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Effect produced by thickness of nanolayers of multilayer composite wear-resistant coating on tool life of metal-cutting tool in turning of steel AISI 321

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Abstract

The paper considers multilayer composite nano-structured Ti-TiN-(Ti,Al,Cr,Si)N coatings for metal-cutting tools. The coatings under the study have identical elemental composition and thickness (3.5 µm), but differ in the thicknesses of the nanolayers (of about 40 and about 80 nm). The mechanical characteristics of the coatings were studied, and the tool life tests were carried out for carbide tools with the above coatings for dry turning of steel AISI 321(HB 180) at v_c = 100, 150, and 200 m/min (f=0.11 mm/rev; a_p=0.5 mm). Uncoated tools and tools with Ti-(Ti,Al)N coatings of traditional type were used as objects of comparison. The studies have found out that coatings with thinner nanolayers demonstrate better performance properties, especially at higher cutting speeds.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Two major directions for improvement of modern modifying coatings are in sophistication of their elemental compositions (in particular, multi-component "highly entropic" coatings) and of their architectures (in particular, nanostructured coatings) [1-3]. These two directions are often combined with each other. In recent years, nanocomposite and nanostructured coatings of various elemental compositions and different spheres of application have been studied extensively. Liu et al [4] consider nanocomposite (Cr,Cu,Ag)N coating, deposited through pulsed DC unbalanced magnetron sputtering. Lawal et al [5] study multi-component nanostructured PVD (Al,Ni,Ti,Si,B)N coating. Monclus et al [6] consider nanocomposite (Cr,Cu)N and (Cr,Ti,Cu,B)N coatings. Bobzin et al [7] studied the properties of PVD (Ti,Hf)N-CrN coating with nanostructured external layer, used for tools designed for metal forming processes. Blinkov and Volkhonskii [8] consider multilayer nanostructured PVD (Ti,Al)N-(Zr,Nb)N-CrN coating. The changes in rotation speed of coated samples relative to sputtered cathodes contributed to formation of various thicknesses of nanolayers, starting from 10 nm. Steyer et al [9] studied superlattice TiN-CrN coating. It is found out that a coating with nanostructure is more resistant to oxidation and aqueous corrosion. Baker et al [10,11] studied properties of nanocomposite PVD (Ti,Al)B,N coatings. A tool with the above coating showed good results in wet-cutting drill tests. In

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the given coating, grain size and grain separation were determined to be 26 and 3 nm, respectively. Sergevnin et al [12,13] studied nanostructured multilayer (Ti,Al)N–Mo_2N coatings. Thickness of nanolayers and grain size in the coating reached 30–50 nm. Steyer et al [14] considered nanomultilayer TiN/CrN and (Ti,Si)N nanocomposite coatings. In particular, it is shown that high oxidation resistance of (Ti,Si)N is attributable to the network of refractory SiNx, which acts as a diffusion barrier for oxygen and insulates the highly reactive TiN nanograins from the aggressive atmosphere. Araujo et al [15] studied nano-scaled multilayer CrN-NbN with thickness of nanolayers of 20 nm, 10 nm, 7.5 nm and 4 nm. It is found out that when thickness of nanolayers decreases, hardness increases, coefficient of friction decreases, and resistance to cohesive failure increases.

