Application of nanostructured Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings for improvement of tool life and performance in end milling of carbides

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Abstract. The paper deals with the challenges of improving the tool life of end mills and performance in end milling of carbides through application of tools with the nanostructured Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings, deposited using the filtered cathodic vacuum arc deposition (FCVAD) technology. The main mechanical characteristics of the above coatings (microhardness and critical fracture load) were determined. The cutting properties were investigated at mill rotation frequency of n = 1250, 1600, 2000 rpm. Samples were compared with uncoated tools and with tools with commercial coatings, including monolayer Ti-TiN and nanostructured Ti-TiN-(Ti,Al)N coatings. The studies have proved that the proposed coatings are not only able to improve the tool life, but they also allow milling at higher mill rotation frequency, and, consequently, with higher performance of milling. Meanwhile, tools with the Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings are characterized by more balanced pattern of wear, without visible signs of brittle fracture.

1. Introduction

Due to the combination of a range of useful properties, titanium alloys are widespread in such areas of modern mechanical engineering as aerospace industry, engine manufacturing and a number of others. Meanwhile, titanium alloys belong to a group of hard-to-cut materials due to their high strength, toughness, oxidability and low thermal conductivity [1-3]. One of the obvious ways of improvement is a further increase in cutting speed, and that is associated with certain difficulties, since modern tool materials commonly used in the manufacture of end mills (mainly carbides) have reached their upper limit in terms of heat resistance [4].

There are a number of papers investigating the effect of different wear mechanisms on cutting tools and the ways for further improvement of the performance in end milling of carbides [5-12]. The use of wear-resistant coatings with multilayer architectures and multi-component compositions in milling titanium alloys can improve the tool life and cutting performance. In particular, the (Ti,Al)CN-VCN [13], (Ti,Al)N-TiN [14], TiN-TiC-TiCN [15], (Al,Ti)N-Si₃N₄ and (Al,Cr)N-Si₃N₄ [16], (Al,Ti)N and (Ti,Al,Cr)N [17], (Al,Ti)N-WN, (Al,Ti)N-MoN, (Al,Ti)N-CrN, (Al,Ti)N-VN and (Al,Ti)N-NbN [18], as well as (Al,Ti)N [19] coatings were considered. It was noted that coatings failed mainly because of the brittle fracture, plastic deformations and interlayer delaminations [15], while adhesive-fatigue, diffusion, and oxidation wear mechanisms were in general typical for coated tools [16, 18, 19].
There are two factors that influence decrease in the tool life:
• the presence of active processes of interdiffusion between the coating material and the material being machined, especially intensifying at high temperatures in the cutting zone;
• the formation of strong adhesive bonds between the material being machined (titanium alloy) and the titanium-containing coating.

Based on the above, it can be assumed that the use of wear-resistant coatings with high performance properties, containing no titanium in their compositions, will further increase the tool life in machining of titanium alloys. Multilayer nanostructured Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings which showed their high performance in machining various materials [20-29] were used as coatings for cutting tools in end milling of titanium alloys. The tools with commercial Ti-TiN and (Ti,Al)N coatings and the uncoated tools were used as reference samples.

2. Materials and experiments

The coating was deposited at the VIT-2 (MSTU STANKIN-IKTI RAN, Moscow, Russia) unit using the technology of filtered cathodic vacuum arc deposition (FCVAD) [30-33]. A workpiece of VT20 titanium alloy (Al 6%, V 2%, Zr – 2%, Mo – 1.5%), widely used in aircraft engineering was machined. VT20 alloy is a typical alloy with a low content of isomorphic p-stabilizers within their solubility in the α-phase. The volume of the residual β-phase is insignificant. The cutting tests were carried out under the following cutting conditions: \( f_z = 0.11 \) mm/tooth, \( a_p = 1 \) mm, with the mill rotation frequency of \( n = 1250 \) rpm, \( n = 1600 \) rpm, and \( n = 2000 \) rpm. \( V_{B_{\text{max}}} = 0.4 \) mm was assumed as a wear criterion. An end mill of R300-016B20L-08L with carbide inserts (R300-0828Z-PM 1130) (Sandvik Coromant, Sweden) was used.

3. Results and discussions

The monolayer TiN coating has a total thickness of about 4 µm. Nanostructured Ti-TiN-(Ti,Al)N, Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings with three-layer architecture also have thicknesses of about 4 µm. The thicknesses of the nanolayers in the wear-resistant layer of the above coatings stay within the range of 60-100 µm (Fig. 1).

