Hardening ion plasma coatings (Ti, Alx)N (x = 3 at. %) for carbide cutting tools

I V Blinkov, D S Belov, A O Volkhostskiy, A O Chernogor and V S Sergevnin

National University of Science and Technology «MISiS», 119049, 4, Leninskiy prospect, Moscow, Russia

E-mail: biv@misis.ru

Abstract. Coatings (Ti,Al0.03)N and comparison samples - coatings (Ti,Al0.25)N and TiN are formed by the arc-PVD method on the WC-Co carbide alloy. The phase composition, the substructure characteristics and the mechanical properties of the coatings were investigated. The addition of Al and its increase in the coating composition is accompanied by a decrease in the value of the lattice parameter, refinement of the coatings subgrain structure and an increase in both microstrains and macrostresses. At the same time, the hardness of the coatings and the values of the parameters H3/E2 and H/E increase with a decrease in the relative work of plastic deformation of the samples, which is a characteristic of their viscosity. Durability tests were carried out using a cutting tools with the investigated coatings showed the advantage of the (Ti,Al0.25)N coating in continuous turning operations. The (Ti,Al0.03)N coating is characterized by increased resistance compared to other tested coatings in milling operations and compared to TiN coating in continuous cutting.

1. Introduction
One of the most popular hardening coatings on cutting tools at present are coatings based on the complex nitride – Ti-Al-N. The reason for this is their high functional characteristics: hardness up to 38 GPa, heat resistance, resistance to high-temperature oxidation up to 800 °C, thermal stability of the composition and structure [1–3]. The hardness of these coatings increases with an increase in the aluminum concentration up to 70 (at. %). At the same time, the operational capabilities of Ti-Al-N coatings in intermittent cutting operations are limited due to the high tendency to brittle fracture [4–6]. An increase in the viscosity of such coatings with a slight decrease in hardness due to aluminum content decrease in them can expand the area of use of the cutting tool both in continuous and interrupted cutting operations (milling, planing, etc.). To study this possibility, the properties of coatings with the composition (TiAlx)N (x = 3 at. %) and comparison samples – coatings TiN and Ti-Al-N with an aluminum content of ~ 25 at. % obtained by the method of ion-plasma vacuum-arc deposition were studied. The resistance properties of a carbide cutting tool with these coatings on continuous and interrupted cutting operations have been evaluated.

2. Experimental details
The deposition of coatings was carried out by filtered cathodic vacuum arc deposition. A three-cathodic evaporation system with droplet phase separators was used in the work. To obtain coatings (Ti0.75,Al0.25)N powder Ti-Al cathodes with an Al content of 50 at. % were used. Coatings (Ti0.97,Al0.03)N were obtained using cathodes made of Ti-Al alloy 6 at. % Al and cathodes made of...
titanium alloy with 99.5 at. % Ti was used to obtain TiN coatings. The nitrogen partial pressure (PN2) was maintained at 0.5 Pa. The deposition time was 60 minutes. The thickness of the coatings was 4–4.5 microns. WC-Co carbide plates were used as substrates. A negative bias voltage (Us) on the substrate was –120 V. A constant electric arc current was ~120 A for all the cathodes. The physical and mechanical properties of the coatings were determined using microhardness tester. Macrostresses were determined by the sin2ψ method. The durability of the coated cutting tool during the processing of the EI 698-VD alloy (nickel base heat resistant steel, C – ~0.05 mass. %, Cr – ~14 mass. %, Ti – ~3 mass. %, Al – ~2 mass. %, Mo – ~3 mass. %, Nb – ~2 mass. %) was estimated by the time during which the tool participates in the cutting process until a predetermined wear is reached. Its criterion for turning was angular wear along the flank surface VB_E = 0.4 μm, and for face milling, the limiting wear of the flank surface of the cutting insert was h3 = 0.5 mm. Turning was carried out in the following modes: dry cutting speed 250 m/min; feed 0.2 mm/rev; cutting depth 1 mm. The selected milling modes were: depth of cut 1.0 mm; feed per tooth 0.125 mm/tooth; cutting speed 25 m/min; spindle speed 50 rpm. A single tooth cutter was used.

3. Results and discussion
The morphology of the investigated coatings is characterized by a cellular surface structure with a roughness (Ra) ~0.1 μm with a relatively small amount of droplet phase. The grain structure of the coatings is columnar (figure 1). The composition of the coatings is shown in table 1.

![Figure 1. Coatings microstructure.](image)

X-ray phase analysis (figure 2) showed the presence of the TiN (B1) phase in the coatings. With the addition of aluminum and its increase, the diffractograms show a shift in the arrangement of the diffraction lines of fcc-TiN towards larger angles. Taking into account the knowledge of datasets published [7], it can be concluded that during the Ti-Al-N system coatings deposition, a metastable fcc-Ti_xAl_{1-x}N phase is formed with lattice parameters close to titanium nitride.

| Coating     | Al, at. % | Ti, at. % | N, at. % |
|-------------|-----------|-----------|----------|
| Ti-N (1)    | –         | 51.9      | 48.1     |
| Ti-Al-N (2) | 3.1       | 48.3      | 48.6     |
| Ti-Al-N (3) | 25.1      | 26.0      | 48.9     |

An analysis of the intensity of the I_{111}:I_{200}:I_{220} diffraction lines of the formed coatings made it possible to establish the presence of the [111] texture in the condensate along the normal to the growth surface.
Table 2 shows the characteristics of the substructure of the coatings and the values of thermal and concentration macrostresses.

