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DIAMOND ABRASIVE TREATMENT: TRIBOLOGICAL ASPECT (REVIEW OF MODERN RESEARCH)

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Abstract. *The importance of developments to overcome friction and wear is largely due to the fact that the energy consumed by the manufacturing industry is almost a third of the total energy consumed. That is, the tribological aspect in the processes of diamond-abrasive processing is quite significant and must be taken into account. Recently, new modern developments have appeared in the literature that somewhat clarify this direction, both from the point of view of the diamond abrasive tool and the tribological behavior of various diamonds, including those with coatings. It is these developments that are covered further in our review of modern publications. Additive manufacturing (AM) methods have significant advantages for obtaining individual products and prototypes, allow to reduce costs, and also speed up the release of products to the market. Nowadays, this direction has begun to be used for diamond-abrasive tools. Of course, new binders for the working layer of the diamond tool have been developed for such energy-efficient AM technology. It is shown that the cutting forces and friction coefficients of microtextured diamond tools are significantly reduced. The tribological behavior of diamonds against various materials is fundamental for their use in the abrasive and bearing industries. It has been proven that, in comparison with ordinary diamond grains, porous diamond grains with an increased number of microedges effectively reduce the cutting force and heat generation. It is shown that the application of the effect of further mechanochemical influence during the coating of diamond abrasives, both on the diamond-bond boundary and on the contact of the surface of the diamond grain with the processed material, allows to increase the efficiency of the use of the diamond-abrasive tool. Attention is drawn to what kind of impurities are introduced into the contact zone during diamond-abrasive processing to change the tribological parameters. At the same time, the most widely used is h–BN, which with a layered crystal structure is one of the types of effective solid lubricants, especially at elevated temperatures. Attention has been paid to emerging materials such as graphene oxide and carbon dots (CD), a kind of carbon-based nanomaterials, which have been widely used as highly effective lubricant additives.*
Keywords: *diamond abrasive treatment; tribological behavior; diamond tool; diamonds; coatings; solid lubricants; graphene oxide.*

At one time, in the article [1], the energy consumption in diamond abrasive processing processes was analyzed and it was proved that the share of friction energy in the total processing energy can be from 17 to 45 % for the processing of hard alloys, from 29 to 42 % for the processing of non-tungsten solids alloys, from 20 to 29 % when grinding oxide-carbide ceramics and from 52 to 98 % when grinding oxide ceramics. The importance of developments to overcome friction and wear is also shown in a modern article [2], where it is indicated that the energy consumed by the manufacturing industry makes up almost a third of the total energy consumed. Wherein 20 % of the energy is used to overcome friction, and 14 % of the energy loss is caused by friction that is a wear-related energy loss, including the energy for making new parts and equipment downtime. In addition, taking into account the cost of maintenance work due to wear, the overall cost of wear represents 35 % of the cost of friction. The industrial production field causes a lot of energy consumption due to overcoming friction and wear. That is, the tribological aspect in the processes of diamond-abrasive processing is quite significant and must be taken into account. Recently, new modern developments have appeared in the literature that somewhat clarify this direction, both from the point of view of the diamond abrasive tool and the tribological behavior of various diamonds, including those with coatings, especially such coatings that contain additives to reduce friction, primarily the newest – graphene and h-BN. It is precisely these developments that we will highlight in our review of modern publications.

DIAMOND ABRASIVE TOOL WITH CHANGED TRIBOLOGY CHARACTERISTICS

The article [3] presents a new, modern, in contrast to the traditional, but energy-consuming, technology of pressing and sintering, a strategy for manufacturing grinding tools with conventional crystalline structure by 3D printing using multi-jet fusion technology (MJF), and five structures were selected to evaluate its feasibility and achieve grinding performance. The analysis of the results shows that the crystalline structure ensures the same macroscopic rigidity of the tools and introduces a microscopic anisotropy of compliance (Fig. 1). The crystalline structure resulted in a reduction of the grain pullout ratio by more than 82.60%, and also facilitated adhesion and prevented the abrasive layer from falling off, resulting in longer tool life. In addition, the grinding tools with crystalline structure achieved better material removal capacity, lower surface roughness, and higher energy efficiency, and they used only 29.06% to 36.22% of the materials compared to the tool with dense structure. It is noteworthy that the material removal rate of a tool with a star structure can reach 94.72% of a tool with a dense structure.

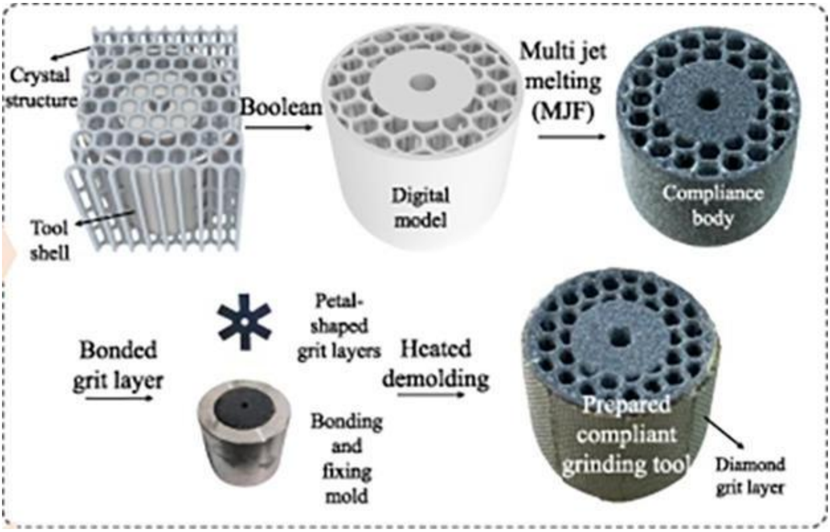

Fig. 1. Schematic sequence of obtaining a diamond tool with a crystal structure by the method of 3D printing [3].

Of course, such an energy-efficient technology of additive manufacturing (AM) also requires new binders for the working layer of the diamond tool. AM production methods have significant advantages for obtaining individual products and prototypes, allow to reduce costs, as well as accelerate the release of products to the market. The purpose of the article [4] was to study binders based on acrylate resin with different mechanical and thermal characteristics for 3D printing of grinding wheels. A noticeable improvement in grinding characteristics was achieved due to the use of a heat-resistant bond, both for mild aluminum and hardened steel. It was established that the use of a bond with higher mechanical and thermal characteristics allows for good grain retention at elevated temperatures, which contributes to reducing the grinding effort (up to 58 % and 18 % for soft and hard metals, respectively). As a result, it allows you to significantly extend the service life of the tool, for example, up to 80 % for hardened steel, and also to increase the accuracy of dimensions.

To improve the retention of diamond grains in the working layer of a diamond tool in the study [5], the surface of diamond grains was modified by applying a layer of SiO_2 by the method of isothermal hydrolysis. The results show that due to the presence of hydrate ions on the surface of the diamond grains, a thin film of SiO_2 was uniformly grafted to the surface of the diamond and this significantly increased the adhesion to the bond.

In order to mitigate the problems of low processing quality, short tool life, and low processing efficiency in the processing of 2.5D needle-like C/SiC composites, a bionic idea was adopted in research [6] to develop a new single-layer galvanic ordered tool (Fig. 2). The influence of ordered grinding wheels on surface roughness, microstructure, grinding force, grinding temperature and wear conditions was investigated. Compared with the unordered grinding wheel, the A-type and B-type ordered grinding wheels can reduce the surface roughness of the bottom surface of the C/SiC composite groove by 40.7 % and 35.8 %, respectively. In addition, they can reduce the grinding force Fy to 68.3 % and 53.2 %, respectively, and the grinding force Fz to 70.4 % and 46.9 %, respectively.

