Research of mechanical and cutting properties, wear and failure mechanisms of nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N

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Abstract

The paper studies mechanical properties (in particular, adhesion characteristics), as well as wear and failure pattern of nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N. Cutting properties of a carbide tool with the above coating are studied in turning of steel C45, in comparison with an uncoated tool and a tool with reference coating TiN. It was found that tool life of the tool with the coating under study is 2.7–3.6 times higher than tool life of the uncoated tool and 1.8–2.2 times higher than that tool life of the tool with coating TiN. The conducted microstructural studies have shown a significant difference in wear and failure mechanisms and, in particular, in mechanisms of cracking, for the coating under study and the coating TiN. Failure mechanism of coating in the course of the study of strength of adhesion bonds is consistent with its failure mechanism during the study of cutting properties.

Keywords: nanoscale multilayered coatings, tool life, carbide tool, wear mechanism, crack formation

1. Introduction

In recent years, modifying surface coatings, in particular, wear-resistant coatings for metal cutting tools have been a subject of numerous studies. A series of innovative coatings has been developed and studied to significantly improve reliability and tool life of cutting tools, enhance cutting conditions, and hence increase the processing efficiency. Meanwhile, ordinary mono-layered coatings of the first generation (in particular, coatings TiN and TiAlN) are still actively used in the manufacture of metal cutting tools.

Out of various types of wear-resistant coatings, developed and implemented in recent years, multilayered composite coatings with gradient structure, as well as multi-component coatings should be noted [1-14].

The objective of this study was to conduct a comparative analysis of wear and failure mechanisms of a reference mono-layered coating TiN in comparison with nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N.

The coating Ti-TiN-(NbZrAl)N under study has a three-layered architecture [1-4], including adhesive sublayer Ti, intermediate layer TiN, and wear-resistance layer (NbZrAl)N.

Nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N was selected as an object of the study due to the following factors [1,3,4]:

- a good combination of high hardness and resistance to brittle fracture, which was shown by the coatings on the basis of system (NbZrAl)N during earlier studies;

- a role of coating Ti, confirmed during earlier studies, as an optimal adhesive sublayer that provides good adhesion both between tool substrate and coating and between adhesive and intermediate layers of coating;
- good results in tool life of metal cutting tool with the above coating shown during tests conducted earlier [1,3,4].

One of the objectives of this research was to study failure mechanism of nano-layered multi-component systems operating under conditions of high thermal and mechanical stresses arising in the cutting zone. The tests of wear-resistant coatings conducted earlier, including such elements as Nb, Zr, Al, and Ti in various combinations showed high hardness of such coatings, their brittle fracture behaviour and high wear resistance of metal cutting tools with such coatings.

Holleck et al [5] found that in the ternary nitride systems of Group IV–VI transition metals, continuous ranges of solid solutions (Me_x Me_{II}1–_x)N with NaCl-type face centered cubic structures exist. Such solid solutions may be considered as quasi-binary systems of two cubic nitrides, e.g. d-(MeI)N and d-(MeII)N.

Boxman et al [6] presented the results of the studies of the properties of the ternary nitride coatings of (Ti,Zr)N, (Ti,Nb)N and (Zr,Nb)N. The phase composition analysis shows that in all cases a single-phase composition was formed (δ-(Ti,Zr)N, δ-(Ti,Nb)N). Coating had a columnar structure, whereas in the case of (Ti,Nb)N the coating is built of equiaxed grains.

Beresnevet et al [7] and Maksakova et al [8] presented results of the studies of properties of the coatings on the basis of system (TiZrNb)N. X-ray diffraction spectra have shown that the main phase is the phase with face-centered cubic crystal lattice; meanwhile, cutting properties of carbide tool with coatings under study, as well as patterns of their wear and failure are not considered in these studies.

A series of studies have tested the properties of multi-component nano-structured coatings [9-12]. Braic et al [9,10] studied the properties of nitride system (TiZrNbHfTa)N, which composition, in addition to Zr, Nb and Ti, also includes Hf and Ta. Pogrebnjak et al [11] and Blinkov et al [12] considered the study of the properties of multi-composite coatings on the basis of nitride systems (TiHfZrVNb)N, which composition also includes Hf and V, as well as systems (TiAlCrZrNb)N and (TiAlCrZrNb)N, which composition is modified through introduction of Al and Cr. It should be noted that the above studies were focused only on coatings with mono-layered architecture, including coatings with nano-scale structure.

