Tribological and cutting performance of TiAlCrN films with different Cr contents deposited with multilayered structure

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**Abstract**

Increasing requirements on high speed and dry cutting applications open up new demands on the quality of cutting tool materials. In this study, we evaluated the effect of Cr additions on the properties of Ti(Al)N/Cr(Al)N multilayered films deposited be magnetron sputtering. In particular, we studied the high temperature tribological properties and the cutting performance in real service drilling tests and compared the results with a monolayer Ti0.47Al0.46N reference film. Dry sliding experiments were performed using a pin-on-disc tribometer at room temperature and at 650 ºC with Al2O3 balls as counterparts. The drilling performance of the coatings was evaluated at cutting speeds in the range 50-200 m/min. Wear of the drills in different zones (chisel edge and flank edge) was mapped after each 15 holes.

Keywords: Multilayer TiAlCrN films, High temperature tribology, Cutting performance

**1. Introduction**

High performance dry machining is one of the major trends in modern manufacturing. This is a very hot topic inside the tribology community; PVD tool-coaters and cutting tools costumers are seeking innovative coating solutions which could improve the performance and lifetime of tools, as well as, increase the material volume removal rates through increasing cutting speeds [1, 2]. Dry machining cutting conditions generate severe shear stresses and high temperature harsh conditions on the cutting zone which, consequently, lead to a premature degradation of the tool. Thus, a promising coating should exhibit simultaneously high toughness, low friction coefficient, low wear rate and thermal stability at high temperature conditions. TiN and CrN hard coatings deposited by sputtering were the first generation of protective coatings used for cutting tools. However, their low oxidation resistance (onset point of oxidation of ~600 °C [3] and 700 ºC [4], respectively) resulted in the development of ternary alloys improving thermal stability and oxidation resistance. The most used system, Ti1−xAlxN with cubic NaCl structure, where Al substitutes the Ti positions in the TiN lattice, has been widely used as coating for cutting tools. However, there are two limiting factors of Ti–Al–N-based coatings: (i) significant hardness reduction at higher temperatures [5], and (ii) relatively high coefficient of friction at high temperature [1]. In order to further improve the properties of NaCl type TiAlN films, various doping elements have been added to the coating system, such as Cr [6, 7], Si [8, 9], Nb [10], Ta [11, 12], Y [13], Zr [14] or Hf [15]. Most of the works have shown that if these elements are added in a mole fraction < 0.1, they typically have a positive effect on the mechanical and thermal stability properties. Regarding the specific case of the influence of Cr addition to the NaCl type films, it has been shown that it can hinder the spinodal decomposition by slowing the diffusion and the formation of c-TiN and c-AlN domains [16], which is related to the failure of the coatings in service. Moreover, chromium improves the oxidation resistance and the tribological performance of the coatings. Design of tough and wear protective films for such a coating system was further developed by depositing them in a multilayered configuration [2, 17]. This coating structure has been reported to exceed the mechanical, thermal and tribological performance due to the so called superlattice effect. In fact, a significant increase of the coatings hardness was observed due to blocking of the dislocations motion at the layers interfaces and the coherency strain related with the periodical strain-stress fields [2]. To achieve such high mechanical properties, sharp interfaces with abrupt change in the chemical composition should be produced with multilayered period thickness of films ranging from 2 up to 10 nm [2]. Studies of the multilayer TiAlCrN structure systems deal mostly with their structural properties, thermal stability and oxidation, and tribological properties at room temperature. Barshilia et al. [18] analysed the structure, hardness and thermal stability of TiAlN and nanolayered TiAlN/CrN multilayer films. Tam et al. [19] evaluated the influence of Ti and Al additions on the structure, mechanical properties and tribological performance at room temperature of CrTiAlN films deposited as multilayered structure. However, the tribological behaviour of the films at high temperature, particularly their in-service performance, is still rare. At our best knowledge, only Fox-Rabinovich et al. published a series of works dealing with the cutting performance of monolayer TiAlCrN [20] and multilayered TiAlCrN/WN [21], TiAlCrN/NbN [22], TiAlCrSiYN/TiAlCrN [23] films. They observed that TiAlCrN films with high Al content performed better than TiAlN reference and that multilayer coatings exhibited even better tribological properties due to their superior oxidation resistance, crack propagation resistance and formation of protective lubricious oxides in the sliding contact. Polcar and Cavaleiro [24] focused on the thermal stability, oxidation resistance and high temperature tribology of multilayered AlTiN/CrN films. They observed that the multilayered structure had a beneficial effect on the tribological performance of the films due to the stopping of perpendicular crack propagation from the worn surface at 800 ºC. Recently, we have reported on the influence of Cr content on the structure, mechanical properties and, essentially, oxidation behavior of Ti(Al)N/Cr(Al)N multilayered coatings, with Ti/Al and Cr/Al occupying substitutional solid solution in the fcc NaCl-type structure. We observed that the higher the Cr content in the films, the higher their oxidation resistance due to the formation of a passive Cr(Al)O protective layer on the top of the oxidized film. Herein, we extend our previous study to examine the coating tribological properties at room and high temperatures, as well as the cutting performance in real service drilling tests, and we compare them to a standard industrial TiAlN coating.

