Novel Wear Resistant Nitride Coatings for Metal Cutting Tools[1]

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Abstract – The latest published results concerning to novel nitride compositions are reviewed. A special attention was attended to promising coatings on the tools for dry metal-working. TiAlN coatings are the most often used at present to increase durability metal cutting tools. The most wear resistant coatings contain 50–67 at % of Al (without nitrogen account) and are deposited on the surface of high speed steel and hard alloy tools by CVD or PVD (magnetron or vacuum arc) method in nitrogen containing medium. A main reason of high durability of the tools, coated with TiAlN, is an outstanding heat resistance of the nitride. TiAlN nitride keeps high hardness up to 800–900 °C being heated in air. A doping silicon to TiAlN results in additional improvement of coating properties. The coatings containing 7–9 at % Si have nanocrystalline structure and hardness nearly twice higher then TiN hardness. Silicon raises the heat resistance of the coatings and at the same time reduces a friction coefficient at sliding on steel. It results in raise of the durability of tools covered with nitride coatings doped by silicon. Resent years a number of novel promising nitride compositions have been investigated as coatings on metal cutting tools. Most of them contain chromium, added to conventional compositions TiN, AlN, TiAlN. Silicon doping is useful for the properties of the novel nitride compositions too. The coatings demonstrate the better durability as compared with TiAlN.

1. Introduction

Over years titanium nitride (TiN) films has been the most widely used as a protective and wear resistant coatings. The most often they are used for metal cutting tools. However, TiN starts to oxidize rapidly at about 500 °C and forms rutile structure TiO_2 which leads to deteriorating mechanical properties. Alternative compositions of wear resistant coatings are diamond-like coatings (DLC) and multilayered coatings. DCL coatings have a low dry friction coefficient against steels, however there oxidation resistance don't exceed that of TiN. Multilayered coatings on metal cutting tools are designed to get low friction coefficient of outer layer against steel and simultaneously to prevent oxygen penetration trough barrier inner layer.

During last two decades a novel multicomponent nitride coatings have been developed. The coatings are deposited on the substrate from multicomponent plasma containing ions of nitride-forming metals (Ti, Al, Zr, Cr etc.) and some metalloids (Si, B) or the metals that don't form nitrides (Cu, Ni, Y). Multicomponent nitride coatings, as a rule have a larger hardness as compared with that of simple nitrides. Doping of some elements (Al, Cr, Si) to basic nitride forming metal (Ti) gives the lower friction coefficient and more high oxidation resistance of multicomponent nitride coatings. As a result a durability of the tools with the coatings rises.

2. Compositions of multicomponent nitrides

2.1. Ti–Al base nitrides

The incorporation of Al into face-centered cubic (fcc) structure of TiN results in the formation of metastabile ternary solid solution $Ti_{1-x}Al_xN$. Aluminium doping results in high hot hardness due to age hardening and excellent oxidation behaviour up to temperatures of 800 °C due to formation of a protective Al-rich oxide layer at the film surface. The higher the Al content, the less oxidation could be observed [1]. Coated tools durability at the face milling tests correlates with the oxidation resistance (Fig. 1). Drastic tool life reduction for Al content exceeding $x = 0.66$ (Fig. 1) can be associated with the cubic- to hexagonal-structure transformation of AlN. Aluminium content $x = 0.50$–0.66 corresponds to maximum hardness of the coatings.

