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Formation of the cutting relief of a metal-bonded diamond wheel through continuous electrochemical dressing in combined electro-diamond grinding of composite materials: toward the development of hybrid machine tool equipment

Vadim Skeeba [1, a, *], *Andrey Yanyushkin* [2, b], *Dmitry Lobanov* [2, c], *Alexander Yanyushkin* [2, d], *Alexey Chernikov* [1, e], *Maria Yavorskaya* [1, f], *Alexander Nasonov* [1, g]

[1] Novosibirsk State Technical University, 20 Prospekt K. Marksa, Novosibirsk, 630073, Russian Federation
[2] I.N. Ulianov Chuvash State University, 15 Moskovsky Prospekt, Cheboksary, 428015, Russian Federation

[a] https://orcid.org/0000-0002-8242-2295, skeeba_vadim@mail.ru; [b] https://orcid.org/0000-0002-5744-8987, andreyyanyushkin@gmail.com;
[c] https://orcid.org/0000-0002-4273-5107, lobanovdv@list.ru; [d] https://orcid.org/0000-0003-1969-7840, yanyushkinas@mail.ru;
[e] https://orcid.org/0009-0006-9412-7687, aleksey.chernikov.97@mail.ru; [f] https://orcid.org/0000-0002-2449-8638, ivanova777888@yandex.ru;
[g] https://orcid.org/0009-0001-3177-0732, a.nasonov@corp.nstu.ru

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ABSTRACT

Introduction. One of the key trends in modern mechanical engineering is the development of hybrid machine tool equipment that integrates mechanical and surface-thermal technological operations within a single machine platform. In the context of the *Industry 4.0* paradigm and increasing demands for precision, productivity, and equipment multifunctionality, combined electro-diamond grinding (*CEDG*) – which combines mechanical cutting by diamond grains with electrochemical action on both the tool and the workpiece – is of particular relevance. Grinding of high-strength composite materials based on zirconium diboride (ZrB_2) under conventional conditions leads to intensive clogging of metal-bonded diamond wheels and a critical loss of their cutting ability, rendering the conventional process inefficient. Despite existing results in the field of electro-diamond machining, the issues of stage-by-stage formation of the cutting relief on the wheel working surface under continuous electrochemical dressing, the mechanisms of oxide film formation on bond elements, and their functional role as solid lubricants in the contact zone remain insufficiently studied. ***The purpose of this work*** is to establish the formation mechanisms of the surface layer of a metal-bonded diamond wheel under continuous electrochemical dressing with simultaneous electrochemical anodic dissolution of the stock allowance during combined grinding of a ZrB_2-based composite material, and to substantiate the prospects for integrating this technology into the concept of hybrid machine tool equipment. **Methods.** Experiments were conducted on a modernized *PP-600F* surface grinding machine equipped with two independent electrical circuits: a continuous electrochemical dressing circuit (current density 0.1–0.6 A/cm^2) and an anodic dissolution circuit for stock removal (current density 15–30 A/cm^2). Diamond wheels *AC6 125/100 M1* – 100% on a copper-zinc-aluminum bond were used as the tool. The working medium was a nitrite-nitrate electrolyte (3% $NaNO_3$, 1% $NaNO_2$, 0.5% Na_2CO_3). Mechanical parameters: cutting speed 35 m/s, longitudinal feed 0.5–2.5 m/min, depth of cut 0.01–0.04 mm. Surface topography of the wheel and workpiece was investigated by scanning electron microscopy (*SEM*) with energy-dispersive X-ray spectroscopy (*EDS*). **Results and Discussion.** It is established that continuous electrochemical dressing ensures selective anodic dissolution of the metal bond components (primarily aluminum, copper, and zinc), forming a stable cutting relief with exposed diamond grains and intergranular cavities for electrolyte and debris accommodation. It is shown that under simultaneous operation of the dressing and workpiece etching circuits, oxide films form on the diamond grain surfaces and bond elements, functioning as solid lubricants and reducing the intensity of adhesion-diffusion interaction in the contact zone. Implementation of additional electrochemical weakening of the stock allowance reduces cutting forces and contact temperatures, preventing deformation damage to the workpiece surface layer. It is substantiated that the developed *CEDG* technology constitutes a technological basis for designing hybrid machine tool equipment integrating mechanical and electrochemical actions, meeting modern requirements for modularity, adaptability, and digital control. The obtained results contribute to the formation of a theoretical and methodological framework for designing next-generation hybrid metalworking systems.