![Figure 1. The microstructure of the coatings under study (SEM)](image)

The results of the cutting tests at mill rotation frequency of \( n = 1250 \) rpm, \( n = 1600 \) rpm and \( n = 2000 \) rpm are presented in Fig. 2.
Following the analysis of the data obtained through the study of the cutting properties, it can be concluded that tools with the nanostructured coatings under study are not only characterized by a noticeably longer tool life compared to uncoated tools and tools with Ti-TiN coatings, but they also allow machining at a higher mill rotation frequency with higher performance. Meanwhile, the longest tool life at all mill rotation frequencies and the least intensive decrease in the tool life with an increase in mill rotation frequency was shown by the tool with the Zr-ZrN-(Zr,Cr,Al)N coating.

To understand the reasons for the high cutting properties of the tools with nanostructured coatings, let us consider the pattern of tool wear at mill rotation frequency of \( n = 1600 \) rpm. As known, failure of carbide tools occurs because of parallel mechanisms of abrasive, adhesive-fatigue, oxidation and diffusion wear. Let us consider the wear pattern on uncoated carbide tools and carbide tools with the proposed coatings after 12 min of cutting (Fig. 3).

It can be seen that the development of wear centres on the tools with nanostructured coatings proceeds significantly slower compared to the uncoated tools and the tools with the Ti–TiN coating. Meanwhile, the uncoated tools and the tools with the Ti–TiN coatings showed signs of chipping of the carbide substrate, while no such signs were noticed on the tools with the proposed coatings.

Let us consider the nature of failure for the tools with the coatings under study in a plane passing perpendicular to the cutting edge, approximately in the centre of the cutting zone. The tool with the Ti–TiN coating (Fig. 4a) shows signs of brittle fracture with the formation of a series of longitudinal cracks. Such a pattern of cracking is usually typical for the adhesive-fatigue mechanism of wear [26]. The nature of failure for the Ti-TiN-(Ti,Al)N coating (Fig. 4b) with the nanolayer architecture is very close to the above considered nature of failure for the Ti–TiN coating. Here it is also possible to see an example of brittle fracture with extensive longitudinal cracks, in this case also combined with delaminations between the nanolayers. Such nature of failure also indicates the predominance of adhesive-fatigue processes. When considering the tool with the Zr-ZrN-(Zr,Al)N coating (Fig. 4c), it is possible to see noticeable differences in the nature of failure for this coating and the coatings considered above. This coating shows no pronounced brittle fracture. The interlayer delaminations formed in the coating structure indicate the presence of adhesive-fatigue wear processes, but these processes are less pronounced than those on the tools with the coatings considered earlier. Based on the pattern of wear, we can assume in this case the predominance of the mechanisms of abrasive, oxidation and diffusion wear. A similar pattern of failure is observed for a tool with the Zr-ZrN-(Zr,Cr,Al)N coating (Fig. 4d). The tool with this coating showed the longest tool life at all mill

![Figure 2. Relation between the tool life and the mill rotation frequency in end milling of VT20 carbide (\( f_z = 0.11 \) mm/tooth, \( a_p = 1 \) mm)](image)

![Figure 3. Wear patterns for contact pads of carbide inserts after 12 min of milling at \( n = 1600 \) rpm, \( f_z = 0.11 \) mm/tooth, and \( a_p = 1 \) mm)](image)
rotation frequencies. In this case, there are only minor delaminations, while no traces of chipping and brittle fracture of the tool are registered. The tool life is limited only by flank wear, which in this case is quite balanced. It can be concluded that the tool with the Zr-ZrN-(Zr,Cr,Al)N coating showed not only the longest tool life, but also the most favourable wear pattern in terms of predicting the cutting properties.

![Images of wear patterns](image)

**Figure 4.** The pattern of wear on the tool with coatings

4. Conclusions

Thus, following the result of the study of the cutting properties and the patterns of wear for carbide end mills with the nanostructured Ti-TiN-(Ti,Al)N, Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings, as well as the monolayer Ti-TiN coating, the following conclusions can be drawn:

- The use of wear-resistant coatings does not only contribute to significantly improvement of the tool life, but also enhances the cutting performance by increasing the mill rotation frequency.
- The tools with the nanostructured Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings containing no titanium in their compositions showed the longest tool life at all mill rotation frequencies not only compared to the tool with the monolayer Ti-TiN coating, but also to the tool with the nanostructured Ti-TiN-(Ti,Al)N coating.
- The patterns of wear for tools with the nanostructured Ti-TiN-(Ti,Al)N coatings containing no titanium in their compositions are characterized by less pronounced adhesive-fatigue wear processes compared to those for the tools with the Ti-TiN and Ti-TiN-(Ti,Al)N coatings. This is manifested in the significant reduction in cracking and the formation of interlayer delaminations.

So, it can be argued that the use of tools with the nanostructured Zr-ZrN-(Zr,Al)N and Zr-ZrN-(Zr,Cr,Al)N coatings under study are not only able to improve the cutting performance of titanium alloys, but also provide a more balanced predictable pattern of wear. Thus, tools with the coatings under study can be successfully applied in computer-aided manufacturing.

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