**2. Experimental**

**2.1. Deposition of coatings**

TiAlCrN films were deposited in AdvaMat, s.r.o. company by dc reactive magnetron sputtering as multilayered structure in an industrial CemeCon 880/9 MLT coating apparatus (400 x 400 x 430 mm) using d.c. power supply. The chamber has four cathodes: cathodes 1 and 2 are positioned with an angle of 40º and the other two facing these ones with the same geometry. Two Ti targets, containing 48 Al pellets evenly distributed along the race track, were placed in cathodes 1 and 2 together with Al and Cr targets in cathodes 3 and 4. A schematic representation of the chamber configuration is shown in Figure 1. The targets dimension were 500×88×10 mm and target material purity 99.9%. The coatings comprise three multilayered TiAlCrN coatings with increasing Cr and constant Ti content and a TiAlN coating deposited as a reference, which was deposited from four TiAl targets each with 48 Al pellets. The period thickness of Cr rich coatings were 21, 30 and 39 nm with increasing Cr content. The multilayered films consisted of alternating layers of TiAlN and CrAlN, with Ti/Al and Cr/Al occupying substitutional solid solution in the fcc NaCl-type structure, respectively. The increase of Cr content was achieved by increasing and decreasing the power applied to the Cr and Al targets, respectively, whilst a constant power was applied to the remaining TiAl targets. Taking into account the targets distribution inside the deposition chamber and the increase and decrease of the power applied to the Cr and Al targets, and also the low enthalpy formation of CrN as compared to TiN and AlN, multilayer coatings with: i) TiAlN phase with a constant thickness and increasing CrAlN phase thickness, and ii) CrAlN phase richer in Cr, as the power applied to the Cr target was increased, were deposited [25]. Reference TiAlN film was deposited as a monolithic film. All the depositions were performed with constant argon flow (110 sccm); the N2 flow was adjusted to ensure keeping constant the deposition pressure at 0.58 Pa. A pulsed negative bias of 40 V (240 kHz) was applied. The coatings were already characterized in our previous work in relation to morphology, structure, hardness, oxidation resistance and oxide scale growth [25]. Summary of the deposition parameters used for the coatings production and their chemical composition determined by energy dispersive spectroscopy (EDS) are shown in Table 1. The denomination of the samples, as presented in the table, will be adopted throughout the manuscript in order to help the coatings identification. The subscript in Ti, Al and Cr letters represents the ratio between the at.% of each element in the coating in relation to the at.% of nitrogen. Polished tungsten carbide coupons (diameter 20 mm, thickness 3 mm, for hardness measurements and tribological evaluation), FeCrAl alloy (20 × 20 × 1 mm, for structural analysis) and tungsten carbide drills (2 flutes, 5.5 mm diameter, helix 30º, for drilling evaluation) were used as substrates.



