Application of Adaptive Materials and Coatings to Increase Cutting Tool Performance: Efficiency in the Case of Composite Powder High Speed Steel

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Abstract: The paper proposes a classification of adaptive materials and coatings for tool purposes, showing the ability to adapt to external heat and power influences, thereby improving tool life. Creating a cutting tool made of composite powder high speed steels containing refractory TiC, TiCN, and Al₂O₃ compounds for milling 41CrS4 steel demonstrated the effectiveness of the adaptive materials. The tool material characteristics under the external loads’ influence and the surface layer adaptation to the heat–power exposure conditions were shown by the temperature field study using a semiartificial microthermocouple method (the level of fields is reduced by 20%–25% for 80% HSS + 20% TiCN), frictional interaction high-temperature tribometry (the coefficient of friction did not exceed 0.45 for 80% HSS + 20% TiCN at +20 and 600 °C), laboratory performance tests, and spectrometry of the surface layer secondary structures. Spectral analysis shows the highest spectrum intensity of TiC₂ after 5 min of running in. After 20 min of milling (V = 82 m/min, f = 0.15 mm/tooth), dicarbide decomposes and transits to thermally stable secondary phase films of good lubricity such as TiO (maximum) and TiN (partially). There was an increase in tool life of up to 2 times (>35 min for 80% HSS + 20% TiCN), and a decrease in the roughness of up to 2.9 times (Rₐ less than 4.5 µm after 25 min of milling).

Keywords: adaptive coating; adaptive material; composite powder HSS; cutting tool; secondary structures; surface layer; thermal-force loads; wear resistance

1. Introduction

Currently, it is necessary to design, create, and use innovative materials with an improved complex of physical, mechanical, and operational properties based on structural and tool materials, ceramics, and topocomposites (materials with functional coatings) to ensure improved performance of critical engineering products (elements of aviation equipment, power plants, turbocompressors, metalworking tools, and others) operating in difficult and variable conditions associated with the impact of increased thermal and power loads that cause high wear rates of contact surfaces. One of the most promising and dynamically developing scientific approaches aimed at solving the above problem, within the framework of which the most authoritative research groups around the world are working, is the development and use of adaptive materials and coatings, characterized by a particular structural–phase state in bulk and close to the surface layers [1–4].

Scientists and specialists use various terms such as adaptive, self-organizing, self-healing, intelligent, “chameleons” to designate such materials and coatings [5–10]. They have a “common denominator”, which means the ability to adapt to operational loads (wear, damage, thermal power conditions, stress–strain state, etc.) with all the variety
of existing terms, thereby allowing the functionality of a machine-building product and ensuring the operability of the entire system as a whole [11–14].

Muratore et al., in their research, understand “chameleon” coatings to be adaptive nanocomposite coating materials (solid lubricant with size scales of $10^{-10}$–$10^{-8}$ m, MoS$_2$ coatings) that adjust their surface composition and morphology by multiple mechanisms for reducing friction and wear intensity in aerospace applications [5]. They were the first to introduce this term. However, earlier works can be found that did not use these terms concerning friction reduction.

Pogrebnyak et al. discussed the structural, phase, and chemical composition of adaptive multicomponent nanocomposite coatings. They conducted review work concerning research of hardness, friction, and wear intensity at elevated temperatures of adaptive coatings and analyzed their adhesive strength [4]. The adaptive coating materials with low friction coefficients and wear rate in a wide temperature range were divided into five groups:

- Diamond-like carbon coatings;
- Metal nitrides (TiN, CrN);
- Transition metal and dichalcogenide materials (MoS$_2$, WS$_2$);
- Polymers;
- Soft metals of the copper subgroup (with a filled pre-external $(n−1)d$-sublevel—$3d^{10}4s^1$, $4d^{10}5s^1$, $4f^{14}5d^{10}6s^1$ such as silver, copper, gold).

The main disadvantage of these materials (ceramics and metal ceramics, composites) was indicated as poor lubricating properties at room temperature and an unstable friction coefficient in a broad temperature range up to 1000 °C. The authors conclude that the problem can be solved only by application of nanocomposite coatings with different internal structures based on the obtained material group, such as Al/Au, Mo$_2$N/Ag, TiN/Ag, NbN/Ag, TaN/Ag, CrN/Ag, ZrN/Ag, VN/Ag, and CrAlN/Ag composites.

Zekonyte et al. [15] researched transition metal dichalcogenides (self-adaptive W–S–C coatings), which belong to a small family of solid lubricants with potential to produce an ultralow friction state using friction force microscopy. These materials form well-oriented films on the sliding surface with a thickness of 10 nm with a decrease in friction coefficient when the load increases. The well-ordered tungsten disulfide (WS$_2$) layers (tribolayers that peel off as ultrathin flakes) were formed on the coating surface. The observed nanoscale tribological behavior of WSC coatings replicates a deviation of Amonton’s law.

Yuan et al. [16] researched a nanomultilayer TiAlCrSiYN/TiAlCrN that was deposited by physical vapor deposition (PVD) on cemented carbide turning inserts for milling DA718 Inconel. It was shown that an initial short-term cutting speed increase during the running-in stage noticeably improves tool life by formation of protective/lubricious tribo-ceramic films on the friction surface.

Sergevnin [12] studied wear resistance and failure of PVD Ti-Al-Mo-N coatings of 14 µm under different conditions. The coefficient of friction was established as 0.42 and 0.51 at +20 °C and 500 °C and 0.63, 0.71 for TiAlN coating, respectively. The wear of the cutting inserts in 18 min of operation was reduced by 14% comparing TiAlN coating, when uncoated tool had failure (critical wear of 0.47 mm) after 16 min of turning.

The scientific and technological principles for creating adaptive materials and coatings (AMCs) developed by research groups are highly diverse and mainly specialized for specific engineering products (machine parts and cutting tools) in practice. There are no universal methods and technological approaches. First, it is necessary to assess the specifics of the operational loads experienced by the product in AMC’s development and practical application. If the cutting tool is considered an object of research, it should be considered a separate class of machine-building products, the operational loads for which have pronounced distinctive features. The processes of friction and wear in cutting materials proceed under specific conditions in comparison with friction and wear of machine parts:
- extremely high level of contact pressures on the tool working surfaces, often exceeding 100 MPa;
- the temperature on the friction surfaces during cutting reaches 600 °C and above;
- rubbing surfaces slide at high speed relative to each other, reaching 60 m/min and more [16–19].

