Wear-resistant coatings based on niobium nitride

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Abstract. The results of studies of the use of niobium nitride and its modifications as a material of wear-resistant coatings are presented. It is shown that coatings based on niobium nitride have higher values of mechanical properties. The use of such coatings changes the thermal and stress state and increases the shape stability of the cutting wedge of the tool, which reduces the intensity of wear.

1. Introduction

To create the high-efficient cutting tool with wear-resistant coatings it is necessary to continuously improve their performance characteristics by means of searching for new compositions and the coating architecture [1 – 6]. Niobium nitride can be considered as one of non-conventional materials for the application as coatings of the cutting tool. In comparison with titanium nitride, niobium nitride exhibits the best combination of mechanical and thermal-physical properties. There are almost no data in both domestic and foreign literature about the application of niobium nitride or of its multicomponent modifications as coatings for the cutting tool including but not limited to as layers of multi-layer coatings. There are some publications about the application of niobium as an alloying element in coatings based on titanium nitride [7 – 10]. In them it is demonstrated that its incorporation in the composition of coatings gives an opportunity to change mechanical properties and to improve the efficiency of the cutting tool. Few papers in which NbN coatings are considered as separate layers or layers in multi-layer coatings of TiN/NbN type, are dedicated to studying of deformations and the properties stabilization of these coatings [11, 12].

Objective of this paper is to study the opportunity to use niobium nitride and its modifications as wear-resistant coatings.

2. Methodology of Experiment

Coatings NbN, NbTiN, NbTiZrN and NbTiCrN were studied in comparison with the coating TiN. These coatings were applied using the apparatus «Bulat-6» on plates of the hard alloy MK8, the quick-speed steel P6M5 and the wear-resistant steel 20X13. Chemical composition of coatings was determined by the quantitative X-ray spectroscopic analysis method using the apparatus MAP-4 taking into consideration ZAF-modifications. Structural parameters of coatings (the lattice spacing a for coatings TiN, a and c for coatings based on NbN, the half-width of the X-ray diffraction line β),
residual compressive stresses $\sigma_0$ were studied using the X-ray diffraction meter «ДРОН-3М», sizes of coherent scattering regions (CSR) $D$ were calculated using the method described in the paper [13]. Micro-hardness $H_{\omega}$, elasticity modulus $E$ and stress intensity coefficient $K_{IC}$ of coatings were determined using methods described in the paper [15]. Resisting strength of coatings to the abrasive wear $H_{\omega}/E$ and to the plastic deformation $H_{\omega}^{3.1}/E^2$ was also estimated. Adhesion strength of coatings with the instrumental base was estimated by the stripping coefficient $K_0$ [1]. Wear rate of carbide plates MK8 with wear-resistant coatings was determined during the turning process of workpieces of steel 30ХГН.

3. Research Results and Discussion

Multicomponent coatings were applied using two niobium cathodes located opposite each other and composite titanium cathodes with the insertion of zirconium or chrome. Chemical composition of coatings is described in the Table 1.

| Coating   | Content of elements, % at. |
|-----------|----------------------------|
|           | Nb | Ti | Zr | Cr |
| NbTiN     | 55.6 | 44.4 | - | - |
| NbTiZrN   | 46.5 | 41.9 | 11.6 | - |
| NbTiCrN   | 43.8 | 48.1 | - | 8.1 |

Analysis of the phase composition and X-ray diffraction patterns of coatings showed that niobium nitride NbN has the hexagonal lattice with the preferential texture (110). As can be seen in the Figure 1, a, for the coating NbN applied to the steel base 20X13 the presence of the peak is characteristic at the sliding angle $2\theta$ equal to 62 grades which is identified as NbN (110) and corresponds to the hexagonal structure. In comparison with titanium nitride, niobium nitride has greater values of the half-width of the X-ray diffraction line $\beta$ (by 2.6…3.2 times), residual compressive stresses $\sigma_0$ (by 3.1…3.4 times) and less values of CSR sizes $D$ (by 2.5…3.2 times) (Table 2).