Figure 1 - Schematic illustration of the deposition chamber used for the films deposition

Table 1 – Coating denomination, deposition parameters, chemical composition and mechanical properties of reference TiAlN and multilayered TiAlCrN films.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sample designation | | Ti0.47Al0.46N | Ti0.30Al0.46Cr0.26N | Ti0.28Al0.34Cr0.42N | Ti0.28Al0.31Cr0.51N |
| Period thickness (nm) | | - | 21 | 30 | 39 |
| Power applied to target TiAl48 (W) | | 4 × 7000 | 2 × 7000 | 2 × 7000 | 2 × 7000 |
| Power applied to target Al (W) | | - | 2200 | 1000 | 500 |
| Power applied to target Cr (W) | | - | 1750 | 3000 | 3700 |
| Base pressure (Pa) | | 1.5 × 10-4 |  |  |  |
| Plasma etching | | Ar plasma for 60 min under substrate bias -650 V and 350 kHz (RF power supply) | | | |
| working pressure (Pa) | | 0.58 |  |  |  |
| Substrate temperature (ºC) | | 300 |  |  |  |
| Ar flow (sccm) | | 240 |  |  |  |
| N2 flow (sccm) | | 110 | 110-130 | 110-130 | 110-130 |
| RF substrate bias (V) | | -40 V (250 kHz) |  |  |  |
| Coating thickness | | 2.2 | 3.6 | 4 | 4.3 |
| Chemical composition (at.%) | | Ti - 24.4±0,14 | Ti - 14.7±0,17 | Ti - 13.6±0,1 | Ti - 13.3±0,14 |
| Al - 24.0±0,03 | Al - 22.8±0,1 | Al - 16.7±0,1 | Al - 14.8±0,03 |
| Cr – 0.0 | Cr - 12.8±0,15 | Cr - 20.7±0,11 | Cr - 24.3±0,06 |
| N - 51.6±0,07 | N - 49.7±0,06 | N - 49.0±0,06 | N - 47.5±0,27 |
| Hardness (GPa) | | 23,8±3,32 | 17,0±4 | 16,8±4,68 | 19,8±1,9 |
| E (GPa) | | 685±25,1 | 459±59,2 | 444±65,2 | 469±21,2 |
| Elastic strain to failure - H/E | | 0,035 | 0,037 | 0,038 | 0,042 |
| Oxidation weight gain (mg/cm2) | 800 ºC | 0.055 | - | - | - |
| 900 ºC | Totally oxidized | 0.045 | 0.055 | 0.062 |
| 1000 ºC | - | 0.283 | 0.209 | 0.129 |

**2.2. Structural, mechanical characterization and oxidation resistance of the films**

The crystal structure of the films was analyzed by X-ray diffraction (X' Pert Pro MPD diffractometer) using Cu Kα radiation (45 kV and 40 mA) with a parallel beam in θ–2θ geometry. The hardness and Young's modulus of the films were evaluated by depth-sensing indentation (Micro Materials NanoTest) using a Berkovich diamond pyramid indenter and 30 s of loading, unloading and holding time. In order to avoid the effect of the substrate, the applied load (10mN) was selected to keep the indentation depth less than 10% of the coating's thickness. A total of 16 measurements were done in each specimen in order to ensure the measurements accuracy. Oxidation resistance of films was assessed by thermogravimetric analysis (TGA) using industrial air (99.99% purity). Reference Ti0.47Al0.46N films was exposed at 800 and 900 ºC, whilst, Cr rich films were tested at 900 and 1000 ºC for 2 hours due their high onset point of oxidation. The coating-substrate adhesion of films in as deposited condition and after annealing at 700 0C was characterised by scratch and Mercedes test apparatus. The scratch tests were performed using a Rockwell C indenter with a spherical tip with a radius of 0.2 mm, a scratch speed of 10 mm/min and a loading speed of 100 N/min, as the normal force was increased linearly from 5 to 100 N. On the other hand, a Rockwell C indenter with a spherical tip with a radius of 0.2 mm, applying a load of 100 N was used in Mercedes test to produce spherical indentations in coated coupons. Typical failure modes presented on the scratch tracks and wear scars produced by these tests were identified by optical microscopy and proper labeled according to the scratch standards ([26] and [27]).

**2.3. Tribological characterization**

The tribological performance of the coatings was analysed at room (RT) and high temperature (650 ºC) using a high temperature tribometer; Al2O3 balls were used as counterpart. The radius of the wear track was set to 5.5 mm. The tests were conducted with a load of 5 N, sliding speed 10 cm.s-1, relative humidity 48±5% and a number of laps of 5000. Two identical sliding tests were performed under identical conditions for each of the specimens in order to ensure the reproducibility of the results. The friction coefficient was continuously measured and the wear rate of the films determined from the wear track using a Zygo – NewView 7200 3D profilometer; an average from three different measurements was used. After tribological tests, the wear track and the wear debris were characterized by scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM – EDS). Wear mechanisms were also identified and correlated to the friction coefficient and the wear rate.

