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To the Question of the Mechanism of the Effect of Coating on the Durability of Tools from PCBN

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TO THE QUESTION OF THE MECHANISM OF THE EFFECT OF COATING ON THE DURABILITY OF TOOLS FROM PCBN

Abstract

The paper discusses the results of the tool-life tests of PCBN cutting tool with PVD coating and the mechanism which could be accounted for declining of its wear rate. The results of research showed that in condition of finishing of hardened steel (52-54 HRC), PCBN with (TiAlSiY)N/CrN PVD coating demonstrated significantly lower wear rate parameter in comparison with a standard composite. The evidences were found of intensive plastic deformation occurring on the clearance face of the tool with protective coating caused by wear land topography peculiarities. Plastic flow-zone formed at this area can significantly reduce the abrasive effect on the tool surface and thus to increase the overall tool-life.

Introduction

The most obvious mechanism of the influence of the coating on the wear resistance of the cutting tool in the range of low and medium cutting speeds is to reduce the intensity of abrasive rubbing of the contact surface due to the increased hardness relative to the base material of the tool. This mechanism is well illustrated in [1]. When cutting AISI1045 steel (v = 250 m/min, S = 0.32 mm/rev, t = 1.9 mm) with a carbide tool coated with TiN-Al_2O_3-TiCN profilograms and images taken using electron microscopy through certain time gaps demonstrate a gradual opening of the layers of protective coating, which, after its breakthrough, is quickly replaced by intensive destruction of the base due to the abrasive-adhesive interaction with the material being processed. The contact of hard alloy with steel occurs after the 12th minute of cutting, when the hardest component of the coating, TiCN, is destroyed. It is noted that the layers of TiN and Al_2O_3 are destroyed much faster: both of these layers are abraded already at the 4th minute, and the traces of the impact of abrasive particles of cementite on them are more intense in comparison with the section of titanium carbonitride.

The literature often cites the low thermal conductivity of nitride coatings as an important factor contributing to an increase in tool life [2–4]. In this case, the effect is due to an increase in the proportion of heat withdrawing by the chips, which reduces the amount of heat that discharges into the cutter body. In our opinion, the implementation of such a mechanism is possible only in case of an extreme idealization of the cutting process in models where the destruction of the coating and/or abrasion is not considered. Calculations show that the observed effect may be significant if the thermal conductivity of the coating material is about 1–2 W/mK.

In the general case, the mechanism determining the increase in tool life due to coating can be quite nontrivial, as demonstrated by Vnukov Yu. H. when studying the patterns of cutting with high-speed steel with a TiN protective coating [5].

It is shown that the maximum efficiency of such tools is observed outside the zone of accretion ($v > 0.7$ m / min) with relatively thick cross sections of the cut ($a \geq 0.3$ mm). Moreover, the main role in increasing tool life is played by the coating applied to the front surface. It was found that the friction conditions on the majority of the crater in a tool with a wear-resistant coating can be attributed to friction in the conditions of plastic contact due to the presence of a stable adhered layer. The contact length and crater width of the coated tool remains smaller throughout the durability period, and the presence of a coating allows to maintain the growth of the width of the crater, maintain high normal loads and thereby maintain the stability of the inhibited layer in the contact zone. This stagnant zone of a coated tool has a more rational form, which makes it possible to form a larger actual rake angle γ than on an uncoated tool. A more rational form of the stagnant zone allows to better cover the shelf near the cutting edge and the back surface of the tool from wear. Thus, wear-resistant coating, restraining the growth of the hole in the zone of chip separation from the front surface, allows for a long time to provide favorable conditions for the flow of the blade around the processed material, to maintain a more rational form of the stagnant zone and thereby increase tool life.

Obviously, the first and second mechanisms discussed above for improving wear resistance when machining hardened steels and other difficult-to-work materials cannot be implemented, since in this case there is a destruction of the coating in the contact zone in the initial cutting period [6]. This is evidenced by the results of numerous studies of the wear of tools with PVD coatings of various chemical compositions obtained by the vacuum-arc method [2, 7–11]. At the same time, we did not find any information about the opposite results in the publications.

Speaking about the mechanism of the effect of coating on reducing the wear rate of tools with superhard composites, it is necessary to consider the effects associated with the optimization of the conditions of contact interaction in the cutting zone. In [12], the concept of increasing the wear resistance of cutting tools with PSHM (polycrystalline superhard materials) was proposed, based on reducing the temperature in the contact cutting zone by applying an amorphous-crystalline coating-solid lubricant to the working surfaces of the tool, reducing the friction coefficient. The effect of the formation of a solid lubricant can also be obtained with the help of self-adaptive coatings [13, 14], when polyoxide films having good lubricity are formed in the contact zone under the conditions of the cutting process.

The purpose of this study was to analyze the concept of the effect of protective PVD coating on the wear rate of a PSHM tool when cutting hardened steel, as well as evaluating the effectiveness of such a coating.

Experimental studies

Testing of tools for durability was carried out at finishing turning of steel HVG with hardness of 52–54 HRC at $v = 100$ m/min, $S = 0.10$ mm/rev, $t = 0.20$ mm. The size of the chamfer of wear on the flank face of the tool after each pass was measured using a microscope mounted on the bed of the lathe. Error estimating the width of the flank wear chamfer is ± 4 microns.