Today, a large body of knowledge and results of theoretical and experimental research on AMC development and improvement has accumulated to improve the performance of various metal-cutting tool types in a wide range of operating loads. This work aimed to develop an easy-to-understand and capacious classification of AMC options that can improve the machining performance and cutting tool service life. In addition, the authors of the work aimed to assess the effectiveness of one of the technological approaches developed at Moscow State University of Technology “STANKIN” for creating adaptive materials using composite powder high speed steels (CPHSSs) containing refractory compounds such as TiC, TiCN, and Al₂O₃ for milling 41CrS4 steel. The change in the material characteristics under the influence of external loads and the formation of secondary stable structures (oxides and nitrides), i.e., operating conditions, was shown by conducting metallophysical and tribological studies and operational tests in laboratory conditions.

The novelty of the work is research of adaptive coatings of HSS + TiC, TiCN, and Al₂O₃ additives systems under conditions of 41CrS4 steel milling at normal temperature and in the conditions of elevated temperatures (600 °C), classification of adaptive materials and coatings, and creating a cutting tool made of composite powder high speed steels containing refractory compounds.

The following four types of tool materials:
- 100% HSS (HS6-5-2C steel powder);
- CPHSS samples of 80% HSS, 20% TiC (option 1);
- CPHSS samples of 80% HSS, 15% TiC, 5% Al₂O₃ (option 2);
- CPHSS samples of 80% HSS, 20% TiCN (option 3).

were researched by temperature field studies using a semiartificial microthermocouple method, frictional interaction high-temperature tribometry, laboratory performance tests, and spectrometry of the surface layer secondary structures. The main findings are:
- The coefficient of friction did not exceed 0.45 for 80% HSS + 20% TiCN at +20 °C and 600 °C;
- A graphical visualization of temperature fields in the tool cutting wedge section showed development of the maximum temperature from the tip to the flank face over time for HSS material. The zone of maximum temperatures remains at the top of the cutting wedge for CPHSS material. The temperature rise at the very beginning of the working stroke is less intense, and the level of fields is reduced by 20%-25%.
- Spectral analysis shows the highest spectrum intensity of TiC₂ after 5 min of running in. After 20 min of milling (V = 82 m/min, f = 0.15 mm/tooth, B = 5 mm, and t = 0.5 mm), dicarbide decomposes and transits to thermally stable secondary phase films of good lubricity such as TiO (maximum spectrum intensity) and TiN (partially);
- There was an increase in tool life of up to 2 times (>35 min for 80% HSS + 20% TiCN);
- There was a decrease in the roughness of up to 2.9 times (Ra less than 4.5 µm after 25 min of milling).

1.1. Cutting Tool Performance and AMC Challenges

New materials and coatings for tool purposes with improved physical, mechanical, and operational properties are of particular interest for modern machine-building enterprises. A cutting tool with higher efficiency can significantly improve the quality of machined parts and minimize energy and resource consumption for cutting when using expensive multi-axis computer numerical control (CNC) machine tools for high speed machining [20–24]. The operation of such machines is characterized by a high machine hour cost, increased cutting tool heat and power loads due to the need to intensify cut-
ting conditions, and an increase in tool consumption per output unit. The acting loads' level increases many times when difficult-to-machine structural materials are cut. The processes of adhesion–friction interaction on the tool's working surfaces are enhanced, and accelerated wear occurs with a simultaneous deterioration in the dimensional accuracy of the workpiece being processed and an increase in its roughness. In such conditions, the cutting tool requires increased efficiency and operational stability, mainly determining the efficiency of metalworking [25–28].

Although the types of cutting tools, tool materials, operating conditions, and the natures of the acting heat and power loads are highly diverse, they are united by common characteristic features. A wide range of acting loads is primarily determined by the type of material to be machined (carbon and low-alloy structural steels, cast and ductile irons, hardened steels and hard cast irons, heat-resistant Fe-, Ni-, or Co-based and titanium alloys, aluminum alloys, Zn-, Mg-, or Cu-based alloys and non-ferrous metals). Additionally, the most critical operating conditions are the cutting shear thickness or cutting feed, which determines the force impact level (increased during preliminary roughing and low during finishing and semifinishing) and the value of the cutting speed (increased and moderate), which determines the thermal effect level on the cutting tool contact pads. The stability of the loads acting on the cutting tool is also important: constant (with continuous contact of the cutting edges of the tool with the workpiece, for example, during turning) and intermittent (during milling, planing, chiseling, intermittent turning, etc.).

An analysis of the wear options and the reasons for the tool operability loss in practice can assist in formulating a problem set to be addressed by developing and applying AMCs. Thus, despite the variety of operating conditions, all AMC practical tasks can be reduced to the following:

- reducing the possibility of the development of creep and dynamic recrystallization processes, which weaken the cutting edge at the flank face and lead to catastrophic wear (typical for high speed steels);
- a decrease in the intensity of crater formation on the rake face, which reduces the strength of the cutting edge and leads to its destruction and rapid catastrophic wear of the cutting part of the tool;
- a decrease in the intensity of abrasive and adhesive wear on the tool flank, leading to an increase in temperature and catastrophic wear;
- reducing the possibility of plastic deformation of the cutting part of the tool (lowering or indentation), which worsens the removal of chips from the cutting zone, and reduces the workpiece dimensional accuracy and surface quality;
- prevention of the formation of or obstacle to the development of thermal microcrack networks on the tool cutting edge, which increases the risk of the cutting part chipping and reduces the tool resource;
- a decrease in the intensity of build-up on the rake face, which reduces the dimensional accuracy of the part and the quality of the surface (periodic detachment of the build-up leads to the formation of cracks near the cutting edge, reducing the tool life);
- minimization of the possibility of tool material chipping of microvolumes, which causes intensive wear of the flank face and a decrease in the accuracy of the workpiece dimensional accuracy and surface quality.

A decrease in the intensity of adhesion of the machined material to the tool’s rake and flank faces significantly increases the machined part roughness and reduces the tool resource.

### 1.2. AMC Type Classification for Cutting Tools

The options for wear and the reasons for cutting tool efficiency loss when varying within a wide range of their operating conditions were considered above. All AMCs for cutting tool purposes must withstand high contact pressures and temperatures to function directly in the cutting zone or near it. Authoritative research groups develop and apply in practice various technological approaches considering these specific conditions, thanks
to which the working sections of the cutting tool can adapt to the external environment effects. The authors of this work propose an array of available scientific and technological approaches in the field of AMCs for cutting tools to classify them into three main groups (Figure 1 shows a variant of the graphical visualization of the proposed classification):

1. Materials and coatings with active control function;
2. Self-organizing materials and coatings;
3. Self-repairing materials and coatings.

