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Wear Resistance of the Surface Layers of Hard Alloys with a Multilevel Structural Phase State

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Abstract—The results of studying the effect of the electron–ion plasma treatment of the surface of tool hard alloys in plasma-forming gases at varying ionization energy and varying atomic weight on the structural phase state and abrasive-wear and metal-cutting resistance of the surface layer are described.

Keywords: hard alloy, wear resistance, electron beam treatment, structural phase state of the surface, plasma-forming gas

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INTRODUCTION

A common global trend in the development of methods for increasing the service life of hard-alloy metal-cutting plates is improvement in their cermet structure via doping the metal binder and selecting the ceramic component in conjunction with the modes of sintering of powder mixtures. A recent development in this direction is the sintering of hard alloys of metal nanopowders. Nanostructured hard alloys exhibit high strength, hardness, and crack and wear resistance [1]. A major disadvantage of these materials is their high cost, which is due to the cost of nanoscale powder components of cermet composites and the specifics of procedures of the sintering process; these features limit the development of this direction in Russian industry.

An alternative solution to the problem of increasing the service life of hard-alloy metal-cutting plates lies in the hardening of their surface layers via the formation of a multilevel structural phase state (in micro-, submicro-, and nanoscale regions). The authors of [2] showed that the formation of a multilevel structure requires the creation of conditions for localization of a plastic deformation in the bulk of the material at the lowest scale level of the internal structure. Fulfillment of this requirement provides a more uniform distribution of elastic stresses in the material and leads to an increase in the nucleation energy of critical stress concentrators. This is particularly important for considering the mechanisms of surface hardening of tool hard alloys, for which the outer surface is a source of nucleation of destructive microcracks.

The formation of a multilevel structure in the surface layers of conventional hard alloys can be implemented through the targeted formation of additional levels of the structural phase state in submicron and nanoscale regions in the metal binder of the cermet composite and dispersion of the ceramic component particles to nanometer size. This aim can be achieved via treating the surface with a submillisecond low-energy high-intensity electron beam in plasma-forming gases at varying ionization energy; this treatment makes it possible to radically modify the structure of the surface layer with a thickness of a few tens of micrometers via transferring it into a multimodal structural phase state, while maintaining the structure of the bulk of the alloy almost unchanged [3].

MATERIALS AND METHODS

Experimental studies were conducted on hard-alloy samples with a high (50 vol % TiC/50 vol % NiCr) and low metal binder content (75% WC + 14% (Ti, Ta, Nb) C)/11% Co). Electron–ion plasma treatment of the hard-alloy surfaces was conducted in gas-

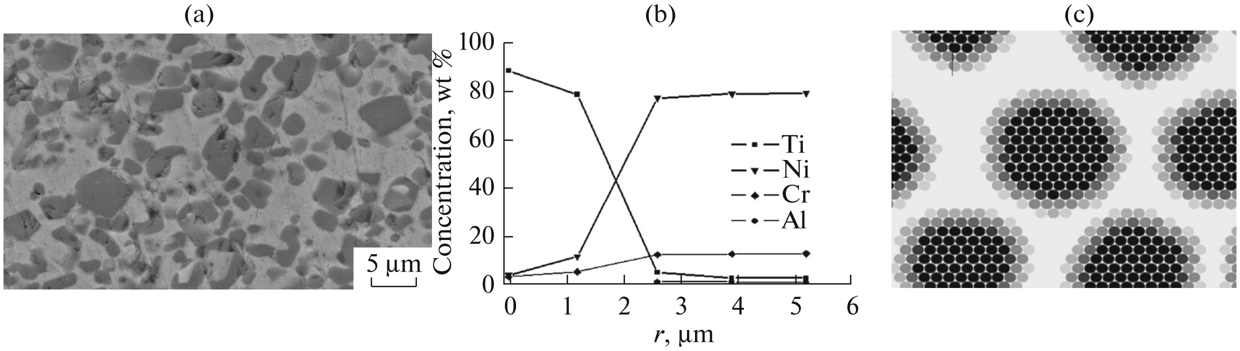

Fig. 1. (a) Surface microstructure of the 50 vol % TiC/50 vol % (Ni–Cr) hard alloy; (b) distribution of the elemental composition of the cermet alloy at the interface between the carbide particles and the metal binder; and (c) computer model of the hard-alloy structure with the region of transition from the carbide particles to the metal binder.

