

IMPROVING THE WEAR RESISTANCE OF CUTTING TOOLS AND MACHINE PARTS THROUGH THE APPLICATION OF COATINGS.

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Abstract: In this work, a high-speed cutting tool with a complex surface treatment of the teeth — including nitriding, alloying, and coating — was used for machining a hard-to-process chromium–nickel material. One of the most urgent problems in modern mechanical engineering is the rapid wear of cutting tools. This article is devoted to the study of strengthening the base casting of the tooth surface up to a thickness of 60 μm using the nitriding process. After the alloying process, the surface of the cutting tool is coated with various nitride-forming elements. The treated, high-strength cutting tool was tested in the tool shop of a machine-building plant.

This study presents innovative combined methods of nitriding, alloying, and coating application for the complex treatment of cutting tools. In this research, chemical-thermal treatment and coating are carried out through strain hardening caused by the passage of an elastic wave generated by a precisely pulsed electron beam.

The main purpose of the study is to significantly reduce the plastic deformation of the coating on the surface of the cutting tool operating under increased and high loads.

Keywords: ion nitriding, microalloying, wear-resistant coating, cutting tools accuracy, tool wear resistance, plastic deformation, high-speed tools, surface coating, crack resistance, oxidation resistance, friction reduction, adhesion, workpiece quality, systematic shape errors

Introduction. In modern automated mechanical engineering, great attention is paid to the wear resistance of cutting tools, and efforts are being made to implement innovative and resource-saving technologies. In the mechanical engineering industry, many parts and cutting tools made of hard-to-machine alloys are used for various purposes. With the emergence of new complex materials, the issue of their machining inevitably comes to the forefront.

Materials strengthened by chemical-thermal treatment and coating are characterized by high specific hardness and strength, low weight, high corrosion resistance, and a low coefficient of thermal expansion. They are widely used in various branches of mechanical engineering, especially in the aviation, aerospace, and related industries. The hardness, Young's modulus, impact toughness, and adhesive/cohesive strength of coatings strongly depend on the aluminum content. Furthermore, mechanical properties deteriorate at high aluminum concentrations. However, the high-temperature properties — including thermal stability and oxidation resistance — of Zr–Cr–Al–N coatings have not yet been fully studied and require further research [1].

For this reason, it is necessary to select the coating composition and deposition technology individually for each type of high-speed tool (Fig. 1). Worldwide, numerous scientific studies have been conducted on the modification of surface layers using ion-plasma methods to increase the durability of cutting tools, improve cutting conditions, wear resistance, friction, and heat

dissipation.

At present, the method of **ion nitriding** is considered one of the fastest-developing and most widely used technologies in the metallurgical industry. Ion nitriding technology is simpler and more economical compared to carburizing and nitrocarburizing and is considered one of the final stages in the production of high-strength components. The method of **ion alloying** is also highly promising for mechanical engineering technologies. This method has several advantages over others, such as diffusion, melting from solution, and epitaxial formation [2].

It is known that the wear surface of a milling cutter, on the rear face, has a wavy pattern with a wavelength equal to the feed value. Each time the feed changes, partial running-in occurs, forming new waves with a step corresponding to the new feed. The intensity of radial wear at the initial moment after the feed change may increase slightly due to faster wear of the protruding crests (waves). It should be noted that when working with variable feeds, the roughness of the machined surface, in some cases, does not increase with feed but even tends to slightly decrease [3].

After analyzing the main studies on the wear mechanism of high-speed tools under intermittent milling, it can be concluded that the reduction in tool life occurs primarily due to alternating high thermal and mechanical loads on the cutting tool, leading to severe wear and failure [4].

Cutting tools used in production play a very important, and in some cases decisive, role in the correct machining of material surfaces. The main reason for the low durability of cutting tools is their rapid wear or failure of the working surface. There are several ways to increase their stability, among which the most common today is the **application of coatings**. These coatings are applied to the surface of cutting tools and components in two ways: **physical vapor deposition (PVD)** and **chemical vapor deposition (CVD)** [5].