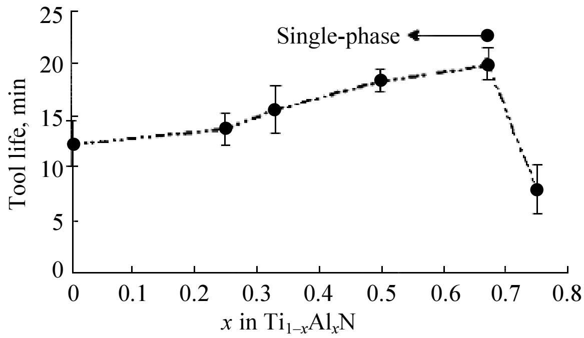

Fig. 1. Influence of Al content x in $Ti_{1-x}Al_xN$ coatings on tool life at face milling tests [2]

Further improvements of TiAlN coatings were made by Si doping to nitride. Additions of 7–9 at % Si

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results in drastic rise of hardness and elastic modulus of the coatings (Fig. 2). Similar influence of Si additions can be observed in TiSiN coatings too (Figs. 3, 4).

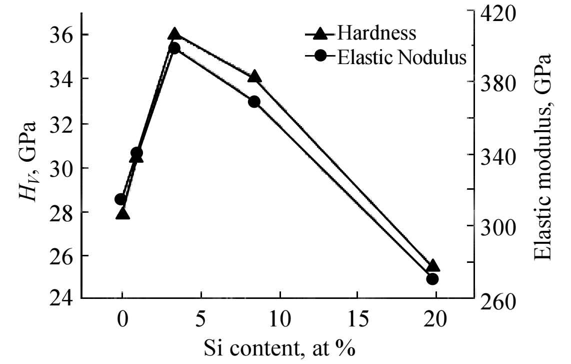

Fig. 2. Hardness and elastic modulus of the Ti–Al–Si–N films as a function of Si content [3]

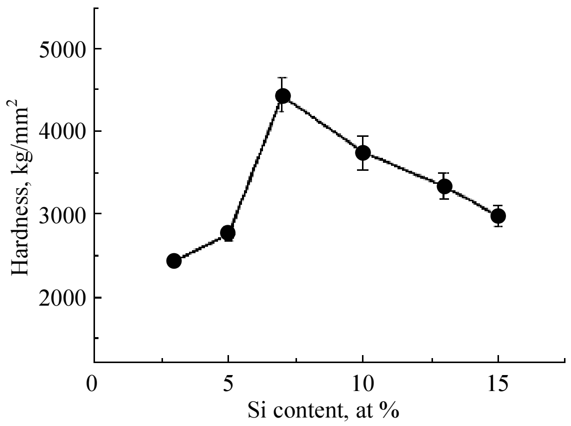

Fig. 3. Microhardness values of Ti–Si–N coating layers as a function of Si content [4]

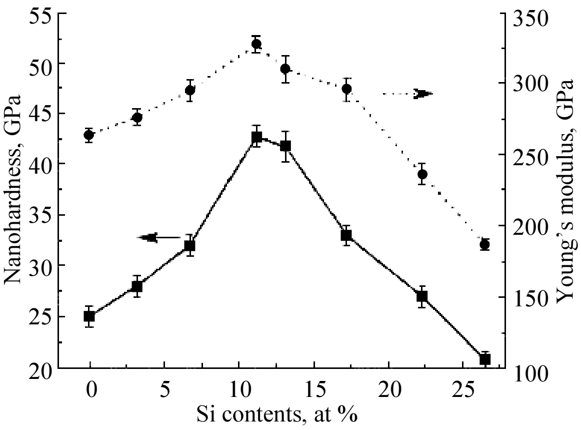

Fig. 4. Nanohardness and Young's modulus of Ti–Si–N coatings as a function of Si contents for an indentation load of 5 mN [5]

According to structure investigations TiSiN films have a microstructure composed of *nc*-TiN/*a*-Si_3N_4 i.e., nano-sized TiN crystallites embedded in an amorphous silicon nitride matrix. The presence of nanometer scale grains can hinder the generation and movement of dislocations, stop crack propagation and suppress grain boundary sliding. Above-listed reasons are evidently responsible for high hardness of TiASiN coatings too. The Si content in TiAlSiN and TiSiN films resulting in high hardness covers an interval from 5 to 15 at % according to different authors.