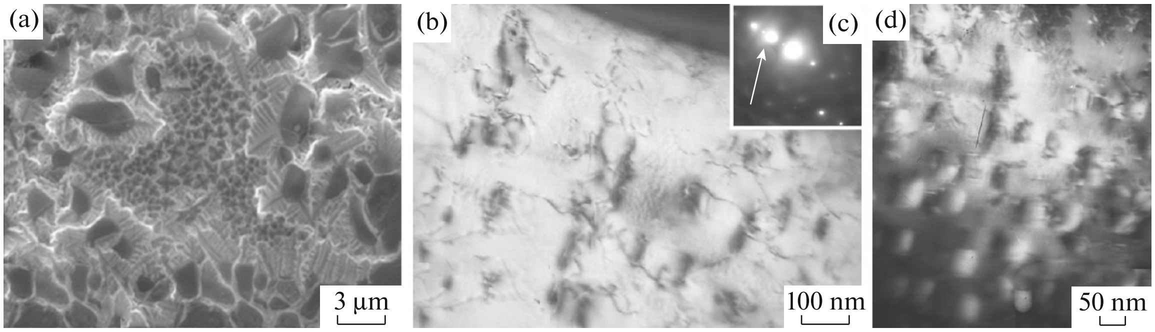

Fig. 2. Microstructure of the surface layer of the TiC/(Ni–Cr) hard alloy after electron beam treatment (electron-beam energy density of 40 J/cm^2; number of pulses of 15; pulse repetition frequency of 1 s^{-1}; and pulse length of 200 ms) in gas-discharge plasma containing (a) Ar and (b–d) Ar + N according to (a) scanning and (b–d) transmission electron microscopy.

discharge plasma containing argon, nitrogen, krypton, or xenon. The microstructure of the surface layers was studied by scanning electron microscopy after ion etching. The abrasive wear resistance of the surface layers of the hard alloys was determined according to the ASTMG65 international standard; the metal-cutting resistance was examined by the lathe turning of steel ST45.

RESULTS AND DISCUSSION

After sintering, the initial cermet alloy is characterized by the presence of three levels of the structural phase state: ceramic-component particles (carbides, carbonitrides, borides, etc.) of the “mesoscopic” scale (1–10 µm); interparticle layers of the metal binder (~4 µm); and particle/binder transition regions with a width of ~1 µm (Fig. 1).

Computer modeling of the effect of individual levels of the structural phase state on the strength of a hard alloy subjected to dynamic loading at a given volume ratio of the cermet-composite components showed that, within the framework of a three-level structure, the dominant effect on the strength of the alloy is exerted by the strength and geometrical dimensions of the region of transition from the carbide particles to the metal binder: with an increase in strength and width of the transition region, the maximum increase in the strength of the alloy is no more than threefold [4]. In other words, the possibilities of increasing the service life of a hard alloy with a cermet structure made up of three levels of the structural phase state by powder metallurgy methods (sintering of cermet-powder composites) are quite limited.

It was found that, in the case of the pulsed electron-beam treatment of a hard alloy with a high metal-binder content in the cermet composite (50.0 vol %

Characteristics of the plasma-forming gases

Plasma-forming gas	Ionization energy, kJ/mol	Atomic mass, g/mol
Nitrogen	1401.5	14.00674
Argon	1519.6	39.948
Krypton	1350.0	83.8
Xenon	1170.0	131.29