2. Materials and Methods

It should be noted that all existing methods for determining the machinability of metals and establishing the dependence of wear resistance are based on studying the regularities of tool wear. The relationships of wear resistance express the connection between the cutting speed and the degree of wear of the tool's cutting elements. The parameters characterizing wear include the width of the wear land on the rear surface, the size of the crater on the rake face, the radial shortening of the cutter (dimensional wear), and the loss of tool mass, among others.

At present, to achieve more effective complex surface treatment of high-speed tool steels, it is necessary to improve the quality of surface preparation — including chemical-thermal treatment, frictional passivity, surface roughness, the presence of chips or cracks, load modes, and uncontrolled quantities of gases and metal ions accelerated on the working surface — which directly affect the thickness and phase composition of the nitrided layer.

Hard coatings are increasingly required to ensure the wear resistance of tools, dies, molds, and components used in the automotive and aerospace industries, which are constantly exposed to

severe tribological and thermal conditions [6].

The experiments were carried out in parallel with traditional durability tests, in which the cutting path length was measured using a milling cutter equipped with a high-speed steel insert. After each machining stage, the cutting tool was examined under a microscope to detect any surface changes [7].

In modern mechanical engineering, more and more components are made of complex alloyed steels and alloys, commonly referred to as **hard-to-machine materials**. These materials differ significantly in their properties and applications: high-strength and ultra-high-strength, corrosion-resistant, heat-resistant, refractory, magnetic and non-magnetic, etc. They also differ in structure (austenitic, cermet, cellular, etc.) and main alloying elements (nickel, cobalt, titanium, aluminum, tungsten, and others).

The performance of a cutting tool largely depends on the operating conditions and is determined by the **coefficient of variation of tool life** [8]. This work presents some results of tool durability tests performed with different coating options (KIB coatings). The analysis of the obtained data allows the following observations to be made.



Figure 1. High-speed steel milling cutters (R6M5).

After milling, the geometry of the cutting edge (i.e., the tip of the cutter) was measured by determining the radius r of the rounded cutting edges and checking their stability under a metallographic microscope. The obtained results were compared with the initial radius, as this parameter is one of the most important factors affecting the cutting process [9].

To determine the power consumed in cutting, as well as the strength and uniformity of the tool and certain machine components, the cutting force $\mathbf{R}$ was decomposed along three coordinate axes: $\mathbf{X}$, $\mathbf{Y}$, and $\mathbf{Z}$. The $\mathbf{X}$ -axis is oriented vertically, while the $\mathbf{Y}$ and $\mathbf{Z}$ axes are perpendicular and parallel to the workpiece axis in the horizontal plane. The force $\mathbf{P_z}$ represents the main tangential (shear) component, $\mathbf{P_x}$ is the radial force, and $\mathbf{P_y}$ is the axial (thrust) force (Fig. 2) [10].

Due to the simplicity of its manufacturing technology, the low cost of raw materials, and its high operational performance, **(TiAl)N coatings** currently account for about 80% of all industrially used coatings [11].

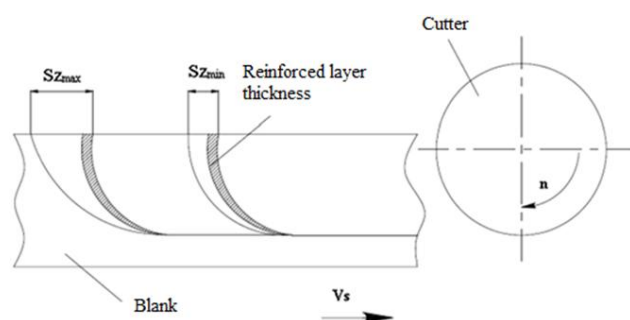


Figure 2. The effect of shear velocity S_z on the components of transverse forces at various shear layer thicknesses.