![Classification of AMC types to improve the performance of the cutting tool.](image)

**Figure 1.** Classification of AMC types to improve the performance of the cutting tool.

### 1.3. Materials and Coatings with Active Control Function

The group of materials and coatings with active control function should include AMCs, which in their essence play the role of sensors that, when exposed to external influences, recognize (detect) critical changes during the cutting tool operation and transmit the corresponding signals wirelessly to the control system of the metal-cutting machine. The system carries out a control (adaptive) effect on cutting according to the built-in algorithms, depending on the information received and the technological problems to be solved. For example, it adjusts the cutting speed, feed, or depth to reduce the likelihood of brittle fracture of the cutting part or reduce tool excessive wear. In emergency cases, it stops machining, thus realizing the active control principle.

When implementing this approach, coatings can be applied to the cutting tool (for example, thin-film thermocouples), or heat-sensitive and elastic-sensitive inserts can be used in the tool design, located near the cutting zone, which demonstrate deformations or other physical parameters characterizing the machining and cutting tool state [29–31]. It is advisable to use these AMCs in the manufacture of the most critical products in the aerospace, nuclear, and other industries when there is a technological task of manufacturing either an extended (large) part or a complex-shaped part for which a cutting tool failure during machining will inevitably lead to a failure of expensive products. Another application area is special alloys, difficult-to-machine composites, and machining of other materials when there is a high probability of unexpected cutting tool failure.

There has been research on online monitoring of cutting temperature during continuous turning of titanium and nickel alloys using interchangeable triangular and tetrahedral cutting inserts made of WC–Co hard alloy with built-in chromel–alumel thermocouple sensors. Microgrooves with a depth of about 100 µm are etched on the flank face using laser action to accommodate thin-film thermocouples on carbide inserts near the cutting edge, and the surface of the cutting tool is covered with a thick insulating layer [29]. The sensors can be staggered concerning the direction of the chip flow to increase the measurement ac-
accuracy. Detailed technological principles and options for thin-film thermocouples forming on the tool surface are described in [29–32]. Well-known studies have demonstrated the possibility of high-precision measurement in cutting temperature values in the range of up to 1000 °C. In this case, the natural wear of the cutting edge of the carbide inserts does not affect the performance of the sensors and the reliability of the received diagnostic data. There are experimental data on the efficiency of using the above-described cutting plate-sensors during operation under intermittent cutting with difficult-to-machine material conditions [30]. Under such conditions, sensors based on chromel–alumel thermocouples demonstrate high sensitivity and low inertia. There has been some research in which thin-film thermocouples were embedded in polycrystalline cubic boron nitride cutting inserts by diffusion bonding to control turning of very hard materials [31].

Additionally, it should be noted that it is promising to use sensors based on flexible piezoelectric polymer films to design structures and for cutting tool production. This gives an excellent response under mechanical stress action and allows for assessing the components of the cutting force according to the degree of their deformation, which is an informative diagnostic (troubleshooting) sign of wear and tear of tool surfaces and the state of the entire metalworking system as a whole [33,34]. For these purposes, it is most convenient to use PVDF (polyvinylidene fluoride) sensors (film) with a multilayer structure consisting of a PVDF film sandwiched between two electrodes and protective coatings [35]. The locations for installing the sensors are variable, but they should be as close as possible to the processing area (in this case, it is necessary to consider that the working temperature of the PVDF film is 700 °C). They are installed in seats under each cutting plate in the tool body as a rule (in the case of using a multiblade assembly tool) or in special recesses made in the tool holder, into which the cutting plate abuts with the working surfaces and where elastic deformations arise under the action of cutting forces. The timely response of the control system to the signals transmitted by the sensors allows the cutting tool to be adapted to changed conditions, thereby preserving its performance for a longer time.

1.4. Self-Organizing Materials and Coatings

This group should include AMCs capable of providing the structural self-organization of the surface layer of the cutting tool during contact interaction with the environment and workpiece being machined under conditions of heat–power loads typical for cutting processes due to secondary structure (phase) formation. It is the most extensive AMC group in terms of implementation options and research depth, with which many authoritative world-class teams work [15,36–45]. A classic example of secondary structures is those formed at elevated cutting temperatures in conditions of interaction with the natural environment (air) or artificially introduced external media of oxide and sometimes nitride compounds of metals of IV–VI groups of the periodic table. Secondary structures have thermal stability and improved lubricity in the tribocontact zone, significantly reduce the intensity of frictional interaction, and increase the wear resistance of the tool contact pads.

A schematic diagram demonstrating the stages of secondary structures forming during physicochemical processes in the contact zone in cutting materials is proposed by the authors in Figure 2. At the initial stage (stage 1, Figure 2), when the cutting wedge separates the chips from the workpiece, chemically clean surfaces (often called juvenile) are formed on the tool and the workpiece, on which there are no oxides and adsorbed films. “Freshly” formed surfaces are of a very active energetic and electronic state, and they are ready to interact with the components of the external environment (stage 2, Figure 2), which can be characterized by various sorption processes, primarily physical and chemical adsorption [46–48]. The energy of the broken molecular bonds of the juvenile surface is such that the external environment molecules can undergo destruction and decay into atoms, ions, and radicals. These formed particles are also chemically active and can enter into chemical interaction with freshly formed metal surfaces. At the next moment, the formation of new chemical compounds (secondary structures) is observed in the “tool-processed material” contact zone due to reactions between chemically pure
surfaces and components of the external environment, that is, the processes of ion and chemisorption (stage 3, Figure 2). The physicochemical processes in the contact zone with protective (lubricating) films and secondary structures forming at the interface with thermal stability and improved lubricity passivate the adhesion and frictional interaction between chemically pure surfaces. The secondary structures represent a stable zone with an increased internal energy level from the thermodynamics point [49–51]. The transformation of the conditions for contacting the cutting wedge working surfaces of the tool with the machined material is the consequence. The formed lubricating films and secondary structure function are integral parts of the tool material and participate in cutting. The formed protective films cannot be exclusively continuous. In addition, their inevitable local abrasion and destruction occur together with the tool material with the formation of chemically pure freshly formed surfaces, which again interact with the external environment in the contact zone at increased heat and power loads (stage 4, Figure 2) and the formation of secondary structures occurs. These stages are cyclically repeated several times throughout machining the part until the cutting tool reaches critical wear.

