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Tribological properties of (Ti, Al)N films with different Al/Ti atomic ratios deposited by magnetron sputtering

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Abstract

Magnetron sputtering was used to deposit (Ti, Al)N films with different Al/Ti atomic ratios by changing the current of the Al target and to study their tribological properties. The phase composition, microstructure and elemental distribution of films were characterized by x-ray diffraction (XRD), scanning electron microscopy (SEM), x-ray photoelectron spectroscopy (XPS) and energy dispersive spectroscopy (EDS). The influence of the ratio between Al and Ti atoms on the tribological properties and the mechanical properties of the films was analyzed. The conclusions showed that there was a tendency for films to shift from the crystalline to the amorphous state as the Al/Ti atomic ratio increases. Herein, changes in film microhardness were related to the substitution relationship between Ti atoms and Al atoms. Especially, when the Al/Ti atomic ratio was 0.54, coefficient of friction (COF) and specific wear rate were the lowest. Compared with TiN film, (Ti, Al)N films have higher microhardness due to the solid solution hardening caused by the substitution between Al and Ti atoms to produce lattice distortion. These factors make films have excellent tribology performance.

1. Introduction

In the past few decades, transition metal nitride films modify the surface properties of substrate materials as a protective material for cutting tools. The deposition of nitride hard films on the surface of high-speed machining tools by magnetron sputtering was widely used in the metalworking industry due to its high hardness, good wear resistance, oxidation resistance and corrosion resistance [1–3]. For many years, TiN has been used widely for cutting tools and wear-resistant parts as the first generation of hard films [4]. However, the formation of TiO\(_2\) oxide layers and poor tribological properties have limited its application in the wider field [5]. Alloying element (Al, Cr, Mo, Si etc) was subsequently added in improving the properties of the film [6–9]. The addition of Al element forms a particularly attractive ternary (Ti, Al)N film, which has high hardness, low friction, high temperature resistance and other excellent performances. At present, ternary (Ti, Al)N films are generally have a thickness of 1–5 \(\mu\)m, a hardness of 25–45 GPa, a COF of 0.25–0.7 and a maximum operating temperature of 800 °C–900 °C [10–13]. It has been found that the properties of (Ti, Al)N films largely depend on the content (at%) between Al and Ti [14, 15].

Nitride hard films with high hardness and low friction integration characteristics have been the target of research [16]. The appropriate amount of Al into the fcc-TiN matrix during the sputter deposition process, the Al atoms replaced the Ti atoms and changed the microstructure, resulting in compressive residual stresses and bond changes. The formation of (Ti, Al)N metastable ternary solid solution makes it better than TiN film in hardness and wear resistance [17–19]. Mirosław Szala [20] et al found that with the increase of Al content, the adhesion of (Ti, Al)N film to substrate is higher, and (Ti, Al)N film showed better resistance to plastic deformation. In addition, Pang [21] et al found that the composite film formed by using (Ti, Al)N as the intermediate layer not only improved the bonding strength, but also enabled the stress to be effectively released to achieve the effect of wear resistance. Recently, Du [7] et al studied the Al\(_{1–x}\)Cr\(_x\)N nano-multilayer film
prepared by doping Al in CrN and found that as the grain size of the film increases, the interlayer interface coherence was destroyed, and the mechanical properties of the film also decrease. Therefore, the content of alloying elements will be one of the important factors that determine the properties of the film. When Al concentration increases to 39%, the hardening mechanism of (Ti, Al)N film is considered to be the combined effect of fine grain strengthening and bulk modulus [17]. When Al concentration exceeds 60% or more, the dense-row hexagonal structure (hcp) AlN phase was formed [22, 23]. The concentration exceeds 81%, the film with the amorphous structure exhibits the characteristics of brittle fracture [18]. It can be seen that changes in composition and structure will ultimately affect the tribological properties of the film. However, the influence of the exact ratio of Al and Ti atoms on the microstructure and the tribological properties of (Ti, Al)N films has yet to be investigated.

In this article, (Ti, Al)N films with different Al/Ti atomic ratios were prepared by magnetron sputtering, and the microstructure and tribological properties of films were analysed. This article innovatively proposed to study the tribological properties of films in terms of the ratio between Al and Ti atoms (0 ~ 1.25), demonstrating the effect of the Al/Ti atomic ratio on the wear resistance of (Ti, Al)N films from several perspectives. The friction coefficients of the film at different line speeds were creatively compared to evaluate the wear resistance. The Al/Ti atomic ratios and the resulting microstructure and tribological properties of films were investigated.