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*** Corresponding author**
Skeeba Vadim Yu., Ph.D. (Engineering), Associate Professor,
Leading researcher
Novosibirsk State Technical University,
20 Prospekt K. Marksa,
Novosibirsk, 630073, Russian Federation
Tel: +7 383 346-17-79, **e-mail:** skeeba_vadim@mail.ru

Introduction

The modern machine tool industry is experiencing ever-increasing demand for the development of multifunctional equipment capable of performing, within a single technological cycle, operations that are heterogeneous in physical nature – mechanical machining, surface-thermal hardening, and electrochemical treatment [1, 2]. The concept of hybrid machine tool equipment, which integrates mechanical and surface-thermal technological operations on a single machine platform, establishes a new paradigm for the design of metalworking systems founded on the principles of modularity, adaptability, and digital control [3, 4]. Under conditions of growing component complexity, increasing demand for multifunctional equipment, and the necessity to reduce production cycles, the integration of advanced technologies into machine tool systems - including electrochemical machining, robotization, digital modeling, and process parameter prediction - becomes an essential prerequisite for industrial competitiveness [5, 6]. Existing methodological approaches to machine tool design often fail to account for the multitasking nature of hybrid systems, the complexity of the pre-design research phase, and the requirements for structural modularity, while the fragmented use of disparate machining technologies leads to an increased number of operations, longer processing times, and reduced accuracy [7, 8].

A particularly significant role in the context of hybrid technologies is played by combined electro-diamond grinding (*CEDG*), which represents a synthesis of mechanical microcutting by diamond grains and electrochemical processes occurring at the contact surfaces of the tool and the workpiece materials [9–11]. This technology constitutes a direct embodiment of the principle of integrating heterogeneous technological actions, which underlies the concept of next-generation hybrid equipment. The implementation of *CEDG* requires resolving a number of fundamental issues related to the formation and maintenance of the cutting ability of diamond tools, the control of electrochemical processes in the cutting zone, and the assurance of stable machining quality for high-strength materials [12, 13].

The grinding process, regardless of the type of technological operation, is characterized by two dominant physical mechanisms - plastic deformation and friction in the contact zone between the tool and the workpiece. All concomitant phenomena - the stress state of the surface layer, grinding wheel wear, temperature gradients, and the quality of the generated surface - are consequences of these fundamental processes [14, 15]. The diversity of machinable structural and tool materials, the broad spectrum of grinding wheel types on various bonds, and the specificity of particular technological operations determine considerable variability in the processes involved and necessitate the search for general fundamental regularities [9, 16].

A central position among the fundamental aspects of the grinding process is occupied by surface phenomena occurring at the interface between the tool and workpiece materials [17, 18]. The formation of the boundary layer takes place at the atomic-molecular level at localized points of actual and physical contact - active centers possessing the highest free surface energy. These processes are discrete in nature, and their intensity is determined by the totality of physicochemical and thermomechanical factors: temperature and pressure in microvolumes of the contact zone, the composition of the medium, and the chemical affinity of the contacting materials [19, 20]. In all cases, boundary processes exert a substantial influence on both the rate of grinding wheel wear and the quality of the generated workpiece surface, which directly determines its service properties [21, 22].

A particular challenge is presented by the grinding of modern high-strength composite materials, specifically ceramic nanocomposites based on zirconium diboride (ZrB_2), which exhibit high hardness (HV up to 22–25 GPa), thermal stability, and chemical inertness [23, 24]. These materials find application in aerospace engineering, nuclear power generation, and other high-technology industries where extreme requirements are imposed on the operational characteristics of components [25]. Grinding of such materials under conventional conditions is accompanied by intensive adhesion of the workpiece material to the working surface of the wheel - a phenomenon known as *loading* - which leads to a critical loss of the cutting ability of the tool [26, 27]. The loading process is exacerbated by sharp temperature dynamics in the contact zone, localized regions of elevated stress and excessive pressure, which collectively render grinding inefficient and necessitate frequent wheel dressing [28].