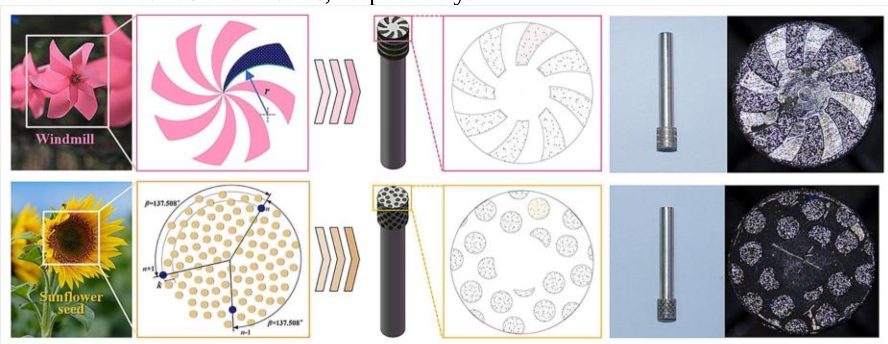

Fig. 2. Variants of the ordered end layer of a single-layer galvanic tool based on the bionic idea [6].

In work [7], another new production process was used for the development of a single-layer diamond wheel using bulk metallic glass (BMG) as a matrix and diamond particles as abrasives. BMG effectively prevents graphitization and damage to diamond abrasives due to the lower forming temperature. The coating of titanium (Ti) on the surface of diamond abrasives contributed to the formation of diffusion between the two components, creating a mechanical bond at the BMG-diamond interface. In addition, the fabricated BMG-bonded single-layer diamond wheel was preferentially worn uniformly instead of abrasives falling out during grinding of Al_2O_3 ceramics. Compared to modern electroplated grinding wheels, the developed diamond wheel demonstrated a reduction in normal and tangential grinding forces by 32.64 % and 35.86 %, respectively, and an increase in the grinding coefficient by

28.22 %, making it an excellent solution for grinding conditions of hard and brittle materials.

Grinding of railway rails can effectively remove their defects, such as cracks and corrugations, to ensure the safety and stability of railway vehicles, because the heat generated during grinding becomes a critical cause of pre-fatigue or burn on the rail surface. In work [8] rail grinding wheels with different porosity were produced. The results show that the pore structure can reduce the previous fatigue caused by grinding. Importantly, grinding efficiency improves and grinding effort/heat decreases with increasing porosity (Fig. 3). That is, such softer porous wheels significantly reduce friction and temperature in the grinding zone.

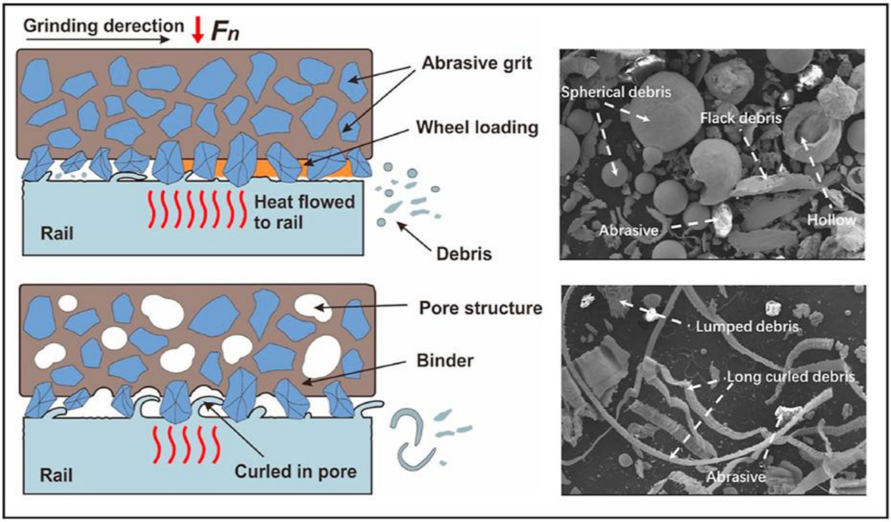

Fig. 3. Comparison of the structure and differences of chips when using solid and porous wheels for grinding rails [8].

Soft tool grinding is known for its advantages, such as large contact areas, conforming to curved surfaces based on deformation and effective vibration absorption, resulting in increased efficiency and good surface quality. In the article [9], a model of elastic extrusion was proposed, developed to calculate the pressure distribution between soft tools and hard complex surfaces of the processed workpiece (Fig. 4). The proposal lays new foundations for setting parameters during precise grinding with a soft tool.

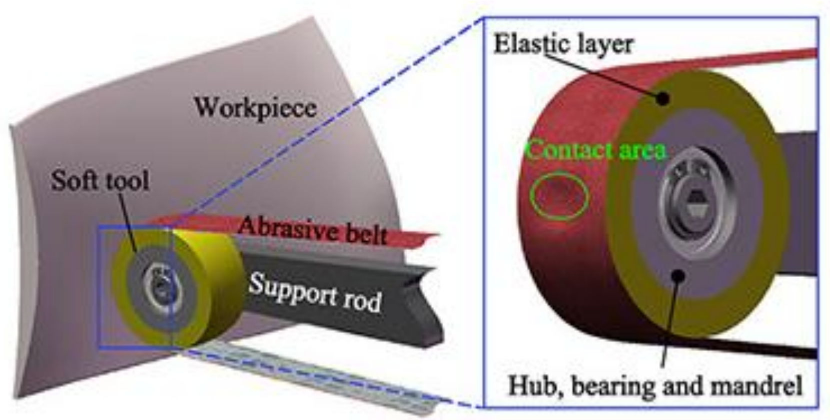

Fig. 4. Towards an elastic model of elastic extrusion in contact between soft tools and complex hard surfaces [9].

At the same time, discontinuity and elasticity can cause friction force fluctuations, which is analyzed in the article [10]. A real-time Coefficient of Friction (COF) analysis method combined with an *in-situ* contact area measurement method is used here to determine friction behavior and material removal. The results show that the material removal rate (MRR) is not correlated with the average friction coefficient, but shows a strong relationship with the frictional force fluctuations, i.e. the intermittent sliding phenomenon. In addition, a wavy topography is observed on the treated surface, which is caused by the phenomenon of intermittent sliding.

The above indicates that, among other things, it is necessary to pay attention to the condition of the cutting edge, which performs the cutting process, which was done in the article [11]. An abrasive wheel for solid phase chemical mechanical polishing (SPCMP) and effective sharpening of the cutting edge of a carbide tool (WC–Co) was developed here. X-ray diffraction and electron backscatter diffraction measurements showed that the SPCMP method removes latent scratches from the surface of WC–Co materials applied by a diamond wheel. The 100 mm diameter grinding wheel developed for SPCMP was produced in a phenolic binder using green silicon carbide (GC) as the abrasive component. This made it possible to avoid the transition from the WC phase to the W2C phase during the processing of the hard alloy, and to provoke the oxidation of the WC phase and its removal by GC. When cutting with WC–Co tools with cutting edges sharpened by SPCMP treatment, the cutting resistance was low and the degree of wear was reduced. In addition, the cutting speed of WC–Co tools when cutting Ti–6Al–4V and Inconel 718 after SPCMP wheel sharpening was about two times higher than before SPCMP.

