The effect of wear-resistant coatings composition based on niobium nitride on the structural parameters, mechanical properties and efficiency of the cutting tool

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Abstract. Single-layer wear-resistant coatings based on niobium nitride deposited on a carbide cutting tool are considered in this article. The influence of one and two alloying elements on the change of the coating structure, mechanical properties and efficiency of the cutting tool was studied. It was revealed that in all cases, alloying with titanium, zirconium, aluminum and chromium leads to a change in the microstructure and an increase in the mechanical properties of the coatings and the inclusion of two elements into the composition of coatings increases mechanical properties to a greater extent. Research has shown that cutting tools with coatings based on niobium nitride are characterized by a decrease in the stress state of the tool base and an increase in the total compressive stresses in the coating. Compared to titanium nitride, the niobium nitride coating reduces the temperature on the front surface of the cutting tool, but for complex-alloy coatings, there is a slight increase in contact temperatures. Changing the heat-stressed state and increasing the mechanical properties leads to an increase in the crack resistance of such coatings. It is shown that the use of developed compositions of multi-element coatings can improve the efficiency of the cutting tool.

1. Introduction
Great importance is given today to improving the efficiency of the cutting tool. Therefore, most high-speed and carbide cutting tools are applied with wear-resistant coatings to improve performance [1–5]. This cutting tool has higher mechanical properties, crack resistance and, therefore, efficiency [6–10]. Coatings based on simple and complex nitrides of refractory elements, primarily titanium, zirconium, chromium, molybdenum, and aluminum nitrides, are most widely used among wear-resistant coatings. Coatings based on niobium nitride are particularly interesting among the coatings which have low thermal conductivity, which allows to reduce the heat flux into the cutting wedge of the tool [10, 11].

2. Methodology of Experiment
Coatings based on niobium nitride NbN, NbTiN, NbZrN, NbTiZrN, NbTiAlN and NbTiCrN with a thickness of 6 mkm were studied. These coatings were applied to MK8 carbide plates using the apparatus «Bulat-6». The chemical composition of coatings was determined using the method of quantitative x-ray diffraction analysis at the MAP-4 installation, taking into account ZAF corrections.

Lattice constants a and c and the residual compressive stresses σ_0 were investigated by means of an x-ray diffractometer 'DRON-3M' [12]. Micro-hardness H_μ, elasticity modulus E, yield stress σ_y and fracture toughness K_{IC} of coatings were determined as in [10]. The calculation of the crack resistance of coatings was carried out according to the method of work [13]. The efficiency of carbide tool was determined during longitudinal turning of workpieces of structural steel 30KHGSA (alloying systems: 0.28–0.34% C, 0.8–1.1% Cr, 0.8–1.1% Mn, 0.9–1.2% Si).

3. Research results and discussion

The chemical composition of the coatings, the crystal lattice parameters a and c, the Burgers vector b and the length of the germ microcrack l_0 are presented in Table 1.

It was found that coatings based on niobium nitride are single-phase and have a tetragonal crystal lattice. The presence of titanium in composition of coatings leads to an increase in the values of Burgers vector b and the length of the germ microcrack l_0.

Values of the mechanical properties of the coatings are presented in table 2. Coatings of complex composition are characterized by greater microhardness and high values of elastic modulus and yield strength. Moreover, three-element coatings are characterized by a significant increase in fracture toughness: by 21–30% as compared to the coating of niobium nitride.

Table 1. Chemical composition and structural parameters of coatings.

Coating	Content of elements (% at)					a (nm)	c (nm)	b (nm)	l_0 (nm)
	Ti	Nb	Zr	Al	Cr				
TiN	100	–	–	–	–	0.4241	–	0.2999	0.5998
NbN	–	100	–	–	–	0.3015	0.5715	0.3015	0.6030
NbTiN	42.6	57.4	–	–	–	0.4399	0.8684	0.4399	0.8798
NbZrN	41.8	–	58.2	–	–	0.3007	0.5715	0.3007	0.6014
NbTiZrN	46.5	41.9	11.6	–	–	0.4372	0.8791	0.4372	0.8744
NbTiAlN	49.2	40.0	–	10.8	–	0.4449	0.8704	0.4372	0.8898
NbTiCrN	43.8	48.1	–	–	8.1	0.4458	0.8404	0.4458	0.8916

Table 2. Mechanical properties of coatings.

Coating	H_μ (GPa)	E (GPa)	K_{IC} (MPa·$m^{\frac{1}{2}}$)	σ_y (MPa)
TiN	26.2	327	8.76	9.53
NbN	29.8	467	9.78	9.67
NbTiN	31.3	422	10.16	10.7
NbZrN	32.1	428	9.97	10.61
NbTiZrN	32.9	496	11.84	11.12
NbTiAlN	32.1	455	12.76	10.91
NbTiCrN	33.4	448	12.69	11.42

Determination of the contact characteristics of the cutting process, temperatures and stresses acting in the cutting wedge of the tool was carried out by analytical calculation of the current unit loads and temperatures acting on the front and back surfaces of the cutting wedge of the tool according to the methods of [14, 15], followed by numerical calculation by the finite element method in a package ANSYS programs.

