Influence of ionic modification of high-speed steel surface on tribological characteristics

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Abstract. The article discusses some ways to improve the wear resistance of technical coatings on the surfaces of cutting tools. These coatings were formed in two stages: diffusion saturation with nitrogen (nitriding) and the use of (Ti, Cr) N solid coatings through the process of applying a cathode arc discharge plasma. The proposed coating option also includes an additional ion doped layer implanted on the previously nitrated surface of high-speed steel. Such a multi-layer coating significantly increases (2.1–2.4 times) the wear resistance of the cutting tool due to the expansion of the stage of normal wear. The influence of 16 chemical elements and four antifriction materials implanted into the base surface on the wear resistance of a high-speed steel cutter with technical surface coating was investigated.

The technology of improving surface properties has recently become the main way to improve wear resistance of cutting tools and productivity. There are several ways to improve the surface properties of cutting tools. One of the most advanced methods for modifying the surface of high-speed steel cutting tools is to treat the surface with a stream of ions. The most widely used method of this type of treatment is ion nitriding. This method makes it possible to increase the wear resistance of tools made of high-speed steel 1.3–1.5 times during cutting [1–4]. At the same time, the nitrated substrate significantly (1.5 times) increases the wear resistance of the tool with coatings after the physical deposition of films due to the effect mentioned above. “Dual” surface treatment, which combines nitriding and the application of a hard coating (technological surface coating) [1, 3–5, 8], is promising for widespread use especially for high speed steel cutting tools. Such technological surface coatings were considered as the main ones in this study.

The reason for the interest in such coatings is explicable. It is known that the high wear resistance of tools with hard coating is determined by the fact that they function as a screen for the contacting surfaces of the tool, thereby protecting them from external influences during cutting. This mainly occurs during normal wear. However, the inevitable wear of the coating leads to further effects on the base of the tool, whose frictional properties are much worse than the properties of the coating. As a result, tool wear quickly enters its catastrophic phase. Extending the stage of normal friction, however, is quite feasible. This is achieved in multilayer coatings by applying an additional bottom layer to the surface of the tool base. This layer must combine the properties and the ability to create protective secondary structures in the interphase layer of the coating and the substrate [3–6]. One of the ways to create such layers is ion modification (doping or mixing) of the tool surface.

The purpose of this work is to study the effect of the antifriction composition of the substrate on the wear resistance of the cutting tool and to determine the best basis for developing multi-layer coatings with programmable changes in properties that ensure the function of wear resistance for each coating.
layer to perform the wear resistance function at the appropriate stage of wear.

Theoretical and experimental studies of multilayer triplex coatings. The coating was applied using three devices. The high-speed steel used as the base was pre-nitrated in a glow discharge. Then the tool surface was modified by adding ions before applying a hard coating. Finally, the modified layer (Ti, Cr) N was coated using a physical coating deposition (PVD) method.

Ion nitriding of the substrate from high-speed steel was carried out in a special device for ion nitriding in combination with heating. Technological parameters were as follows: current density in a glow discharge - 3 A/m²; nitrating time - 0.5 h; gas pressure - 266 Pa; gas composition - 25% (N₂) + 75% (H₂) (dissociated ammonia); temperature - 500 °C.

The hard coating was applied with a cathode arc discharge plasma (CAPDP). Coating parameters: gas pressure (nitrogen) - 3 x 10⁻¹ Pa; arc current - 100 A; bias voltage - 200 V; focusing current in the coil - 0.2 A; coating temperature - 500 °C.

The microstructure and properties of the solid coating and ion-nitrided substrate, depending on the technological parameters of the application of FOP - coating and ion nitriding were studied in detail earlier [3]. The surface layer was cleaned before implantation with a special small time treatment in a glow discharge [1, 7] to improve the PVD adhesion - the coating with the substrate. Before applying the PVD coating, each of the samples was implanted with ions from one of sixteen different elements using a high-energy ion implant with an energy of approximately 60 keV at room temperature. Typically used doses were 4 x 10¹⁷ ions per cm². Prior to ion implantation of the elements under study, the surface was etched with argon ions. To reduce surface contamination a cooled trap was used to maintain a low background pressure of ~ 2x10⁻⁶ mm Hg. The basis of the tool material was high-speed steel R6M5 and it contained: 0.8 - 0.88 % C; 5.0 - 5.5% W; 5.0-5.5 % Mo; 3.8 - 4.2 % Cr; 1.7 - 2.1 % V balance Fe as a percentage of weight.

The concentration of atoms of the implanted elements in the surface layer of the samples was determined using X-ray microanalysis using a JSM-U3 scanning electron microscope equipped with a spectrometer on two crystals to scatter the waves. These concentrations were about 1.0–1.5 atomic percent.

The kinetics of In oxidation implanted into high-speed steel instruments was investigated using X-ray photoelectron spectroscopy (XPS) on an ESCLAB-MK2 electronic spectrometer using Ka-radiation (1486.6 eV).

The energy transmission was 100 eV, the energy transmission band and a gap of 1 mm, which gives an effective resolution of ~0.8 eV for Au 4f7/2. The energy scale of the spectrometer was calibrated using Cu 2p3/2 = 933 eV, Ag 3d3/2 = 372.9 eV of photoelectron lines. High-speed steel plates of 10x10x0.5 mm in size were heated to temperatures of 423.623 and 823 K in the working chamber of the electronic spectrometer under oxygen pressure within 2.5x10⁻⁶ Pa. The exposure time varied up to 25 minutes.