2. Experimental details

2.1. Film deposition
DC reactive magnetron sputtering was utilized to deposit (Ti, Al)N films with different Al/Ti atomic ratios on p-type (100) single crystal silicon wafers and M2 HSS (W6Mo5Cr4V2) substrates (TDG Cutting Tools Inc.). A Ti target (99.99%) and an Al target (99.99%) were placed symmetrically on the two cathodes. The substrates were ultrasonically cleaned respectively in acetone and alcohol, and then placed on a rotating sample holder located in the centre of the vacuum chamber. The substrates at a distance of 80 mm from the target were rotated with the sample holder and turned on the Ti and Al target current to deposit (Ti, Al)N film on the substrate surface in a gas mixture of Ar and N2. Firstly, the vacuum chamber was pumped to a vacuum level above 3 × 10−2 Pa before films were deposited. Secondly, the working gas Ar was introduced into the chamber at a flow rate of 30 sccm. The Ti target current was turned on and then the ion bombard cleaning was performed for 20 min by applying −400 V bias voltage to substrates. Thirdly, a Ti-based layer was deposited on the substrate for 10 min to improve the adhesion strength between the film and the substrate. Fourthly, the reaction gas N2 was introduced at a flow rate of 25 sccm and the bias voltage was decreased to −60 V. The Al target current was turned on and slowly increased to a set value over 15 min to deposit the (Ti, Al)N transition layer. Finally, substrates were deposited in a vacuum chamber at a working pressure of 0.25 Pa for 180 min (Ti, Al)N functional layer, the film and the substrate temperature was generally between 41.1 °C and 57.2 °C due to plasma heating and the Ti target current was kept at 2 A. The total deposition time was 225 min. The other details of deposition parameters and film properties were shown in table 1.

2.2. Film characterization
The x-ray diffractometer was used to analyze the phase composition, particle size and lattice constant of (Ti, Al) N films (XRD-7000 s, accelerating voltage: 40 kV, tube current: 40 mA, grazing angle: 2°, scanning speed: 10° min−1). The residual stresses of (Ti, Al)N films were also determined by sin2Ψ method using grazing incident x-ray diffraction. The microstructure of (Ti, Al)N films were investigated with a high-resolution scanning electron microscope (SEM, JEM-6510, Nippon Electron Co., Ltd). The x-ray photoelectron spectrometer (XPS) was also conducted on the deposited films to study the composition and chemical valence state of the films. The concentration of each element was determined from the intensity of characteristic x-ray peaks in the spectra with the software peak.fitting. The concentration of each element was determined from the intensity of characteristic x-ray peaks in the spectra with the software peak.fitting.
(XPS, voltage: 10 kV, current: 10 mA) was used to determine the chemical information and elemental composition of (Ti, Al)N films. The monochromatic Al Kα radiation source was used to obtain core-level XPS spectra from all samples in the receiving state. The electron emission angle was 0°. The analysis area was 300 × 700 μm. In order to prevent the edge effect of the sample, the selected area of the middle part of the sample was etched by Ar⁺ ion before analysis. The Ar⁺ ion gun with an energy of 3.8 kV was used for etching, and the incident angle was 55°. The etching rate and time were 10 nm min⁻¹ and 60 s, respectively. The charged neutralizer was used during the test, and the base pressure was 3.2 × 10⁻⁸ torr (4.3 × 10⁻⁷ Pa). Since samples exposed to air have adventitious carbon bonds (C−H/C=O) corresponding to the C 1 s peak, the work function method was used to calibrate the sample [24, 25]. Image J 6.0 software was used to test the particle size distribution on the surface of the film according to the surface SEM pictures. The hardness of the film was measured by an indentation tester with a standard Vickers indenter (CSM, Micro-Combi Tester). The working load was 100 mN, and the loading and unloading speeds during the indentation process of the Vickers indenter were both 300 mN min⁻¹. A scratch tester was used to measure the adhesive strength of the film (WS-2005, Chinese Academy of Sciences). Using a Rockwell indenter with a diamond tip with a radius of 200 microns, under a setting load of 30 N, at a loading speed of 15 N min⁻¹, a length of 3 mm was scored on the surface of the film. Loading accuracy was 0.1 N. The roughness of the film was tested by a surface roughness tester (TR-210, China). In order to minimise standard deviations, the hardness, adhesive strength, and roughness of each film were statistically calculated from five valid measurements.