A **multiphase complex structure** was obtained by ion alloying in an exothermic chemical reaction between the coating metal and the substrate. A thin layer of nitride-forming elements (Zr alloy targets) was deposited on the surface of the cutting tool prior to precision electron beam treatment [12].

This coating is characterized by high oxidation resistance, heat resistance, and hardness. It forms a **thermal barrier** that effectively surrounds the cutting tool material, redistributing the thermal flux so that most of the heat is removed through the cutting zone. The (TiAl)N coating is mainly used for machining operations under high thermal loads. In high-performance industrial environments, where increased cutting parameters cause a significant rise in the temperature at the tool–workpiece interface, such coatings play a crucial role [13].

During cutting, the resistance to plastic deformation of the material acts against the cutting edge of the tool. The total cutting force must be sufficient to overcome this resistance. The main factors influencing the cutting forces include the physical and mechanical properties of the workpiece material, the geometric parameters of the tool, cutting conditions, and the lubricant-cooling medium. For materials with the same chemical composition, the increase in shear stress with reinforcement exceeds the decrease in slag penetration coefficient. Thus, as tensile strength or Vickers hardness increases, the shear strength components also rise [14].

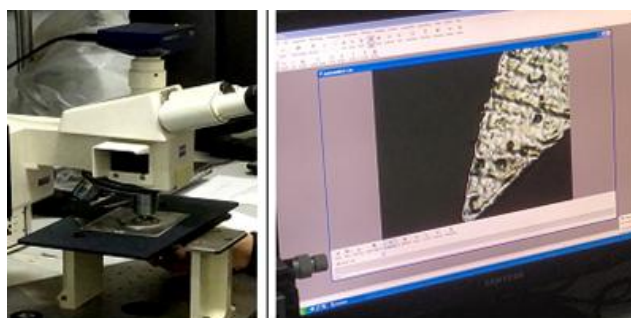


Figure 3. Surface structure of the cutting tool under the SteREO Discovery V12 microscope:
 a) surface of nitrided high-speed steel after HSEP treatment;
 b) same surface after electron-beam alloying with zirconium.

Powerful electron beam donors are unstable iron nitrides formed during nitriding of high-speed steel. The outer layer is enriched with refractory nitride phases which, due to extremely high cooling rates, remain fine and uniformly distributed in the final product. The depth of the surface layer with a modified steel structure ranges from **2 to 10 μm** , depending on the alloying composition [15].

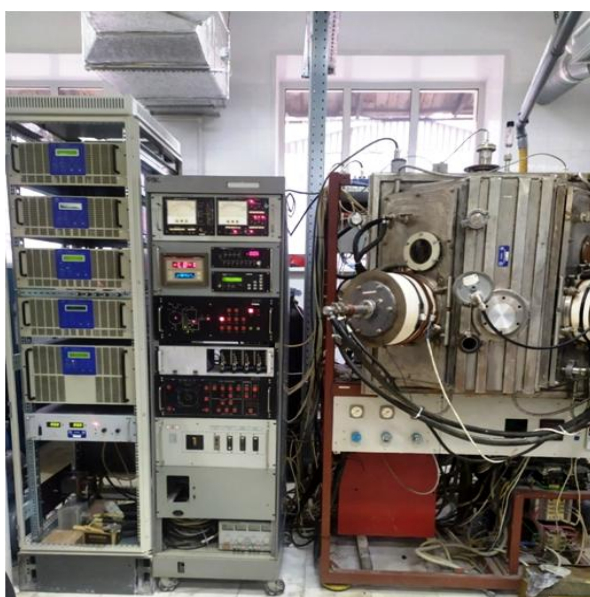


Figure 4. Nitriding process of a disk cutter in the APP-2 ion nitriding unit for cutting tools.

The phase composition and structure of the ion-nitrided layer were studied using **X-ray diffraction (XRD)** on a DRON-4 diffractometer with automated data collection and spectrum registration (Fig. 4).