**Table 2. Coatings substructure analysis results.**

| Coating              | Substructure characteristics |            |            |            |            |
|----------------------|-----------------------------|------------|------------|------------|------------|
|                      | Lattice parameter (a), Å    | CSR size, nm | Microstrain (ε), % | Macrostress (σ), GPa |
| TiN                  | 4.2478 ± 0.0013             | 48.1 ± 4.3 | 0.15 ± 0.02 | -2.2       |
| (Ti<sub>0.97</sub>,Al<sub>0.03</sub>)N | 4.2386 ± 0.0003             | 16.0 ± 2.0 | 0.60 ± 0.10 | -3.7       |
| (Ti<sub>0.75</sub>,Al<sub>0.25</sub>)N | 4.1646 ± 0.0005             | 14.0 ± 2.0 | 0.70 ± 0.10 | -8.9       |

The presented results indicate that with the addition and increase of Al in the coatings composition [8], the value of the lattice parameter of the coating phase decreases, the coating subgrain structure is refined and microstrains grow. The coatings are characterized by compressive macrostresses, the value of which increases with the addition of aluminum into their composition and an increase in its content. At the same time, there is an increase in hardness (H), elastic modulus (E), values of the coating material parameters H/E<sup>2</sup> and H/E (table 3). In this case, there is a decrease in the relative work of the samples plastic deformation (W_p), which is a characteristic of their viscosity [9]. This property, along with hardness, can play an important role in determining the effectiveness of hardening coatings operating under impact loads.

**Table 3. Physical and mechanical characteristics of coated samples.**

| Coating            | Characteristics |            |            |            |            |
|--------------------|----------------|------------|------------|------------|------------|
| TiN                | H, GPa         | E, GPa     | H<sup>2</sup>/E<sup>2</sup>, GPa | H/E        | W_p, %     |
|                    | 25 ± 1.0       | 476 ± 16   | 0.069      | 0.052      | 61         |
| (Ti<sub>0.97</sub>,Al<sub>0.03</sub>)N | 29 ± 1.2       | 529 ± 13   | 0.087      | 0.054      | 58         |
| (Ti<sub>0.75</sub>,Al<sub>0.25</sub>)N | 35 ± 1.0       | 546 ± 16   | 0.143      | 0.064      | 45         |

The results of carbide cutting tool tests with (Ti<sub>0.97</sub>,Al<sub>0.03</sub>)N coating and comparison samples – coatings (Ti<sub>0.75</sub>,Al<sub>0.25</sub>)N and TiN for resistance during continuous turning and milling are shown in figure 3. According to the obtained results, the tool life with coatings containing aluminum is significantly higher than that of TiN coatings. At the same time, for the coating (Ti<sub>0.75</sub>,Al<sub>0.25</sub>)N, the operating time during continuous turning to critical wear is 27 % longer than for the coating (Ti<sub>0.97</sub>,Al<sub>0.03</sub>)N. However,
for the \((\text{Ti}_{0.97}\text{Al}_{0.03})\text{N}\) coating, the operating time to critical wear during milling increases by 10\% compared to the \((\text{Ti}_{0.75}\text{Al}_{0.25})\text{N}\) coating.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Comparative tests histograms for the resistance of WC-Co carbide tool inserts with coatings during turning (a) and milling (b) of the EI698-VD alloy.}
\end{figure}

4. Conclusions
The obtained results give a reason to recommend this coating, as a hardening one, for use on cutting tools under both constant and impact loads.

Acknowledgments
The research was supported by the Russian Science Foundation (project No. 19-19-00555).

References
[1] Mayrhofer P H, Rachbauer R, Holec D, Rovere F and Schneider J M 2014 Comprehensive Materials Processing 355–83
[2] Ratayski U, Motylenko M, Šíma M, Jílek M and Rafaja D 2018 Surface & Coatings Technology 344 322–9
[3] Hörling A, Hultman L, Odén M, Sjölén J and Karlsson L 2002 Journal of Vacuum Science & Technology A20 1815–23
[4] Sui X, Lin G, Qin X, Yu H, Zhou X, Wang K and Wang Q 2016 Ceramics International 42 7524–32
[5] Vereschaka A A, Grigoriev S N, Sitnikov N N and Batako A D 2017 Wear 390–391 209–19
[6] Beake B D, Ning Li, Gey Ch, Veldhuis S C, Komarov A, Weaver A, Khanna M and Fox Rabinovich G S 2015 Surface & Coatings Technology 279 118–25
[7] A´vila R F, Mancosu R D, Machado A R, Vecchio S D, DaSilva R B and Vieira J M 2013 Wear 302 1192–200
[8] Tavares C J, Rebouta L and Almeida B 1998 Thin Solid Films 317 124–8
[9] Zhou Ya, Asaki R, Soe W -H, Yamamoto R, Chen R and Iwabuchi A 1999 Wear 236 159