2.2. Cr containing nitride coatings

CrN coatings, with their good oxidation, anticorrosive and anti-adhesive properties, find a wide industrial use in metal forming and plastic molding operations [6, 7]. The low hardness and abrasive wear resistance are the main reasons, why CrN has not used successfully in steel cutting applications. To further improve these properties, alloying with another metal to form a ternary hard coating has been applied. The most promising alloying metal is aluminum that would form Al–Cr–N system.

One of the big advantages of ternary Al–Cr–N system is the stabilization of the cubic AlN phase even at very high Al-concentrations. Al concentrations of 65–75% have been reported to stabilize the fcc-AlCrN [8]. Another positive effect of Al and Cr alloying is higher Al–Cr–N hardness as compared with AlN or CrN hardness (Fig. 5). Not only hardness but also the wear resistance is improved in comparison to conventional TiN and TiAlN

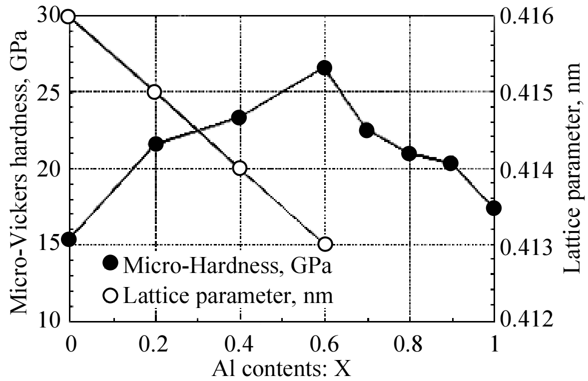

Fig. 5. Changes in micro-Vickers hardness and lattice parameter of $Cr_{1-x}Al_xN$ films [9]

Together with the mechanical properties, the thermal stability and oxidation behavior is improved by Cr addition. The start temperature of remarkable oxidation shifts from 800 °C for TiAlN to 1000 °C for TiAlCrN (Fig. 6).

Figure 7 shows result of high speed milling tests against hardened die-steel in comparison with conventional TiAlN coatings [11]. This superior performance of (Ti, Cr, Al)N coating is due to combination of increased hardness and oxidation resistance.

Similar favorable Cr influence on oxidation resistance was found out in AlCrN films, at that the best oxidation resistance corresponds to 65–70 at % Al concentration interval [11]. Higher oxidation resistance of CrAlN coatings results in the better tools durability, as compared with the tools coated by TiAlN films (Fig. 8).

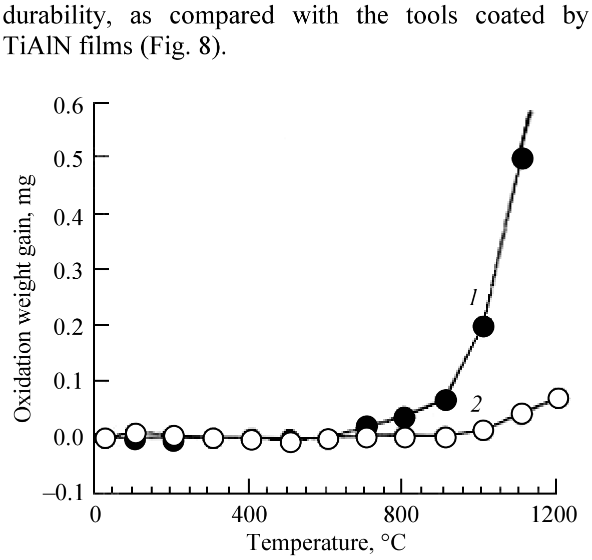

Fig. 6. Oxidation weight gain curves of TiAlN and (TiCrAl)N coating measured by thermo-balance [10]: *1* – $(Ti_{0.5}Al_{0.5})N$; *2* – $(Ti_{0.11}Cr_{0.2}Al_{0.69})N$