| Instrumental base | Coating   | $a$, nm | $c$, nm | $\beta$, grad | $D$, nm | $\sigma_0$, MPa |
|-------------------|-----------|----------|----------|---------------|----------|-----------------|
| 20X13             | TiN       | 0.42525  | -        | 0.44$^b$      | 23.19    | -920±84         |
|                   | NbN       | 0.2994   | 0.5594   | 1.13$^b$      | 9.24     | -2893±94        |
|                   | NbTiN     | 0.4358   | 0.8704   | 0.86          | 11.24    | -1744±313       |
|                   | NbTiZrN   | 0.4402   | 0.8744   | 0.95          | 10.30    | -1236±161       |
|                   | NbTiCrN   | 0.4403   | 0.8535   | 0.84          | 11.50    | -1234±597       |
| P6M5              | TiN       | 0.4252   | -        | 0.38$^a$      | 27.82    | -1389±23        |
|                   | NbN       | 0.3020   | 0.5751   | 1.20$^b$      | 8.60     | -4716±348       |
|                   | NbTiN     | 0.4381   | 0.8684   | 1.12          | 8.55     | -2319±50        |
|                   | NbTiZrN   | 0.4470   | 0.8764   | 0.83          | 11.65    | -2904±312       |
|                   | NbTiCrN   | 0.4403   | 0.8404   | 0.64          | 15.30    | -1407±317       |

$^a$ measured by peaks (111)
$^b$ measured by peaks (110)

Insertion of titanium, zirconium and chrome in the composition of niobium nitride leads to changes in the lattice pattern of the coating material. Multicomponent coatings based on NbN have the tetragonal lattice with the preferential texture (004) (Figure 1, b). As can be seen from data in the Table 2 changing of the lattice pattern of coatings is reflected on structural parameters. Multicomponent coatings have greater values of the lattice spacing, lower values of the half-width of the X-ray diffraction line, greater CSR sizes (by 1.1…1.7 times depending on the base material). In comparison with niobium nitride, multicomponent coatings have the lower level of residual
compressive stresses (by 1.7...2.3 times for coatings precipitated on steels 20X13 and by 1.6...3.4 times on the steel P6M5). When transferring from two-element coatings to three-element coatings there is a reduction tendency of the half-width of the X-ray diffraction line, residual compressive stresses and the increase of CSR sizes.

![Figure 1. Fragments of X-ray diffraction patterns of coatings NbN (a) and NbTiZrN (b)](image)

Studies of mechanical properties (Table 3) showed that in comparison with TiN, the coating NbN has the greater micro-hardness (by 1.2 times), elasticity modulus (by 1.5 times), cracking resistance and adhesion strength (the stripping coefficient of coatings is less by 4.1 times). At the same time, it has the lower value of the resisting strength to the abrasive wear $H_{\omega}/E$ and to the plastic deformation $H_{\omega}^{3}/E^2$. Multicomponent coatings, in comparison with NbN, have some greater micro-hardness (up to 12 %), stress intensity coefficient (by 8.4 %...29.7 %) which is illustrative of the greater cracking resistance and the worse adhesion strength (the stripping coefficient of multicomponent coatings is higher by 1.6...2.2 times in comparison with NbN). Elasticity modulus of multicomponent coatings is some lower and the resisting strength to the abrasive wear and to the plastic deformation is higher in comparison with coatings NbN. Coating NbTiZrN is an exception.

| Coating   | $H_{kist}$, GPa | $K_0$  | $K_{IC}$, MPa·m$^{1/2}$ | $E$, GPa | $H_{\omega}/E$ | $H_{\omega}^{3}/E^2$ |
|-----------|----------------|--------|-------------------------|----------|----------------|---------------------|
| TiN       | 24.7           | 0.50   | 9.23                    | 315      | 0.078          | 0.152               |
| NbN       | 29.8           | 0.12   | 9.78                    | 467      | 0.064          | 0.121               |
| NbTiN     | 31.8           | 0.23   | 12.01                   | 449      | 0.070          | 0.159               |
| NbTiZrN   | 32.6           | 0.19   | 10.60                   | 575      | 0.057          | 0.105               |
| NbTiCrN   | 33.4           | 0.26   | 12.69                   | 448      | 0.075          | 0.186               |

*instrumental base MK8*

Integration of obtained data gives an opportunity to note that coatings NbN have different common factors in comparison with coatings TiN for changing of structural parameters and mechanical properties when inserting additional elements into their composition. Compared to coatings TiN the transfer from the one-element coating NbN to the multi-element coating is accompanied with the reduction of the half-width of the X-ray diffraction line and residual compressive stresses, slight increase of the micro-hardness, reduction of the elasticity modulus. In addition to the above, common factors peculiar to coatings TiN exist: the increase of the cracking resistance and the decrease of the adhesion strength for coatings with the complex composition [16].

Using the method described in the paper [17] we estimated the wedge shape stability of the carbide-tipped tool with coatings NbN during the longitudinal turning of workpieces of the constructional steel 30XГCA. Contact characteristics of the cutting process, temperatures and stresses acting in the tool wedge were determined by the analytical calculation of current unit loads and temperatures acting on the front and back surfaces of the tool wedge using methods described in
papers [18, 19] with the further numerical computation using the finite elements method in the program pack ANSYS.