Similarly, diamond grains must be sharp in order to obtain good dry grinding performance. In the article [12], monocrystalline synthetic diamond grains with different strength and fragility were used for the development of diamond circles with a random and patterned distribution of grains (Fig. 5). Grinding wheels containing loose diamond grains with an irregular grain structure showed better results during dry grinding experiments on WC-6Co hard alloy than high-strength cubo-octahedral grains.

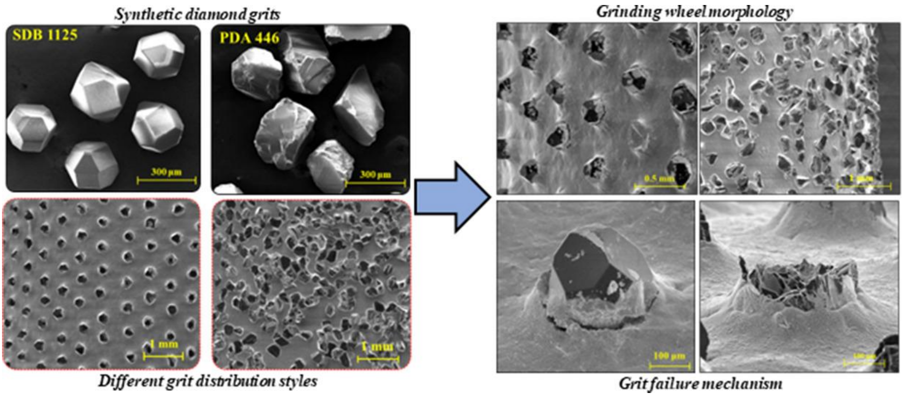

Fig. 5. High-strength (SDB 1125) and loose (PDA 446) diamonds in a single-layer tool and the difference in their destruction during grinding [12].

The article [13] presents a new grinding wheel containing the porous (loose) diamonds we mentioned above to improve ultra-precision processing. Thermochemical etching is used to obtain porous diamond grains with varying degrees of corrosion, and the cutting and wear mechanisms of these grains are investigated using MD modeling and scratch tests with individual grains. Compared to ordinary diamond grains, porous diamond grains with an increased number of microedges effectively reduce the cutting force and heat generation. It is interesting that the sizes of corrosion pores in the range from 2 to 5 µm reduce their damage during cutting. Conventional diamond grains are primarily damaged due to graphitization of the crystal surface and block crushing, while porous diamond abrasive grains are damaged primarily due to microcrushing and microfracture. Tests during final grinding of 4H-SiC showed that ordinary diamonds here give cracks and punctures on the polished surface. Meanwhile, diamonds with corrosion pores of 2 μm showed mostly ductile removal with minimal cracks and pitting. Diamond abrasives with corrosion pores of 5 μm also demonstrated satisfactory performance.

At the end of this part of the review, let's pay attention to the features of the latest processing methods with the use of additional influence on the processing process.

Elastic Emission Machining (EEM) is one of the most effective technologies for obtaining an ultra-smooth surface. A polishing particle is fed to a certain place on the surface of the part by means of a polishing wheel and enters into a chemical reaction with the workpiece, ensuring the removal of material. In the study [14], the mutual dynamic interaction between the polishing wheel and the suspension is considered in a three-dimensional state, and the rolling model is developed to analyze the energy transfer during the removal of atoms. The rolling model explains how a particle can disrupt the feedback of atoms on the workpiece surface to achieve material removal. The results of the study indicate that the energy needed to remove atoms is primarily supplied by the liquid. This understanding of the energy source provides valuable information for proposals for methods to increase material removal rates. Finally, in an experiment on surface polishing, the application of EEM leads to the retention of an ultra-smooth surface with an rms roughness of 0.1 nm, which demonstrates the excellent ability of EEM to effectively reduce surface roughness [14].

In the article [15], a new technology of dynamic friction polishing of diamonds with a low rotation speed using now ultraviolet irradiation is proposed. This method is based precisely on the effect of ultraviolet radiation and the surface of the diamond in combination with the friction between the diamond and the metal disc to realize material removal. The process of phase transformation and oxidation, which is facilitated by ultraviolet light, is the main mechanism for achieving effective material removal at low rotation speed (Fig. 6). That is, under the synergistic effect of ultraviolet light and frictional heating, the diamond can undergo oxidation and interaction with iron at a low rotation speed of 8 m/s and, finally, this allows to obtain an ultra-smooth diamond surface with a surface roughness of R_a=0.18 nm.

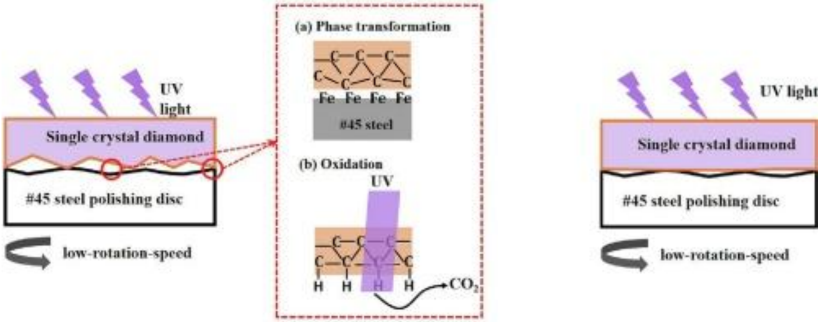

Fig. 6. Illustration of the mechanism for achieving effective diamond polishing when applying ultraviolet irradiation [15].

TRIBOLOGICAL BEHAVIOR OF DIAMONDS DURING DIAMOND ABRASIVE PROCESSING

The tribological behavior of diamonds against various materials is fundamental to their application in the abrasive and bearing industries. In the article [16], friction and wear on GCr15 steel and Si_3N_4 ceramics of two types of diamonds were investigated: HFCVD - hot filament chemical vapor deposition and PCD polycrystalline diamonds - sintered under high pressure and high temperature (HPHT). It was established (Fig. 7) that, firstly, the coefficient of friction (COF) increased with an increase in the roughness of the diamond surface; second, both the COF and wear rate (k) of the Si_3N_4 ceramic balls were generally lower than those of the GCr15 steel balls, except for the COF of the HFCVD sample; third, the wear rate (k) increased with increasing PCD grain size, which was accompanied by a decrease in residual cobalt content. As we can see from fig. 7 CVD diamond has the lowest coefficient of friction, and in terms of wear rate it is inferior only to polycrystalline diamond with a grain size in the structure of 2 µm.

Modified diamond tools (MDT) with the help of a focused ion beam (FIB) have to a certain extent reduced wear during dry single-point diamond turning, which was proved in the article [2]. The reason why MDT cutting performance is better than that of unmodified diamond tools is the reduced surface energy of modified diamonds. It was found that the implantation of Ga ions (Fig. 8) reduces the surface energy by 33% compared to pure diamond.

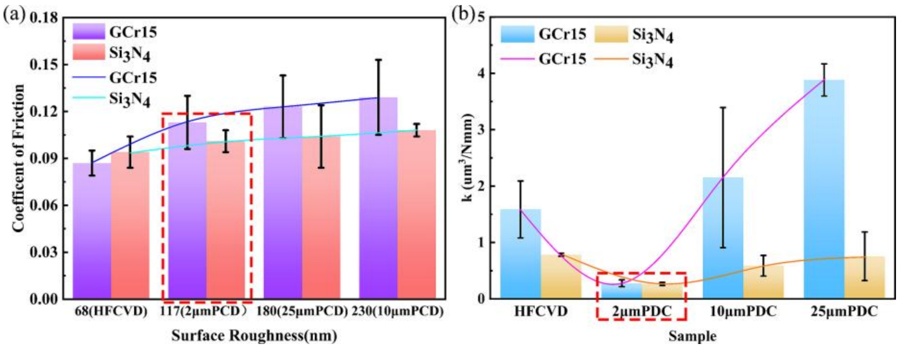

Fig. 7. Change in coefficient of friction (COF) of PCD and HFCVD samples with increasing roughness (a) and change in wear rate (k) of Si_3N_4 ceramic and GCr15 steel balls with increasing PCD grain size (b) [16].