A considerable number of grinding wheel dressing methods exist - mechanical dressing with diamond pencils and rollers, electrical discharge dressing, electrochemical dressing, laser dressing, and ultrasonic dressing [29–31]. However, periodic dressing inevitably entails interruption of the machining process, loss of productivity, and disruption of the stability of quality parameters. An alternative is continuous electrochemical dressing, performed simultaneously with the grinding process, which ensures the maintenance of a stable cutting ability of the wheel in a self-sharpening mode [32, 33]. The combination of continuous electrochemical dressing with additional anodic dissolution of the stock removal allowance of the workpiece material creates a qualitatively new technological process - combined electro-diamond grinding – in which a synergistic effect of the joint action of mechanical and electrochemical influences is achieved [9, 34].

Despite the existing results in this area, a number of fundamental issues remain insufficiently studied. The regularities of stage-by-stage formation of the cutting relief on the working surface of a diamond wheel under continuous electrochemical dressing, the mechanisms of formation and functional role of oxide films on the bond elements under simultaneous operation of two electrical circuits, and the influence of electrochemical processes on adhesion-diffusion interaction in the contact zone - all these issues require detailed experimental investigation and theoretical interpretation [35, 36]. Furthermore, it is of principal importance to consider this technology in a broader context – as a technological basis for the design of hybrid machine tool equipment integrating various types of actions on the workpiece material [37, 38].

The purpose of this study is to establish the regularities of the surface layer formation on a metal-bonded diamond wheel at various stages of its operation - from the initial dressing of a new tool to stable grinding in a self-sharpening mode - during combined electro-diamond grinding of ZrB_2-based composite material with simultaneous continuous electrochemical dressing and additional anodic dissolution of the stock removal allowance, as well as to substantiate the prospects for integrating this technology into next-generation hybrid machine tool systems.

To achieve this objective, ***the following tasks*** were addressed:

– investigate the surface topography of a new diamond wheel and identify factors precluding its direct use without preliminary dressing;

– establish of the regularities of anodic dissolution of metal bond components during electrochemical dressing and determine rational current density ranges for dressing;

– study of the mechanisms of oxide film formation on the surfaces of diamond grains and bond elements under simultaneous operation of the dressing and workpiece etching circuits;

– evaluate of the effectiveness of combined electro-diamond grinding of zirconium diboride according to criteria of machined surface quality and tool performance;

– substantiate of the prospects for utilizing the developed technology as a basis for the design of hybrid machine tool equipment.

Methods

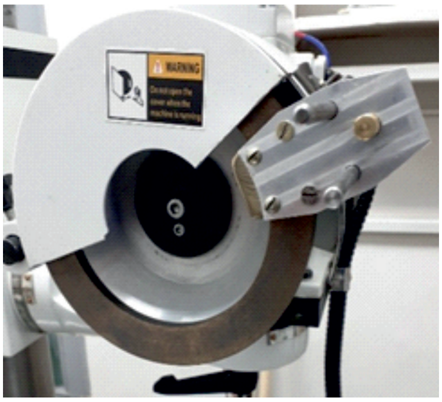
Object and conditions of investigation

Diamond grinding wheels of the *AC6 125/100 M1 – 100%* grade with a copper-zinc-aluminum metal bond were used as the tool. This type of bond is widely used in the grinding of high-strength materials and is characterized by high electrical conductivity, which is a necessary condition for the implementation of electrochemical dressing [9]. The grit size of 125/100 µm provides a balance between the material removal rate and the achievable surface roughness.

The workpiece material was a composite based on zirconium diboride (ZrB_2), belonging to the class of ultra-high-temperature ceramics (*UHTCs*). This material is characterized by high hardness (22–25 GPa *Vicikers*), a melting point exceeding 3,000 °C, and high oxidation resistance at elevated temperatures [23, 24]. These properties determine its promise for aerospace components and simultaneously pose significant difficulties for its mechanical processing by conventional methods.

Equipment and machining scheme

The experiments were conducted on a modernized *PP-600F* surface grinding machine equipped with a specialized system for combined electro-diamond machining (Fig. 1). The modernization of the machine included the installation of two independent electrical power sources and specially designed electrode systems: a dressing cathode mounted in close proximity to the working surface of the wheel (Fig. 1, *a*), and a current-collecting device for supplying current to the workpiece. The electrical circuit for wheel dressing is presented in Fig. 1, *b*.