Kovalev et al [16] studied nanostructured (Al,Ti)N and (Ti,Al,Cr)N PVD coatings. It is found out that grain sizes for such coatings reach 5–20 nm. Cutting tests were conducted when turning hardened tool steel H13 (HRC 50–52) and aerospace materials. It is found that nanostructured (Ti,Al,Cr)N coating shows the best results in machining of steel, while it is characterized by higher hot hardness and oxidation stability at high temperatures. In turn, Yamamoto et al [17] showed that due to introduction of Cr to the Ti–Al–N system, the cubic B1 structure can be stabilized at a higher Al content. Fox-Rabinovich et al [18] investigated properties of PVD (Al,Ti)N and (Ti,Al,Cr)N coatings in machining of hard-to-cut materials (end milling of hardened H 13 tool steel and Ni-based superalloy). It is found out that (Ti,Al,Cr)N coating with grain sizes of 10-30 nm shows the best results in machining of hardened H 13 tool steel, since it is characterized by combination of high hot hardness and improved oxidation resistance at elevated temperatures. In subsequent studies, Fox-Rabinovich et al [19] investigated nanostructured PVD (Ti,Al,Cr,Si,Y)N and (Ti,Al,Cr,Si,Y)N-(Ti,Al,Cr)N coatings. It is shown that multilayer coating is characterized by better wear resistance than monolayer coating, while multilayer coating demonstrates more stable wear mechanism. Kumar et al [20] consider nanostructured multilayer (Ti,Al,Si)N-(Ti,Si)N-(Ti,Al)N coating, deposited through DC reactive magnetron sputtering (DCRMS). The coating proved to be markedly superior to (Al,Ti)N and (Al,Cr)N coatings during hard machining of AISI 52100 steel (62 HRC). Multilayer composite coatings of various compositions and archtectures were also studied in [21–27]. The effect produced by thickness of nanolayers on performance properties of multilayer composite Ti-TiCN-(Ti, Al)CN coating was studied in [28]. However, it should be noted that the effect produced by thickness of nanolayers in modifying coatings on performance properties of metal-cutting tools was investigated in few studies only.

2. Materials and Methods

For the deposition of coatings, a vacuum-arc VIT-2 unit was used, which was designed for the filtered cathodic vacuum-arc deposition (FCVAD) process [21-29]. The parameters for deposition of Ti-TiN-(Ti,Al,Cr,Si)N coatings are identical, and they differ only by rotation speeds of planetary table, which is 3 rev/min and 7 rev/min, respectively. The higher rotation speed forms lower thickness of nanolayers. For microstructural studies of samples of carbide substrates with coatings, a scanning electron microscope (SEM) FEI Quanta 600 FEG with energy-dispersive X-ray spectroscopy (EDS) equipment was used.

The hardness (HV) of coatings was determined by measuring the indentation at low loads according to the method of Oliver and Pharr [30].

The tests of coating adhesion strength were carried out on a Nanovea M1 scratch test tester according to [31].

Austenitic steel AISI 321 (HB 180) is widely used in manufacture of products operating in different corrosive media (acid, alkali, salt solutions) in the chemical industry, food industry, and civil building, but it also presents an increased interest in machine constructions and households. However, mechanical machining of steel AISI 321 presents a certain difficulty.

The cutting tests were conducted on a CU 500 MRD lathe in longitudinal turning of steel AISI 321. For the study, the cutters featured mechanical fastening of carbide inserts (WC+12% TiC+5% Co; Kirovgrad Carbide Plant–KZTS) with square shape (SNUN ISO 1832:2012).The following geometry of the cutting part was used: γ = -6°; α = 6°; K = 45°; λ = 0; R = 0.4 mm. The tests were conducted in longitudinal steel at cutting speeds v_c =100, 150 and 200 m/min; f=0.11 mm/rev; a_p=0.5 mm. Flank wear land VB_{max} = 0.4 mm was taken as a wear criterion.

3. Results and Discussion

The conducted investigation of microstructure of the coatings under the study found that they have fairly uniform structures with clearly detected nanolayers. There are almost no internal defects (microdroplets, micropores, etc.) in structure of the coatings, although their surfaces include microdroplets formed at the final stage of the coating deposition (Fig. 1.). Unlike microdroplets embedded in the coating structure, such superficial microdroplets do not usually pose significant threat to performance of coated tools [25, 26].