The cutting tools had a rake angle $\gamma = -10$ °. In experiments on the study of comparative durability, wear kinetics and morphology of worn-out areas of the tool, the Borsinit PSHM cutting plates RNUN-070300 (PCBN) were used.

For research, we chose a nanolayer PVD coating of the composition (TiAlSiY)N/CrN, which was applied by vacuum arc spraying on a modernized BULAT-6 unit. Before coating, ion plates were cleaned in a nitrogen gas plasma followed by spraying of a chromium underlayer (50 nm). The coating is nanolayer: period ~ 20 nm, total thickness – 5 microns. The hardness of the coating when measured with a "Micron-gamma" [15] nanohardness tester by the Berkovich pyramid with a load of 50 g is 31.4 ± 1.2 GPa, the Young's modulus is 356 ± 17 GPa.

The parameters of the craters on the rake face of the tool were determined using a "Micron-alpha" [16] instrument. The topography of the worn area of the tool from the flank face was fixed using an RT-10 digital profilograph. A comparative analysis of the wear kinetics shows that under the test conditions, the coating significantly reduces the tool wear rate on the flank surface: within 24 minutes of the cutting time, the maximum h_z value of modified tools is 3.2 times less
(Fig. 1).

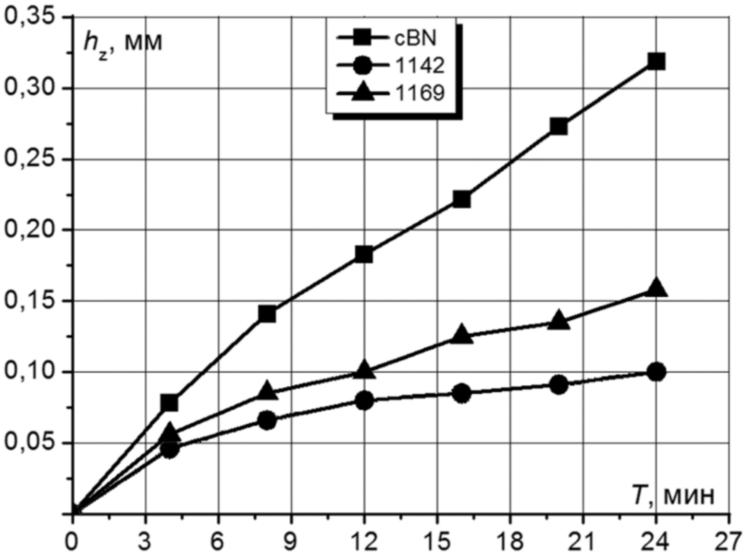


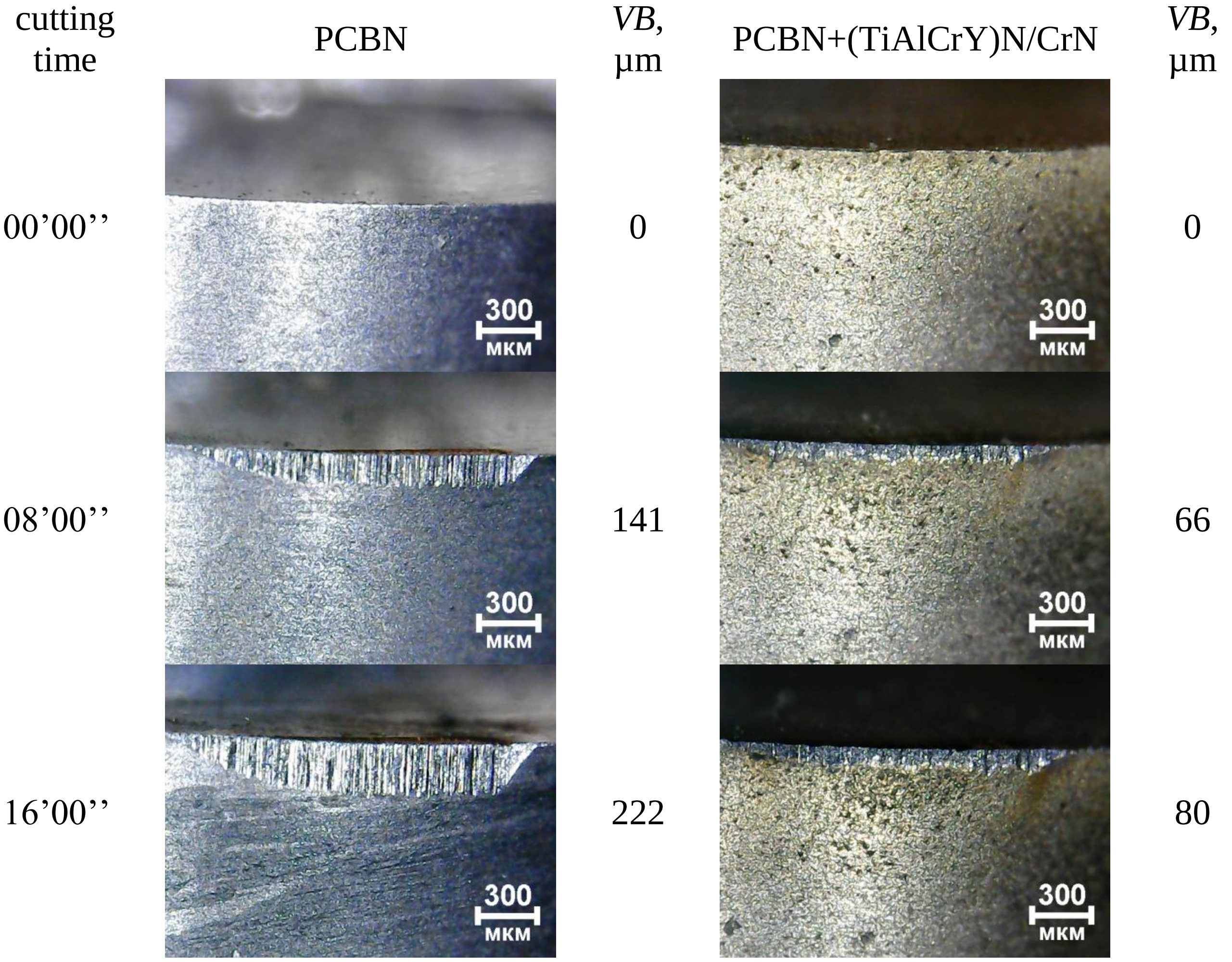
Figure 1. Tool wear kinetics: – □ - without coating, – ○ - with coating; – Δ- coated on flank face only