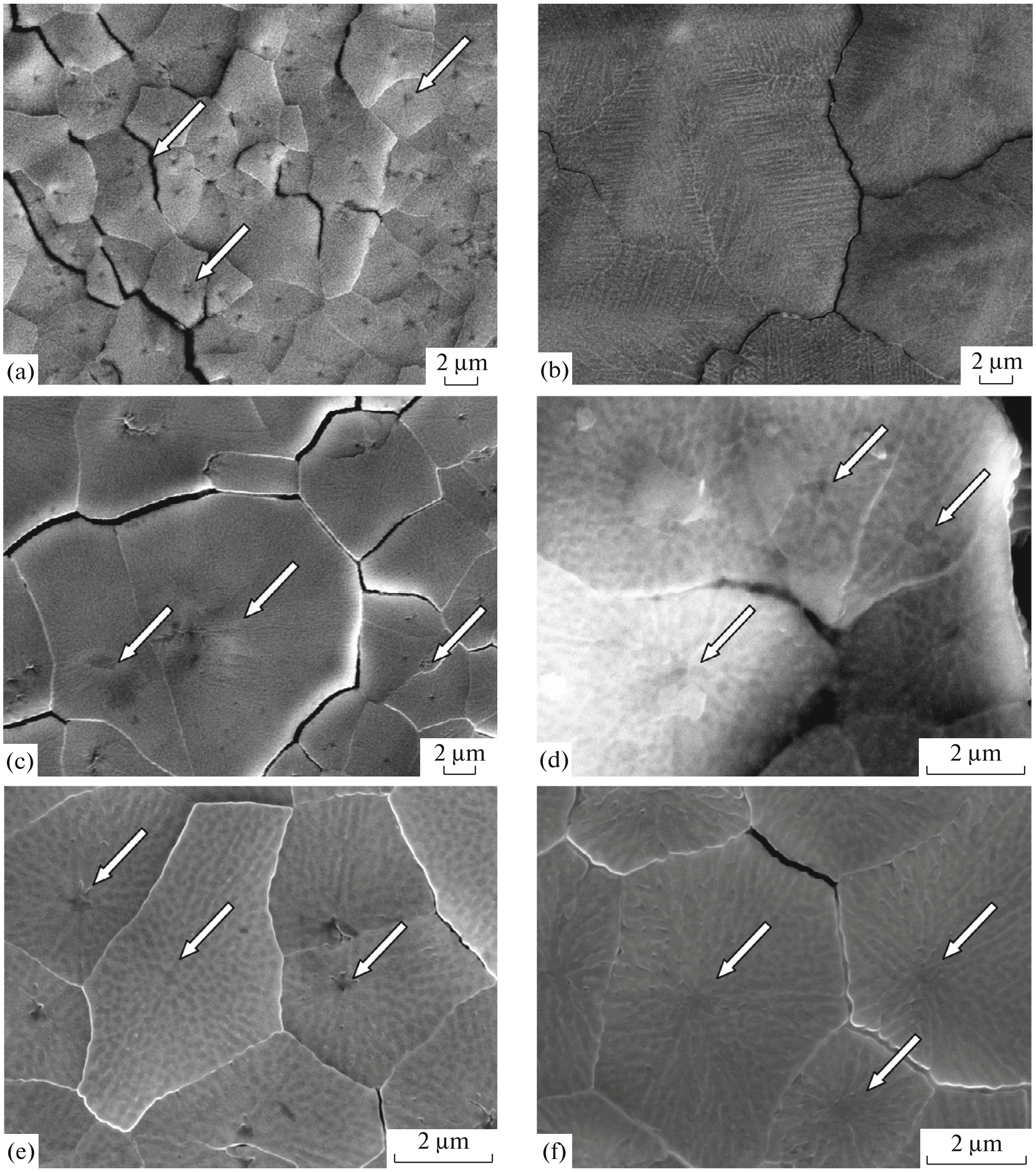

Fig. 3. Surface microstructure of the cermet alloy after pulsed electron-beam treatment in gas-discharge plasma containing (a, b) krypton; (c, d) xenon; and (e, f) xenon + nitrogen: (a, c, e) 40 J/cm^2, 150 μs, and 15 pulses and (b, d, f) 50 J/cm^2, 150 μs, and 15 pulses (the arrows show the initial titanium-carbide particles incompletely dissolved in the melt of the metal binder).

TiC/50.0 vol % Ni–Cr) in an Ar-containing gas-discharge plasma (Ar ionization energy of 1519.6 kJ/mol), the decomposition of a supersaturated solid solution of titanium and carbon in the melt leads to the formation of nanoscale (200 nm) secondary titanium-carbide particles in the metal binder of the surface layer; the particles form a fourth level of the structural phase state. Exposure to gas-discharge plasma containing a mixture of nitrogen and argon (N ionization energy of 1401.5 kJ/mol) leads to the formation of aluminum-nitride (AlN) particles with a size of 50 nm in the interlayers of the metal binder; these particles form a fifth level of the structural phase state of the hard-alloy surface layer (Fig. 2).