2.3. Tribological behavior evaluation
The tribological properties of (Ti, Al)N films were evaluated by the ball-on-disc tribometer (XLGT-200, China). The counterpart was the GCr15 steel ball with a diameter of 5 mm. The test was performed at room temperature and a relative humidity of 63%−71%. Under a load of 2 N, the sliding at different speeds of 6.28, 9.42, 12.56, 18.84 and 25.12 m min⁻¹ for 40 min. The depth of wear was obtained by optical microscope measurements of the width of the film wear marks and observation of the wear cross-section profile under a scanning electron microscope. The wear was normalized to the total sliding distance and the applied load in order to calculate a wear rate. The weightlessness of wear was defined as the difference in the quality of the sample before and after the experiment measured by an electronic precision balance (American Society for Testing and Materials, ASTM D4213–1996 (2003)).

3. Results and discussion

3.1. X-ray diffractions
Figure 1 shows the XRD patterns of (Ti, Al)N films deposited with different Al/Ti atomic ratios. The film is a fcc structure of TiN when Al target current is 0 A. When the Al/Ti atomic ratio increases to 0.54, the film composes primarily of fcc structures and a wurtzite hexagonal structure of Ti₂AlN (106). Meanwhile, the preferred orientation of the film changes from the (111) to the (200) plane. The (200) diffraction peak moves to a higher angle (about 0.3°). Greene [26] et al found that the preferred orientation of the film is related to the deposition parameters, where important variables include the ratio between atoms. The bombardment of Ar⁺ ions leads to an increase in the density of defects in the crystal grains, which causes the residual stress of the film changed (table 1) and shifts the diffraction peaks. According to the report [22], the covalent radius of Al (0.143 nm) is smaller than that of Ti (0.146 nm), which indicates that the partial replacement of Ti atoms by Al atoms leads to a contraction of the lattice [27]. Correspondingly, the average lattice parameter and average grain size of (111) orientated grains calculated from XRD patterns are shown in figure 2. The average lattice parameter and average grain size of films decrease with the increase of Al/Ti atomic ratio. As Al atoms change the surface diffusion behavior of Ti and N atoms [12], the resulting hexagonal Ti₂AlN and AlN prevent the growth of TiN grains, which leads to a decrease in the average grain size of the film. When the Al/Ti atomic ratio increases to 0.54, the AlN (002) peak becomes sharp. The increase in the Al target current leads to an increase in the sputtering intensity of the energetic ions, resulting in more plasma [3]. As the Al content increases, it is difficult for Al atoms to enter the TiN lattice. The AlN phase forms when the required energy exceeds the formation energy of AlN. When the Al/Ti atomic ratio is 1.25, the broadening of the diffraction peaks of the hexagonal and cubic phases can be attributed to the changes in the composition of the film [28]. At higher Al content, the growth of TiN is suppressed and eventually becomes amorphous.

3.2. Microstructure
The differences of (Ti, Al)N films in surface morphology with different Al/Ti atomic ratios are shown in figure 3. It can be seen that as the Al/Ti atomic ratio gradually increases, the surface particles of films change from irregular shapes to round shapes, and the particle size gradually decreases (figures 3(a)−(d)). When the Al/Ti
atomic ratio is 0.54, the gap between the film particles becomes narrower and the pores become smaller, showing a denser structure. With the further increase of Al target power, under the continuous bombardment of high-energy Ar$^+$ on the Al cathode target, the low melting point Al target may emit Al atoms with a higher density and the Al atoms continue to compete with each other for nucleation and growth. Grains with the lowest surface energy include more materials and grow on grains with highest surface energy due to the migration of Al atoms between neighboring grains [3]. As a result, small particles on the surface of the high Al content (Ti, Al)N films...
aggregate into a large particle structure. The aggregation of particles leads to the formation (figure 3(f)) of larger structures (300–400 nm). Correspondingly as can be seen in table 1, the surface roughness of films rise sharply.