2. Experimental details

2.1 Deposition method

For coating deposition, a vacuum-arc VIT-2 unit was used, which was designed for the synthesis of coatings on substrates of various tool materials [1-3,13]. The unit was equipped with an arc evaporator with filtration of vapour-ion flow, which in this study were named as filtered cathodic vacuum arc deposition (FCVAD) [1-4,13,14], which were used for deposition of coatings on tool of significantly reduces the formation of droplet phase during the formation of coating.

Coatings were deposited through fused cathode (85%Zr+15%Nb) (on standard arc evaporator), cathode 99.8% Ti (on standard arc evaporator) and cathode 99.8% Al (on arc evaporator with filtration of vapour-ion flow).

2.2 The adhesion characteristics study

The adhesion characteristics were studied on a Nanovea scratch-tester, which represents a diamond cone with apex angle of 120° and radius of top curvature of 100 µm. The tests were carried out with the load linearly increasing from 0.05 N to 40 N. Crack length was 5 mm. Each sample was subjected to three test repetitions. The obtained curves were used to determine two parameters: the first critical load, L_{C1} , at which first cracks appeared in coating, and the second critical load, L_{C2} , which caused the total failure of coating. The indenter displacement (mm), the normal force L_n (N) and the level of acoustic emission (intensity in relative units) were registered during the tests. In the formation of the coating cracking, peeling, chipping and other damage, the acoustic emission signal has bursts, since the destruction of flowing at a high speed, energy is released, which generates elastic (acoustic) waves.

2.3 Study of cutting properties

The studies of cutting properties of the tool made of different grades of carbide with developed NMCC was conducted on a lathe CU 500 MRD in longitudinal turning of steel C45 (HB 200).

The study used cutters with mechanical fastening of inserts made of carbide (78% WC-14% TiC- 8% Co) with square shape (SNUN ISO 1832:2012) and with the following figures of the geometric parameters of the cutting part: $\gamma = -8^\circ$; $\alpha = 6^\circ$; $K = 45^\circ$; $\lambda = 0$; $R = 0.8$ mm. The study was carried out at the following cutting modes: $f = 0.2$ mm/rev; $a_p = 1.0$ mm; $v_c = 200$ and 300 m·min⁻¹. Flank wear-land values (VB_Σ) were measured with toolmaker's microscope MBS-10 as the arithmetic mean of four to five tests and a value of $VB_\Sigma = 0.45$ -0.5 mm was taken as failure criteria.

2.4 Microstructural studies

For microstructural studies of samples of carbide with coatings, a raster electron microscope FEI Quanta 600 FEG was used. The studies of chemical composition were conducted with the use of the same raster electron microscope. To perform X-ray microanalysis, the study used characteristic X-ray emissions resulting from electron bombardment of a sample.

3. Results and discussion

3.1 The adhesion characteristics study

As a result of the conducted studies, it was found out that coating completely failed at load L_{C2} equal to 30-33 N. Meanwhile, the first cracks started to form under load (L_{C1}) equal to 17-20 N (see Fig. 1).

Fig. 1. Curve and panorama of a crack on progressive load scratch test of carbide sample with coating Ti-TiN-(NbZrAl)N.

1. ábra Lineáris karcolási vizsgálat eredménye és képe karbid mintán Ti-TiN-(NbZrAl)N bevonattal.

Fig. 2. Pattern of failure of coating Ti-TiN-(NbZrAl)N on progressive load scratch test. The arrow indicates the direction of motion of the indenter, 1 - substrate, 2 - adhesive sublayer, 3 - intermediate layer, 4 - wear-resistant layer.

2. ábra Ti-TiN-(NbZrAl)N bevonat tönkremeneteli képe lineáris karcolási vizsgálat során. A nyíl jelzi az alaktest mozgási irányát. 1 - alaprét, 2 - adhézió alsó réteg, 3 - köztes réteg, 4 - kopásálló réteg

A typical feature of the process of destruction of coating is failure of adhesive bonds not only between substrate and coating, but also between separate layers and sublayers of the coating (see Fig. 2). Meanwhile, the most extensive areas of failure of adhesive bonds are observed in the system of *adhesive sublayer-substrate*, less extensive areas of failure of adhesive bonds in the system of *adhesive sublayer-intermediate layer*, and, finally, the most durable adhesive bonds are observed in the system of *intermediate layer-wear-resistant layer*. It should be noted that coating TiN started to fail under load of 13-15 N (L_{C1}), and its total failure occurred at load (L_{C2}) of about 25 N.

