Application of nanostructured PVD-coating to increase the service life of metal working tools

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Abstract. The article is devoted to the application of nanostructured TiN/CrN coating for axial cutting tools for metalworking. The technological process of applying this coating, studies of physical, mechanical and tribological characteristics, as well as adhesion and thickness are presented. The results of experiments on metalworking of aluminum alloy and 40X steel for tools with and without coating are presented. The test results showed that TiN/CrN coating increases the durability of cutters by 2.5...2.6 times, drills by 2.1...3.1 times compared to cutting tools made of high-speed steel R6M5 without coating.

1. Introduction

Ultrathin periodic multilayer PVD coatings, which are called superlattice in foreign literature [1-3], have a number of advantages over traditional single-layer coatings (TiN, TiAlN, AlCrN, etc.) due to the periodic multilayer structure. These coatings have a higher hardness and ductility [4-7]. This combination of properties gives a more significant increase in the durability of metal-cutting tools. One of the least studied is the superlattice TiN/CrN coating, which is not found in the Russian literature. The purpose of this work was to determine the physical, mechanical and tribological properties of this coating, as well as industrial testing of axial metal-cutting tools with this coating.

2. Materials and methods

When applying the TiN/CrN superlattice coating on the UNICOAT 600 SL+ unit (ELAN-Praktik NPF, Russia), a circuit with two magnetrons in the center of the chamber was used. With this arrangement, the products pass through the processing zones opposite each magnetron, providing a uniform multilayer periodic structure [8]. As a rule, the coating thickness on the tool is from 3 to 5 microns with a layer thickness of 2 to 9 nm. The technological process of superlattice coating consisted of several stages, which are described in table 1. During the tests to determine the physical-mechanical and tribological characteristics, SCM equipment (Switzerland) was used, on which the following studies were performed: indentation, scratch testing, Calo testing and tribometer tests [9].

Nanoindentation was performed on an open platform with an instrumental nanoindentation module, which measures the depth of immersion when the indenter is pressed, which determines the hardness, modulus of elasticity, latent and scattered strain energies, dynamic and static modulus of elasticity, plastic deformation, fracture toughness (crack resistance). Indentation was performed with the following parameters: loading force 0.02 N, load holding time 10 seconds.
Table 1. Parameters of the technological process of applying coatings of TiN/CrN.

| stages                                      | Operating pressure, PA | ITi, A | ICr, A | Offset voltage on the product, V | Ar Concentration, sccm | N2 Concentration, sccm |
|---------------------------------------------|------------------------|--------|--------|---------------------------------|------------------------|------------------------|
| 1 Ion cleaning of products                  | 0.18                   | 2 – 3  | 2 – 3  | 800 – 1000                      | 240 – 270              | 0                      |
| 2 Application of a metallic adhesion layer Ti | 0.18                   | 15 – 18| 0      | 40 – 50                         | 240 – 270              | 0                      |
| 3 Applying the TiN transition layer         | 0.18                   | 15 – 18| 0      | 40 – 50                         | 240 – 270              | 50 – 70                |
| 4 The application of a jet of the working layer TiN/CrN | 0.18 | 15 – 18 | 15 – 18 | 50 – 80 | 240 – 270 | 60 – 80 |

$I_{Ti}, I_{Cr}$ - current strength on the Ti and Cr magnetrons respectively.

3. Results
The measurement results for superlattice coatings are shown in table 2.

Table 2. Comparative analysis of superlattice coating measurement results

| Coating   | Vickers Hardness HV, kg / mm2 | Nanohardness Hit, HPa | Modulus of elasticity $E^*$, HPa |
|-----------|--------------------------------|-----------------------|---------------------------------|
| TiN/CrN   | 3792.6                         | 41.3                  | 306                             |
| TiN/AlN   | 3870.2                         | 41.8                  | 298                             |
| AlN/CrN   | 3776.4                         | 41.1                  | 276                             |
| Cr/C      | 3850.1                         | 40.8                  | 282                             |

As a result of the scratch test, the adhesion of the coating to the substrate material is determined, and the amount of force at which the coating begins to break off from the product is determined. During the scratch test, linear scratching was performed with a progressive load from 0.1 N to 30 N, the load speed was 14.95 N / min, the loading speed was 3 mm / min. The track length was 5 mm, Rockwell indenter type, material-diamond, maximum radius of 100 microns. The results of the scratch test are shown in Fig. 1, a. Analysis of the graphs showed that at a load of 9.33...9.36 N, the TiN/CrN coating begins to break off from the substrate.