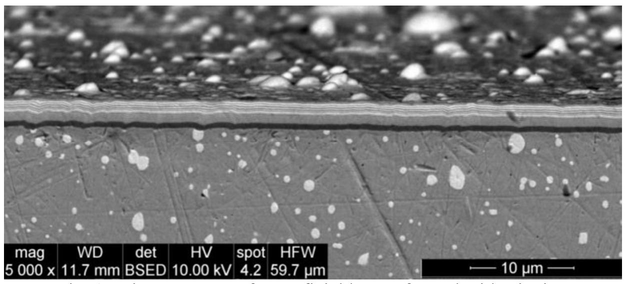


Fig. 1. Microstructure of superficial layer of a tool with Ti-TiN-(Ti,Al,Cr,Si)N coating.

The investigation of thickness and microstructure of the Ti-TiN-(Ti,Al,Cr,Si)N coatings under the study and the "reference" Ti-(Ti,Al)N coating is presented in Fig. 2. Ti-(Ti,Al)N coating has no nanostructure, and its typical columnar structure can be clearly seen. The Ti-TiN-(Ti,Al,Cr,Si)N coatings under the study have clear nanostructures with nanolayer thickness of about 40 and 80 nm, respectively.

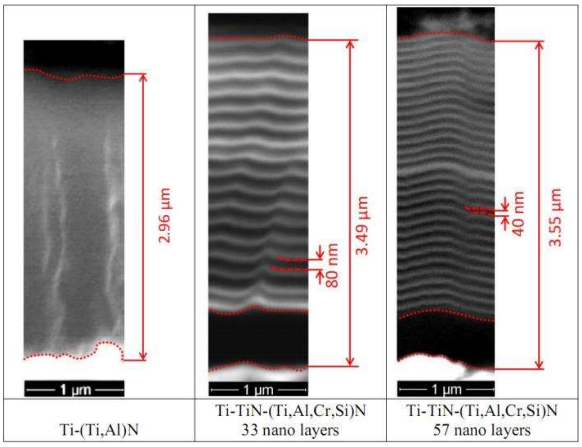


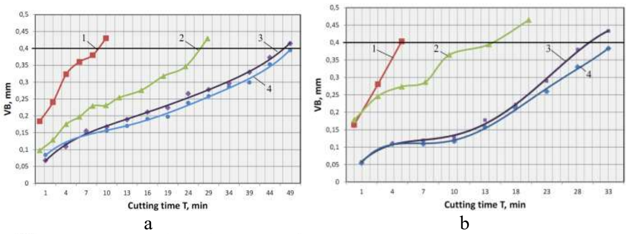
Fig. 2. Micro- and nanostructure of the coatings under the study.

The mechanical properties of the coatings under the study are presented in Table 1. The investigation of the mechanical properties did not detect any noticeable difference in these properties of Ti-TiN-(Ti,Al,Cr,Si)N coatings with different thickness of nanolayers.

Table 1.Mechanical properties of coatings under study.

#	Composition of coating	Adhesion,N	Hardness HV, GPa
1	Uncoated	-	-
2	Ti-(Ti,Al)N	31	26
3	Ti-TiN-(Ti,Al,Cr,Si)N (80 nm)	>40	28
4	Ti-TiN-(Ti,Al,Cr,Si)N (40 nm)	>40	28

The results of the cutting tests are presented in Fig.3 and 4.



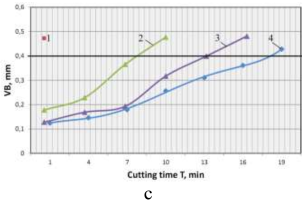


Fig. 3. Relation between flank wear land VB and cutting time at cutting speed v_c = 100(a), 150 (b), and 200 (c) m/min (f=0.11 mm/rev; a_p=0.5 mm).

Cutting tools with nanostructured composite Ti-TiN-(Ti,Al,Cr,Si)N coatings showed significantly longer tool life both in comparison with uncoated tools and tools with monolayer Ti-(Ti,Al)N coating. Meanwhile, with an increase in cutting speed, the difference in tool life grows. At cutting speed v_c = 200 m/min, it is not possible to use an uncoated tool, since the tool reaches its wear limit already after the first minute of cutting, while coated tools show the tool life sufficient to use them under these cutting modes. If at cutting speed v_c = 100 m/min, tools with Ti-TiN-(Ti,Al,Cr,Si)N coatings with various thickness of nanolayers show very similar values of tool life, then at cutting speed v_c = 200 m/min, a tool with Ti-TiN-(Ti,Al,Cr,Si)N coating with thinner nanolayers (40 nm) shows markedly longer tool life than a tool with coating of similar composition and thicker nanolayers (80 nm).

