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# Influence of tribological properties of Zr-ZrN-(Zr,Cr,Al)N and Zr-ZrN-(Zr,Mo,Al)N multilayer nanostructured coatings on the cutting properties of coated tools during dry turning of Inconel 718 alloy

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## Abstract

The article studies the tribological properties of multicomponent nanostructured coatings of Zr-ZrN-(Zr,Cr,Al)N and Zr-ZrN-(Zr,Mo,Al)N, as well as the wear resistance and fracture behaviour of cutting tools with the mentioned coatings during the turning of Inconel 718 alloy. The Ti–TiN-(Ti,Cr,Al)N coating was also considered as a reference coating. While the Ti–TiN-(Ti,Cr,Al)N coating is characterized by high hardness, it also demonstrated high coefficients of friction (COF) at temperatures of 600 °C and above (i.e., at temperatures in the cutting zone). The Zr-ZrN-(Zr,Mo,Al)N coating has a balanced combination of high hardness and low COF at cutting zone temperatures. As a result, the Zr-ZrN-(Zr,Mo,Al)N-coated tool demonstrated wear resistance 2.4 times higher than that of the Ti–TiN-(Ti,Cr,Al)N-coated tool. During the process of cutting, zirconium (Zr) and chromium (Cr) oxides are formed in the Zr-ZrN-(Zr,Cr,Al)N coating, and the formation of zirconium and molybdenum (Mo) oxides is detected in the Zr-ZrN-(Zr,Mo,Al)N coating, which can have a positive effect on cutting conditions. Under the cutting conditions, the oxidizing action caused an almost complete transformation of a nitride coating structure into an oxide structure, while the nanolayer structure was partially preserved.

## Introduction

The austenitic nickel-chromium heat-resistant alloy Inconel 718 is designed for operation at temperatures up to 700 °C and is one of the most common alloys of the Inconel family [[1], [2], [3]]. Inconel 718 is based on an austenitic solid solution of the nickel-chromium-iron system (see Table 1). Such properties as low thermal conductivity (resulting in a significant heating of the rake face of the tool), tendency to deformation hardening, presence of abrasive carbide particles in the structure, as well as a considerably high hardness and active adhesive interaction and interdiffusion with the tool material make the considered alloy difficult-to-cut [[4], [5], [6]]. Turning of the considered alloy causes an increased wear of cutting tools [5,6].

While there is a large body of research considering the turning of Inconel 718 with coated carbide tools, only several coating compositions are usually studied (see Table 2). Most often, the studies are focused on TiN or TiAlN single-layer coatings, as well as TiAlN and TiN/AlTiN coatings with multilayer/nanolayer architecture. Besides, the coatings of CrN and $Al_2O_3$ are also used. Table 2 exhibits a generalized review of tool materials (carbides), coatings, and cutting modes during the turning of Inconel 718 under the conditions of dry cutting. The use of tools with wear-resistant coatings can significantly increase the cutting speed due to a decrease in temperature in the cutting zone and in the wear rate. At the cutting speed $v_c$ = 100 m/min for a TiN/TiC-coated tool, the temperature in the cutting zone is about 1050 °C [10], while for an uncoated tool, the temperature reaches 1000 °C even at the cutting speed of $v_c$ = 35 m/min [6].

The comparison of the wear resistance of tools with different coatings makes it possible to build a generalized scale for the effectiveness of using coatings of various compositions during the turning of Inconel 718 (in terms of wear intensity along the flank of the tool) [9,12,13,17]:Uncoated < $Al_2O_3$ (CVD) < TiN (PVD) < TiAlN (PVD) < TiN/AlTiN nanolayer.

Of course, this ranking is not absolute due to some difference in the conditions of the experiments, but according to the authors, it can be used to select the objects of comparison in this work.

The use of tools with innovative coatings can further improve the Inconel 718 machining performance. At a high temperature in the cutting zone, which is typical for turning Inconel 718, the diffusion and oxidation processes are of particular importance [10,21,22]. As is known, the oxides of such metals as aluminium (Al), molybdenum (Mo), and chromium (Cr) can have a positive effect on the cutting process at high temperatures [[23], [24], [25], [26]]. On the one hand, dense films of oxides of Al, Mo, and Cr formed on the rake face of the tool protect it from further oxidation, and on the other hand, they can favourably transform the cutting conditions by decreasing the coefficient of friction [[27], [28], [29]]. In turn, with regard to the resistance to cracking and brittle fracture, the introduction of zirconium into the coating composition can have a positive effect on its properties [30,31].