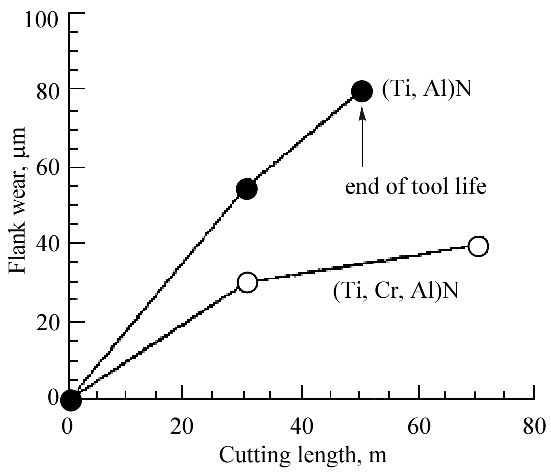

Fig. 7. Result of high-speed milling test against hardened die-steel in comparison with conventional TiAlN coatings [10]

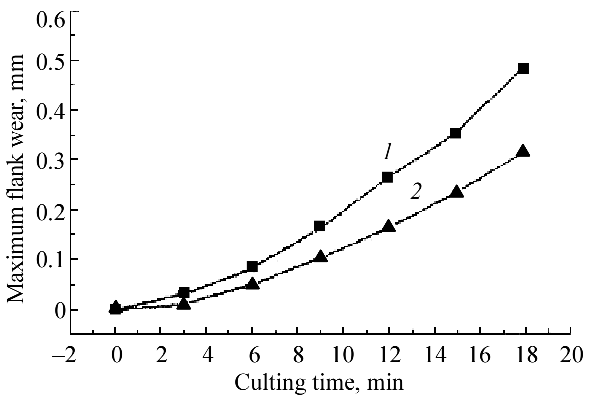

Fig. 8. The progress of flank wear measurements for $(Ti_{0.34}Al_{0.66})N$ (*1*) and $(Cr_{0.28}Al_{0.72})N$ (*2*) coatings by coatings by continuous turning of stainless steel with CNMG120408 style insert [12]

Si dopping is useful for the properties of Cr-containing nitride films too. The drastic hardness rise occurs at about 7–9 at % Si dopping to base composition (Figs. 9, 10).

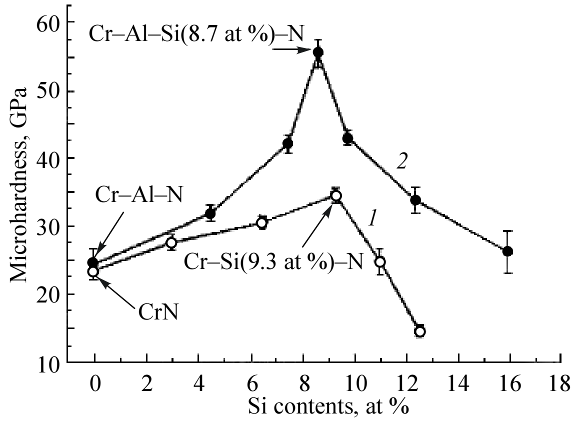

Fig. 9. Microhardness of the Cr–Si–N (*1*) and Cr–Al–Si–N (*2*) coatings as a function of Si content [13]

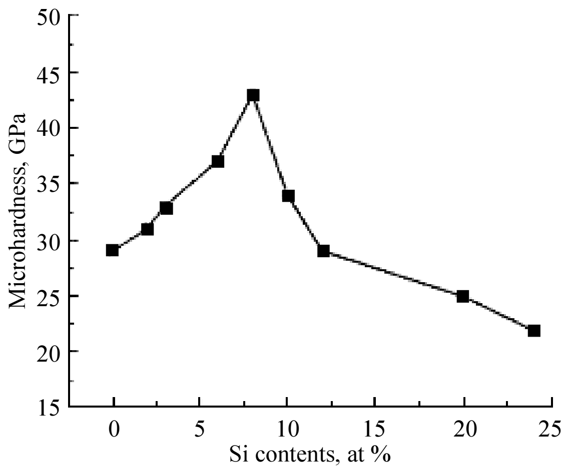

Fig. 10. Microhardness values of the Ti–Cr–Si–N coatings with various Si contents [14]

Along with hardness rise Si dopping results in the decrease of friction coefficient against a steel (Fig. 11).