![Figure 2. Schematic diagram of the secondary structures’ physicochemical formation in the contact zone of the cutting wedge and the workpiece to be machined.](image)

The understanding of physicochemical processes described above for contacting a tool and a workpiece provides researchers with an excellent toolbox for creating self-organizing materials and coatings. It is possible to purposefully design and implement the composition and structure of the tool material and/or the surface coating applied to the tool and predict the formation of certain secondary structures necessary for specific operating conditions, taking into account the thermal effect. It is important to emphasize that obtaining reliable diagnostic information about the changes that have occurred in the ultrathin surface layer of the tool material or coating is possible only by high-precision techniques based on spectroscopy principles. Only by systematically investigating and understanding the nature of the changes and the formation of secondary structures can a scientifically grounded choice of architecture and chemical and phase composition of the tool material and coating be made for high speed and carbide tools and also for ceramic tools and for specific operating conditions to ensure the maximum possible wear resistance.

The basic concept in self-organizing AMCs is based on the elements in their composition, which form oxide phases with weak bonds between atomic planes during heating [52,53]. These phases have good thermal stability and resistance to oxidation at the tribocorrection spot with the workpiece being machined (for example, W, Mo, V, and Ti form...
a series of oxides with a layered structure). One of the most studied compounds that forms stable oxide phases upon oxidation is vanadium nitride. Since VN is a compound potentially capable of imparting antifriction properties to existing coatings during oxidation, there are solutions for creating superlattice coatings [54], in which layers of nanosized thickness TiAlN/VN alternate. The coefficient of friction of coatings of this type is relatively low at temperatures of 700 °C and is no more than 0.5. TiAlN/VN coatings show a lower friction coefficient than hard coatings with superlattice TiAlN/CrN or CrN/NbN [55,56].

The mechanism of formation and the type of secondary structures formed are separate for each coating in their temperature range, and a transition from one joint to another is possible during cutting with an increase in temperature on the contact pads of the tool [57]. For example, the beginning of the formation of oxide phases in the tribocontact zone is noted for a TiAlN/VN coating at 500 °C, and a complex structural analysis reveals the presence of vanadium pentoxide V$_2$O$_5$ in the near-surface layer. The specified compound melts with its removal from the surface layer at 685 °C, forming high-temperature modifications of other vanadium oxides.

The well-known studies of the mechanism of self-organization in milling with a tool made of WC-Co substrate with multilayer nanosized coatings based on complex nitrides of TiAlCrSiYN/TiAlCrN [16] are very indicative. This coating provides mass transfer of many elements, primarily Al and Si, to the friction surface, accompanied by the formation of dissipative structures due to a high nonequilibrium state and a complex nanocrystalline/layered structure. Ultimately, this leads to a substantial decrease in entropy production and the corresponding wear rate because of self-organization already occurring at the initial stage of wear. The formation of synergistic complex tribooxides endows the surface layer with increased thermal barrier properties. It creates the effect when the intense heat flux accompanying cutting is minimally accumulated in the surface layer of the cutting tool and is maximally transferred to the environment, ensuring the working condition of the tool for a longer time.

The authors of this project comprehensively studied the processes of wear and changes in the structure of the tribocontact zone of the surface of tools from high speed steels and WC-Co substrate and oxide–carbide and oxide–nitride ceramics, including those with TiNbAlN/TiZrN coatings, etc. which were deposited by magnetron sputtering bombarded with fast argon atoms [58–61]. Forming nonstoichiometric amorphous oxide films on the surface of ceramic samples was revealed during the research. Nitride and carbide phases from the surface layer were partially transformed into simple or complex oxides in the contact zone due to tribooxidation. The formation of these secondary structures made it possible to increase the wear resistance of ceramic tools up to two times during turning and milling.

As a typical example of the practical use of the adaptation mechanism in the conditions of frictional and adhesive contact interaction, it will be interesting to consider the results of research of the scientific group of MSTU “STANKIN” devoted to the multilateral study of the structural state and performance properties of improved tool high speed steels.

1.5. Self-Repairing Materials and Coatings

This group should include AMCs which can provide a spontaneous response to external mechanical, thermal and physical impacts by changing (restoring) the structure and microgeometry. Examples of the implementation of this approach are self-sharpening cutting edges of metalworking tools with blades, for example, equipped with hard laminar or laminated coatings [62]. Nevertheless, the greatest research interest for scientists today is tool materials and coatings that have a shape memory effect (high damping alloys). This effect consists of restoring the original shape of the plastically deformed material, which occurs after its heating to a specific temperature [63,64].

The self-healing phenomenon is associated with martensitic transformations in the crystal lattice of the material, during which an ordered movement of atoms occurs. Martensite in shape memory materials is thermoelastic and consists of crystals in the form of thin
plates that stretch in the outer layers and shrink in the inner layers [65]. The sources of deformation are interphase, twinning, and intercrystalline boundaries. After heating the deformed alloy, internal stresses appear, tending to return the metal to its original shape. The nature of spontaneous recovery depends on the mechanism of the previous exposure and temperature conditions.

Among some known shape memory alloys used in mechanical engineering, an intermetallic compound based on titanium nickelide (Ni-Ti system) has the maximum thermal cyclic strength, but its hardness and heat resistance are insufficient for use as a material for the cutting part of the tool [66]. At the same time, there are examples of using Ni-Ti or analogs as inserts in the construction of cutting tools, particularly for the machining of rocks and building materials. For example, there are known variants of using such materials as compact drives for bringing the worn cutting part of the cutters of drill bits to the working position due to the form restoration of the alloy under a particular thermal effect. There are technical solutions for the manufacture of tool bases from shape memory alloys for fixing diamond elements. In the event of overheating and an unacceptable increase in temperature, the contact area with the workpiece material decreases and the position of the cutting diamond inserts is corrected to minimize their abrasion. Recently, new high-entropy alloys of the Fe-Ni-Co-Al-Nb-Ti type have come to replace traditional alloys of the Ni-Ti system, which have certain advantages and significant prospects for application in tool production. There are examples of assembled tool constructions with CBN inserts including damping elements. This ensures improved vibration resistance and durability of the tool [67].

An analysis of the latest progressive research results shows that the use of high-entropy alloys (HEAs) in their manufacture has attracted the most significant interest in creating tool materials with a self-healing effect today [68–70]. In particular, HEAs based on Fe-Co-Cr-Ni-Al and Co-Cr-Fe-Ni-Ti-Al are already effectively used as binders (mass fraction up to 20%) in the production of TiCN-TiB₂ composite cermets by vacuum hot pressing. After receiving the samples, the binder structure based on the HEA is a solid solution, which tightly binds TiCN and TiB₂. The use of the HEA makes it possible to obtain a fundamentally new tool material with a unique set of physical and mechanical properties compared to using a traditional binder (Ni-Co) in the manufacture of cermets. There is research on the creation of tungsten-containing hard alloys of the WC group using the Al-Co-Cr-Cu-Fe-Ni binder, which makes it possible to operate the material at higher thermal loads compared to samples in which Co is used as a binder [71]. The use of an HEA makes it possible to obtain a new class of tool material for a broader range of technological applications than traditional materials.