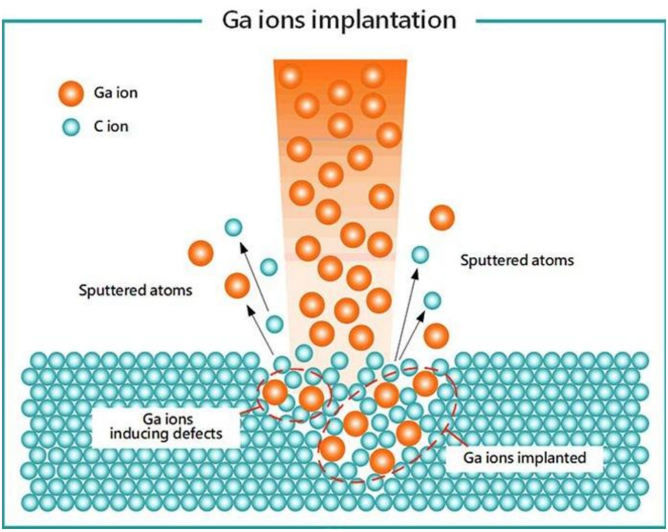

Fig. 8. Scheme of modification of the surface of a diamond tool using a focused ion beam [2].

Under conditions of high friction temperatures, polycrystalline diamond (PCD) can wear due to graphitization. PCD with cobalt removed and, as a friction pair, silicon nitride balls in the article [17] were selected for friction wear experiments at temperatures of 200, 300, and 400 °C, respectively (Fig. 9).

The results showed that the coefficient of friction and the rate of wear increase with increasing temperature. No graphitic phase was found by XRD, indicating that the cobalt pre-removal process itself can effectively inhibit the graphitization of polycrystalline diamond at high temperature. SEM images showed that increasing the temperature does not contribute to the formation of a friction film, which can increase the wear resistance of materials.

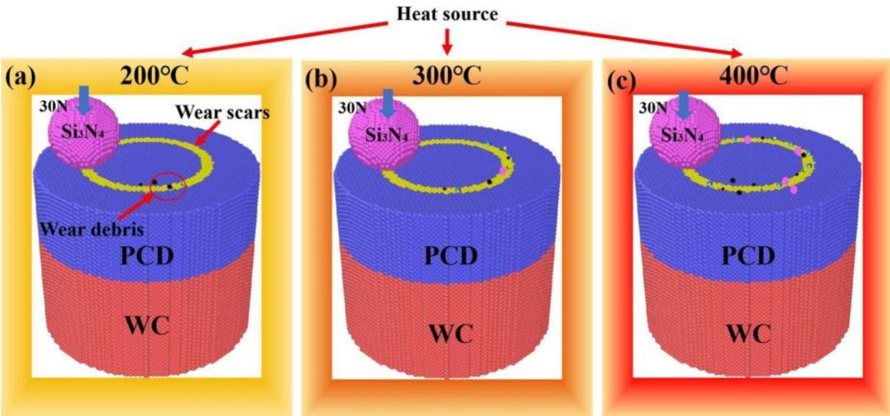

Fig. 9. Scheme of experiments on frictional wear and the difference in wear debris on wear scars [17].

In [18], the high-entropy alloy (HEA) $FeCoCrNiB_{0.15}$ and the diamond composite based on it were produced by the spark plasma sintering (SPS) method at a temperature of 950 °C. For comparison, samples of $FeCoCrNiMo_{0.15}$ and its diamond composite were made and their friction and wear behavior on Si_3N_4 balls under conditions of dry sliding in air on a ball-on-disk tester was compared (Fig. 10). The results showed that in both HEAs, a chromium-rich phase separated from the metastable matrix was observed on the friction surface. The wear resistance of $FeCoCrNiB_{0.15}$ was higher than that of the $FeCoCrNiMo_{0.15}$ alloy, and the Si_3N_4 grinding speed of the $FeCoCrNiB_{0.15}$/diamond composite was higher than that of the $FeCoCrNiMo_{0.15}$/diamond composite. This study shows that the boron-doped HEA matrix in diamond composites is a promising candidate for the manufacture of diamond tools with a long service life and high processing efficiency.

As we have already indicated above, the rubbing behavior of raw surfaces of polycrystalline diamond (PCD) is important for its application. The article [19] shows the influence of the water environment on this. Here, the interfacial capillary adhesion force at the contact surfaces and its effect on the frictional response between the colloidal microsphere and rough PCD films before and after

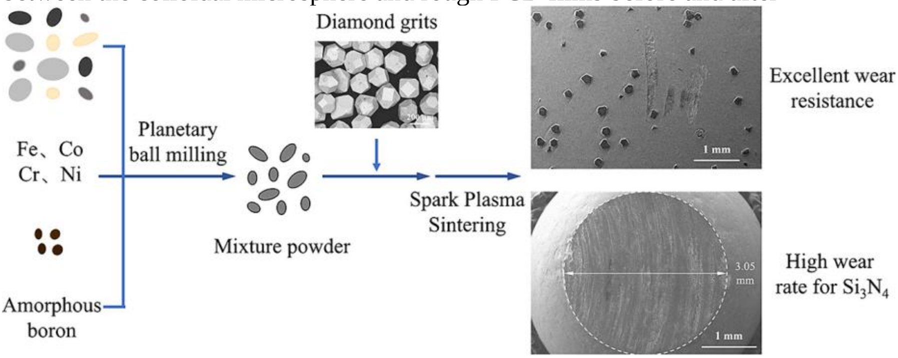

Fig. 10. Scheme of obtaining a diamond composite based on the high-entropy $FeCoCrNiB_{0.15}$ alloy [18].

electrochemical corrosion under conditions of immersion in water, low relative humidity, and humid air are quantified (Fig. 11). The combined results convincingly indicate that the observed increase in the frictional force on electrochemically corroded PCD surfaces (for microcrystalline MCD and nanocrystalline NCD) is regulated by the strengthening of the capillary effect on the contact surface, which depends on the hydrophilicity of the surface and the humidity of the environment. Compared to MCD, NCD surfaces, which have a larger intercrystalline area, experience more intense electrochemical corrosion and exhibit higher observed frictional forces as a result of lower surface roughness and greater surface hydrophilicity. The increased adhesion force of the capillaries contributes to normal loading and reduces the interfacial gap (increases the contact area of the solid body), thus increasing the frictional force. That is, the presence of water under conditions of high humidity changes the contact conditions, increasing the force of friction.

As we can see above, the microrelief of the diamond surface plays an important role in evaluating its frictional characteristics. In [20], the effect of special microtextures on the frictional and cutting characteristics of monocrystalline diamond tools was considered. Four types of microtextures, including an array of straight grooves, a concentric circular texture, a ring sequence, and a mesh texture, were created on their front surface using a femtosecond laser. The results of the experiments showed that the cutting forces and friction coefficients of the microtextured diamond tools decreased significantly, except for the concentric round texture. At the same time, the cutting characteristics of monocrystalline diamond tools were significantly improved.