Pulsed electron-beam irradiation in plasma-forming gases at a lower ionization energy and higher atomic masses (table) changes the structural phase state of the hard-alloy surface layer. Under constant conditions of electron-beam treatment, as in the case of exposure to gas-discharge plasma containing Ar or an Ar–N$_2$ mixture, the carbide-component particles undergo nanostructuring. The carbide particles of the

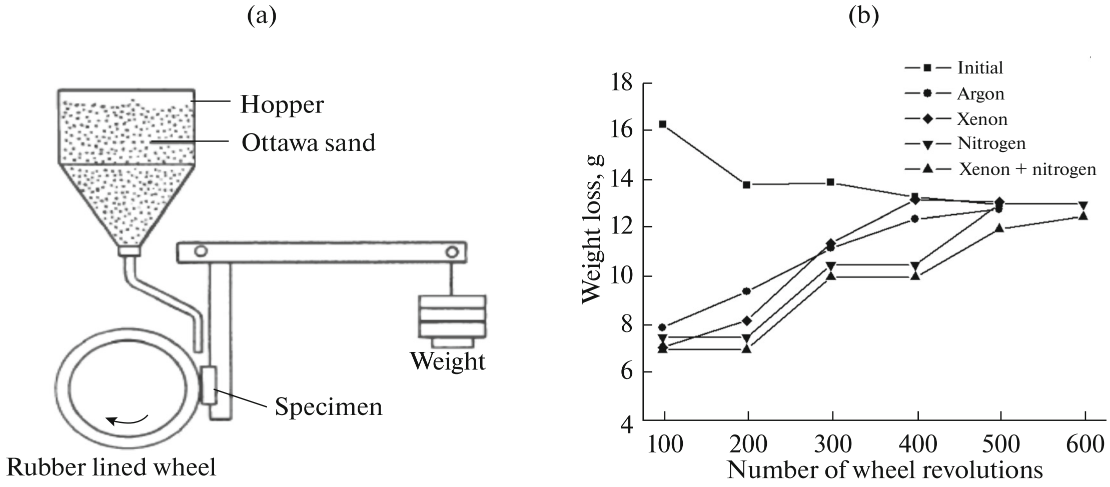

Fig. 4. (a) Kinematic diagram of the setup for abrasive-wear testing of the materials in accordance with the ASTMG65 standard and (b) intensity of abrasive wear of the surface layer of the TiC/(Ni–Cr) hard alloy before and after irradiation of the samples in plasma-forming gases at varying ionization energy versus the number of revolutions of the abrasive wheel.

cermet composite undergo decomposition into a large number of nanoparticles to form a polycrystalline structure with a dendritic carbide skeleton in each crystal under irradiation in Kr-containing plasma and nanoscale distribution of the carbide component in the crystals when exposed to Xe-containing gas-discharge plasma (Fig. 3).

Owing to a lower ionization energy and the occurrence of impact ionization during the collisions of ions of heavy inert gases with neutral atoms, the use of krypton or xenon as plasma-forming gases provides conditions for more complete ionization of the plasma-forming gas and contributes to switching from the electron-beam irradiation mode to the electron–ion plasma irradiation of the hard-alloy surface. In addition, a significant contribution to the pulsed electron–ion plasma treatment of the surface layer of a hard alloy comes from the impact action of ions of heavy inert gases. In other words, nanostructuring of the surface layer occurs due to both the interfacial interaction of the cermet-composite components upon ultra-high-rate heating of the surface layer to abnormally high temperatures and its subsequent high-rate cooling and the mechanical (impact) action of heavy ions of krypton or xenon on the ceramic-component particles. The role of heavy ions in the nanostructuring of the ceramic component of the surface layer should become more significant with increasing ceramic-component content in the hard alloy.

Figure 4 shows the kinematic diagram of a setup for the abrasion-wear testing of materials in accordance with the ASTMG65 international standard and the intensity of abrasive wear of the surface layer of the TiC/(Ni–Cr) alloy samples before and after pulsed electron-beam treatment in plasma-forming gases at varying ionization energy versus the number of revolutions of an abrasive wheel. A planar test sample was pressed against a rubber-lined wheel with a diameter of 218 mm, which rotated at a speed of 200 rpm, with a force of 36 N. An abrasive powder (13A fused alumina, 20P grain size, GOST (State Standard) 28818-90) with a particle size of 200–250 μm was fed onto the friction surface. The consumption of the abrasive was 270–280 g/min.