Durability tests were carried out at the **Navoi Mechanization Plant** of the **Navoi Mining and Metallurgical Combine** during the turning of forged billets made of hard-to-machine 34KhN1MA alloy at a cutting speed of $V = 20 \text{ m/min}$, feed $s = 0.15 \text{ mm/rev}$, and cutting depth t

= 4 mm.

The criterion for tool failure was defined as a wear degree of **0.4 mm** on the rake and flank surfaces. The obtained results showed that the relative wear of the cutter, measured during the initial stage of normal wear, remains nearly constant even when the test duration is increased three to four times. Thus, the established patterns of radial wear variation can serve as a basis for **accelerated methods of determining metal machinability and wear resistance** [16].

To extend the service life of wear-resistant coatings, **multilayer coatings** and tools with complex surface treatments are applied. One of the most important aspects of automated and adaptive manufacturing systems is the wear resistance of cutting tools.

Considering that most cutting tools used in domestic mechanical engineering are imported and exhibit low wear resistance, conducting scientific research in this field is a timely necessity. With the increasing complexity of components and the widespread use of hard-to-machine metals and alloys, the design and localization of new wear-resistant cutting tools have become essential.

3. Results and Discussion

As a result of the conducted study, it was established that the load on the electric motor of a vertical milling machine — both in idle and working modes — differs depending on whether cutters with coatings or without coatings are used. It was found that, compared to cutters without coatings, the motor load is noticeably lower when using cutting tools subjected to complex surface treatment, as measured with ammeters (Fig. 5).

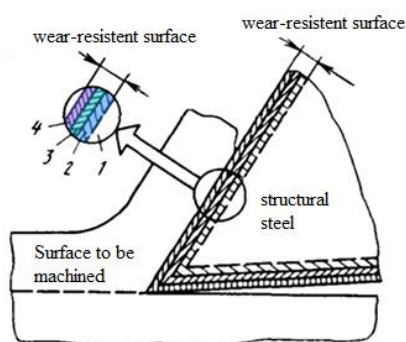


Figure 5. Complex lytreat edsurface:

1–toolsteel 2–adhesive heat-resistant nitride layer 3–alloyed substrate 4 – coating layer.

During the saturation of tool material with diffusing elements, diffusion layers are formed, the crystallochemical structure and properties of which differ significantly from those of the base

material. These diffused elements improve surface properties, corrosion resistance, and wear resistance (Fig. 6).

The formation rate, growth kinetics, structure, and properties of the coating are determined by the process temperature, saturation time, diffusion parameters of the alloying components into the tool material, and, importantly, the chemical composition and structural features of the coating itself.

The total force acting on the cutting tool during machining must be sufficient to overcome the overall resistance of the material being cut.

During testing, cutting tools with complex surface treatment were used to machine heat-resistant forged chromium–nickel alloys of high hardness. The chemical composition of this alloy was determined using the **SpectroLAB** spectrometer.

To investigate the difference in wear between cutting tools with complex treatment (including microalloying of the surface followed by wear-resistant coating) and tools with coatings only, experiments were carried out on machining **34KhN1MA** alloy specimens.

When cutting with untreated tools, the characteristic wear zone appeared at the tip of the disk milling cutter. In machining hard-to-cut materials using complexly treated cutting tools, it was shown that the motor load was smaller and the cutting force was reduced. The adhesion of the workpiece material to the cutter's working surface was analyzed using the **SteREO Discovery V12** stereomicroscope. The rounding radius (r) of the cutting edge was measured with the **MicroCAD lite** system (Fig. 7).