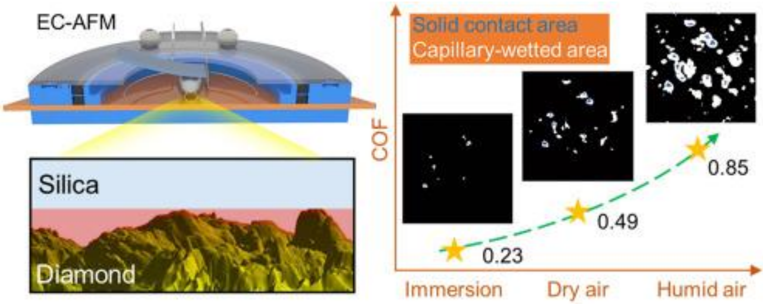

Fig. 11. Scheme of the electrochemical-atomic-force microscopy (EC-AFM) installation in section and evaluation of the friction coefficient for the conditions of submerged state, low and high humidity [19].

At the end of this part of the review, let's pay attention to the shape of diamond grains during abrasive processing of brittle materials. Abrasive processing can be simplified by presenting a series of scratches with indenters of various shapes. In the article [21], a model of the stress field caused by scratches was built to analyze the behavior of cracking when brittle materials are scratched. The model takes into account conical, pyramidal and spherical (CPS) indenters. The results show that the scratch load is reduced when a sharper indenter or a spherical indenter with a smaller radius is used. The greater the depth of the scratch, the easier it is for radial, median and lateral (RML) cracks to appear. A side crack easily occurs when the indenter becomes sharp. Radial crack nucleation changes from the position in front of the indenter to the position behind it as the depth of the scratch increases or the angle at the top decreases. RML crack sizes increase with increasing scratch depth or apex angle. The study provides recommendations for choosing the geometry of abrasive grains to increase the speed of material removal and reduce cracks in the process of abrasive processing of brittle materials.

In the study [22], the mechanism of plasticity with a deformation gradient was used to study the dimensional effect in the behavior of single-crystal copper during scratching. The results of this study showed a significant effect of size on scratch hardness values and the amount of layering. This indicates that the degree and nature of the dependence of these two parameters on the size differ significantly and oppositely depending on the direction of scratching. For example, although the [001] direction exhibits the greatest degree of dimensional effect on scratch hardness, it exhibits the least dimensional effect of side layers. Such an opposite effect is explained by the contribution of different sliding systems to the resistance to dislocations and slander. It is also shown that the scratch hardness, which takes into account both the size effect and the dependence on the crystallographic direction, is a suitable material property for wear evaluation.

The hydrogen index (pH) of the process fluid is important for diamond abrasive processing processes. Thus, the article [23] shows the effect of a liquid medium with different pH on the wear of a WC/Co hard alloy with different percentages of cobalt. Diamond scratch tests were conducted on three grades of WC/Co, with a Co content of 6, 11, and 28% by mass and in liquids: distilled (pH6), acidic (pH2), and alkaline (pH10) water. It was established that the cobalt content significantly affects the load in the scratch zone and the coefficient of friction. The latter increases with increasing CO content due to a greater degree of plastic deformation. In addition, it has been proven that at loads less than 62 N, the hydrogen index of the liquid does not affect friction. But at higher loads, the influence of the liquid medium is statistically significant, and distilled water gives a lower coefficient of friction. It should be noted that the influence of the pH of the electrolyte on the change in the composition of the cathode films on the cutting surface of the diamond wheel was also addressed in the article [24]. It was shown that, under such conditions, the polarization of the liquid changes the content of the cathode film on the surface of the wheel in contact with a hard alloy, and with a decrease in the pH of the liquid from 10 to 4, the composition of the film changes dramatically, in which the content of elements of the hard alloy, which is in contact with the grinding medium, increases significantly around. In fact, this means that as the pH value increases, the machinability of the hard alloy deteriorates, since cobalt is less lost from the hard alloy, and therefore, according to [23], not only the loads in the cutting zone, but also the friction coefficient increase.

THE INFLUENCE OF COATINGS ON THE TRIBOLOGICAL BEHAVIOR OF DIAMONDS DURING DIAMOND ABRASIVE PROCESSING

In the article [25], to apply the mechanochemical effect, the diamond film was polished using a grinding wheel containing nickel-plated (Ni) diamond abrasives. The rapid reaction of removing the diamond film is explained by the catalytic effect of the Ni coating, which causes the graphitization of the diamond film at the contact points of the interface under the influence of the high temperature generated during friction; later it can be removed by mechanical action of abrasives (Fig. 12).

Another variant of grinding diamond films (DF) is considered in work [26], based on the application of mechanochemical influence when coating diamond abrasives with titanium (Ti) coatings sprayed in a vacuum. The coating layer forms

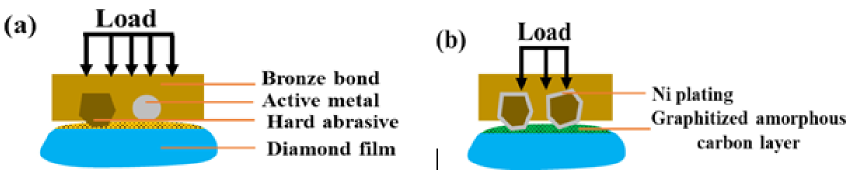

Fig. 12. Scheme describing the interaction of uncoated diamond (a) and nickel-coated diamond (b) with the processed diamond surface [25].

a diamond-TiC-Ti structure extending from the diamond matrix in the direction of the Ti coating. The material removal rate (MRR) of DF is significantly increased as a result of the available active Ti-coating on diamond abrasives, which reacts with DF at the contact points.

In the article [27], another option for accelerating DF grinding based on the mechanochemical effect is proposed. The vacuum evaporation method was used to apply a catalytically active Cr coating on diamond abrasive grains. During grinding, the Cr coating on active abrasives reacted with the diamond film with the formation of Cr_3C_2 or caused graphitization at the contact points at high temperature due to friction. It was shown that the chrome-coated grinding wheel exhibited a higher MRR compared to the uncoated diamond grinding wheel.

In the article [28] thin films of turbostratic boron nitride (t-BN) and cubic boron nitride (c-BN) grown on B-doped polycrystalline and monocrystalline diamond were considered. High-resolution transmission electron microscopy analysis revealed that the cubic boron nitride thin films consist of a mixture of c-BN and t-BN phases, with c-BN being the dominant phase. These findings provide valuable information on the characteristics of c-BN and diamond interfaces and are important for temperature control in their applications.

In work [29], to increase the wear resistance of diamond cutting tools, carbon nanosheets (CNS) were obtained in a strong covalent diamond-graphite structure obtained by laser-induced solid-phase diffusion by electrochemical removal of a graphite layer on a diamond matrix. After 14,400 cycles of reciprocating sliding on a GCr15 ball under a normal load of 2–8 N, friction decreased by 45.9–65.6% with high durability. During this process, the oxygen content is reduced by an order of magnitude, suggesting that CNS can prevent oxidation at the sliding edge. In comparison, the relative wear rate of bare diamond was 4.1–15.4 times higher than that of CNS.

The low interfacial strength between the iron-based matrix and the diamonds causes the diamond particles to fall off prematurely, which significantly affects the cutting efficiency of diamond composites. Work [30] was aimed at optimizing the interfacial microstructure and mechanical properties of diamond/Fe-Ni-WC composites by applying a Mo_2C layer on diamond particles. Mo_2C-coated diamonds were obtained using the molten salt method (Fig. 13). Diamond/Fe-Ni-WC composites were sintered by hot pressing under vacuum. Energy dispersive spectroscopic scanning showed that the Mo_2C coating layer changed the interfacial composition between the matrix and Fe–C alloy diamonds to Mo_2C, improving the interface strength.