Calculations show a change in the thermal and stress state of cutting tools with coatings based on niobium nitride (table 3).

As it was shown in [10, 16], niobium nitride coatings have low thermal conductivity. This makes it possible to slightly reduce the temperature on the front surface of the cutting tool under the coating in the carbide base both by changing the contact characteristics of the cutting and by reducing the thermal conductivity of the coatings. NbN coating has the lowest maximum contact temperature T_{max}, while composite coatings have a temperature slightly higher (by 1.2–2.8 %) than titanium nitride.

Table 3. Heat-stressed condition and characteristics of crack resistance of coatings and tool base.

Coating	Tool base			Coating			t_1 (min)	t_2 (min)	t_Σ (min)
	T_{max} (°C)	σ_x (MPa)	σ_0 (MPa)	σ_1 (MPa)	σ_{therm} (MPa)	σ_Σ (MPa)			
TiN	1106	831	−775	513	−1910	−2172	1.63	7.28	8.91
NbN	1039	815	−2280	718	−3075	−3075	10.74	8.11	18.85
NbTiN	1120	779	−1497	620	−2709	−2709	6.55	12.16	18.71
NbZrN	1130	788	−2661	636	−1934	−1934	5.04	12.27	17.31
NbTiZrN	1132	736	−1704	689	−3021	−2729	11.36	15.76	27.12
NbTiAlN	1126	747	−1923	641	−2729	−3021	12.80	16.07	28.87
NbTiCrN	1137	751	−1941	534	−2819	−2819	9.83	16.58	26.41

At the same time, coatings with complex composition reduce the stress value in the tool base σ_x by 4–9 % as compared to NbN coating and by 5–12% as compared to TiN coating.

Taking into account the thermophysical properties of the coatings, the temperature and stress state of the cutting wedge of the tool were calculated the stresses arising in the coatings due to the difference with the tool base of their elastic modulus σ_1 and the thermal expansion coefficients σ_{therm} were calculated. The total stresses in coatings, taking into account the residual stresses σ_0 arising during deposition, allow us to state a more favorable picture for NbN coatings and three-element coatings of complex composition.
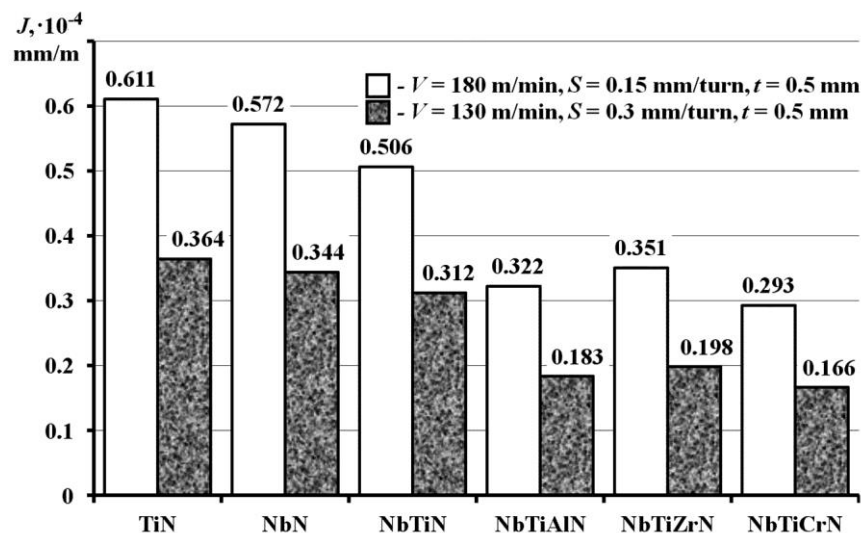

Figure 1. Influence of the coating composition on the wear intensity of the cutting tool with the wear-resistant coating.

Calculation of fatigue crack growth time by the method of [12] showed that niobium nitride-based coatings more effectively resist crack formation processes. High values of compressive stresses

combined with a more favorable combination of thermal and stressed states provide the cutting tool with niobium nitride-based coatings an increase in the time t_1 before the crack development starts in the coating by 3.1–7.9 times. Different coatings resist differently to the development of a crack at the stage of its growth. In this case, coatings of a complex composition having high mechanical properties are characterized by longer time t_2 before a through crack is formed in the coating.

As a result, the total time before the occurrence of cracks starts in the coating (time of fatigue crack growth) t_Σ has the highest values for three-element coatings NbTiCrN, NbTiZrN and NbTiAlN. In comparison with NbN coating, the time value of t_Σ increases approximately by about 1.5 times for these coatings, and in comparison with TiN coating by 3–3.2 times.

The study of cutting tool efficiency with coatings showed a correlation between a decrease in the intensity of wear of the cutting tool and an increase in the crack resistance of coatings (Figure 1).Use of coatings of complex compositions allows to reduce wear intensity of cutting tool by 1.8–2.1 times compared to coatings of TiN and NbN and by 1.6–1.9 times compared to coating of NbTiN.

4. Conclusions
Conducted research has shown high efficiency of using cutting tools with developed coatings based on niobium nitride.

Acknowledgment

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