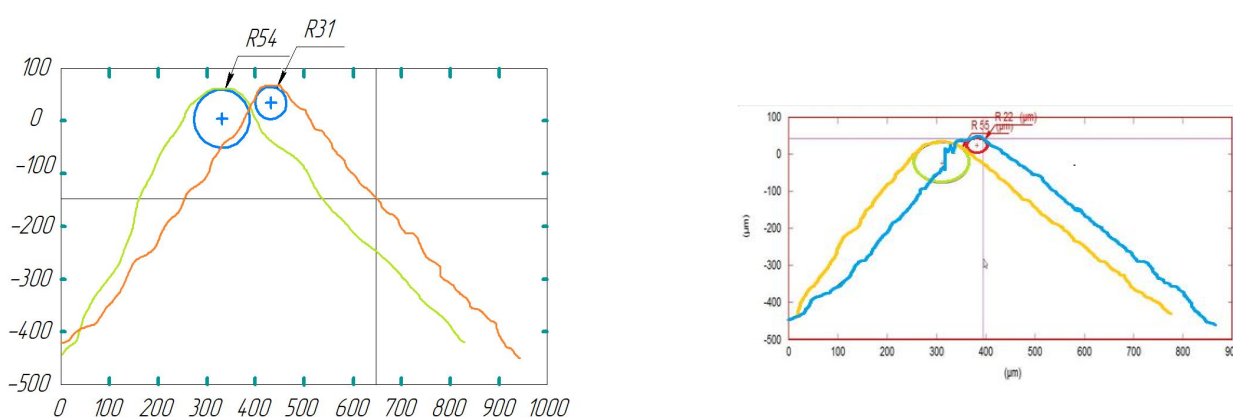


Figure 7. Change in penetration radius (p) of the cutting edge after 5 minutes of operation.

- a) Cutting tool with (TiAl)N coating,
- b) Complexly treated cutting tool (3D scanner GFM).

After milling, the geometry of the cutting edge was analyzed by measuring the rounding radius r and checking the edge stability under a metallographic microscope. The results were compared to the initial state, since the rounding radius is one of the most important parameters in the cutting process.

Before applying wear-resistant coatings, the rounding of the cutting edges of the disk cutter formed more slowly, and the cutting tool withstood higher cutting forces, delaying the onset of accelerated wear. No cracks were observed on the tool surface. In case of partial surface damage, the cutter rapidly underwent localized oxidation and was easily resharpened.

In mechanical engineering, many components made of hard-to-machine alloys are used for various purposes. The machining of such alloys has its own specific features; therefore, special cutting tools have been developed for them, providing appropriate cutting angles and ensuring unobstructed chip removal.

A particular feature of high-performance machining is the high spindle rotation speed corresponding to the cutting depth, which can lead to the rapid failure of high-speed cutting tools due to severe vibrations and dynamic loads. For this reason, the composition of the coating and its deposition technology must be selected individually for each type of cutting tool [24].

The quality of manufactured parts, the level of accuracy, productivity, and efficiency of machining processes, as well as the overall performance of automated and adaptive manufacturing systems, largely depend on the quality, reliability, and durability of the cutting tools used in mechanical engineering.

In comprehensive studies of **nanoscale coatings**, one of the most informative methods is **X-ray photoelectron spectroscopy (XPS)**. This method makes it possible to analyze the coating–substrate interface and study the reactions occurring there under temperature and radiation effects for coatings of nanometer thickness.

XPS analysis is particularly valuable for solid materials because it allows the investigation of a surface layer 2–6 nm thick **without destroying the specimen**. Since no single coating method is universal, it is important to define their optimal application areas, taking into account the heat resistance of the tool material.

Ion nitriding and microalloying are also recommended. In particular, this treatment, which is advised to be performed before applying a wear-resistant coating, affects the wear processes not only of high-speed but also of high-performance tools, thereby increasing the wear resistance of the tool by 3-4 times and reducing plastic deformation.

The relevance of the study lies in the fact that one of the factors affecting the quality of the manufactured product is the inaccuracy of cutting tools, which in many cases is directly transferred to the workpieces, causing systematic errors in the shape and dimensions of the surfaces of the workpieces.

Coating the surface of cutting tools with wear-resistant coatings improves their essential

properties—wear resistance, crack resistance, plasticity, oxidation resistance—and reduces friction and adhesive interaction with the processed material.

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