**2.4. Drilling tests**

In-service machining tests were carried out to evaluate the coated drills lifetime. The drilling tests were performed in vertical milling machine FC 16 CNC. The feed force and torque were continuously measured during drilling using a triaxial Dynamometer 9272. The experiments consisted on the production of blind holes, without cutting fluid, to a depth of 10 mm in a block of tool steel 55NiCrMoV7 (50 HRC), up to the failure of the tool. The failure criterion for drills was the total loss of cutting performance usually caused by cracking of the drill edge or the excessive increase of the cutting force. The steel block was a commercial alloy steel, used for the production of shafts, bearings and plastic moulds. The drilling performance of the coatings was evaluated at different cutting speeds (50, 100 and 200 m/min). The feed rate was 0.05 mm per rotation. A thermal imaging camera was used to evaluate the temperature on the contact block/tool during the machining tests. The morphology of the chips resulting from the drilling process was also visually observed.

Additionally, the wear of the drills in different zones, through the analysis of the critical wear length in the chisel edge, cutting edge and flank edge, was mapped after each 15 drills. The values were correlated with the tool life, chip types and cutting speeds used in the experiments. It should be stressed here that this method of wear measurement is a practical technique well suited, particularly in industry, since it indicates directly the extent of drill wear and, hence, the appropriate time at which the drill should be replaced and/or re-sharpened.

3. Results and discusion

**3.1. Structure, mechanical properties and oxidation resistance**

Firstly we will summarize the main properties and the oxidation resistance of TiAlN and TiAlCrN films published in our previous study [25]. All the investigated coatings displayed a columnar morphology with columns extending from the substrate to the top of the film, independently of the Cr content (see as an example Figure 2a) for Ti0.47Al0.46N and Ti0.28Al0.31Cr0.51N films). The analysis of the X-ray diffraction patterns (Fig. 2b) showed that the coatings presented a rock salt type structure with peaks located at position between that of TiN (ICDD card 87-0633), AlN (25-1495) and CrN (76-2494); this suggests that a solid solution is always being formed either in the individual layers of the TiAlN/CrAlN multilayer or in the monolithic TiAlN coating. The broadening of the XRD diffraction peaks of Cr rich coatings, in relation to the reference TiAlN film, is related to two factors. Firstly, multilayered structure with different chemical composition (TiAlN and CrAlN) gives rise to small differences in the lattice parameters and, thus, the overlapping of the corresponding diffraction peaks. Secondly, the existence of interfaces with a gradient in the chemical composition between the TiAlN and CrAlN layers also gave rise to the progressive shift in the diffraction peaks positions in relation to the individual layer phases.



Figure 2 – a) cross section morphology of Ti0.47Al0.46N and Ti0.28Al0.31Cr0.51N films, b) XRD diffraction patterns of as deposited films.

Cr-rich coatings are softer than the reference Ti0.47Al0.46Nfilm (see Table 1). Relatively high thickness of individual layers eliminates the superlattice effect [17], more details can be found in our previous work [25]. The higher hardness of the coating with the highest Cr content in relation to other Cr-containing coatings was interpreted by the change in the diffraction peaks intensity from (111) to (200), as detected by XRD [28, 29]. The elastic strain to failure of the coatings, represented through the ratio H/E [30], shows that reference Ti0.47Al0.46N film has the lowest resistance to plastic deformation, this reveals the beneficial influence of the multilayered arrangement in stopping or deflecting the propagation of the cracks, thus improving the toughness fracture resistance of the films [24] .

The isothermal oxidation showed that Cr additions improved the oxidation performance of the coatings (Table 1) due to the type of oxides formed during the oxidation process. Coatings with high Cr content displayed better oxidation resistance due to the formation of a continuous and compact Cr-based oxide layer (Cr(Al)2O3), in comparison to the reference Ti-Al-N film, where the protective layer is based on Al-O [25].