Conducted computations (Table 4) show that the application of the coating NbN with thickness of 5 micron gives the opportunity to reduce the temperature of the heat flow rate on the front surface of the cutting tool $\Delta T$ by 90°C while the application of the coating TiN leads to the reduction in the temperature $\Delta T$ only by 12°C.

Table 4. Influence of the coating composition on changing of the temperature on the front surface of the cutting tool

| Coating | $\lambda$, W/(m·°C) | $\Delta T$, °C | $T_f$, °C | $T_{max}$, °C |
|---------|---------------------|---------------|----------|---------------|
| TiN     | 29.3                | 12            | 815      | 1108          |
| NbN     | 3.77                | 90            | 801      | 1057          |

Reduction of contact average $T_f$ and maximum $T_{max}$ temperatures together with normal and shearing stresses when increasing the contact length of the cutting with the front surface leads to changing of the heating and the stress condition of the tool wedge with the coating NbN. When using the coating NbN in comparison with the coating TiN the movement of temperature pattern isotherms and stress isobars in the tool wedge away from the back surface and the cutting edge is observed. The reason is a long contact length of the cutting with the front surface in comparison with the coating TiN. Major reduction of contact temperatures on the front surface of the cutting tool when using the coating NbN leads to the less heating of the tool and moving of isotherms to the front surface.

Figure 2. Distribution of plastic deformations $\varepsilon_y$ (%) in the tool wedge of the hard alloy MK8 with the coating TiN (a, c) and NbN (b, d) after 5 min (a, b) and 15 min (c, d) of the paper

Using obtained data of the thermal and stress condition and recommendations of the paper [15] we received the distribution of relative plastic during the plastic flow in the tool wedge of the hard alloy MK8 (Figure 2). As we can see, the creep deformation is undergone by instrumental base layers sited adjacent to both the front (along the contact with the cutting) and the back surfaces. Maximum deformation at the front surface exists midway of the contact between the cutting and the front surface where the high level of contact temperatures intensifies creeping processes. Creep deformations on the part of the back surface are also maximal in the region of highest temperatures. As can be seen in the Figure 2, the longer the working time of carbide plates is, the greater the value of both plastic deformations and the area of distribution. Using data obtained by the thermal and the stress condition,
we calculated the value of plastic deformations of the tool wedge top caused by creeping of the instrumental material.

![Figure 3. Shape modification of the carbide-tipped tool wedge with coatings TiN (1, 2) and NbN (3, 4) depending on the working time of the carbide-tipped tool: 1, 3 – 5 min; 2, 4 – 15 min](image)

As can be seen in the Figure 3, using NbN as the coating for the cutting tool in comparison with TiN provides the lower value of deformations by 2.1…2.5 times suggesting the greater shape stability of the wedge and the more advantageous heat-stressed condition.

Analysis of obtained results gives an opportunity to note that the greater the wedge shape stability of the tool with the coating NbN is related to both changing of contact processes existing on the front and the back surfaces of the cutting tool and lowering the value of heat flows to the instrumental material. Interestingly, the greatest influence on lowering the value of deformations from the high-temperature creep has the heat-barrier function of this very coating.

Obtained data related to mechanical properties of multicomponent coatings based on niobium nitride and the estimation of the wedge shape stability of the cutting tool with the coating NbN give an opportunity to conclude that the application of this very coating and its modifications can improve the efficiency of the cutting tool in comparison with the traditional coating with titanium nitride.

To check this provision we undertook studies of the wear intensity of carbide plates MK8 with different coatings. Results of these studies are presented in Figure 4.

Studies found that the application of multicomponent coatings based on niobium nitride gives an opportunity to reduce the wear intensity of carbide plates by 1.1…2.1 times depending on the coating composition and cutting conditions. The greatest reduction of the wear intensity is provided by the application of the coating NbTiCrN. It is found that coatings with the lower condensation temperature provide the reduction of the wear intensity of plates in average by 1.2 times in comparison with coatings precipitated at high temperatures.

![Figure 4. Influence of the coating composition on the wear intensity of the cutting tool with the wear-resistant coating (a: V=130 m/min; S=0.3 mm/turn; t=0.5 mm; b: V=180 m/min; S=0.15 mm/turn; r=0.5 mm)](image)

Undertaken studies showed the application perspectiveness of multicomponent coatings based on NbN both as one-layer coatings and as functional layers of multicomponent coatings.

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