The morphology of the worn areas of the coated tool (Fig. 2) has certain features: the chamfer width on the flank surface of the coated tool varies along the length of the edge, and the peripheral (distal from the cutting edge) edge of the chamfer has a developed «notched» shape, which indicates instability friction conditions at various points in the contact zone. Specified, probably due to the relatively high surface roughness of the coating, which leads to instability of interaction in the areas of plastic contact.

To answer the question about the causes of a decrease in the intensity of tool wear in the presence of a coating, let us consider the state of the contact surfaces of the tool after machining. In fig. 3 the holls on the front surface of the tool are shown. Although visually noticeable changes in their shape in length, no significant quantitative differences have been identified. The width of the crater after 20 minutes of cutting is ~ 100 microns, depth close to 30 microns. Additional tests in which tools were used, on which the coating from the front surface was ground, showed only a slight increase in the intensity of their wear (Fig. 1).

This allows us to conclude that a coating of this type on the front surface of the instrument has little effect on the contact phenomena in the area of the instrument from the rear surface.

According to Yu.N. Vnukov «under cutting conditions with thin sections and high speeds, the application of films on the back surface contributes significantly to the tool's wear resistance. In this case, the increase in durability is promoted by the intrinsic wear resistance of the film in the region of unstable friction, i.e. in the zone of separation of the cutting surface from the rear face». It is obvious that the role of the coating in the peripheral contact zone, i.e., in the zone of separation of the cutting surface from the back surface of the tool can be significant only with a small width of the wear facet. With increasing *VB*, the relative area of the contact zone of the tool, covered by the film, decreases (Fig. 4, *a*). Maximum contact loads are localized near the cutting edge. On the same area of the contact surface, the maximum intensity of the hearths of microfracture of the tool's surface occurs when it interacts with the material being processed, elastically-plastic-molded underside. In this regard, it is difficult to explain how a narrow portion of the film, covering only about 20% of the entire contact area already at *VB* = 0.15 mm and located at a considerable distance from the main source of damage, can significantly affect the wear rate of the back surface of the tool.