In order to further analyze the elemental composition of the film, figure 4 shows the high-resolution XPS spectra of Ti 2p, Al 2p, N 1 s, and O 1 s. The binding energy (BE) associated with Ti metal is mainly composed of three peaks centered at 461.0 eV, 455.5 eV and 453.8 eV, which are derived from Ti 2p 1/2 and Ti 2p 3/2 electrons in Ti-N and Al-Ti [28, 29]. With the increase of the Al/Ti atomic ratio, the high BE of the Ti-N bond shifts to a low angle by about 0.4 eV, which may be caused by high Al content. As the Al/Ti atomic ratio increases, the Al-Ti bond BE decreases from 453.8 with Al/Ti = 0.05 to 453.3 eV with Al/Ti = 1.25. Correspondingly, the material in the film changes from AlTi3 to Al3Ti. The spectrum of Al 2p shows a single peak whose intensity is proportional to the Al/Ti atomic ratio. The characteristic peak at the BE of 73.9 eV corresponds to AlN [30]. The spectrum of N 1 s shows that the TiN peak at 396.9 eV broadens to the lower side of the BE [31]. The high Al content results in a lower BE of 396.2 eV, which corresponds to AlN. Since the BE of TiN and AlN are very similar, it can be judged that the movement of the characteristic peak corresponds to N in TiN or AlN, which is consistent with the conclusion that the film has a dual-phase structure by XRD. The low intensity peak centered at approximately 399.0 eV can be attributed to impurities in the film, such as oxygen attached to the surface after the sample is taken out of vacuum drying oven, or free N2 or nitrogen attached to the carbon during the test [19].

Figure 5 shows the changes in the content of different elements. When the Ti target current is constant, the Al/Ti atomic ratio increases, the Al-Ti bond BE decreases from 453.8 with Al/Ti = 0.05 to 453.3 eV with Al/Ti = 1.25. Correspondingly, the material in the film changes from AlTi3 to Al3Ti. The spectrum of Al 2p shows a single peak whose intensity is proportional to the Al/Ti atomic ratio. The characteristic peak at the BE of 73.9 eV corresponds to AlN [30]. The spectrum of N 1 s shows that the TiN peak at 396.9 eV broadens to the lower side of the BE [31]. The high Al content results in a lower BE of 396.2 eV, which corresponds to AlN. Since the BE of TiN and AlN are very similar, it can be judged that the movement of the characteristic peak corresponds to N in TiN or AlN, which is consistent with the conclusion that the film has a dual-phase structure by XRD. The low intensity peak centered at approximately 399.0 eV can be attributed to impurities in the film, such as oxygen attached to the surface after the sample is taken out of vacuum drying oven, or free N2 or nitrogen attached to the carbon during the test [19].

Figure 3. The surface morphology and particle size of (Ti, Al)N films with different Al/Ti atomic ratios: (a) 0, (b) 0.05, (c) 0.48, (d) 0.54, (e) 0.79, (f) 1.25.

The cross-sectional morphology of (Ti, Al)N films with different Al/Ti atomic ratios can be found in figures 6(a)–(f), which clearly shows the working and inter layers of (Ti, Al)N films (Ti bottom and transition layers). It can be seen that the average diameter of the columnar structures are finer near the substrate/film interface and gradually increase away from the interface. The columnar microstructures are observed in the TiN film (figure 6(a)), which become smaller in diameter and being more tightly bound with the addition of Al (figures 6(b)–(c)). When the Al/Ti atomic ratio is 0.54 (figure 6(d)), the columnar structure becomes blurred and considerably reduced in size. The gaps between the film columnar structures becomes narrow and compact. Figures 6(g)–(i) are respectively partial enlarged views of the red area in figure 6(d)–(f). It can be calculated that the cross-sectional columnar structure of the film with an Al/Ti atomic ratio of 0.54 has a diameter of approximately 52 nm and a columnar structure spacing of 83 nm. Due to the increased mobility of Ti and Al adsorbed atoms under the high bias voltage and target power density [8, 33]. The refinement of the film grain size causes the columnar structure to become compact, thereby eliminating pores and forming a dense structure. When the Al/Ti atomic ratio is 0.79 and 1.25 (figures 6(e)–(f)), the columnar structure diameters approximately are 234 nm and 311 nm, the columnar structure spacing is 163 nm and 109 nm, respectively. In the case of high Al/Ti atomic ratio, the size of the columnar structure increases and the structure becomes loose. The nucleation
and growth of TiN grains are hindered by the fact that the TiN grains are surrounded by amorphous AlN in the Al-rich film [22]. The bombardment of high-energy Ar⁺ causes the Al target to produce enough atoms that have not reacted with Ti and N to deposit on the surface of the substrate, which provides conditions for the growth of the coarse columnar crystal structure. Figure 7 provides the deposition rate of films with different Al/Ti atomic ratios. When the Al/Ti atomic ratio is 1.25, the calculated maximum deposition rate is 13.91 nm min⁻¹. It is well known that the deposition rate of the film is closely related to the sputtering rate of the target. The sputtering rate and ionization rate also increase as the power density of the Al target increases (table 1). Therefore, bombardment of the Al target with high-energy ions (Ar⁺) will drag out a large number of Al atoms during the sputtering process, thus accelerating the deposition rate.