Sixteen chemical elements selected in advance for this work were used for ionic modification on the surface. These elements can be grouped as follows: elements (gases) with high oxidizability, creating stable dynamic protective surface films during friction, for example - O, N, J and Cl; non-metals (B, C, Si), capable of creating compounds with high tribological properties when interacting with basic materials and surrounding elements; metals, including those with a low melting point (in particular, In, Mg, Sn, Ga), used as lubricants or antifriction materials; related metals with a hexagonal lattice and anti-friction properties; metals (Al, Cr), capable of forming oxide-like films, resistant to cutting, with good antifriction properties and low thermal conductivity; metals with a low coefficient of friction when in contact with the materials being processed (steel, nickel and titanium alloys), for example, Ag and Cu.

When choosing metallic materials, we took into account known studies on the tribological compatibility of contacting elements. For ion implantation, chemical elements with the least compatibility in tribocouples with iron, nickel and titanium were chosen, i.e. with metals that are part of the processed materials: low-alloyed, heat-resistant and non-corrosive steels, as well as titanium and nickel alloys, widely used in machine parts [2–5].
Tool wear with coatings was investigated when machining carbon steel containing 0.45% carbon (steel 45). The cutting speed was 70 m/min, the cutting depth was 0.5 mm, the feed was 0.28 mm / rev. Cutting was carried out both with and without coolant. The wear of four-sided quick-change high-speed steel plates with multilayer coatings was investigated. The influence of ionic surface modification on the wear resistance of the cutters was evaluated by comparing the periods of tool life with the proposed multi-layer coatings of tools with surface technological coatings without additional ionic modification. The tool durability coefficient was defined as the ratio of the time required for cutting up to the technical conditions the value of wear of a tool with a multilayer coating to the time required for cutting with a technological technological coating (Ti, Cr) N + ion nitriding.

The friction coefficients were determined using an adhesiometer of a special design, presented in detail in [1, 3–7]. To evaluate the anti-friction properties of the layer, we used the adhesion component of the friction coefficient. This component is important for estimating and predicting the intensity of wear during metal friction. It was defined as the ratio of the shear resistance $\tau_{nm}$ caused by the adhesive interaction between the tool materials and the workpiece to the normal voltage $P_{nn}$ arising at the plastic contact at test temperatures ($\tau_{nn}/P_{nn}$).

In general, the results of wear resistance tests showed that the effect of implantable elements on the tool durability is largely determined by the cutting conditions. The working temperature for high-speed cutting is about 600 °C (870–900 K). If coolant is used, the temperature is reduced by at least 100 °C [6–10]. In this case, the effect of implantation varies depending on whether cutting is performed with or without coolant. In our opinion, the complex combination of numerous interrelated factors influences the increase in wear resistance of the cutter. These include factors that make it possible: to form liquid and gaseous phases or a low-melting eutectic, which act as lubricants; create amorphous oxygen-containing films with low friction coefficients and thermal conductivity; reduce the adhesion of the tool surface to the material being processed and at the same time increase the adhesion of the FOP hard coating with a modified base. In this case, the most preferable, as regards the complex of properties, is a coating with an implanted indium layer, which makes it possible to increase the tool durability to the maximum. At the same time, the adhesion between the coating and the main layer modified with indium is also quite high, which confirms the reliability of the coating as a whole.

Investigation of the dependence of the friction coefficient on temperature for samples with a modified surface showed that indium (In) improves the frictional properties of high-speed steel (figure 1).
Acting as a lubricant, In reduces the shear resistance $\tau_{nn}$ of adhesion bonds that have arisen in tribopairs, as well as in addition to indium in the metal mass, in the wear zone, indium oxide, resulting from the decomposition of both indium and indium nitride, is detected when heated during friction.

To identify the characteristics of the behavior of indium implanted into the surface, samples of high-speed steel after ionic modification were examined. The ion modification modes were the same for the samples and cutters. X-ray photoelectron spectroscopy (XPS) showed the presence of oxide - $\text{In}_2\text{O}_3$ and nitride - $\text{InN}$. As the upper solid (Ti, Cr) N coating wears, the modified layer becomes unprotected on the rubbing surface. Under conditions of high loads and at high temperatures, the partial oxidation of In will most likely begin before the destruction of the OPD coating, which still plays its protective role. Dissolved indium In improves the frictional properties of the surface and reduces the intensity of adhesion to the frictional surface. Based on the obtained results, it can be assumed that the oxygen-containing $\text{In} - \text{O}$ phase, which appears when interacting with the environment, exists as a dynamically stable amorphous film, which significantly improves the friction conditions in the contact zone of the tool. Indium, belonging to the same group as Al in the periodic table, creates oxygen-containing phases having a low thermal conductivity. This protects the tool surface from overheating, improves thermal cutting conditions and prevents the onset of catastrophic wear. Thus, the effect of In is twofold: on the one hand, it acts as a metallic lubricant on the other - creates protective oxygen-containing phases.

This together greatly increases the tool’s wear resistance. The positive effect of In ion implantation on tool wear resistance can be explained by complex processes. Acting as a liquid phase at cutting temperatures, indium helps reduce the friction coefficient. In addition, when the cutter is heated by friction, the indium-containing oxygen-containing phases formed on the wear surface protect the tool, preventing the transition from normal to catastrophic wear. This allows you to increase the stage of normal wear and significantly increase the wear resistance of the tool.

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