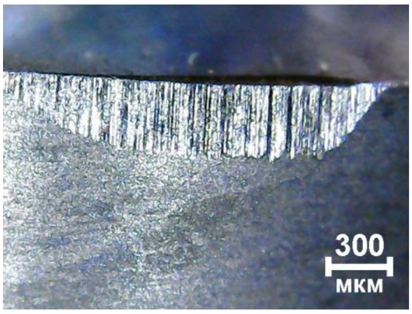
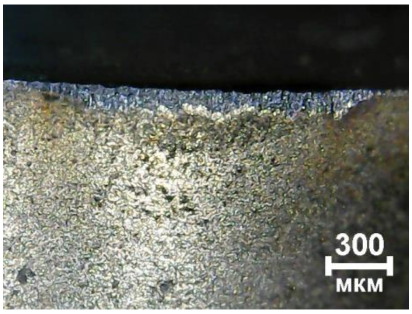
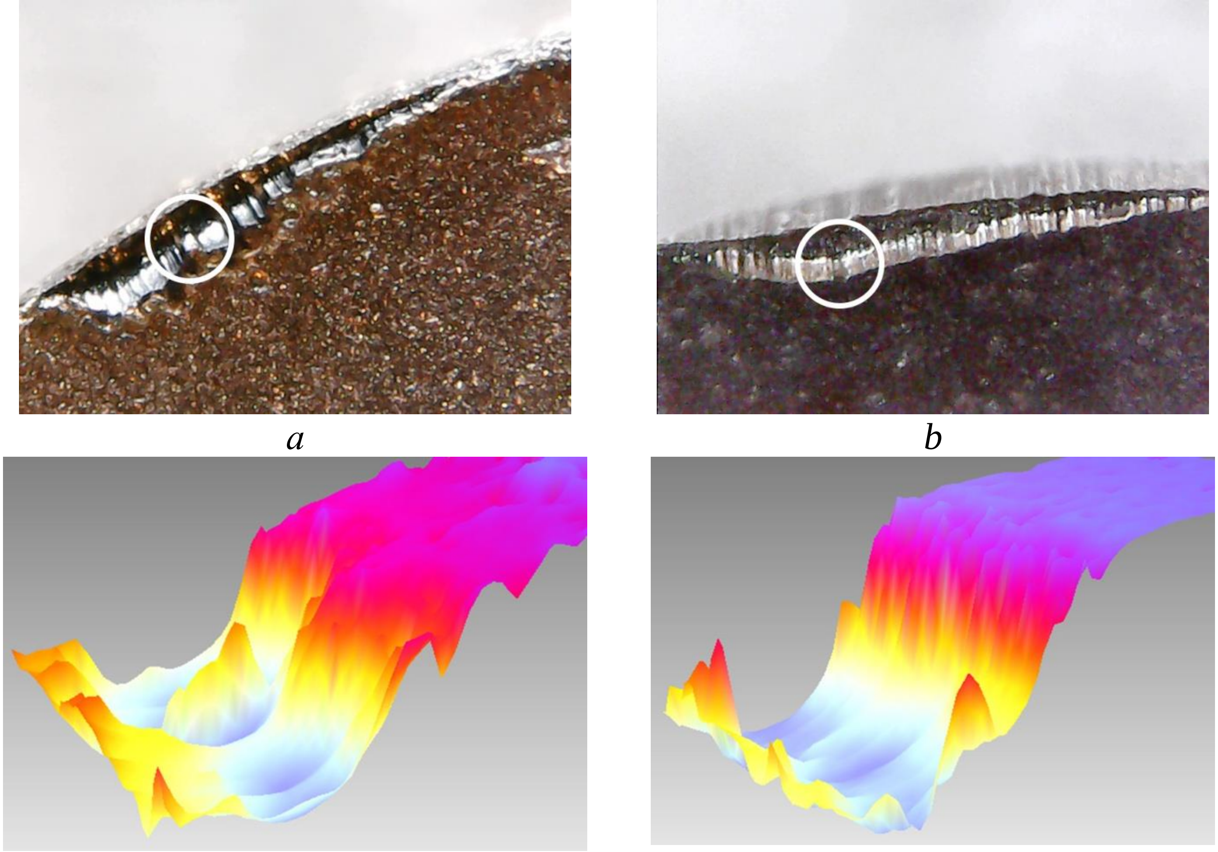
24’00’’		319		100

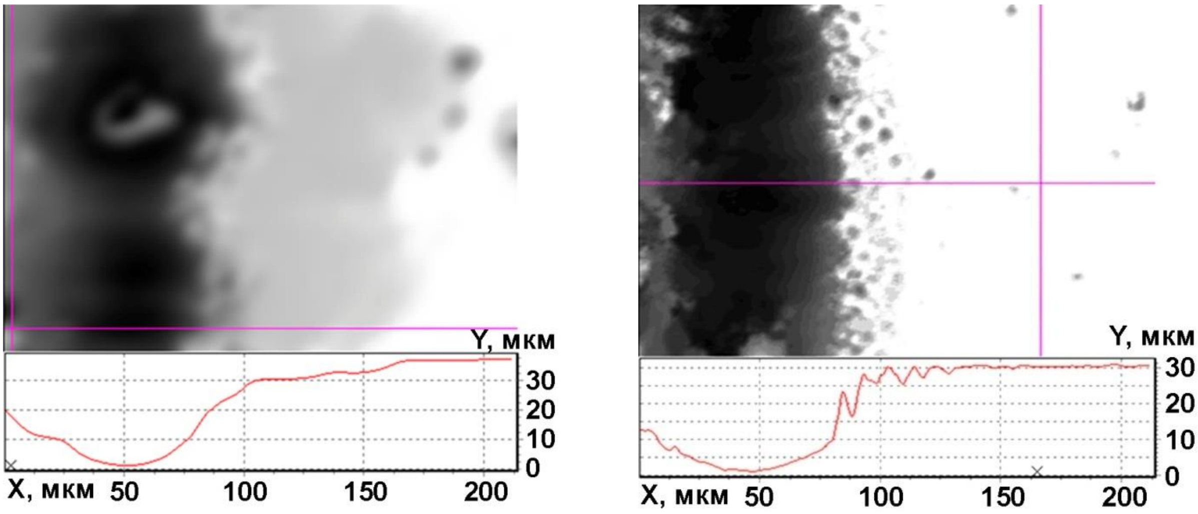
Figure 2 – Worn areas of the tool from the back surface at different points in time

Dependence in fig. 4, *a* reflects the change in the area of the contact area with an idealized variant of wear, which is possible only in the case of coating, which forms a wide transitional zone with a topography that does not differ from the worn areas of the contact area directly with the base (Fig 4, *b*, *c*). It should be noted that the CrN/MoN coating, which is characterized by such a worn area morphology, under the conditions of our experiments did not have a significant effect on the tool wear rate.