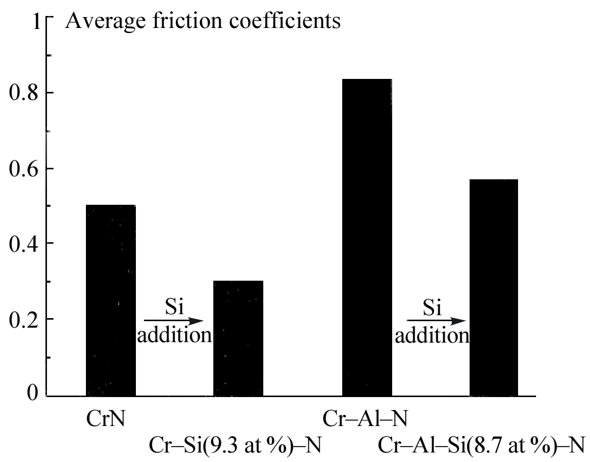

Fig. 11. Average friction coefficients of CrN, Cr–Si (9.3 at %)–N, Cr–Al–N, and Cr–Al–Si (8.7 at %)–N coatings against steel ball [13]

This result would be caused by smoother surface [15] due to the existence of amorphous Si_3N_4 and SiO_2 phases in the Cr–Si(9.3 at %)–N and Cr–Al–Si(8.7 at %)–N coatings, and would be also caused by following tribochemical reactions between Si and ambient humidity [16]

$$Si_3N_4 + 6H_2O = 3\ SiO_2 + 4NH_3,$$

$$SiO_2 + 6H_2O = Si(OH)_4.$$

These products of SiO_2 and $Si(OH)_4$ were known to play a role as a self-lubricating layer [17]. The formation of tribo-layer would be more activated with increasing Si content in the Cr–Si and Cr–Al–Si coatings.

The total influence of Si on hardness rise and friction coefficient decrease results in the durability of the tools with Si containing nitride coatings. A durability maximum is located at 9 at % Si (Fig. 12).

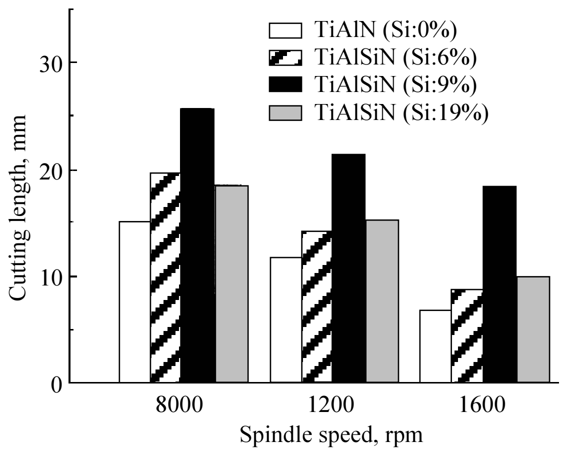

Fig. 12. The comparison of tool life according to Si contents in a series of spindle speed (8000, 12 000, 16 000 rpm) [18]

That is agree with Si content in coatings with maximum hardness (Figs. 2–4, 9, and 10).

3. Conclusions

1. The novel Cr containing nitride coatings demonstrate superior durability being deposited on metal cutting tools. The main reason of the durability enhancement is a higher oxidation resistance of the novel nitride films.

2. Si dopping to TiAlN, CrAlN, TiCrAlN nitride films results in additional durability enhancement due to drastic hardness rise and the decrease of dry friction coefficient against hardened steel.

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