Research of mechanical and cutting properties, wear and failure mechanisms of nanostructured 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 have 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 monolayered 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 (MeI–(MeII)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.
**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 was named as filtered cathodic vacuum arc deposition (FCVAD) [1-4,13,14], which was 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: \( \gamma = -8°; \alpha = 6°; K = 45°; \lambda = 0; \)

### 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 formunder load (\( L_{c1} \)) equal to 17-20 N (see Fig. 1).

#### 3.2 Study of cutting properties

The cutting tests were carried out on a lathe CU 500 MRD in longitudinal turning of steel C45 (HB 200). The studies were focused only on coatings with mono-layered architecture, including coatings with nano-scale structure.
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:

\[
V_B = C(1) \cdot v_A^{(1,1)} \cdot T_A^{(1,2)}
\]

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

**Fig. 3.** Dependence of wear \( V_B \) on cutting time at dry turning of steel C45 at \( a_p = 1.0 \) mm; \( f = 0.2 \) mm/rev; \( v = 200 \) m min\(^{-1} \) (a) \( v = 300 \) m min\(^{-1} \) (b) 1 – Uncoated; 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. 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 szerzám homlokfelületén – C45 acél, megmunkálási paraméterek: \(V_c=200\), \(f=0.25\), \(a_p=1\) mm

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 mikrozárványok hatása a repedésképződési folyamatra.

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 szerzám 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 \( V = 200 \text{ m/min} \), 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 \( V = 300 \text{ m/min} \), 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 proves 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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