In addition, development is currently underway to use Fe-Co-Cr-Ni-Mo-based HEAs to create diamond and ceramic composites through spark plasma sintering and other advanced technologies [72–75]. The use of an HEA as a tool matrix in which diamond particles are embedded allows, by adjusting the technological conditions of sintering, various microstructures at the HEA/diamond interface and sufficient interfacial bond strength to be obtained. Researchers have discovered an interstitial strengthening effect, which has a very beneficial effect on the mechanical properties of the new tool material.

2. Materials and Methods

2.1. CPHSS-Based Tool Materials

The object of the study was composite powder high speed steels (CPHSSs), the components of which have a powder composition according to the chemical composition corresponding to the widespread industrial high speed HS6-5-2C steel (AISI M2 according to ISO 4957 [76]) with the addition of 20% refractory compounds TiC, TiCN, and Al₂O₃. CPHSS occupies an intermediate position between the classic tool materials such as high speed steels (HSSs) and carbide alloys in their properties. The introduction of refractory carbides, carbonitrides, and oxides into the CPHSS composition provides them with high
hardness and heat resistance and the high speed powder base with high viscosity and ductility. CPHSS can be classified as a generic class of adaptive tool materials [77–80].

The industrial technology of hot isostatic pressing of powder compositions followed by pressure treatment by heated blank extrusion was used to obtain experimental samples (Figure 3). Sixteen samples of each tool material were tested. All experiments were repeated five times to obtain data. The following variants of samples of tool materials based on HSS with and without additives of refractory compounds were studied:

- 100% HSS (basic version made of HS6-5-2C steel powder);
- CPHSS samples from 80% HSS, 20% TiC (option 1), 80% HSS, 15% TiC, 5% Al₂O₃ (option 2), 80% HSS, 20% TiCN (option 3).

![Figure 3. Produced samples of HSS and CPHSS compounds.](image)

Preliminary studies carried out at MSTU “STANKIN” showed that an increase in the content of refractory compounds over 20% significantly reduces the strength characteristics of the material [47,49]. The research was limited to the specified content of alloying additives since it was focused on the process of interrupting cutting (milling) when the risk of brittle fracture of the tool material increases.

Different values of the fundamental physical and mechanical properties characterized the samples prepared for research, precontrolled in the laboratories of the university (Table 1).

**Table 1. Physical and mechanical properties of research samples.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Rockwell Hardness HRC</th>
<th>Flexural Strength, MPa</th>
<th>Average Coefficient of Friction on Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% HSS</td>
<td>63–65</td>
<td>3300</td>
<td>0.75</td>
</tr>
<tr>
<td>CPHSS</td>
<td>70–72</td>
<td>2400–2500</td>
<td>0.5–0.6</td>
</tr>
</tbody>
</table>

2.2. Study of the Structure, Elemental Composition, and Tribological Properties

The study of the samples’ structure was carried out on a scanning electron microscope VEGA 3 LMH manufactured by Tescan (Brno, Czech Republic). This instrument was equipped with an Oxford Instruments INCA Energy energy-dispersive X-ray spectroscopy (EDX) system.

Two spectroscopic techniques were used for an analysis and study of the elemental composition of the near-surface layer of the samples of the cutting tool and the workpiece being processed:

- Secondary ion mass spectrometry (SIMS) through analysis on an XT 300M mass spectrometer manufactured by Extorr Inc. (New Kensington, PA, USA);
- Auger electron spectroscopy (AES) by analysis on a JAMP-10S spectrometer manufactured by JEOL, Ltd. (Tokyo, Japan).

The evaluation of the coefficient of friction (COF) of the surface layer of the samples was carried out on a TNT tribometer manufactured by Anton Paar TriTec SA (Corcelles-
Cormondrèche, Switzerland) according to a pin-on-disc method (ASTM G99 17 standard [81]) under the following test conditions (Table 2).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion pattern</td>
<td>Rotation of the sample (disc) relative to a stationary counter body</td>
</tr>
<tr>
<td>Counter body</td>
<td>A pin made of 100Cr6 steel with a diameter of 6 mm</td>
</tr>
<tr>
<td>Applied load, N</td>
<td>1</td>
</tr>
<tr>
<td>Radius of movement, mm</td>
<td>2</td>
</tr>
<tr>
<td>Sliding speed, cm/s</td>
<td>10</td>
</tr>
<tr>
<td>Test temperature, °C</td>
<td>+20.0, 600.0</td>
</tr>
</tbody>
</table>

Samples were made from various types of tool materials such as discs with a diameter of 19 mm and a height of 8 mm for tribological tests. The same samples were used to evaluate the resistance of the surface layer of the samples to abrasion by testing on a CALOTEST device manufactured by CSM Instruments (Needham Heights, MA, USA) under the conditions of force acting on the sample of a rotating sphere when a water-based abrasive slurry was fed into the contact zone. Optical analysis of the geometric dimensions of the wear hole and its measurement on a Dektak XT stylus profilometer manufactured by Bruker AXS GmbH (Karlsruhe, Germany) to quantify the intensity of samples’ wear was carried out.

2.3. Investigation of Temperature Fields in the Cutting Wedge

The semiartificial clamped microthermocouple method was used [82] to study the temperature fields in the cutting wedge of the tool. Composite plates of various tool materials were used, divided by the main intersection plane (cutting edge normal plane) into two parts, tightly (without a gap) compressed by pins before sharpening, excluding the possibility of their relative displacement to lay semiartificial microthermocouples. The articulating surfaces of each part of the plate were carefully lapped until a roughness $R_a$ of no more than 0.04 µm was achieved. The position of the interface plane corresponds to the cutting zone at the tool–chip interface section position, in which the temperatures caused by the contact interaction of the tool and the workpiece are maximum. A constantan wire with a diameter of 0.1 mm, insulated with spacers, was placed at a given point of the cutting zone at the tool–chip interface section along a groove in one of the parts of the composite plate. An uninsulated flattened end with a wire thickness of less than 10 µm was compressed between two ground surfaces of the composite plate portions. The wire contact area with the plate (thermocouple hot junction) was adjusted to a size of 0.15 mm × 0.15 mm. The studies were carried out on a ZMM-Sliven CU500/1000 screw-cutting lathe (ZMM, Nova Zagora, Bulgaria) when simulating the interrupted machining in longitudinal turning with a constant cut section of a workpiece made of 41CrS4 steel (HB 240), on which the grooves were previously milled. It provided the conditions for intermittent operation of the tool close to the milling process. The tests were carried out at a cutting speed $V = 68$ m/min, feed $f = 0.15$ mm/rev, depth $t = 2.0$ mm with a working stroke length of 90 mm, and an idle stroke of 45 mm.