That is, the above in [25–30] indicates that the application of the effect of further mechanochemical influence, both on the diamond-bond boundary and on the contact of the surface of the diamond grain with the material being processed, when coating diamond abrasives, allows to increase the efficiency of using diamond abrasives. - abrasive tool.

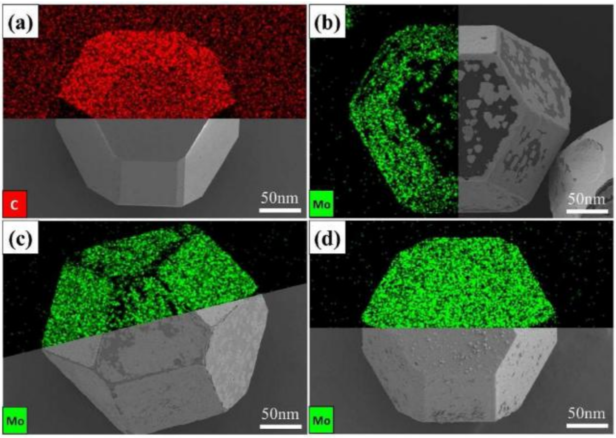

Fig. 13. Micro-morphology of uncoated diamond (a) and Mo_2C-coated diamond prepared at 1050 °C for 15 (b), 30 (c), and 60 min (d) [30].

In the article [31], the microtexture of the CVD-diamond coating was investigated, which, along with the function of retaining wear particles, can to a certain extent reduce the coefficient of friction due to the graphitization of the diamond coating. Graphitization of the textured surface allows to quickly reduce and stabilize the coefficient of friction at the initial stage of friction. After stabilization, the friction coefficient of the diamond coating decreases as the degree of graphitization increases. This is of great importance for expanding the field of application of diamond coatings [31].

In the article [32], the use of solder coating on different types of diamond grains is proposed to improve their retention in the working layer of grinding wheels on a polymer bond. Brazing can successfully cover most of the diamond grains with a layer of additive alloy. Pores and bulges several micrometers in size were observed, as well as the formation of titanium carbide between the coating and the surface of the diamond grains. The viscosities of monocrystalline coated diamond grains (RVD) decreased only slightly, but increased more significantly for polycrystalline coated diamond grains (PDGF1). The wheel containing PDGF1 diamond grains showed the lowest grinding force and the highest performance, while the wheel with RVD coated diamond grains had the highest grinding force and a fairly low grinding ratio.

In the article [33], to determine the features of the reaction of the diamond surface with various types of metals and metal oxides, the activation energy of the reaction between diamond and metals, as well as between diamond and metal oxides, was calculated from the first principles. For the transition metals of the fourth period of the Periodic Table of the Elements, when they react with diamond to form the corresponding metal carbides, the order of increasing activation energy for the metals is: Mn, Fe, V, Ti, Cr, Co, Ni, Zn, and Cu. And when diamond reacts with MnO, FeO, CoO, NiO and CuO to form metals and CO, the calculated activation energy in descending order is: MnO, FeO, CoO, NiO and CuO. Thus, it has been established that NiO and CuO are reduced by diamond to Ni and Cu, which indicates that an oxidation-reduction reaction takes place between diamond and metal oxides.

In [34], a chemical vapor deposition method was proposed, when a diamond coating with CuO particles was applied to a WC/Co substrate. For comparison, a pure diamond coating was produced. The surface morphology proved that the diamond coating can be deposited on a substrate with CuO particles. But CuO particles can lead to the formation of amorphous carbon. Indentation tests showed that the diamond coating with CuO particles showed higher adhesion strength and cracking resistance than the diamond coating without CuO particles. That is, the content of CuO particles affected the crack resistance of the diamond coating. Thus, the dispersion of CuO particles on the surface of the substrate can be considered as a potential technology for adjusting diamond grains due to the inclusion of carbon phases, which, in turn, can increase the crack resistance of the diamond coating to meet industrial requirements.

In work [35], diamond particles were covered with aluminum oxide by the method of atomic layer deposition. As a result, the temperature at which the decomposition of diamond to CO_2 begins shifted towards higher temperatures (≈ 50 K) due to the protective effect of Al_2O_3. It was concluded that the mechanism of diffusion through the protective layers is responsible for this moderate increase in the oxidation temperature. The authors [35] claim that although the amount of improvement is small enough to be used for high-temperature applications, these results indicate that this type of protective coating can be used to protect diamond grains from oxidation.

This was confirmed in [36], where Ti–B–C protective coatings on diamond particles were investigated. The results showed that it is the boron content that is important for the adhesion of the Ti–B–C coating to diamond. Such a coating with a boron content of 60% (at.) protected the diamond from oxidation for more than 1 hour when heated to 1000 °C in air. That is, oxides play a very important role. Thus, in the case of annealing coated diamond in air, the a priori formed B_2O_3 and TiO_2 protected the diamond from oxidation as oxygen-impermeable layers. In addition, with the help of the formation of B_2O_3, it was possible to avoid the delamination of TiO_2 caused by volume expansion during oxidation [36].

INFLUENCE OF ADDITIVES IN THE CONTACT ZONE ON TRIBOLOGICAL INDICATORS DURING DIAMOND ABRASIVE PROCESSING

At the end of this review, let's pay attention to what kind of impurities are introduced into the contact zone during diamond-abrasive processing to change the tribological indicators. At the same time, the most widely used is h–BN, which with a layered crystal structure is one of the types of effective solid lubricants, especially at elevated temperatures.

Obtaining a surface of fused silica at the atomic level with a high MRR with the help of chemical mechanical polishing (CMP) is a difficult task. To solve this, a new suspension for CMP was developed based on potassium oleate and deionized water using CeO_2 abrasive coated with hexagonal boron nitride (h-BN), which reduces friction in the contact zone [37]. Cerium abrasives have implemented a new superlubrication function during CMP thanks to this coating, preventing damage and achieving an ultra-smooth surface (Fig. 13).

In the article [38], the formation energy and stability of h-BN clusters on 10 types of transition metal surfaces were investigated. The results show that h-BN clusters on different metal substrates can undergo a transition to the most stable structure at a critical size, but it is different for metal substrates. The most stable structures for BN clusters on Cu, Pd, and Co surfaces change from chain-like to sp^2-cell at critical size n = 8, 7, and 8, respectively. After that, the cellular structure becomes the most energetically beneficial and continues to grow until it covers the entire substrate. The study of BN nucleation at the atomic scale can be useful for planning experiments on the fabrication of h-BN films.

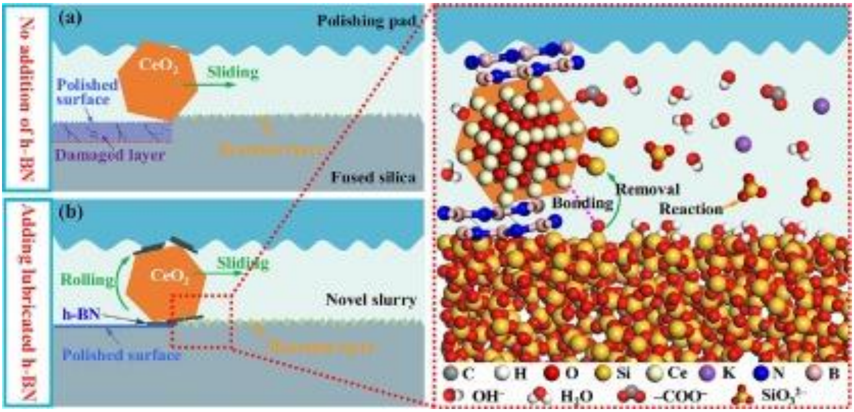

Fig. 13. Schematic representation of the mechanism of superlubrication using h-BN during CMP of fused silica [37].