3.2 Cutting tests

The results of cutting tests were processed using parametric identification of exponential stochastic multiplicative mathematical model by least squares method. Used formula of the form:

$$VB = C(1) \cdot v_c^{A(1,1)} \cdot T^{A(1,2)} \quad (1)$$

Curves obtained by mathematical processing of the experimental data are shown in Fig. 3.

Fig. 3. Dependence of wear VB on cutting time at dry turning of steel C45 at $a_p = 1.0$ mm; $f = 0.2$ mm/rev; $v_c = 200$ m·min⁻¹ (a) $v_c = 300$ m·min⁻¹ (b) 1 - Uncoated; 2 - TiN; 3 - Ti-TiN-(NbZrAl)N.

3. ábra Kopás (VB) mértéke a megmunkálási idő függvényében (C45 acél); paraméterek: $a_p = 1.0$ mm; $f = 0.2$ mm/rev; $v_c = 200$ m·min⁻¹ (a) $v_c = 300$ m·min⁻¹ (b) 1 - bevonat nélkül; 2 - TiN; 3 - Ti-TiN-(NbZrAl)N.

Based on the obtained results, the following can be noted.

At both cutting speeds of 200 and 300 m·min⁻¹, the tool with nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N showed better wear resistance. The tool life of a tool with the above coating at cutting speed of 200 m·min⁻¹ was by 2.2 times longer than tool life of a tool with coating TiN,

and by 3.6 times longer than tool life of an uncoated tool. At cutting speed of 300 m·min⁻¹, the tool with the above coating showed the tool life, 1.83 times longer than tool life of a tool with coating TiN, and 2.75 times longer than tool life of an uncoated tool. Thus, the difference in tool life decreased at higher cutting speeds.

3.3 Study of mechanism of adhesive-fatigue wear of carbide tool with developed NMCC

Wear and failure patterns of reference coating TiN and nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N have a number of significant differences. For coating TiN, abrasion wear was typical, as well as adhesive-fatigue wear with formation of distinct transverse through cracks, in some cases extending into substrate structure (Figs. 4a, 5a, 6a). Meanwhile, for coating Ti-TiN-(NbZrAl)N, it is typical when transverse cracks turn into longitudinal delamination, in some cases, with tear-out of fragments of coating between two transverse cracks (Figs. 4b and 5b). Active formation of transverse cracks, including through cracks, is observed only in areas around microdroplets embedded in the structure of the coating (Figs. 6b and 7). A massive pick-up of the material being machined is formed in the area of coating failure, and in some cases, charging of the material being machined in areas of chipping of carbide substrate is observed (Fig. 4b).

Fig. 4. Wear and failure pattern of the system coating-substrate on rake face of tool: coating TiN (a) and nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N (b) in turning of steel C45 at the following cutting modes: $V_c = 200$, $f = 0.25$, $a_p = 1$ mm

4. ábra Kopás és tönkremenetel bevonat-alapréteg rendszerben a megmunkáló szerszám homlokfelületén: TiN (a) és nanoszerkezetű többrétegű Ti-TiN-(NbZrAl)N kompozit (b) bevonat esetén - C45 acél, megmunkálási paraméterek: $V_c = 200$, $f = 0.25$, $a_p = 1$ mm

a

b

Fig. 5. Pattern of crack formation in coating TiN (a) and multilayered composite nano-structured coating Ti-TiN-(NbZrAl)N (b) on rake face of tool in turning of steel C45 at the following cutting modes: $V_c=200$, $f=0.25$, $a_p=1$ mm
5. ábra Repedésképződés TiN (a) és nanoszerkezetű többrétegű Ti-TiN-(NbZrAl)N kompozit (b) bevonat esetén a megmunkáló szerszám homloklapfelületén – C45 acél, megmunkálási paraméterek: $V_c=200$, $f=0.25$, $a_p=1$ mm

a

b

Fig. 6. Pattern of crack formation in coating TiN (a) and nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N (b) in turning of steel C45 at the following cutting modes: $V_c=200$, $f=0.25$, $a_p=1$ mm
6. ábra Repedésképződés TiN (a) és nanoszerkezetű többrétegű Ti-TiN-(NbZrAl)N kompozit (b) bevonat esetén – C45 acél, megmunkálási paraméterek: $V_c=200$, $f=0.25$, $a_p=1$ mm

Fig. 7. Influence of microdroplets embedded into the structure of the coating on the process of cracking in nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N

7. ábra A nanoszerkezetű többrétegű Ti-TiN-(NbZrAl)N kompozit bevonatban kialakuló mikroárványok hatása a repedésképződési folyamatra

a

b

c

d

Fig. 8. Wear and failure pattern of coating on tool flank wear land in turning of steel C45 – coating ($V_c=200$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (a), – coating TiN ($V_c=300$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (b), – coating Ti-TiN-(NbZrAl)N ($V_c=200$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (c), – coating Ti-TiN-(NbZrAl)N ($V_c=300$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (d).

