The efficiency of diamond-like coatings for increased wear resistance of end mills at the machining aluminum alloys

S N Grigoriev, M A Volosova, S V Fedorov, A A Shein, M A Zykova and N Kapustina

Department of High-Performance Processing, Moscow State University of Technology “STANKIN”, 127055 Vadkovsky per. 1, Moscow, Russia

E-mail: volosova1978@gmail.com

Abstract. The efficiency of diamond-like carbon (DLC) coatings deposited by CVD- and PVD-technologies to increase the wear resistance of tungsten carbide end mills for aluminum alloy processing was experimentally studied. A complex of metallophysics studies was carried out including SEM analysis of coating surface, microrelief, a ratio between sp3- and sp2-bonds, and the microhardness of coatings obtained by nanoindentation. The final stage of the research addresses the operational testing of end mills during processing of high-strength aluminum alloy AlZn5.5MgCu.

1. Introduction

At the current stage of development of the aerospace industry, aluminum alloys are the main engineering materials from which parts for functional applications are manufactured. High-speed CNC multi-axis machines and tungsten carbide end mills are used for processing of such alloys [1]. Cutting tools must ensure maximum productivity and durability throughout the entire operating life.

Wear-resistant coatings are widely used in industry to improve the performance of cutting tools and ensure the required quality of products [2, 3]. Among the well-known coatings of separate interest are DLC coatings containing carbon atoms with diamond (sp3) and graphite (sp2) bonds [4, 5].

In this research, we have studied two well-known technologies used in the industry for the deposition of DLC coatings on cutting tools - chemical vapor deposition (CVD) and physical vapor deposition (PVD). The main purpose of the study was to compare two DLC coating deposition technologies to study the characteristics of coatings and their influence on the wear resistance of carbide end mills during aluminum alloy processing. The experiments were performed on the basis of the Collective Use Centre MSUT “STANKIN”.

2. Experimental materials and specialized technological equipment

In the present study, the end mills with a diameter of 6 mm were used in the experiments; tool material was a tungsten carbide MC241 (WC=92%); material to be processed was high-strength aluminum alloy AlZn5.5MgCu (Al=88%) with the material strength of 520 MPa and hardness of 150 MPa.

Two types of industrial technologies CVD and PVD were used for the deposition of DLC coatings on tungsten carbide end mills. Principle schemes of used vacuum process equipment based on CVD- and PVD-technologies are shown in figure 1:

1) Technological equipment (model PLATIT PI311) based on CVD-process (figure 1(a)).
2) Technological equipment (model ViT DLC) based on PVD-process (figure 1b).

![Figure 1](image.png)

**Figure 1.** Schemes of technological equipment for DLC coating deposition based on different physical principles: CVD (a) and PVD (b).

CVD technology based on the synthesis of DLC coatings with a thickness of 1.5–2 µm is carried out by means of chemical vapor phase deposition on a carbide substrate. Synthesis of DLC vapor phase contains hydrocarbon mixture C\(_2\)H\(_2\) and (CH\(_3\))\(_4\)Si, which is subjected to thermal degradation. To reduce the level of internal stresses in the DLC coating and improve the adhesion bond with the hard alloy substrate before coating deposition, a nitride sublayer based on (CrAlSi)N 1.5–2 µm thickness was formed (this nitride layer is formed by a standard PVD process). For this purpose, the equipment is provided with cylindrical cathodes of Cr and AlSi alloys.

PVD technology is based on the deposition of DLC coatings with a thickness of 1.5–2 µm from carbon plasma, which is generated by impulse source with a graphite cathode in high vacuum conditions. Before coating, the adhesive layer based on Ti was deposited on a hard alloy substrate. The equipment is provided with a special filter in the form of a jalousie to eliminate the specific problem of microdroplets formation at coating.

3. Complex studies of the structure and properties of DLC coatings deposited by CVD- and PVD-technologies

A complex of metallophysics studies was carried out to determine the differences between DLC coatings deposited by CVD- and PVD-technologies.

SEM images of DLC coatings provide an overview of surface morphology (figure 2). It can be seen that the CVD-process provides the formation of a heterogeneous surface containing sufficiently large microparticles. The surface of the coating formed in the PVD-process is much more homogeneous, it shows only typical scratches from the previous abrasive treatment (such scratches are observed on the hard alloy mills before coating).

The results of the study of the microrelief of the sample’s surface on the profilometer are shown in figure 3. It can be seen that the CVD-process provides the formation of a coating with higher roughness. The maximum microroughness height of CVD-coatings is 1.3 µm, for PVD-coatings is no more than 0.7 µm. It is evident that microparticles formed during the CVD-process create increased surface roughness. It is important to supplement that similar surface morphology was observed at different technological conditions of CVD- and PVD-processes (i.e. it is the specificity of technological processes).