The objective of this study was to compare the tribological properties of the Zr-ZrN-(Zr,Cr,Al)N and Zr-ZrN-(Zr,Mo,Al)N multicomponent nanostructured coatings, as well as the wear resistance and fracture behaviour of the cutting tools with these coatings during the turning of Inconel 718 alloy. The Ti–TiN-(Ti,Cr,Al)N coating was chosen as a reference coating. Particular attention was paid to the diffusion and oxidation processes, as well as the process of cracking in the structure of the coatings under study. The previously proposed three-layer coating architecture was used, including an adhesive layer (providing maximum adhesion to the substrate, 30–50 nm thick), a transition layer (providing a smooth change in mechanical properties between the substrate and the wear-resistant layer, as well as additional barrier functions, 1.0 ± 0.3 μm thick), and a wear-resistant layer (directly in contact with the flow of the material being machined, having a nanolayer structure, 3.0 ± 0.3 μm thick) [[32], [33], [34]]. Thus, the total thickness of the coating is about 4.0 ± 0.6 μm.

Three coatings with different mechanical properties were considered:

- Ti–TiN-(Ti,Cr,Al)N reference coating, characterized by high hardness and wear resistance, but quite brittle. Of the elements potentially forming tribologically active oxides, this coating includes chromium and aluminium [[35], [36], [37], [38]].

- Zr-ZrN-(Zr,Cr,Al)N coating, characterized by a slightly lower hardness compared to the (Ti,Cr,Al)N coating, but demonstrating at the same time higher resistance to cracking and brittle fracture [[39], [40], [41]]. This coating also contains chromium and aluminium, which makes it possible to predict the formation of tribologically active oxide films under cutting conditions.

- Zr-ZrN-(Zr,Mo,Al)N coating, which theoretically can combine good hardness, resistance to cracking, and the possibility of forming tribological films of molybdenum and aluminium oxides [[42], [43], [44], [45], [46]].

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## Section snippets

### Materials and methods

The coatings under study were deposited on the VIT-2 unit (IDTI RAS – MSTU STANKIN, Russia), combining filtered cathodic vacuum arc deposition (FCVAD) [[47], [48], [49], [50]] and Controlled Accelerated Arc (CAA-PVD) [51,52]. During the process of coating deposition, cathode of Al (99.8%) was installed in the FCVAD system, and cathodes of Cr (99.9%), Mo (99.8%), Zr (99.8%), and Ti (99.6%) (depending on the coating composition) were installed on the evaporators CAA-PVD.

The main parameters of...

### Investigation of the mechanical properties and phase composition of the coatings

The comparison of the mechanical properties of the coatings (Table 4) finds that the Zr-ZrN-(Zr,Mo,Al)N coating has the most favourable combination of high hardness and good elastic properties. Thus, this coating will be theoretically characterized by high wear resistance in combination with brittle fracture resistance. The Ti–TiN-(Ti,Cr,Al)N reference coating is also characterized by high hardness, but it also has a high elastic modulus, which may indicate a tendency to brittle fracture. The...

### Discussion

It should be noted that the oxidized region of the coating contains no noticeable amounts of the (Zr,Mo,Al)N or (Mo,Zr,Al)N nitride phases, and only oxide phases of $ZrO_2$ and $MoO_2$ are detected. The presence of Al in this region can indicate both the presence of metallic aluminium and its nitride (hexagonal) phase or oxide. Unfortunately, the methods used to study the phase composition are not able to identify these phases reliably. Thus, under cutting conditions, the oxidizing action can lead to ...

### Conclusions

1. While the Ti–TiN-(Ti,Cr,Al)N coating is characterized by high hardness, it also demonstrated high coefficients of friction at temperatures of 600 °C and above (i.e., at temperatures in the cutting zone). The Zr-ZrN-(Zr,Mo,Al)N coating has a balanced combination of high hardness and low coefficient of friction (COF) at cutting zone temperatures. As a result, the Zr-ZrN-(Zr,Mo,Al)N-coated tool demonstrated wear resistance 2.4 times higher than that of the Ti–TiN-(Ti,Cr,Al)N-coated tool....

2. The study...

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### Novelty statement

The paper offers the findings of the investigation focused on the tribological properties of a sample with the Ti–TiN-(Ti,Al,Nb,Zr)N coating depending on temperature, which varied in the range of 500–1000 °C. The paper also describes the results of the studies of the wear pattern on a metal-cutting tool depending on the cutting speed (vc = 300 and 400 m/min). Particular attention was paid to the investigation of the diffusion processes arising during the cutting of steel. It is found that as...

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

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