a *b*

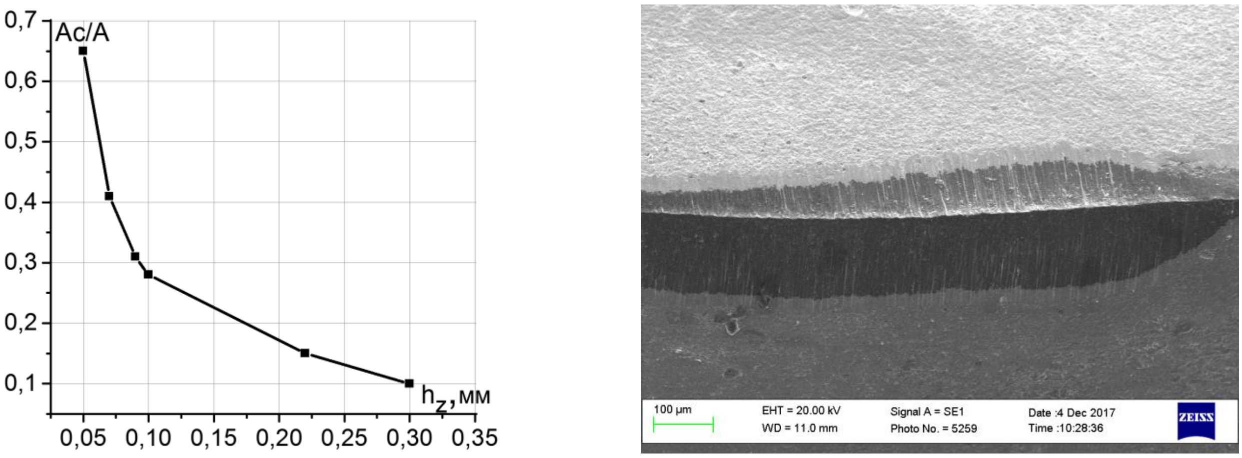
c *d*



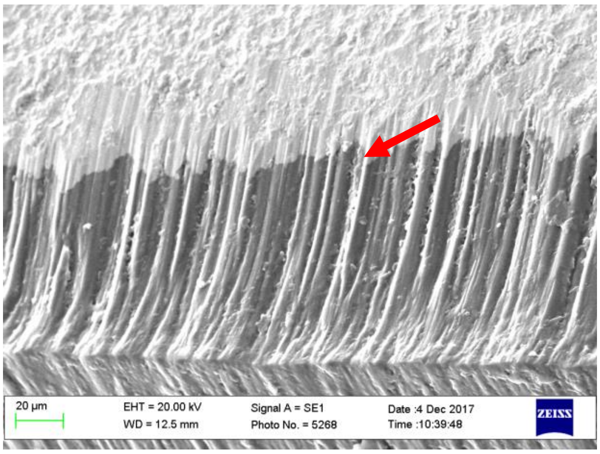
e *f*

Figure 3. Topography of the front surface of coated tools (*a*, *c*, *e*) and without (*b*, *e*, *f*). 3-D image of the hole on the front surface of the tool (*c*, *d*), the profile of the hole in the radial section (*e*, *f*)

The key to understanding the reasons for the increase in tool life can be an analysis of wear chamfer images on the back surface (Fig. 5). The analysis shows the presence of adhered layer on the contact areas. According to X-ray microanalysis of worn-out contact areas, the iron content in the secondary phase on a coated tool is significantly higher – from 38 to 84%, while on an tool without a secondary phase coating that includes iron is significantly less –- up to 30%. It can be assumed that the layer of the secondary phase on the contact surface is directly related to the wear rate of the tool.



a *b*



c

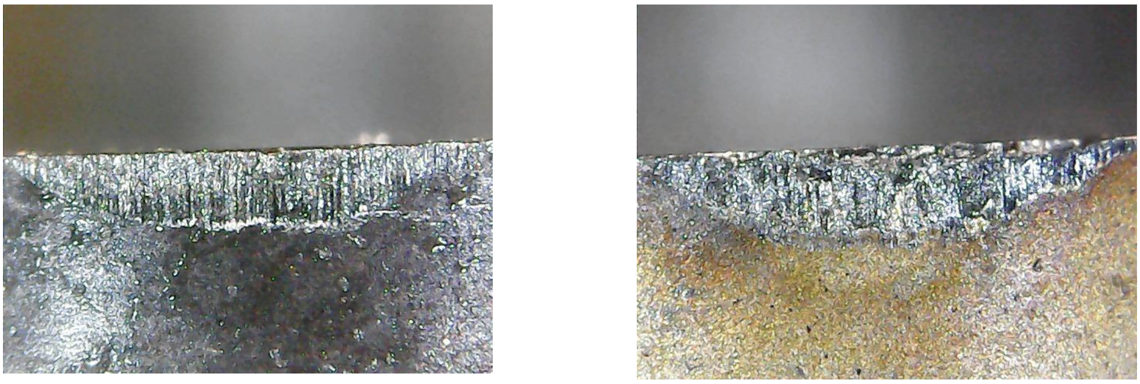
Figure 4. Dependence of the ratio of the area occupied by the coating to the total area of the contact zone on the back surface of the tool (*a*) on the value of *VB*; worn contact areas of the composite with CrN/MoN coating (*b*, *c*)

Let us estimate the stress-strain state of the material being processed in this zone for both types of tools. To do this, we use the topography parameters of the worn contact area of the tool from the back surface, estimated according to the scheme shown in Fig. 6, *a*.