The film to substrate adhesion is critical to achieve longer wear life and durability, particularly for highly loaded components as cutting tools. According to the adhesion critical load values, all coatings adherent well on tungsten carbide substrates (Table 2). First coating cracking LC1 > 100 N was reached for all coatings except for Ti0.30Al0.46Cr0.26N coating where LC1 was 75 N. The Mercedes test (Rockwell C indentation) confirms the excellent adhesion with HF1 failure mode for all films. However, identical adhesion tests on the samples after tribologically tested at 650 ºC showed a significant decrease in adhesion.

Table 2 – Adhesion of the films.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Adhesion critical loads | | | |
|  | As-deposited | | Annealed at 650 0C (after tribology) | |
|  | Scratch tester - LC1 failure | Mercedes | Scratch tester - LC1 failure | Mercedes |
| Ti0.47Al0.46N | >100 N | HF1 | 20 | HF6 |
| Ti0.30Al0.46Cr0.26N | 75 N | HF1 | 20 | HF6 |
| Ti0.28Al0.34Cr0.42N | >100 N | HF1 | 20 | HF6 |
| Ti0.28Al0.31Cr0.51N | >100 N | HF1 | 20 | HF6 |

**3.2. Tribological behavior of the films**

3.2.1. Wear rate

The wear rate of coatings tested at different temperatures is shown in Figure 3. At room temperature, the wear rate of the films was almost unmeasurable and independent of the coatings chemical composition (see wear track in Figure 4 a) and b) for Ti0.47Al0.46N and Ti0.28Al0.31Cr0.51N films). The only surface change was a negligible smoothening of the surface (asperities polishing); this demonstrates the excellent wear resistance of these coatings at room temperature. At 650 ºC, the wear rate of multilayered TiAlCrN was at least 5 times lower than that of Ti0.47Al0.46N reference. At this temperature, an abrupt increase of the wear rate of the Ti0.47Al0.46N coating was observed and a smooth deep wear track was produced (see Figure 4 c)). Ti0.30Al0.46Cr0.26N and Ti0.28Al0.34Cr0.42N films displayed slightly higher specific wear rates when compared to those obtained at room temperature. Wear tracks of these films displayed a rough morphology (see Figure 4 d)) which, as it will be discussed latter, is correlated to the presence of oxidized adhered material to the wear track, which protects the film from further wear. Interestingly, the wear of the coating with the highest Cr content was not measurable (too low) even after testing at high temperature.



Fig. 3 – Specific wear rate of films tested against Al2O3 balls at RT and 650 ºC.



Fig 4 – 3D profiles of the wear tracks of Ti0.47Al0.46N and Ti0.28Al0.31Cr0.51N films tested at: a) and b) room temperature, c) and d) 650 ºC.

3.2.2. Friction coefficient

The coefficient of friction (COF) of the films was quite stable at room temperature. No significant fluctuations were observed during the tribological tests, with the exception of the Ti0.47Al0.46N reference which displayed a broader friction coefficient curve. As expected, two distinct regions, the running-in and the steady state zones could be observed. The running in period for Ti0.47Al0.46N film lasted 300 laps, with the friction coefficient abruptly increasing from 0.2 to 0.63, remaining then stable. Similar evolution and friction coefficient values were reported in references [31, 32] for Ti1-xAlxN films tested against Al2O3 balls. An increase of the COF from an initial low value starting in 0.2 to a higher steady state value 0.5-0.6 was also observed for coatings containing Cr. The running in period in these coatings was kept up to 1500 cycles. As it will be explained latter the longer running in of Cr rich coatings is attributed to the coatings architecture. The average COF values of the steady state stage are plotted in Fig. 5 where it can be clearly observed that Cr rich coatings displayed slightly lower COF values than Ti0.47Al0.46N reference.

At a temperature of 650 ºC, a slight increase of the COF values was observed in all coatings except for Ti0.28Al0.31Cr0.51N film for which the inverse occurred, in a good agreement with its lower wear rate. The friction coefficient values of Cr rich coatings were lower in relation to the reference Ti0.47Al0.46N film and decreased progressively with increasing Cr content. The reference film showed much larger fluctuations of the friction coefficient during the tests when compared to the smoother curves of the other coatings.



Figure 5 - Average friction coefficient of films.