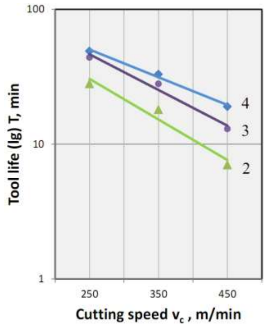


Fig. 4. Dependence of tool life from cutting speed.

One of the possible causes affecting the difference in wear resistance of the coatings under the study at high cutting speeds may be in dissimilarity of wear mechanism typical for these coatings. Fig. 5 presents microphotographs of cross section of a worn coated tool in the area directly adjacent to cutting edge. It can be seen that cracks are actively formed on a tool with coating characterized by nanolayer thickness of 80 nm, while in some cases, these cracks are embedded in structure of carbide substrate (Fig. 5 a). Meanwhile, the study of a similar area of a tool with coating characterized by nanolayer thickness of 40 nm, no formation of such cracks is observed, and balanced wear occurs without noticeable brittle fracture. This phenomenon can be explained by higher crack resistance of coatings with thinner nanolayers, and that in turn may be related to a lower level of internal stresses in such coatings [25, 26]. Considering the fact that with an increase in cutting speed (within the given speed range), the temperature in the cutting zone grows, thermal stresses in superficial layers of a tool, and in particular, in coating, also increase noticeably. A coating with thinner nanolayers demonstrates higher wear resistance under the given conditions.

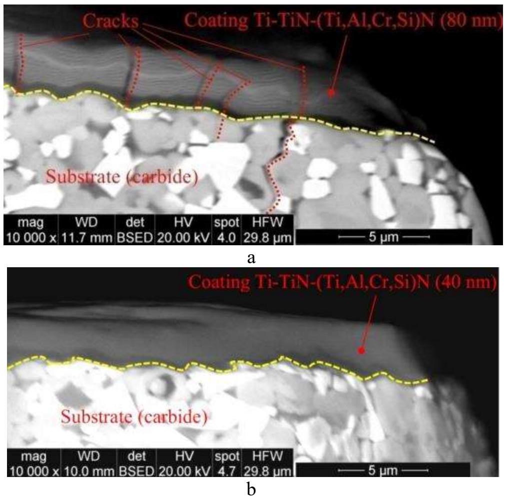


Fig. 5. Difference in the mechanism of failure in Ti-TiN-(Ti,Al,Cr,Si)N coatings with various thickness of nanolayers in the area directly adjacent to the cutting edge. Coatings with thickness of nanolayers of 80 nm (a) and 40 nm (b).

Conclusion

Mechanical and cutting properties of tools with Ti-TiN-(Ti,Al,Cr,Si)N coatings with various thickness of nanolayers

(40 and 80 nm) were investigated. The conducted investigations found out that while the mechanical properties of these coatings (microhardness and strength of adhesion bond to substrate), investigated at room temperature, showed no noticeable differences, cutting properties of tools with such coatings clearly differ. Meanwhile, with an increase in cutting speed, the difference in tool life grows. A tool with coating characterized by thinner nanolayers (40 nm) showed the longest tool life at all studied cutting speeds (v_c = 100, 150, and 200 m/min). The studies of microstructure of superficial layers of a worn tool detected more active cracking in tools with coatings characterized by thicker nanolayers (80 nm). Meanwhile, tools under the study with multilayer composite coatings showed significantly higher tool life both in comparison with uncoated tools and tools with monolayer Ti-(Ti,Al)N coating.

Acknowledgements

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