Wear resistance of adaptive arc-PVD Ti-Al-Mo-Ni-N coatings under impact loading and hydroabrasive wear

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Abstract. The behavior of Ti-Al-Mo-Ni-N coatings obtained by arc-PVD deposition under conditions of impact loading and hydroabrasive wear is studied. Nanostructured coatings samples with a thickness of 4 µm with a modulation period of 30 nm and hardness of 45 GPa were obtained. Under impact loading, the coating performs a protective function up to $10^5$ loading cycles of 250 N without opening the substrate, and during hydroabrasive tests, after 3 hours of exposure to a flow at a speed of 8.5 m/s, there is a spot wear on the coating surface, opening minor segments of the substrate area. It is shown that the introduction of Ni into the Ti-Al-Mo-N system leads to the appearance of coating failure by brittle mechanism with delamination and opening of the substrate under significant loads in the case of impact and hydroabrasive wear.

1. Introduction

Multilayer nitride coatings obtained by arc-PVD method in Ti-Al-Mo-N and Ti-Al-Mo-Ni-N systems are characterized by high hardness (up to 37 and 45 GPa, respectively) [1, 2] with high fracture toughness, as well as a low friction coefficient (up to 0.35) due to the phenomenon of coatings adaptation to intense friction by formation of MoO₃ in the friction zone, acting as a dry lubricant due to low shear strength [3]. This set of characteristics determines an extended range of operating conditions for such coatings, such as the conditions where there are both constant and alternating loads, as well as abrasive wear or sliding friction, including at elevated temperatures (up to 600 °C). The stability of Ti-Al-Mo-N coatings in model tests under impact loads, abrasive wear, and hydroabrasive erosion was demonstrated, as well as full-scale tests of these coatings on a cutting tool, the result of which indicates the prospects of their application in this area [4].

At the same time, it is known that Ni at a content of up to 7 at. % has a positive effect on the Ti-Al-Mo-N system, reducing the average grain size of the nitride phase from 35 to 12 nm by limiting the growth of crystallites during coating formation, being deposited as a thin metallic layer at the boundaries of growing nitride grains. Such structural changes led to decrease in level of residual compressive stresses from -2.25 GPa to -0.58 GPa, which, however, did not lead to reduced hardness, but on the contrary, to its increase from ~37 to ~45 GPa. It indicates that in the case of such structure of arc-PVD coatings a factor determining physical and mechanical characteristics of the coating is not macrostressed state, but refinement of the grain structure. The purpose of this work is to study the...
behavior of arc-PVD Ti-Al-Mo-Ni-N coatings under impact loads and hydroabrasive erosion and to determine their stability and applicability for these types of wear.

2. Materials and methods
The coatings were deposited by arc-PVD method. As substrates we used WC-Co plates, which were subjected to preliminary sandblasting. Coating deposition was carried out in the atmosphere of a mixture of Ar and N₂ (the total pressure was 2.7 Pa, the partial pressure of nitrogen was 0.5 Pa). A three-cathode system with Ti-Al (wt. %: 95Ti + 5Al), Ti-Ni (at. %: 50Ti + 50Ni) and Mo cathodes was used. The currents of the evaporating arcs were 135 A, 120 A, and 135 A, respectively, and the ion flow was separated from the droplet phase by toroidal separators. The bias potential applied to the substrate was -140 V. Deposition was carried out using a kinematic planetary mechanism of rotation of the substrates, which led to formation of a layered structure with alternating layers based on titanium and molybdenum nitrides. The elemental composition of the resulting coating was as follows: 28 at. % Ti, 1% Al, 23% Mo, 7% Ni, 41% N. The coating thickness was 4 µm, the modulation period of the layered coating architecture was about 30 nm.

To study the stability of the obtained coatings under impact fatigue loading, cyclic shock-dynamic tests were performed on the Cemecon impact tester (AG, Germany). The piston of the impact tester with the WC-Co counterbody with a diameter of 5 mm, provided a cyclic load of 250 N for $10^4$, $5\cdot10^5$, $10^5$, $5\cdot10^5$ cycles with a frequency of 50 Hz. During the tests, the deformation zone of the sample was cooled using compressed air. The processes of deformation and erosion of the coating surface were studied using SEM.