3.2.3. Wear mechanisms and surface analysis

The investigation of the interaction between the specimen-counterpart pair, i.e. the dominant wear mechanisms and the wear debris originated during tribological testing, was carried out by SEM–EDS. At room temperature, fine scratches parallel to the relative sliding movement of the ball were observed in the wear track of all coatings, suggesting that polishing wear (abrasion) is the main active wear mechanism. Small adhered wear debris were found evenly distributed over the wear tracks of films; EDS analysis revealed to be a mixture of non-oxidized and oxidized particles detached from the coatings generated by the asperities during the relative movement between the coating and the ball. The amount of these wear debris revealed to be higher in Cr rich films. Similar wear debris was also found adhered to the counter body surface. The formation of oxidized particles occurred due to the continuous movement of the ball and the local increase of temperature on the contact in the top of the asperities. Consequently, a third body was formed and this prevented the direct contact between parts and protected the film from wear. The well-known lubricious properties of the oxide products, i.e. Ti-Al-O for reference Ti0.47Al0.46N film and Ti-Al-Cr-O for Cr containing films, could amplify the protection effect [20]. Moreover, the higher amount of Cr-O in tribolayer of Cr containing coatings, which have been reported to have low friction features than Ti-O and Al-O oxides [33], is in the origin of the reduction of COF on Cr rich films. Therefore, in spite of the lower hardness of Cr multilayered coatings, comparable wear rates were achieved in relation to Ti0.47Al0.46N reference. The better performance of Cr-containing films can be interpreted as a combined effect of: i) better lubricious properties of Cr-O phase formed on the wear track and, ii) the multilayer structure which have been reported to be very efficient to obstruct or deflecting the notch/crack propagation [2]. This effect was clearly demonstrated by Polcar&Cavaleiro who studied the tribological performance of multilayer CrAlTiN films with gradient interfaces [24]. The differences between the running in periods of reference and Cr-rich films can be interpreted based on the coatings architecture. Since reference film and Cr rich coatings have similar surface roughness, the difference in achieving the steady state stage, i.e. the moment when asperities are removed from the sliding contact and a constant wear mechanism is established, should be attributed to the multilayer arrangement and the heterogeneity on the chemical composition distribution. For Cr-rich coatings, individual layers have different chemical composition which can induce different contact conditions. A longer running in period can, thus, be expected, being the steady state reached only when a continuous and steady tribolayer is formed by oxides originated from both layers.

For testing at 650 ºC, significant differences could be observed between the reference and Cr-containing films. Ti0.47Al0.46N showed a smooth wear track with scratches parallel to the relative sliding movement, suggesting an abrasion wear mechanism (see Figure 6 a). EDS analysis performed at the flat worn surface only revealed low O contents suggesting that formed oxides were continuously removed during the sliding process. Small oxidized wear debris particles could be sparsely found adhered to the wear track. On the other hand, an irregular surface with a mixture of smooth (polishing wear) and oxidized (signs of adhered material) wear zones was observed in the wear track of multilayered TiAlCrN films, as shown in Figure 6 b), revealing an incomplete formation of an oxide layer. EDS analysis carried out in the wear tracks (grey zones marked in Fig. 6 b for Ti0.28Al0.31Cr0.51N film which is representative of all the TiAlCrN films) confirmed that they were mainly composed of O, Ti, Al and Cr suggesting the presence of Ti-O, Al-O and Cr-O oxides. Signals from the Cr-O phase increased with increasing Cr concentration in the films, corroborating our previous work [25] where the preferential formation of Cr2O3 over Al2O3 was observed. Based on these observations, we can propose the following explanation for the better wear performance of TiAlCrN films over the Ti0.47Al0.46N reference: (i) in case of Cr-containing coatings, Cr-O is being preferentially formed over Ti-O and/or Al-O; (ii) oxides richer in Cr are known to have better lubricious properties than Al-O and Ti-O oxides [33]; (iii) lower friction of the Cr-O based layers formed on Cr-containing coatings induces lower shear forces during sliding which limits the removal of the adhered layer from the wear track; (iv) the oxides adhered to the wear track protects the surface from further wear; (v) the higher the Cr content, the higher the Cr-O formation and the lower the friction coefficient and the wear rate.



Fig. 6 – SEM pictures of the wear track of films tested at 650 ºC. a) Ti0.47Al0.46N reference, b) Ti0.28Al0.31Cr0.51N film. c) and d) SEM EDS spectra of points 1 and 2, respectively.