3.3. Mechanical and wear resistance
The adhesive strength between the film and the substrate is one of the key factors that determine the conditions in which the material is used. The critical loads (Lc1) of (Ti, Al)N films are shown in figure 8, where the critical load of TiN film is 18.32 N. As the Al/Ti atomic ratio increases to 0.05, the critical load of the (Ti, Al)N film rises to 18.91 N. Continuing to increase the Al/Ti atomic ratio to 0.54, the critical load of the film has a maximum
The Ti interlayer significantly enhances the adhesion of the film [34]. It is found that the film is composed of smaller particles when the Al/Ti atomic ratio is 0.54. The plastic deformation of the film under external force can be dispersed in more particles, the plastic deformation is more uniform, and the damage to the

![Graph](image)

**Figure 5.** The content of elements in (Ti, Al)N films with different Al/Ti atomic ratios.

![Images](image)

**Figure 6.** Cross-sectional morphology of (Ti, Al)N films deposited with different Al/Ti atomic ratios: (a) 0, (b) 0.05, (c) 0.48, (d) 0.54, (e) 0.79, (f) 1.25 and (g), (h), (i) are partial magnifications of (d), (e), (f), respectively.
Figure 7. The deposition rate of (Ti, Al)N films deposited with different Al/Ti atomic ratios.

Figure 8. Critical load of (Ti, Al)N films deposited with different Al/Ti atomic ratios.
film is reduced. According to P Henry [5] et al, structures consisting of small grains (figure 3(d)) can better prevent crack propagation. However, it is observed by XRD that the TiN and AlN crystal phases compete with each other to grow with the increase of Al atoms. The film tends to be amorphous and has more brittle characteristics [35]. Therefore, the TAN-5 film exhibits a smaller critical load.

The friction coefficients (COF) for (Ti, Al)N films with different Al/Ti atomic ratios are presented in figure 9. The film with a small amount of Al shows lower COF values (0.23–0.29) compared to the TiN film (0.32). When the Al/Ti atomic ratio exceeds 0.79, COF rises sharply to 0.38. COF is closely related to the microhardness of films [35, 36]. Figure 10 shows the microhardness and specific wear rates in different Al/Ti atomic ratios of the (Ti, Al)N films. It can be seen that the film microhardness increases from 1324.7 HV to 2819.2 HV as the Al/Ti atomic ratio increases from 0 to 0.54. Interestingly, the specific wear rate significantly decreases from 4.93 ± 0.03 × 10^{-16} m^3 N^{-1} m^{-1} to 1.72 ± 0.02 × 10^{-16} m^3 N^{-1} m^{-1}. When Al content is further increased to an Al/Ti atomic ratio of 1.25, the microhardness of the film quickly drops to 1075.2 HV, and the specific wear rate rises to 7.04 ± 0.03 × 10^{-16} m^3 N^{-1} m^{-1}. The influence of grain size, texture effect and residual stress is the main reasons for the evolution of the hardness [36]. According to Hall-Petch [37] formula, dislocation mobility is hindered by the reduction in grain size to extent that the blocking effect of dislocations increases the strength of materials. It cannot be ignored that the lattice distortion caused by the replacement of Ti atoms by Al atoms [36] makes the plastic deformation of the film difficult, which is the main reason for the increase in the hardness of the film. In addition, the increase in hardness can also be attributed to the combined effect of the hard cubic TiN phase and the hexagonal Ti2AlN phase. The existence of the hard phase reflects the stability of the material and exhibits high abrasion resistance. In the case of higher Al/Ti, the amorphization of the cubic phase reduces the stress of the film. As the surface roughness of the TAN-5 film increases, the wear resistance of the film is affected. Figure 11 shows the comparison of the wear track morphology for (Ti, Al)N films with Al/Ti atomic ratios of 0, 0.54 and 1.25. The width of the wear scar is 85 μm. As can be seen from the figure that wear debris in the contact area provides sliding resistance, but the tribological film in the form of patches remains on the substrate, which is the main reason why the COF curve does not fluctuate up and down significantly. The film with Al/Ti atomic ratio of 0.54 has a smooth, clean and narrow width wear track (37 μm), producing slight abrasive wear and no more obvious wear defects. In contrast, the film with Al/Ti atomic ratio of 1.25 (figure 11(c)) has serious adhesive wear due to its lower hardness, higher surface roughness and weaker adhesive strength, resulting in poor tribological properties of the film.