The study of the behavior of coatings under hydroabrasive wear was carried out on the installation created on the basis of IMASH RAS [5]. The abrasive, which was Al₂O₃ with a fraction of 50 µm (see figure 1), was mixed with water coming from a special tank due to the operation of the pump. The test chamber consisted of a rotating shaft on which a rotor with two radial channels and nozzles was mounted. A test sample is attached to each nozzle at a distance of 5 mm. Water with abrasive coming from the mixer to the entrance of the rotor during its rotation, under the action of centrifugal force, came out of the nozzles in the direction of the samples at a certain speed, producing erosive destruction of the sample surface.

![Figure 1. Al₂O₃ abrasive used for hydroabrasive tests.](image)

We used following parameters: abrasive consumption was 1.2-1.35 kg / h, shaft speed was 20 rpm, liquid consumption was 1.2 m³/h, test time was 3 hours. Under the implemented conditions, the calculated flow rate of the abrasive fluid impacting the samples surface was approximately 8.5 m/s.

This installation is used as a model for studying the wear processes of materials of plunger pumps for pumping the process water into wells during oil extraction.

3. Results and discussion
With a different number of cycles of impact loading, coatings show a changing wear pattern (figure 2).
Figure 2. SEM images of the Ti-Al-Mo-Ni-N coating wear spots after $10^4$ (a), $5\cdot10^4$ (b), $10^5$ (c), $5\cdot10^5$ (d) loading cycles.

Figure 3. Morphology of the Ti-Al-Mo-Ni-N coating wear spots after $10^4$ (a), $5\cdot10^4$ (b), $10^5$ (c), $5\cdot10^5$ (d) impact loading cycles.
The size of the fracture spot does not significantly change until the maximum number of loading cycles, then increases sharply. At the same time, signs of coating failure are present after all tests, which can be seen in detail in high-magnification images (figure 3).

After testing for $10^4$ cycles, in addition to carbide inclusions, dark cavities in the coating are observed on the surface (see figure 3a), which may indicate an opening porosity of the coating. After $5 \cdot 10^4$ and $10^5$ cycles, layer-by-layer failure of the coating is observed (see figure 4b, c) without opening the substrate. It can be assumed that the coating is delaminated or its fragments are pushed inside. According to the morphology of the fracture spot with the maximum number of cycles, it can be concluded that in addition to the sticking of the counterbody wear products, the substrate is opened on certain areas of the surface (see figure 4c).

It should be noted that the Ti-Al-Mo-N coating under similar conditions maintained its continuity, demonstrating plastic behavior with smoothing of the coating relief in the area of the wear spot, without showing signs of brittle failure [4].

The profiles of the coated WC-Co plates before and after hydroabrasive tests are shown in figure 4.

![Figure 4. Surface profiles of the Ti-Al-Mo-Ni-N coating before and after hydroabrasive tests.](image)

As in the case of Ti-Al-Mo-N coatings [4], after hydroabrasive tests there are no signs of coating failure on the surface profiles, and its wear to a depth exceeding the thickness of the deposited film.

On the photos obtained using SEM (figure 5), with a small magnification, it is clear that the main surface area has retained its continuity, however, there are areas of local failure of the coating by a brittle mechanism with the presence of coating delamination signs, similar to that observed during fatigue impact loading tests.

![Figure 5. Ti-Al-Mo-Ni-N coating surface after hydroabrasive tests.](image)
Figure 5a shows that there is a minor spot failure of the coating surface area. After 3 hours of exposure to a flow of liquid with solid abrasive particles at a speed of 8.5 m/s, this amount of erosion can be considered insignificant, but it can be concluded that despite nanostructuring and high physical and mechanical characteristics, the Ti-Al-Mo-Ni-N coating does not provide sufficient resistance under hydroabrasive wear conditions, leading to the opening of the substrate and loss of the coating protective functions.

A possible reason for the appearance of brittle delamination of the Ti-Al-Ni-Mo-N coating may be a reduced level of residual macrostresses in the coating, which are an obstacle to the origin and growth of cracks in the material under various types of loading.

4. Conclusions
The introduction of Ni into the Ti-Al-Mo-N system during the formation of multi-layer wear-resistant arc-PVD coatings does not significantly increase the stability of the coating under fatigue impact loads and hydroabrasive wear.

Erosion of the coating occurs by the mechanism of brittle cracking and delamination of the material, followed by layer-by-layer failure and local opening of the substrate. Under impact loading, the coating performs a protective function up to $10^5$ loading cycles of 250 N, collapsing in layers without opening the substrate, and in the case of hydroabrasive tests, after 3 hours of exposure to a flow at a speed of 8.5 m/s, spot wear is observed on the coating surface, without critical changes in the surface profile.

Acknowledgments
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