3.3 Cutting performance

Cutting tools were coated with the Ti0.47Al0.46N reference as well as the multilayer TiAlCrN coating having the best tribological performance (Ti0.28Al0.31Cr0.51N film) and their wear resistance was further investigated under high-speed dry drilling conditions. We should mention here that uncoated WC tool was tested under identical conditions and failed almost immediately with a maximum of 9 holes produced. Figure 7 a) plots the number of open holes as a function of the cutting speed. For low cutting speed, Ti0.47Al0.46N film, outperformed Cr-rich coating by a factor of 2. This agrees well with the lower cutting force measured during the test (see Figure 7 b)) as well as with the lower flank and/or chisel wear, as shown in Figure 8. Flank and chisel wear grow faster on Ti0.28Al0.31Cr0.51N film; consequently, the insert geometry is deteriorated, weakening the cutting edge and, thus, caused the premature tool failure. Being Ti0.47Al0.46N the hardest coating (at room temperature), its wear resistance during the drilling test with low cutting speed should be enhanced in relation to the Cr-containing multilayer coating. At such low cutting speed, a discontinuous chip was always formed and, therefore, very high temperatures are not expected during the cutting process as the majority of the heat goes into the chips and is dissipated via chip removal [34]. Thermal imaging camera showed a temperature of ~ 330 ºC for Ti0.47Al0.46N and 370 ºC for Ti0.28Al0.31Cr0.51N film. Although the contact temperature is undoubtedly higher, the values above are very low and indicate a very low thermal load in the contact. Consequently, the hardness of the material should be the determinant factor controlling the wear resistance at this cutting speed. Similar to what was observed in tribological testing, abrasive wear mechanism on the cutting surface was observed at low temperature testing for both films. In addition, material from the counter body started to adhere at the cutting edge of the Ti0.47Al0.46N drill after 75 holes. In fact, this event, often named build up edges (BUE) [35], has been reported to contribute to the cutting tool life degradation. It acts as a third body part which promotes the back-adhesion between the cutting tool and the workpiece and, when particles are detached, the hard abrasive particles wear the surface [36]. Nevertheless, this should only occur if the detached particles are oxidized; if the adhered material is steel, which is much softer than coating material, an opposite effect is observed and adhered layer protects the coating material. This should be the case of this work since the O signal acquired at the adhered material by EDS is very low suggesting that hard oxide particles can only be formed if release of metal particles can occur, which are then oxidized in the contact.

 

Figure 7 – a) number of holes as a function of the cutting speed, b) average cutting force.



Figure 8 – a) Flank and b) chisel edge wear evolution as a function of the number of drilled holes for a cutting speed of 50 m/min.

With increasing cutting speed to 100 m/min, an abrupt decrease of the drilling performance (~ 78% in the number of holes) occurred for the Ti0.47Al0.46N film whereas only a minor change (14%) was observed for Ti0.28Al0.31Cr0.51N films. Inversely to the test at 50 m/min, the cutting force showed a slightly lower value for the Cr rich coating and with the latter three times more holes could be drilled. Such behavior corroborates the tribological testing results at high temperature where much lower wear rates were observed. In fact, the degradation of the cutting zone for Ti0.28Al0.31Cr0.51N film is much slower than for Ti0.47Al0.46N reference, as can be concluded from the chisel and flank wear evolution shown in Figure 9. A different chip type was observed during drilling tests at this cutting speed. After 15 and 240 drilled holes for Ti0.47Al0.46N and Ti0.28Al0.31Cr0.51N films, respectively, a chip transformation from discontinuous to continuous was observed. The latter chip type will limit the release of the thermal energy, contributing for the heating of the cutting tool surface, being, thus, much more deleterious for the reference coating. Thermal image camera showed now a temperature of ~ 450 ºC for Ti0.47Al0.46N film and slightly lower value for Cr containing coating. Again, temperatures in the contact should be much higher and coatings tribo-oxidation is now expected with the formation of lubricious Cr-O on the cutting zone of the Cr containing coating which would protect efficiently the film from wearing.



Figure 9 – a) Flank and b) chisel edge wear evolution as a function of the number of drilled holes for a cutting speed of 100 m/min.