At the beginning of the tests, the wear resistance of the irradiated alloy samples is several-fold higher than that of the initial samples; the larger the number of levels of the structural phase state in the surface layer, the higher the resistance. An increase in the number of revolutions of the abrasive wheel leads to thinning of

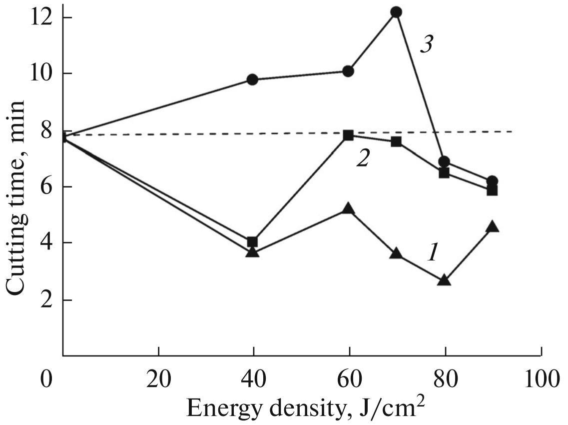

Fig. 5. Dependence of the resistance of the surface layer of the T40 hard alloy to metal cutting (steel St45) over time on the electron-beam energy density upon pulsed irradiation (150 μs, 15 pulses) in gas-discharge plasma containing (*1*) nitrogen, (*2*) argon, or (*3*) xenon.

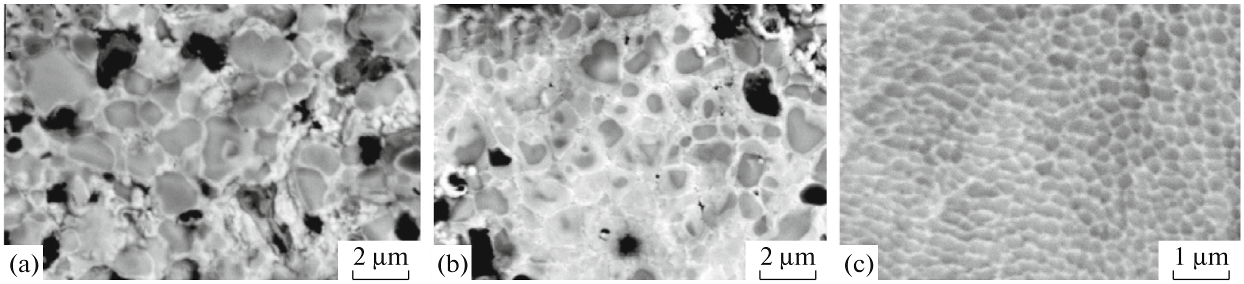

Fig. 6. Surface microstructure of T40 hard alloy (a) in the initial state and after pulsed electron-beam treatment (number of pulses of 15; irradiation time of 150 μs) in gas-discharge plasma containing (a) argon, (b) nitrogen, and (c) xenon.

the surface layer and a change in the structural phase state of the alloy on the surface, i.e., to a decrease in the number of levels of the structural phase state. Eventually, the wear resistance of the surface layer of the hard alloy subjected to pulsed electron-beam treatment approaches that of the alloy in the initial state.

Using the example of a T40 hard alloy with a composition of 75% WC + 14% (Ti, Ta, Nb)C)/11% Co, it was found that the metal-cutting resistance of the hard alloy also depends on the mode of pulsed electron-beam treatment and the gas-discharge plasma composition (Fig. 5). The maximum increase in the resistance of the hard-alloy plates is observed in the case of their exposure to a Xe-containing gas-discharge plasma.

Investigation of the structural evolution of the surface layer of the hard alloy subjected to electron beam treatment in a plasma containing N_2, Ar, and Xe at varying electron-beam energy density showed that the resistance of the hard alloy exposed to a nitrogen- and argon-containing gas-discharge plasma decreases on account of the formation of an irregular and relatively large-scale cermet structure in the surface layer. An increase in the resistance of the hard alloy after irradiation in a xenon-containing plasma is attributed to the formation of a regular cermet structure composed of spherical carbide nanoparticles in the surface layer (Fig. 6).

CONCLUSIONS

The formation of a multilevel structure in the surface layer of hard alloys is a physically based concept of increasing the service life of hard alloys (e.g., used as tool materials). Electron–ion plasma irradiation provides the formation of multilevel structural phase states (on a nanoscale) in the surface layers of hard alloys; these states are responsible for high wear and metal-cutting resistance of the hard-alloy surface layers. The efficiency of electron–ion plasma irradiation as a method of forming a multilevel structural phase state in the surface layers of hard alloys depends on the choice of plasma-forming gases. A decrease in the gas-ionization energy leads to an increase in the efficiency of the thermal impact of the electron beam on the surface layer of the hard alloy. An increase in the atomic mass of the plasma-forming gas leads to an increase in the effect of nanodispersion of the ceramic particles of the hard alloy and an improvement of the wear and metal-cutting resistance of the surface layer of the hard alloy.

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