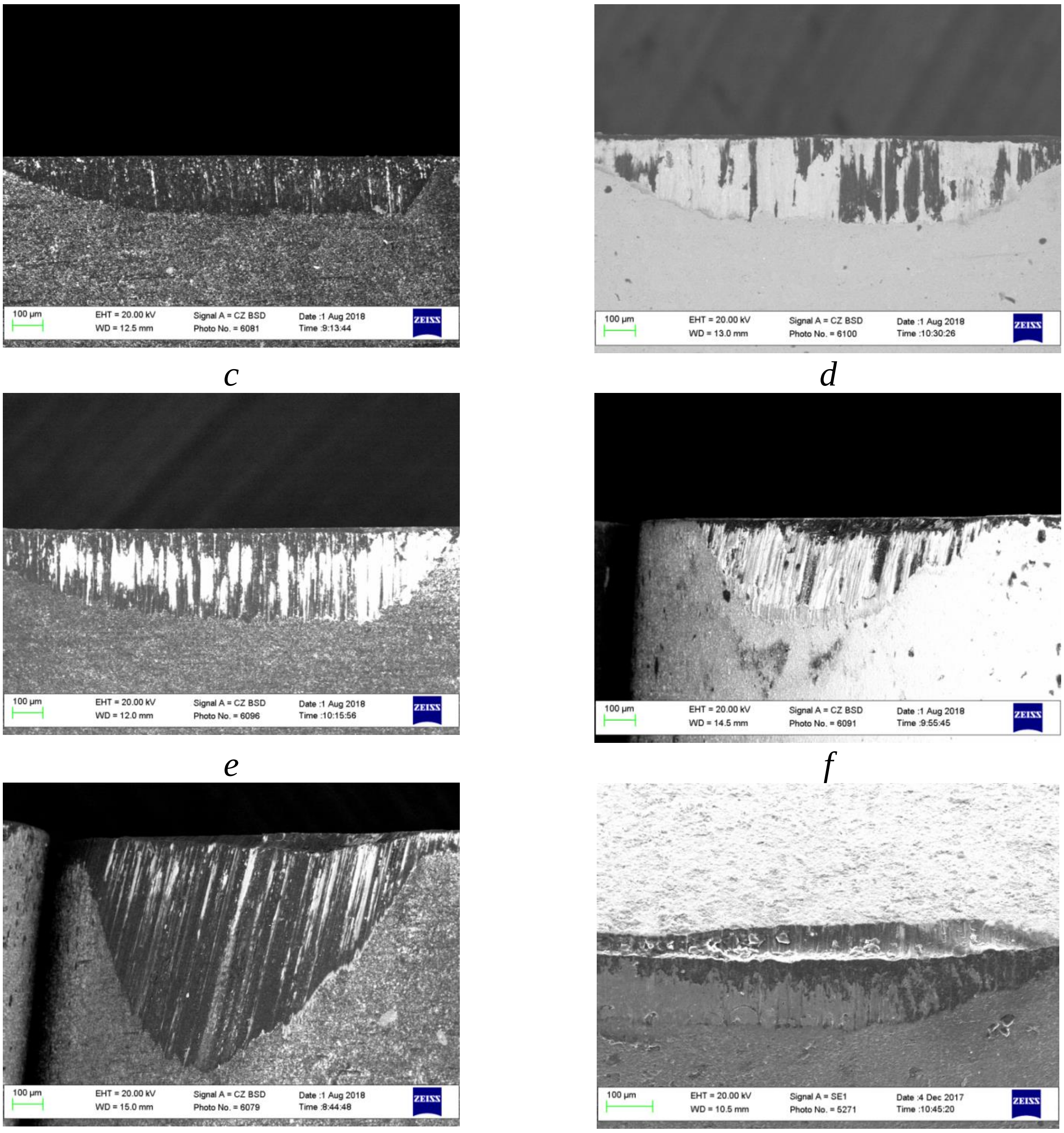
In fig. 6, *b*-*e* the flank wear profiles of the tool with (TiAlSiY)N/CrN and without coating, formed during the turning of the HVG steelare shown. Worn sections of the coated tool are characterized by a developed profile shape in cross section, which is partly explained by the presence of a secondary phase on the surfaces and irregularities in the transition zone from the worn area to the free (side) surface of the cutting tool, which was also observed in electron microscopic studies (Fig. 6, *f*).

These differences in the topography of contact areas indicate the presence of certain changes in the course of thermomechanical phenomena that accompany frictional interaction in this zone. Let us estimate the stress-strain state of the material being processed in the cutting zone. For comparison, we use cutters with a flat wear surface and a surface with asperity of 1 micron in height on the periphery of the contact zone to take into account the real geometry of the wear area with a length of *VB* = 60 microns.