Analysis of sp\(^2\)/sp\(^3\) ratio in DLC-coatings was carried out using Raman confocal spectroscopy. The wavelength of the laser when irradiating samples was 550 nm. Raman spectra were decomposed into
two Gaussian components – G and D, which are located in the areas of 1580 cm\(^{-1}\) and 1380 cm\(^{-1}\), respectively (figure 4). The ID/IG ratios were also calculated. According to these results, it is possible to conclude about the qualitative composition of coatings.

**Figure 2.** SEM-images (x1000) of the surface of DLC coatings deposited using various technologies: CVD (a) and PVD (b).

**Figure 3.** Surface profiles of tungsten carbide end mills with DLC coatings deposited using various technologies: CVD (a) and PVD (b).

The hardness of DLC-coatings on carbide samples was determined by nanoindentation using a Berkovich diamond indenter.

At the final stage of research, the coated carbide end mills were subjected to durability tests. The tests were performed on DMC 635V machining center at the following conditions: rotational speed of 10 000 min\(^{-1}\); feed speed of 1500 mm/min; feed per tooth of 0.037 mm/tooth; milling width of 5 mm; milling depth of 0.6 mm. The wear of the end mills was measured repeatedly after 35 technological transitions. Wear was measured on the cylindrical part of the end mills. Information on the evolution of wear on the surface of carbide end mills with DLC-coatings is shown in figure 5.

### 4. Results and discussion

Figures 2 and 3 show marked differences in morphology of DLC coatings. It is explained by fundamentally different physical and chemical phenomena that underlie the CVD and PVD processes. In the PVD-process, the original material of the cathode is converted into a vapor phase, which is similar in composition to the coating. Under high vacuum conditions, the particles move to the substrate without intermediate impacts. Plasma flow generates favorable temperature conditions on the surface and provides the formation of homogeneous coating at a sufficiently high growth rate.

In the CVD process, the growth rate of the coating is slightly lower, and gases are used as the initial material. The composition of the gas phase and formed coating differ significantly. This process
is accompanied by more complex physical and chemical phenomena in the growth phase of the DLC. The coating is formed from gaseous hydrocarbon components and particles. Some of the particles are coagulated, and the coating has a heterogeneous structure.

Figure 4. Raman spectra of DLC coatings deposited on carbide samples using various technologies: CVD (a) and PVD (b).

Figure 5. Wear dynamics of tungsten carbide end mills with DLC coatings at the machining of aluminum alloys.

The results of Raman spectroscopy show significant differences in coatings (figure 4). In particular, the intensity of Raman spectra for CVD deposited coatings is in 1.7–2 times higher than the
corresponding value for PVD. It was detected that with changes in particle size in the coating structure, the intensity of Raman spectra changes significantly. The values of the registered spectra (Raman shift) are conventional for DLC coatings [5, 6]. The reputable studies demonstrate that as the ID/IG ratio increases (approaching 1), the percentage of the sp³-phase in the DLC coating decreases, therefore, the increased graphite content in the coating [7]. Surprisingly, the coatings produced in this study have a similar ID/IG ratio: 0.43 for coatings deposited using CVD and 0.38 by PVD.

The study of microhardness of DLC-coatings by nanoindentation showed their significant differences. Maximum microhardness values (up to 48 GPa) were detected in samples with PVD coatings. The value of surface microhardness of samples with CVD coatings is not more than 38 GPa. As the depth of the indenter penetration into the PVD coating surface increases, the microhardness sharply decreases. At a depth of about 0.8 µm, the microhardness value is practically equal to the hardness of the end mills. The microhardness of the end mills coated by CVD is gradually reduced from surface to core (tungsten carbide). It is obvious that the deposition of the sublayer (CrAlSi)N before the DLC coating provides a positive effect. The indirectly mentioned above indicates that PVD coatings are in a more complicated state of stress than CVD.

The above-described features of the DLC coatings could not but influence the durability of cutting tools. It was found that with the increase of cutting time (technological transitions) the effect of DLC coatings application becomes more remarkable. Differences in the wear rate of end mills with different DLC coatings are noticeable: the wear rate of end mills with CVD coatings is in 1.2–1.4 times less than that of end mills with PVD coatings (figure 5). Compared to uncoated tungsten carbide end mills, DLC coating deposition reduces the wear rate by up to 2.7 times.

5. Conclusions
It can be argued that DLC coating is an effective technological method to reduce the wear rate of end mills when machining aluminum alloys. Undoubtedly, the coatings have a positive effect on the surface quality of machined aluminum alloy parts, but this should be the subject of individual studies.

It was determined that despite the higher surface roughness and heterogeneous structure of the DLC coating formed by CVD process, this does not show any negative impact on the stability of the end mills. In our studies, these coatings provided a more noticeable effect than the PVD coating. It is important to understand that this conclusion cannot be applied to small-sized end mills.

It was demonstrated that the characteristics of DLC coatings differ significantly with the same ratio of Gaussian components (ID/IG). It seems promising to develop the research in the direction of the stress state reduction of DLC-coatings by alloying various elements, as well as the formation of intermediate sublayers.

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