Further increase in cutting speed to 200 m/min did not influence the drilling performance of Ti0.47Al0.46N reference; however, a significant improvement in the number of drilled holes (34%) was observed for Ti0.28Al0.31Cr0.51N. It should be pointed out that the final number of holes is even higher than that achieved at much less severe cutting conditions (50 m/min). The trend described above for a cutting speed of 100 m/min, particularly for the cutting force, is further enhanced. Formation of higher amount of oxide products in the cutting zone due to the increase of contact temperature (enhanced by both factors, higher cutting severity and continuous chip formed now from the very first drilled holes) protects more efficiently the coating from wear and this is well evidenced by an absence of the flank wear and the slower evolution of the chisel edge wear, as shown in Figure 10 for both films. In fact, the chisel edge wear develops slowly and remains fairly low for a high number of holes, as compared to the tests performed at 100 m/min. Therefore, the cutting zone area remains higher for a longer period of time, extending the cutting performance of the drill. Harris et al. [37] also reported an increase of the cutting performance of TiCrAlN coatings under more aggressive cutting conditions (cutting speed increased from 38 to 51 m/min). Ti0.28Al0.31Cr0.51N film showed a slower chisel wear evolution as a function of the number of drilled holes when compared to Ti0.47Al0.46N. We can conclude here that nanolayered TiAlCrN coating outperform reference monolithic TiAlN at higher cutting speeds and this is more suitable for harsh dry sliding contact conditions. Finally, it should be emphasized that, in any of the tested cutting speeds, the uncoated WC carbide drill never could drill more than nine holes. Thus, any of the coated drill solutions has much better cutting performance than the uncoated WC tools.



Figure 10 – Chisel edge wear evolution as a function of the number of drilled holes for a cutting speed of 200 m/min.

**Conclusions**

The current work reports on the influence of Cr additions on the tribological and drilling performance of Ti(Al)N/Cr(Al)N films deposited as a multilayer by magnetron sputtering, and their comparison to a Ti0.47Al0.46N film deposited as a reference. Tribological behavior of films evaluated in pin-on-disc at room temperature was independent of the coatings chemical composition. However, at 650 ºC, Cr containing coatings displayed a better performance due to the formation of Cr-O tribolayer in the sliding contact, which outperformed lubricious properties of Al-O and Ti-O oxides formed in the wear track of Ti0.47Al0.46N reference. The higher the Cr content in the films, the better the tribological performance, due to the higher amount of Cr-O in the wear track. Drilling performance of Ti0.47Al0.46N reference conducted at low cutting speed (50 m/min) was 2 times better than Cr-rich coating due to its higher hardness, which is the dominant factor in the absence of sufficient oxidation and tribofilm formation. At higher cutting speeds, the drilling performance of Ti0.47Al0.46N reference suddenly dropped due to the combined effect of the change of chip type (discontinuous to continuous) and the higher cutting severity. The latter led to an increase in the overall temperature of the cutting zone. Cr containing coating displayed significantly better cutting performance at higher cutting speeds due to the formation of a protective Cr-O rich tribolayer in the cutting zone. In fact, the total number of holes before tool failure was in case of Cr rich coating increased with cutting speed, which makes these coatings good candidates for high speed dry drilling.

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Figure captions

Figure 1 - Schematic illustration of the deposition chamber used for the films deposition

Figure 2 – a) cross section morphology of Ti0.47Al0.46N and Ti0.28Al0.31Cr0.51N films, b) XRD diffraction patterns of as deposited films.

Figure 3 – Specific wear rate of films tested against Al2O3 balls at RT and 650 ºC.

Figure 4 – 3D profiles of the wear tracks of Ti0.47Al0.46N and Ti0.28Al0.31Cr0.51N films tested at: a) and b) room temperature, c) and d) 650 ºC.

Figure 5 - Average friction coefficient of films.

Figure 6 – SEM pictures of the wear track of films tested at 650 ºC. a) Ti0.47Al0.46N reference, b) Ti0.28Al0.31Cr0.51N film. c) and d) SEM EDS spectra of points 1 and 2, respectively.

Figure 7 – a) number of holes as a function of the cutting speed, b) average cutting force.

Figure 8 – a) Flank and b) chisel edge wear evolution as a function of the number of drilled holes for a cutting speed of 50 m/min.

Figure 9 – a) Flank and b) chisel edge wear evolution as a function of the number of drilled holes for a cutting speed of 100 m/min.

Figure 10 – Chisel edge wear evolution as a function of the number of drilled holes for a cutting speed of 200 m/min.