In [39], the interfacial interaction between diamond and hexagonal boron nitride (hBN) is considered. The weak van der Waals (vdW) interaction between hBN and hydrogen-terminated diamond (H-diamond) provides the basis for introducing the twist angle as a new degree of freedom to modulate the properties of heterostructures. The results showed that the additional free orbitals, which are formed due to the spontaneous relaxation of hBN at higher deformation caused by twisting, can strengthen the vdW bond between hBN and H-diamond, which will promote charge transfer at the interface, thereby weakening the surface scattering of impurities and increasing the accumulation of holes on the H-diamond surface.

In [40] h-BN with a relative density of about 91% was obtained by spark plasma sintering (SPS) technology and its tribological behavior at 1200 °C was investigated. The results showed that the coefficient of friction of h-BN was relatively stable in combination with Si3N4 and remained in the range of 0.215–0.305. It is believed that the low coefficient of friction at 1200 °C is mainly a consequence of weaker interlaminar bonding of h-BN and easier sliding of h-BN plates at high temperature.

The article [41] presents the self-lubricating material Al_2O_3-cBN-hBN. The influence of the cBN/hBN additive on the mechanical and thermal properties of sintered composites was analyzed, and friction and wear tests were conducted. It was established that the addition of cBN particles significantly improves the mechanical and thermal properties of composites. Different hBN content can change the wear mechanism of composites. The release efficiency of hBN particles in the composites was enhanced due to the larger difference in moduli between cBN and hBN. The hardness of Al_2O_3-cBN-hBN composites is improved by at least 54% compared to traditional self-lubricating materials due to the provision of crack resistance and lubricating properties.

The improvement of thermal conductivity is crucial for tribological performance. In [42], a three-dimensional structure with layered elements is obtained by electrostatic assembly of h-BN and graphene oxide (GO) nanosheets. Such a structure helps reduce friction and increase wear resistance based on "synergistic lubrication". As a result, this affects excellent self-lubricating and wear-resistant properties and a noticeable increase in thermal conductivity (1039.16%) of the composite.

Gallium nitride (GaN) is a modern material used for the production of chip boards and powerful devices. In work [43], molecular dynamics modeling was used to study the mechanism of removal of gallium nitride crystals during diamond-abrasive processing using graphene lubrication. The results show that graphene can significantly increase the wear resistance of GaN substrates due to the reduction of surface wear and subsurface damage. That is, graphene has a lubricating and protective effect on the substrate when cutting GaN single crystals with diamond abrasives.

The study [44] studied the nanofriction characteristics of composite thin films of graphene oxide (GO) and cellulose nanocrystals (CNC), as well as reduced graphene oxide (rGO) and CNC, namely GO/CNC and rGO/CNC thin films, under an applied electric potential and humidity using an atomic force microscope (AFM). For all films, the coefficient of friction (COF) depended on the applied electric potential. In addition, the friction force with electric potential increased at low humidity (relative humidity (RH) $< 40\%$) due to the effect of electrostatic force. At high humidity (RH$>40\%$) and high electric potentials (>4 V), the friction force decreases as the electric potential increases due to the phenomenon of electron leakage.

Attention was also paid to the influence of humidity in the article [45], where the characteristics of friction and wear resistance of C/C-CuNi composites under conditions of different humidity were investigated. Lower humidity levels (30–50% RH) led to the formation of a lubricating layer consisting mainly of graphite and CuO, which was manifested in the adhesive wear of the composites together with stable and low coefficients of friction (~0.144) and low wear rates (Fig. 14). While at a relative humidity higher than 70%, there was an increased tendency to form a brittle layer, mainly consisting of $Cu(OH)_2$ and $Cu_2(OH)_2CO_3$ compounds, due to tribochemical reactions between the composites and H_2O and CO_2 in humid air. In the future, this brittle oxide layer led to abrasive wear, which was accompanied by fluctuations in the coefficient of friction and an increase in the rate of wear.

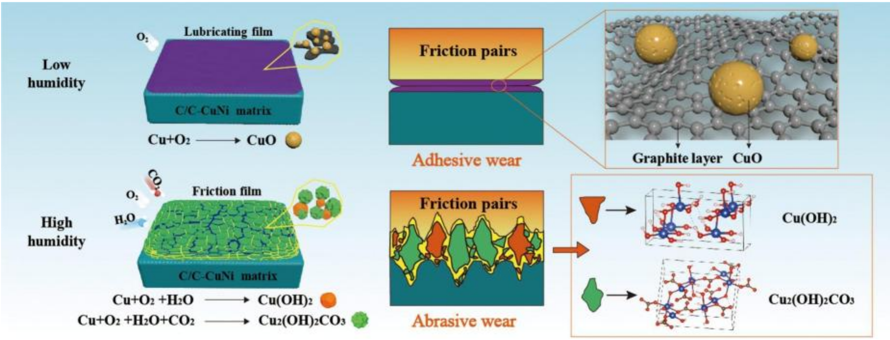

Fig. 14. Schematic presentation of wear mechanisms of C/C-CuNi composites under conditions of different humidity [45].

In the article [46], the microtexture of the CVD-diamond coating has the function of retaining wear particles and can to a certain extent reduce the coefficient of friction due to graphitization. It was established that the degree of graphitization of the microtexture of the diamond coating decreases by an order of magnitude within concentric circles. At the same time, it correlates with the density of the microtexture. Texture depth has a weak positive effect on the degree of graphitization. Graphitization of the textured surface allows you to quickly reduce and stabilize the coefficient of friction at the initial stage of friction (Fig. 15). After stabilization, the friction coefficient of the diamond coating decreases with an increase in the degree of graphitization. A layer of graphite on a microtextured surface with a diamond coating can improve dry friction characteristics. This is of great importance for increasing the accuracy of processing diamond-coated tools.

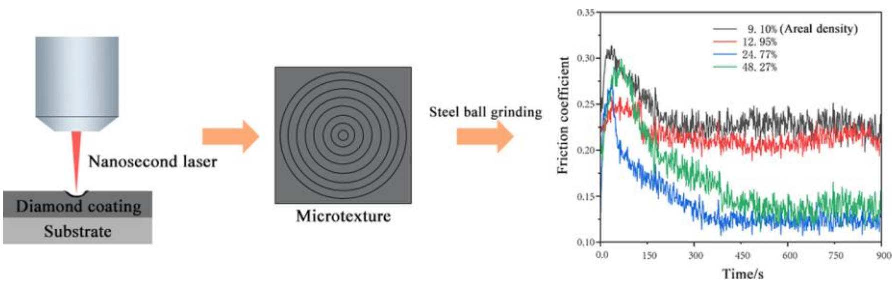

Fig. 15. Schematic representation of the formation of the microtexture of the CVD-diamond coating and the change in the coefficient of friction over time [46].

The above indicates that it is carbon materials that are particularly suitable for reducing friction. Attention is also drawn to this in the article [47], where it is shown that carbon dots (CD), a kind of carbon-based nanomaterials, were widely used as highly effective lubricant additives. Studies show that doping the surface with heteroatoms, especially several heteroatoms, can significantly improve their tribological characteristics. Moreover, it was established [47] that the tribological behavior of N,B,P-CD is better than that of N,B-CD and P-CD under identical test conditions, demonstrating a multiatomic synergistic lubrication effect. The excellent tribological characteristics of N,B,P-CD are explained by their favorable film-forming ability and effect of nanolubrication at various stages of friction.

