cutting speeds.

SEM examinations indicated similar micro-structural wear behavior to be experienced by coated tool inserts under the lower cutting speed (150 m/min). Fig. 9a show the results of a worn insert where uniform wear at the cutting edge can be seen. Also, the grooves parallel to metal flow direction indicate sliding wear and coating spalling can be observed. Fig. 9b was taken at higher magnification and shows that multi-fatigue cracks developed in a direction parallel to the tool edge starting from the largest droplets of (Ti,Al)N (annotated by arrows). Micro-abrasion wear, indicated by fine grooves, can also be seen. This is mainly due to the high temperatures experienced, which may weaken the coating by decreasing its hardness. These results indicate that wear started by severe micro-abrasion, leading to edge chipping, and progressed to micro-fatigue at coating layer and eventually caused coating to spall off the surface of the inserts.

4. CONCLUSION

(Ti, Al)N films were grown on (cobalt-cemented tungsten carbide WC–Co) insert substrates by AC ICM sputtering at 5 kW with cylindrical titanium and aluminum targets. Coated tool inserts were compared to bare WC–Co tool inserts under dry machining conditions to investigate the production of industrially viable coatings for metal machining applications. The main conclusions are:

1. The present ICM configuration can be successfully used to produce single-layer (Ti, Al) N hard coatings for metal machining applications.
2. XRD analysis have indicated the coating to be composed of (Ti, Al) N.

3. (Ti,Al)N-coated tool inserts have shown a much great performance improvements than uncoated tool inserts during dry turning of quenched-tempered tool steel in terms of tool life, surface roughness and cutting force requirements. This implies a great potential for using such coatings for the current application of metal machining.
4. (Ti,Al)N coating produced by the present ICM technique proved to have excellent high-temperature stability evidenced by excellent performance at high-speed cutting conditions.
5. Micro-abrasion and micro-fatigue phenomena were seen to be the dominant types of wear mechanisms during high-speed-dry-cutting conditions.
6. Further research is needed for the optimization of final microstructure and mechanical properties of the produced coatings so that improvements on commercially available "multi-layer" coatings could be achieved.

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