2.4. Durability Testing of Cutting Tools

Durability (fatigue) tests were carried out with the milling of 41CrS4 structural steel (DIN 17210 standard [83]) common in mechanical engineering. It was decided to use an end mill model since wear testing involves a tremendous amount of experimentation and increased consumption of tool material. The designed and manufactured model of the tool was a holder, in which the original insert was fixed (Figure 4), and the operating conditions of which were as close as possible to the operation of a real end mill. The tests were carried out at a cutting speed $V = 82$ m/min, feed $f = 0.15$ mm/tooth, milling width $B = 5$ mm, and depth $t = 0.5$ mm. In all cases, the criterion for the cutters’ failure
was the achievement of wear on the flank surface of a limiting value of 350 μm. Service tool life was defined as the time it took to cut before the cutter reached the wear limit. A Stereo Discovery V12 metallographic optical microscope (ZEISS GmbH, Jena, Germany) was used to quantify wear. The curves of the wear with the cutting time were plotted based on the data obtained (the work shows averaged curves obtained based on tests of five samples of each type of tool material). A portable Accretech Handysurf profilometer (ZEISS GmbH, Jena, Germany) was used to obtain reliable data on the roughness of the processed workpiece throughout the entire test cycle. Laboratory resistance tests were carried out on a vertical milling machine with an infinitely variable feed drive VM 127M of the Russian production of JSC Votkinskiy Zavod (Votkinsk, Republic of Udmurtia, Russia).

![Figure 4](image-url)  
(a) General view of the working area of the machine during performance testing (a) and the design of the model of the tool for milling (b).

3. Results and Discussion

3.1. Material Structure Analysis

The cross-sections of the material’s structure based on 100% HSS and experimental CPHSS samples were studied for comparative analysis. The fine structure of 100% HSS consists of martensite in which carbides of standard alloying elements are distributed (Figure 5a). There is practically no carbide inhomogeneity in the CPHSS with an 80% HSS, 15% TiC, 5% Al₂O₃ structure (Figure 5b). The pronounced inclusions of refractory compounds TiC and Al₂O₃ have an irregular shape and size from 0.5 to 4.0 μm. SEM images of structures of other studied CPHSSs are not shown since they turned out to be similar to Figure 5b.
3.2. Testing of Tool Materials under Stationary Loads

Subsequently, four variants of tool materials were tested under stationary loads (under conditions of abrasion during calostesting). Figure 6 presents experimentally obtained data illustrating the dependence of the volume of worn material on testing time for resistance to abrasive wear; the volume of worn-out material was calculated using the formulas given in [84]. The presented dependences give us a specific idea of the kinetics of the development of abrasive wear of the contact areas of various tool materials over time. The CPHSS samples differ in many respects from the standard HSS, which was expected since the hardness of the latter is lower than that of CPHSS, and the average friction coefficient over steel is higher than that of CPHSS.

Figure 6. Dependences of the abrasion of the contact areas of various samples of tool materials on the time of testing for abrasive wear resistance: (1) 100% HSS; (2) 80% HSS, 20% TiC; (3) 80% HSS, 15% TiC, 5% Al₂O₃; (4) 80% HSS, 20% TiCN.
characteristic of the sample containing 80% HSS, 20% TiCN. The sample containing 80% HSS, 15% TiC, 5% Al₂O₃ had a slightly higher intensity. The minimum wear resistance of all CPHSSs is shown by a sample of 80% HSS, 20% TiC.

![Figure 7](image-url)

**Figure 7.** The 3D profiles of wear centers of various samples of tool materials after 20 min of testing under conditions of force action of a rotating sphere in an abrasive environment: (a) 100% HSS; (b) 80% HSS, 20% TiC; (c) 80% HSS, 15% TiC, 5% Al₂O₃; (d) 80% HSS, 20% TiCN.

The above results are demonstrative but not informative enough since they do not give an idea of the possible adaptive ability of experimental materials and the effectiveness of their use in the manufacture of cutting tools. They require the impact of heat–power loads at a level as close as possible to the operational loads (in machining).

### 3.3. Quantitative Assessment of the Cutting Part Wear and Roughness

Figure 8 shows the laboratory tests’ results of the tool in milling 41CrS4 steel and gives a quantitative assessment of the dimensional wear of the cutting part and the roughness of the processed surface of the workpiece. It can be seen that the curves of the development of wear for CPHSS samples (Figure 8a) over time are of a classical nature, and they mainly show three stages: running-in (I); steady-state wear (II); critical wear (III). At the same time, zone II is noticeably narrowed for a tool made from 100% HSS, and there is no pronounced transition to zone III. Curves of changes in the roughness of the workpiece (Figure 8b) correlate well with the curves of wear development: at the initial stage of testing during running-in (natural blunting) of the tool, no change in roughness is observed; upon transition to the normal wear zone, there is a gradual increase in the contact area of the rear surface of the tool with the surface of the workpiece, accompanied by an increase in the adhesion component of the friction force and a gradual increase in the roughness of both the tool and the workpiece; contact interaction processes are rapidly intensified at the last (critical) stage of wear, and cutting forces increase, which causes a noticeable deterioration in the quality of the surface layer of the workpiece [85]. The tool life is significantly improved for CPHSS compared to a standard tool material and is 17 min for HS6-5-2C and 29–35 min for CPHSS samples. It can be seen that the highest durability (35 min) among the investigated experimental materials is shown by a sample containing 80% HSS and 20% TiCN, and the least (29 min) is shown by the sample containing 80%
HSS and 20% TiC. At the same time, it is evident that the increase in resistance achieved for all CPHSS samples can be regarded as a technologically significant result. The results of testing a sample of 80% HSS and 20% TiC (Figure 6, curve 2) showed the maximum increase in the wear of the contact zone after 15 min of milling and by the end of the tests. The volume of abrasion even slightly exceeds the wear of a sample made from traditional HSS. The intensity of material destruction under an abrasive action is largely determined by the ratio of the counterbody hardness and the test metal surface hardness in the contact zone. A sharp increase in the wear rate of an 80% HSS and 20% TiC sample can be associated with a decrease in the hardness of its surface layer at a certain moment. The specific structure of CPHSS (Figure 5), containing a significant number of refractory inclusions of polyhedral and fragmentary shapes, undissolved in the steel bond, suggests that the level of hardness (and the intensity of abrasive wear directly related to it) of such a material is determined by the degree of preservation of the high-hardness carbide phase. It is most likely that over time and with an increase in the volume of abrasion, hard and, at the same time, very brittle TiC particles (their ductility increases at temperatures above 600 °C) are not retained in the steel bond and crumble, significantly changing the conditions of contact interaction between the tool material and counterbody. For the other two studied CPHSS samples (Figure 6, curves 3 and 4), a high degree of safety in the steel bond of high-hardness components is ensured throughout the entire test cycle. However, it is too early to conclude the prospects of one or another CPHSS variant based on evaluating the resistance to abrasion without thermal action.