The CSM tribometer is used to determine the lifetime of coatings, friction behavior, and wear of solid materials and coatings depending on time, contact pressure, speed, temperature, and vacuum conditions. The wear coefficient is determined based on the amount of material lost during the test. An important feature of the high-temperature tribometer is that the temperature is controlled both in the chamber and in the sample itself. The following parameters were used to study the samples: the sample rotation speed – 400 rpm; the number of revolutions-10000 rpm; the distance covered is 260 m.; the load on the sample is 2N; the diameter of the indenter ball is 3 mm. As a result of the tests, the coefficient of friction of the coating material TiN/CrN for 40X steel was determined, which was 0.2...0.3 (Fig.1, b). For comparison, the coefficient of friction for an uncoated sample is 0.6...0.7.
Fig. 1 Results of the study of the physical and mechanical properties of the tin/CrN coating. 
(a) scratch test; (b) graph of the coefficient of friction.

Calotesting designed for fast and accurate determination of coating thickness. This method is widely used for analyzing coating thicknesses from 0.1 to 50 microns. The system (Fig.2,a) includes: a CSM CALOTEST industrial device, a universal clamp; a rack and a hydraulic tripod; a set of balls with a diameter of 10; 15; 20; 25.4; 30 mm; a high-quality abrasive suspension (particle size 0.5...1 microns). The method of calotesting is as follows: a rotating ball of a known diameter (ball diameter) is pressed against the surface with a pre-set force; the position of the ball relative to the sample and the force of contact of the ball on the sample remain constant; when adding an abrasive suspension to the contact zone of the ball and the sample, the surface and substrate are erased in the form of a spheroidal crater; optical analysis of the projection of a spheroidal notch on the sample surface on the plane gives the measured parameters X and Y, which allows using simple geometric relations to clean the coating thickness Z or the thickness of layers (Fig. 2, b). The coating thickness was determined by the formula: 
\[ t = z = \frac{X \cdot Y}{\varnothing} \]

To check the correctness of the thickness of the coating experiments conducted with an atomic force microscope (AFM) Integra-Aura. The results of the measurements are presented in Fig. 5 the thickness of the coating was 4.57 microns. When nanostructuring on an electron microscope Quanta 200D (ISP. Abramov D. V.), the formation of rounded structures of the TiN/CrN coating was registered (Fig. 3, 4).
Fig. 2. Calotesting of coating TiN/CrN. a) calotest CSM to determine the thickness of the coatings, b) the wear track after measuring the coating thickness (increase 5 times).

Fig. 3. a) The determining the coating thickness of the AFM; b) Image of the structure of the alloy TiN/CrN in an electron microscope.

The experiment was carried out on the milling machine Quaser MV204CU at the spindle speed of 5,000 min⁻¹, injection quantity – when drilling 0.12 mm/Rev, milling - 200 mm/min, depth of cut of 3 mm. For processing, samples were taken from steel 40X GOST 1050-88 and aluminum alloy D16T GOST. 21631-76. The number of tested instruments is 5 in each group. The results of field tests are shown in table 3 (average values are indicated).

Table 3. Durability of tools according to the results of field tests, min

| Uncoated tool  | Without coating | With TiN / CrN |
|----------------|-----------------|---------------|
| Billet material | Steel 40X | Aluminum alloy D16T | Steel 40X | Aluminum alloy D16T |
| Milling cutters | 52 | 187 | 135 | 297 |
| Drills | 85 | 105 | 222 | 325 |

4. Conclusion
Studies have shown that nanostructured coatings can be used for axial tools used in metalworking. The test results showed that TiN / CrN coating increases the durability of cutters by 2.5...2.6 times, drills by 2.1...3.1 times compared to cutting tools made of high-speed steel R6M5 without coating.
References
[1] J. Birch, et al. 2006 *Thin Solid Films* 514 pp10–19
[2] Samano E.C., et al 2010 *Vacuum*, Vol. 85 (1), p.69
[3] Golombek K., et al 2007 *Journal of Achievements in Materials and Manufacturing Engineering*. 2007 №24, pp. 107–110.
[4] Jong-Keuk Park 2005 *Surface & Coatings Technology*, no. 200: pp1519 – 1523.
[5] Lin J., et al. 2009 *Surface & Coatings Technology*, no. 204: pp.936 –940.
[6] Musil J., et al 2002 *Surface & Coatings Technology*, no. 154: pp.304–313.
[7] Morozov V., et al 2019 *Journal of Physics: Conference Series*, Vol. 1331
[8] Fedotov A.V., et al 2008 *Nanoindustry*, 2008 no. 1, pp. 24-26
[9] Levashov E. A. 2009 *Nanometer* 58090State standard №801-78. Ball-bearing steel. Technical conditions. - M.: publishing house of standards, 2004.