8. ábra Kopás és tönkremeneteli módok a megmunkáló szerszám palást felületén (C45 acél)

– bevonat ($V_c=200$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (a),
– bevonat TiN ($V_c=300$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (b),
– bevonat Ti-TiN-(NbZrAl)N ($V_c=200$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (c),
– bevonat Ti-TiN-(NbZrAl)N ($V_c=300$ m/min, $f=0.25$ mm/rev, $a_p=1$ mm) (d).

Following the analysis of wear and failure patterns of coating on flank wear land of the tool, the following conclusions can be drawn:

- a typical pattern of coating wear is abrasive and adhesive-fatigue wear, without visible signs of brittle fracture;
- at cutting speed $V_c=200$ m/min, the tests show penetration of the material being machined into the area of contact *tool material-coating*. Such penetration is more definite for coating TiN (Fig. 8a) and less for coating Ti-TiN-(NbZrAl)N (Fig. 8c). At machining with cutting speed $V_c=300$ m/min, no similar penetration is observed (Fig. 8b,d);
- in the structure of coating Ti-TiN-(NbZrAl)N, longitudinal delamination occurred which do not result in failure of coating.

4. Conclusions

The paper studied mechanical and cutting properties, as well as wear and failure pattern of nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N. It was found that tool life of the tool with the coating under study is 2.75-3.6 times higher than tool life of an uncoated tool and 1.83-2.2 times higher than that tool life of a tool with coating TiN. During the study of strength of adhesive bonds between coating and substrate, as well as between different layers of coating, it was found that with sufficiently good strength of adhesive bonds (it has been found that total failure of coating occurs at load of 30-33 N), there are areas of relatively weak adhesive bonds, where failure of coating starts and develops. These areas primarily include zone of the border of *substrate-adhesive sublayer* and zone of the border of *adhesive sublayer-intermediate layer*. The data of microstructural analysis of failure pattern of coating in the process of cutting of the material being machined are in general consistent with the data of study of strength of adhesive bonds. In particular, the study shows chipping of coating in area of the border of *adhesive sublayer-intermediate layer*, but it does not prove failure of adhesive bonds at the border of *substrate-adhesive sublayer* (Fig. 5b). Based on the above, it can be concluded that the increase in strength of adhesive bonds at the border of *adhesion sublayer* (Ti)-*intermediate layer* (TiN) should result in a general increase in performance properties of the coating. Such an increase is possible through varying of parameters for coating deposition process (temperature, gas pressure, etc.) and through changing of elemental composition of intermediary layer of coating.

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Nano-szerkezetű, többrétegű Ti-TiN-(NbZrAl)N kompozit bevonatok mechanikai és megmunkálhatósági jellemzői, kopásállósága és tönkremeneteli módjai

A cikk bemutatja a nano-szerkezetű, többrétegű Ti-TiN-(NbZrAl)N kompozit bevonatok mechanikai jellegzetességeit, különös tekintettel az adhéziós jellemzőkre, illetve a kopási és tönkremeneteli módokat. A megmunkálási jellemzőket karbid megmunkáló szerszám bevonatainak tanulmányozták (C45 acél), referencia TiN bevonattal és bevonat nélküli esetel összehasonlítva. A vizsgálatok eredményei szerint a nano-szerkezetű, többrétegű Ti-TiN-(NbZrAl)N kompozit bevonattal ellátott szerszám élettartama 2,75-3,6-szor hosszabb, mint a bevonat nélküli szerszámé, és 1,83-2,2-szer hosszabb, mint a referencia TiN bevonattal ellátott szerszámé. A mikro-szerkezeti jellemzők vizsgálata számottevő eltérést tárt fel a kopási és tönkremeneteli folyamatokban.

Kulcsszavak: nano-szerkezetű többrétegű bevonatok, szerszám élettartam, karbid szerszám, kopási mechanizmus, repedésképződés