For the accepted cutting conditions, parameters of the stress-strain state of the material being processed and the temperature in the contact zone under the back surface of the tool (calculated data: $\varepsilon = 1.8–2.4$; $\dot{\varepsilon} = 2500$; $T = 420–450$ °C), yield strength (in accordance with the model adopted for the material being processed) is 1200–1250 MPa.



a *b*



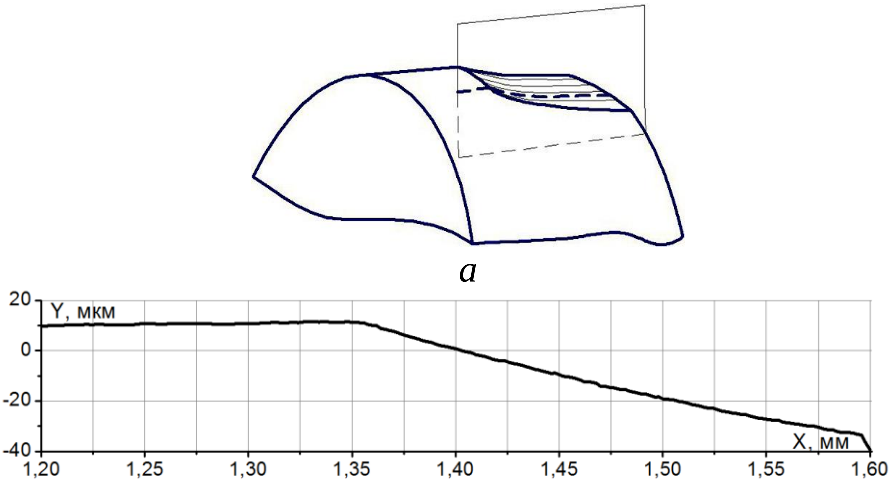
c *d*

e *f*

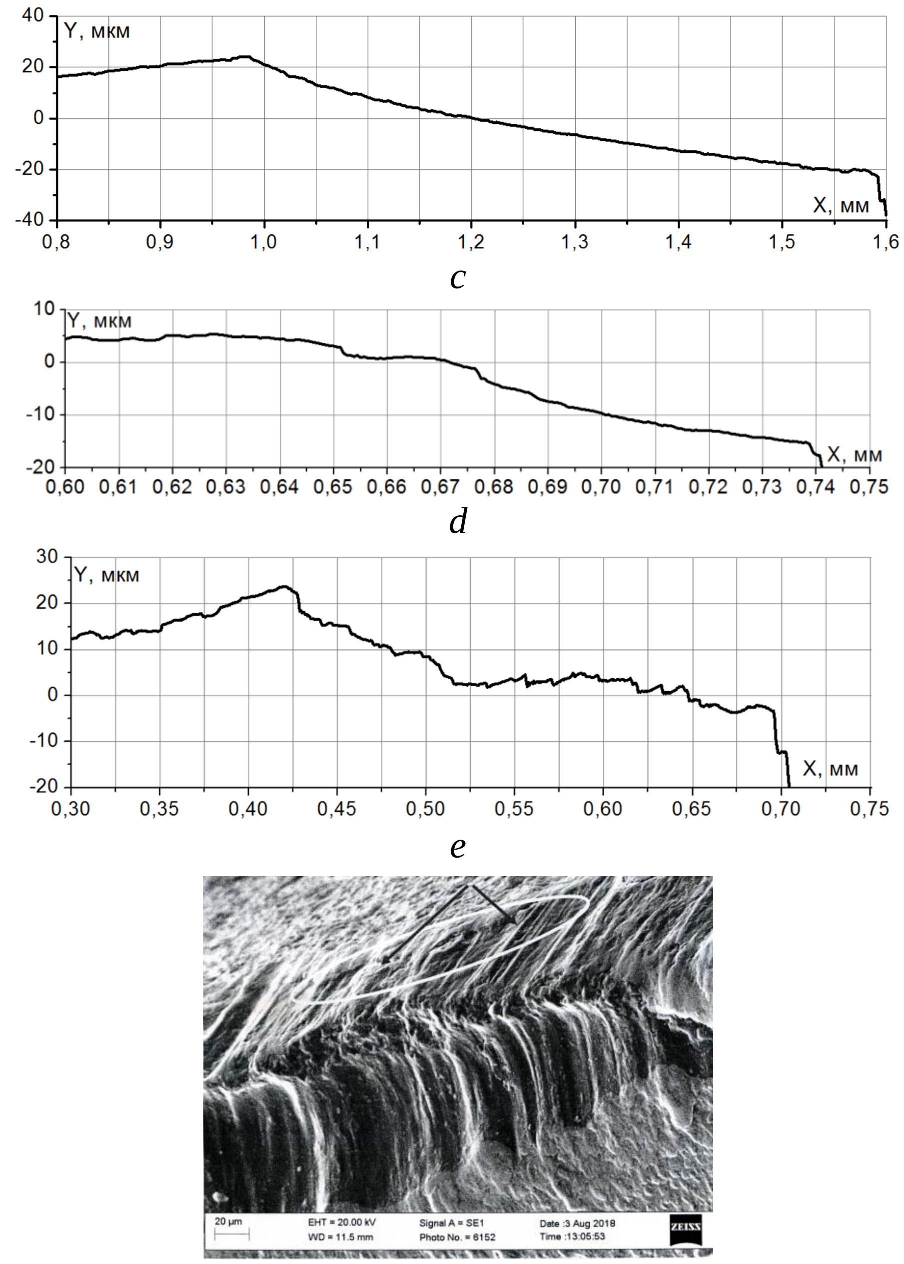
g *h*

Figure 5. Morphology of worn areas of the back surface of the tool (*a*, *c*, *e*, *g*) – without coating; (*b*, *d*, *f*, *h* – with coating)

The value of equivalent stresses exceeding this range characterizes the material being processed in a state of plastic flow.