Figure 8. Dependences of cutting wear of flank face (a) and 41Cr5 steel workpiece’s surface roughness (b) on the time for various tool materials in milling at $V = 82$ m/min, $f = 0.15$ mm/tooth, $B = 5$ mm, and $t = 0.5$ mm: (1) 100% HSS; (2) 80% HSS, 20% TiC; (3) 80% HSS, 15% TiC, 5% Al$_2$O$_3$; (4) 80% HSS, 20% TiCN.

It is well known that the temperature on its contact surfaces has a decisive influence on the tool life during machining [86,87]. The contact areas of the rubbing surfaces of the tool, chips, and workpiece being processed are small, and the pressure and friction rate exerted on them are extremely high. The high temperature in the cutting zone is the cause
of structural changes in the material of the cutting tool and the reason for the rapid loss of its performance [88–90]. Therefore, to explain the physical nature of the increase in the tool material durability, it is crucial to study the changes in temperature fields in the cutting wedge of the tool during operation.

The best values for samples containing 20% TiCN can be explained by the specific physical and mechanical properties of this two-phase compound, primarily determined by the nature of interatomic bonds depending on the ratio of carbon and nitrogen atoms [91]. Some nitrogen atoms are replaced by carbon atoms in titanium carbonitride, forming unlimited TiN-TiC solid solutions. Titanium nitride has the same crystal lattice as titanium carbide, and it is capable of replacing it isomorphically [92]. TiC<sub>x</sub>N<sub>y</sub> compounds [93,94] formed in the structure of CPHSS samples combine the advantages of carbide and nitride phases. The hardness of titanium carbonitride even slightly exceeds the value for titanium carbide when the plasticity is not inferior to that for titanium nitride (which is extremely important for the tool’s operation during milling when the risk of chipping of the cutting edges increases). Titanium carbonitride inclusions have high thermodynamic stability and are closer to HSS in terms of thermal expansion coefficient. In addition, the improved performance for specimens with 20% TiCN compared to 20% TiC results from a lower affinity for iron-containing steels and alloys and a lower adhesive activity when heated [92–94]. The fact that the introduction of Al<sub>2</sub>O<sub>3</sub> particles into a powder composition based on TiC somewhat improves the characteristics of CPHSS, but at the same time it is inferior to samples with TiCN additives, indicates the need for separate studies related to the optimization of the compositions of powder mixtures during sintering of experimental instrumental materials.

3.4. Temperature Fields of the Cutting Wedge and Tribological Tests

Figure 9 shows a graphical visualization of temperature fields in the cutting zone at the tool–chip interface section of the cutting wedge of the tool during interrupted machining 41CrS4 steel. It can be seen that the maximum temperatures develop at the tip of the cutting wedge for a tool made of HS6-5-2C material at the beginning of the working stroke (Figure 9a), but over time the region of maximum temperatures moves from the tip along the flank face. It was revealed that the presence of refractory compounds of the TiCN type (Figure 9b) in the composition of the experimental CPHSS material has a significant effect on the development of temperature fields during the working stroke of the tool. Unlike tools made of standard material, the zone of maximum temperatures remains at the top of the cutting wedge for CPHSS, the temperature rise at the very beginning of the working stroke is less intense, and their level is reduced by 20%–25%. This pattern remains for different periods of the tool’s working stroke due to a significant reduction in the contact area of the material to be machined and the flank face, which has a higher hardness and a lower friction coefficient in CPHSS specimens. As can be seen from the data presented, the temperature field in the contact zone of the cutting wedge stabilizes by the end of the working stroke (at \( T = 0.1 \) s), and the temperature values for the two types of tool material become close. However, with a decrease in the working stroke, as shown in Figure 9, the use of CPHSS material dramatically affects the contact processes on the flank face and significantly reduces the temperature at the tip of the cutting wedge. The influence of the presence of refractory joints in the material structure on the temperature level on the main flank face is less significant and not as noticeable. However, their total effect on the development of temperature fields and the temperature level in the cutting wedge during the working stroke significantly contribute to the tool’s performance, increasing its durability, as shown by performance tests under laboratory conditions (Figure 8).
Figure 9. Temperature fields in the cutting zone at the tool–chip interface section of the cutting wedge of a tool made of HS6-5-2C steel (a) and experimental CPHSS (80% HSS, 20% TiCN) (b), obtained at different periods $T$ of the working stroke during interrupted cutting at $V = 68$ m/min, $f = 0.15$ mm/rev, $t = 2$ mm.
3.5. Tribological Tests

Figure 10 demonstrates the processes occurring in the contact zone of the tool with the workpiece. At room temperature (Figure 10a), the curves of change in the coefficient of friction (COF) of various tool materials in contact with a steel pin have a classical trend, and the coefficient of friction throughout the entire path demonstrates a stable character with small peaks at the initial stage of the tests for all investigated material samples. At the same time, the coefficient of friction is different for different materials: the COF has a maximum value of 0.75 for a sample made of HS6-5-2C (100% HSS), while the COF remains at the level of 0.45–0.6 for samples of CPHSS after running-in and stabilization of the contact interaction. The smallest COF (0.45) among the experimental CPHSS materials under study is shown by a sample containing 80% HSS and 20% TiCN, and the largest (0.6) by a sample containing 80% HSS and 20% TiC. The results of tribological tests under high-temperature heating conditions (Figure 10b) have a completely different form, i.e., a level similar to the thermal effect that tool contact pads undergo in the real operating conditions. The curves of the friction coefficient change for a number of the samples under study have sharp peaks and a pronounced unstable character. It is typical of a sample made of HS6-5-2C material (the nature of the curves was repeatedly checked to eliminate errors), for which COF “jumps” from 0.6 to 1.1 are observed over 70 m of the friction path, and then relative stabilization is observed with a gradual increase (COF is 0.9 at 200 m). A sample containing 80% HSS and 20% TiC shows a somewhat stable character and for the highest COF value of all CPHSS samples, the COF develops abruptly, and its values range from 0.5 to 0.75 at a distance of 40–140 m; a pronounced stabilization of the friction conditions is observed, and the average COF value is 0.65 at a distance of 150 m. The most favorable friction conditions are demonstrated by a sample containing 80% HSS and 20% TiCN:

- The COF curve does not have sharp bursts throughout the entire path, and its value remains at a low level from 0.3 to 0.5 (COF value upon heating has even lower values than those of a similar sample when tested without heating);
- The COF stabilizes even more and amounts to a little less than 0.45 after passing a path of 150 m. The sample containing 80% HSS, 20% TiC, and 5% Al2O3 demonstrates an intermediate value among the CPHSS samples in terms of tribological characteristics.