Figure 9. Friction coefficient of (Ti, Al)N films with different Al/Ti atomic ratios.

![Figure 9](image-url)
By changing the spindle speed and friction ring radius of the ball-on-disc tribometer, the wear resistance of the (Ti, Al)N film with an Al/Ti atomic ratio of 0.54 at different line speeds for one kilometer is studied. The COF is shown in figure 12 and the curve of specific wear rates and weightlessness of wear is shown in figure 13. As the line speed increases from 9.42 m min$^{-1}$ to 25.12 m min$^{-1}$, the COF values decrease from 0.49 to 0.31. Meanwhile, the specific wear rate is decreased from $5.86 \pm 0.01 \times 10^{-16}$ m$^3$ N$^{-1}$ m$^{-1}$ to $4.94 \pm 0.02 \times 10^{-16}$ m$^3$ N$^{-1}$ m$^{-1}$, a 15.7% reduction. Wearing weight loss is reduced from $2.00 \pm 0.16$ mg to $1.23 \pm 0.15$ mg, a 37% reduction. The wear of the film is greatly affected by the rotational speed [38]. The film produces more wear debris at low speeds. The COF increases and the curve fluctuates greatly. The film rotates at high speed but has better abrasion resistance. The researchers believe that this depends on the rate at which the counterpart transfers the wear particles to the sliding interface [39]. When the wear particles quickly form a thin boundary layer on the sliding surface and adhere to the film surface, they can protect the underlying film from further wear.

Based on the above study, the film exhibits better tribological properties during the modulated Al/Ti atomic ratio increase from 0 to 0.54. In particular, the film has the lowest COF (0.23) when the Al/Ti atomic ratio is 0.54. TAN-3 film has the smaller particle size and denser columnar structure, which leads to higher microhardness. When the film is tested for ball-on-disc friction, the TAN-3 film can better overcome the resistance caused by the surface protrusion, and the wear track is smooth and complete. Compared with TiN film, (Ti, Al)N film does not show accumulation of wear debris, which depends on the denser surface structure formed by the hard phase in the film (figure 3(d)). However, the damage of the TiN film surface is more caused...
by adhesive wear. When the Al/Ti atomic ratio increases to 1.25, the film forms a coarse columnar crystal structure and the columnar crystal gap becomes larger (figure 6(i)). In addition, particle agglomeration appears on the surface of the film (figure 3(f)). The plastic deformation resistance of the film and the bonding strength between the film and the substrate determine the reduction of the tribological properties of the TAN-5 film.
4. Conclusion

In this paper, (Ti, Al)N films were deposited on single crystal silicon wafers and HSS substrates via magnetron sputtering by varying the Al target current. The microstructure, morphology, mechanical and tribological properties of as-deposited (Ti, Al)N films were systematically investigated. When the Al/Ti atomic ratio is less than 0.54, the preferential orientation of the film changes from (111) to (200) plane and the film has columnar crystal structures. Also, the densest microstructure of the (Ti, Al)N film was obtained at an Al/Ti atomic ratio of 0.54. It should be emphasized that the film exhibits better wear resistance at an Al/Ti atomic ratio of 0.54 (COF = 0.23) due to its high microhardness (2819 HV) and critical load (28.53 N). On the contrary, when the Al/Ti atomic ratio exceeds 0.54, (Ti, Al)N films tend to transform from the crystalline to the amorphous state. The microhardness of the film decreases to 1075 HV and the COF value increases to 0.38. In conclusion, the (Ti, Al)N film with a modulated Al/Ti atomic ratio of 0.54 has better tribological properties than the TiN film.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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