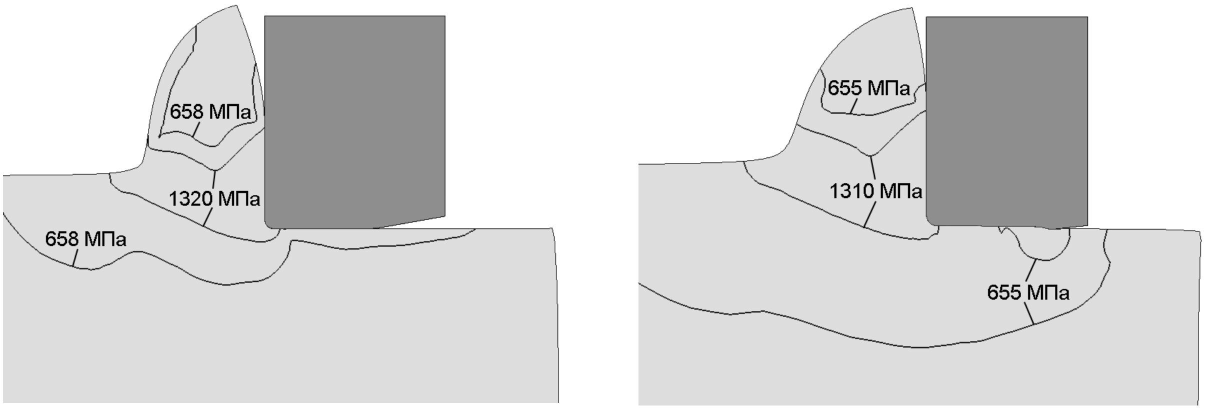
b



f

Figure 6. Section of the cutting plate in which profilometry was carried out (*a*), profile of the chamfer wear on the flank surface: *b* – tool without coating, cutting time 20 minutes; *c* – uncoated tool, cutting time 40 minutes; *d* – coated tool, cutting time 20 minutes; *e* – coated tool, cutting time 40 minutes; *f* – micro irregularities on the periphery of contact area.

Obviously, the above calculation cannot give an accurate picture of the processes that are going on, but at a qualitative level it allows to draw certain conclusions. Evaluation of stress isolines along the contact area shows the possibility of plastic flow of the material being processed not only in the zone adjacent to the cutting edge (Fig. 7, *a*, *b*), but also in the areas where elastic-plastic and elastic interaction is usually observed (Fig. 7, *b*). In case of friction under plastic deformation, the density of heat sources is higher in comparison with external friction. This causes an increase in the contact temperature, which, in turn, softens the processed material and further contributes to its transition to a plastic state.



а *б*

Figure 7. Isolines of equivalent stresses in the material being processed: *a* – when cutting with an uncoated tool; *b* – when cutting with a coated tool

In such conditions, one should expect the presence of a metal layer in the state of plastic flow along the entire contact length, the layers of the material being processed form a sticking zone stuck to the cutter surface. With sufficient thickness, such a layer of adhered processed material, in which plastic flow occurs, can significantly reduce the intensity of the abrasive effect on the tool surface and, accordingly, its wear rate by an abrasive-mechanical mechanism.

CONCLUSIONS

Testing the tools with nanolayer PVD coating of the composition (TiAlSiY)N/CrN for durability during finishing turning of steel HVG with a hardness of 52–54 HRC shows that the coating significantly reduces the wear rate of the cutting tool on the back surface: in 24 minutes the total cutting time the maximum *VB* value of the modified the tool is 3.2 times smaller.

The absence of significant differences in the shape of the crater on the rake surface allows us to conclude that the coating on such a surface has little effect on the contact phenomena in the area where the tool interacts with the chips.

Under the conditions considered, when turning hardened steel on the worn surface of the tool from the flank surface, a secondary phase is observed. At the same time, the amount of adhered material is significantly higher than on an uncoated tool.

Worn areas on the back surface of the coated tool are characterized by a developed profile shape in cross section, which is partly explained by the presence of a secondary phase and unevenness in the transition zone from the worn area to the free (side) surface of the tool.

Evaluation of the results of the simulation of cutting with the coated tool shows the possibility of plastic flow of the material being processed not only in the zone adjacent to the cutting edge, but also in areas where elastic-plastic and elastic interaction is usually observed. Under such conditions, one should expect the appearance of a metal layer in the state of plastic flow along the entire contact length. The formed hindered zone can significantly reduce the intensity of the abrasive effect on the tool surface and, accordingly, its wear rate by the abrasive-mechanical mechanism.

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