![Figure 10](image)

**Figure 10.** Dependences of the coefficient of friction (COF) of various tool materials on the friction path in contact with a steel pin without heating (a) and when heated at +600 °C (b): 100% HSS (1); 80% HSS, 20% TiC (2); 80% HSS, 15% TiC, 5% Al2O3 (3); 80% HSS, 20% TiCN (4).

COF behavior under high-temperature exposure (Figure 10) is directly related to the structural features of the tool materials. The primary structural component is tungsten and molybdenum carbide Fe3(W, Mo)5C for 100% HSS. The available results of the behavior of various grades of HSS when studying at high-temperature frictional contact with low-carbon steels [46,47,59] show that under thermal action with an increase in the number...
of test cycles, there is gradual coagulation and shape change of carbides from spherical to drop-shaped and multifaceted, the crystal lattice of the material changes, and a layer consisting of martensite and austenite forms on the surface. At the same time, a decrease in the hardness and strength of the HSS surface layer is observed. The stability of the crystal lattice significantly affects the coefficient of friction, and the decrease in the tool steel hardness significantly increases the friction force adhesive component.

A different mechanism takes place at high-temperature frictional contact of CPHSS samples. The refractory compounds TiC, TiCN, and Al₂O₃ present in the samples’ structures upon heating contribute to an increase in the density of defects, and a weakening of interatomic bonds occurs, which improves the oxygen access to the surface layer, and the rate of formation of very hard oxide films with metals increases (in particular, titanium begins to interact with oxygen at temperatures of 600 °C and above). Three stages of contact interaction (Figure 3) explain the described mechanism well. In addition, with an increase in temperature, an increase in the plasticity of refractory compounds is observed. Their lubricating effect is manifested. The specific surface energy in the surface layer decreases, and the work expended on surface deformation decreases. This explains the decrease in the COF for the CPHSS samples. Similar phenomena were observed by the authors of other works when studying the frictional interaction of various tool materials with carbides and nitrides of refractory metals-based coatings [12–14,16,22,37].

A comparison of the operational and tribological characteristics based on the test results of various tool materials described above show strong correlations, where the maximum wear rate during cutting and the worst tribological characteristics during high-temperature testing were shown by a sample of HS6-5-2C powder, and the best performance indicators and tribological properties by the sample containing 80% HSS and 20% TiCN. There is no doubt that the presence of refractory compounds of the TiCN type in the structure of the tool material can provide structural adaptation (self-organization) of the surface layer under external heat–power action due to the formation of secondary structures with thermodynamic stability and improved lubricity.

The most informative is spectroscopic methods to identify and prove the formation of secondary phases. In this case, it is important to analyze the thin surface layer of the tool’s contact pads and the workpiece being processed. Figure 11 shows the results of secondary ion mass spectrometry of worn-out contact pads of the tool made of CPHSS material containing 80% HSS and 20% TiCN (Figure 11a) and auger electron spectroscopy of the workpiece’s processed surface (Figure 11b) after specific time intervals of the intermittent cutting process. A CPHSS sample that showed maximum wear resistance in service was deliberately analyzed.

The data obtained show that in machining, the tool material containing refractory inclusions of TiCN interacts with environmental components and elements that make up the workpiece to be processed, forming new (secondary) phases. In turn, the chemical composition of the surface layer of the workpiece also undergoes a noticeable transformation (Figure 11).

Spectral analysis shows very different compositions of the surface of the tool contact pads in the initial period of cutting (during running in) and in the time interval of steady-state wear after 20 min of operation (Figure 11a). Spectral analysis revealed the highest intensity of the spectrum of the metastable compound based on TiC₂ (titanium dicarbide) and less intense spectra of TiN and TiO (in decreasing order of intensity) after 5 min of running in. The wear rate of the contact pads stabilizes with the further operation of the tool under the influence of heat and power loads of the cutting process and the external environment’s effect. Spectrometry shows a sharp decrease in the intensity of the TiC₂ spectrum in comparison with the running-in zone, and one can observe the decomposition of titanium dicarbide and its transition to the oxygen-containing TiO phase (maximum spectrum intensity) and partially to TiN, since the intensity of its spectrum increases markedly in comparison with the running-in zone.
It is precisely thin surface films based on secondary phases such as thermally stable compounds of titanium with oxygen and nitrogen, which have good lubricity, that significantly reduce the intensity of the adhesive and frictional interaction of the tool and the workpiece during milling and provide the previously established (Figure 8) twofold increase in resistance and improve the workpiece surface quality.

4. Conclusions

All available technological approaches can be divided into three groups following the classification proposed by the authors of the types of adaptive materials and coatings (AMCs) for tool purposes, showing the ability to adapt to external negative conditions:

- materials and coatings with active control function;
- self-organizing materials and coatings;
- self-repairing materials and coatings.

The complex analytical studies carried out in this work allow us to judge the current directions of work of the leading research teams in the development and application of AMCs, aimed at maintaining the working capacity of the cutting tool for a longer time. The developed technological approaches are compared with the options of tool wear in practice under various operating conditions, and the areas of their practical application are determined.

It can be concluded that the most extensive group is AMCs from the point of view of implementation options, scale, and depth of research. They can provide structural self-organization of the surface layer of the cutting tool due to the formation of secondary
structures in contact with the environment and the workpiece being machined under the conditions of heat and power loads acting during cutting. The data presented in the paper illustrate how a properly designed surface layer can effectively adapt to external negative conditions.

Based on the experimental results of the authors of the work, composite powder high speed steels (CPHSSs) were proposed and studied as a typical example of a material with adaptive abilities under operational loads, the components of which are refractory compounds such as TiC, TiCN, and Al$_2$O$_3$. It was instrumentally confirmed that the thin surface films formed when cutting based on secondary phases, such as thermally stable compounds of titanium with oxygen and nitrogen, significantly reduce the frictional interaction intensity and redistribute the thermal fields in the cutting zone at the tool–chip interface section of the tool cutting wedge. The established changes in the surface layer provide a twofold increase in tool life during milling, which was confirmed in laboratory conditions and improve the workpiece’s surface quality.

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