In [48], a multilayer composite coating of cBN/NCD (cubic boron nitride and nanocrystalline diamond) with modulation periods of 1 μm, 1.5 μm, and 3 μm was deposited using a linear ion source of radio frequency magnetron sputtering and microwave plasma chemical vapor deposition (MPCVD) on tungsten cobalt hard alloys (YG6) and silicon substrates. It was found that as the modulation periods decreased, the surface roughness of cBN/NCD multilayer composite coatings tended to increase, but the mechanical properties improved significantly. Friction and wear tests proved that the wear resistance of the cBN/NCD multilayer composite coating is related to residual stresses and fracture toughness, the friction coefficient remains stable at about 0.12–0.15, and the rate of wear decreases significantly with a decrease in the modulation period. Thus, the tribological behavior of the N,B,P-CD described above in the article [47] was confirmed in [48].

However, as shown in the article [49], diamond-like carbon (DLC) films quickly lose lubricity due to oxidation and mechanical breakdown when used at temperatures higher than 300 °C. Doping with molybdenum disulfide (MoS_2) is considered as a possible method of improving the high-temperature properties of DLC films. The results showed that MoS_2 was successfully incorporated into the DLC matrix, and the Mo content in the films ranged from 0 to 6.15 at. %. It was established that MoS_2-DLC composite films with 3.78–6.15 at. % Mo retain good anti-friction and anti-wear properties in the temperature range of 25–450 °C. The friction mechanism of the films changed depending on the temperature. At 25 °C, MoS_2-DLC composite films showed good lubricating and antiwear properties, since the carbon bond is passivated by H_2O molecules. At 250 °C, the MoS_2 phase was deposited on the surface of the films, which led to low friction. At 350 °C, a solid solution of $MoS_{2-x}O_x$ was formed on the surface of the wear track, which ensured low values of the coefficient of friction and wear even up to 450 °C.

In work [50], Cu–Sn matrix composites were prepared by the sintering method with the addition of MoS_2, graphite, and the MoS_2/graphite mixture, respectively. Frictional wear characteristics and contact resistance of these composites at different currents were investigated. The results showed that MoS_2 and graphite have a synergistic lubricating effect. The Cu-Sn-graphite-MoS_2 composite showed low wear rates and contact resistance. That is, MoS_2 can effectively promote the formation and integrity of the friction film and optimize the friction wear characteristics.

In the article [51], to enhance the lubricating effect and stimulate the development of methods for manufacturing self-lubricating cutting tools, powders based on Ni, dispersed with MoS_2 and Al_2O_3 particles, were previously planted on the substrate of the tool; subsequently self-lubricating coatings (SLCs) were applied using laser powder melting additive manufacturing (AM) with a nanosecond fiber laser for cutting. The results showed that the developed SLC tools reduced the coefficient of friction by 8.8–11.7%, the cutting forces by 17.6–29.6%, and the cutting power by 17.3–22.0% compared to with conventional high-speed steel (HSS) cutting tools.

Thus, from the above review, dedicated to the features of tribological processes during diamond-abrasive processing and the behavior of diamonds and other carbon-containing materials during friction and wear, it is possible to draw the following conclusions:

Additive manufacturing (AM) methods have significant advantages for obtaining individual products and prototypes, allow to reduce costs, and also accelerate the release of products to the market. Nowadays, this direction has begun to be used for diamond-abrasive tools. Of course, new binders for the working layer of the diamond tool have been developed for such energy-efficient AM technology. It is shown that the cutting forces and friction coefficients of microtextured diamond tools are significantly reduced.

The tribological behavior of diamonds against various materials is fundamental for their use in the abrasive and bearing industries. It has been proven that, in comparison with ordinary diamond grains, porous diamond grains with an increased number of microedges effectively reduce the cutting force and heat generation. It is shown that the application of the effect of further mechanochemical influence during the coating of diamond abrasives, both on the diamond-bond boundary and on the contact of the surface of the diamond grain with the processed material, allows to increase the efficiency of the use of the diamond-abrasive tool.

Attention is drawn to what kind of impurities are introduced into the contact zone during diamond-abrasive processing to change the tribological parameters. At the same time, the most widely used is h–BN, which with a layered crystal structure is one of the types of effective solid lubricants, especially at elevated temperatures. Attention has been paid to such new materials as graphene oxide and carbon dots (CD), a kind of carbon-based nanomaterials, which have been widely used as highly effective lubricant additives.

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АЛМАЗНО-АБРАЗИВНА ОБРОБКА: ТРИБОЛОГІЧНИЙ АСПЕКТ (ОГЛЯД СУЧАСНИХ ДОСЛІДЖЕНЬ)

Анотація. *Попередньою практикою інструментального виробництва та застосування різального інструменту у промисловості доведено, що для досягнення ефективного та економного використання цього сучасного високовартісного інструменту треба не тільки забезпечити високоякісну шліфовану їх поверхню, але і мати доведену різальну крайку. Досягнути цього можливо лише доведенням після шліфування різальної крайки, а і навіть її поліруванням, коли шорсткість передньої та задньої поверхонь інструменту доводиться до R_a 0,05 мкм, а іноді навіть менше, що значно підвищує зносостійкість різального інструменту та якість обробленої ним поверхні. Сучасні дослідження свідчать про ефективність застосування при поліруванні абразивних і хіміко-механічних методів та врахуванні при цьому особливостей абразивів, які застосовуються, тому метою даної статті було дослідити найновіші (2024–2025 рр.) розробки в технологіях доведення та полірування поверхонь широкої гами сучасних матеріалів та визначити напрямки підвищення ефективності таких розробок. При цьому для хіміко-механічного полірування (CMP) дослідниками розглядається два напрямки: вплив різного абразиву, тобто наголос на механічний складовій CMP, та вплив суспензії, тобто наголос на хімічній складовій. Дослідження в напрямку пріоритетності абразивної складової представлені новою стратегією застосування інтерметалічної сполуки Cu_6Sn_5 у якості зв'язки в алмазному шліфувальному крузі для шліфування і доведення пластин SiC з високим терміном служби і обробки з низьким рівнем пошкоджень. Досліджено новий метод двостороннього шліфування із* *застосуванням алмазних плівкових накладок для обробки циліндричних роликів Si_3N_4. Запропонований екологічно чистий метод поліпшення продуктивності поліровки із застосуванням змішаної абразивної суспензії церію і алмаза. Дослідження , як перехідне від механічної до хімічної складової, розкриває хімічну роль абразивної Al_2O_3–частинки при CMP рутенію шляхом порівняння властивостей і продуктивності поліровки Al_2O_3–SiO_2 змішаними частинками і чистими – SiO_2. Представлені нові розробки з виготовлення абразивів типу ядро-оболонка SiO_2@A-TiO_2 в новій суспензії для реалізації високоефективної фотокаталітичної хіміко-механічної поліровки при опроміненні штучним сонячним світлом. Досліджені характеристики CMP за нової суспензії, що містила Fe, Al_2O_3 і новітній матеріал – оксид графена, оскільки останній є чудовим матеріалом-носієм, характеристики якого можуть значно поліпшити каталітичні характеристики суспензії. Окремо звернено увагу на застосування при CMP деіонізованої води, оскільки це є певним сучасним трендом досліджень.*

Ключові слова: *доведення поверхні; хіміко-механічне полірування; алмазні абразиви; оксид графена; деіонізована вода.*