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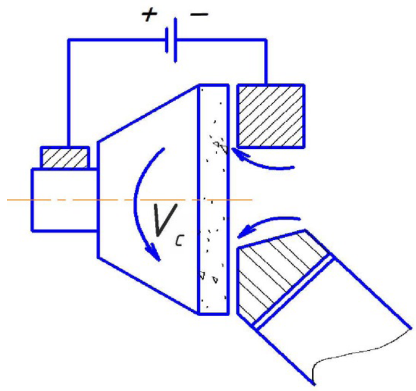


b

Fig. 1. Schematic of electrochemical dressing of the diamond wheel on the *PP-600F* machine:
a – wheel with installed cathode; *b* – electrical circuit for wheel dressing

The principal feature of the developed scheme consists in the simultaneous operation of two electrical circuits: the continuous electrochemical dressing circuit (diamond wheel – anode, dressing cathode – cathode) and the anodic dissolution circuit for the stock removal allowance (workpiece – anode, diamond wheel – cathode). This configuration implements the principle of dual electrochemical action: on the tool side – ensuring a stable cutting ability of the wheel through selective dissolution of the bond; on the workpiece side – weakening of the surface layer of the stock removal allowance through anodic dissolution, which substantially reduces the mechanical component of the grinding process [9, 34].

A general view of the stand for combined electro-diamond grinding and a schematic of the method are presented in Fig. 2.

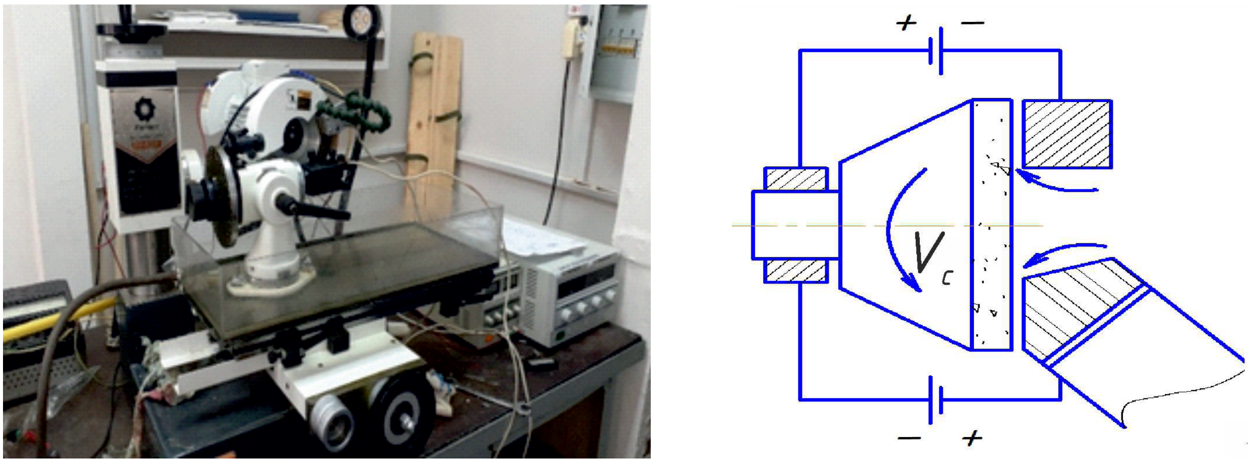
Technological parameters

A nitrite-nitrate electrolyte of the following composition was used as the technological medium: $NaNO_3$ – 3%, $NaNO_2$ – 1%, Na_2CO_3 – 0.5%. The selection of this composition was dictated by its high electrical conductivity, anticorrosive properties, and capability to ensure the formation of passivating oxide films on the surface of the metal bond [32].

Electrical machining parameters: the dressing current density was set in the range from 0.1 to 0.6 A/cm^2; the current density for anodic etching of the stock removal allowance - 15–30 A/cm^2. Mechanical parameters: cutting speed $\boldsymbol{V_c}$ = 35 m/s; longitudinal feed $\boldsymbol{S_l}$ = 0.5−2.5 m/min; depth of cut $\boldsymbol{t}$ = 0.01−0.04 mm. The specified parameter ranges were determined on the basis of preliminary experiments and published data [9, 27, 34].

Analytical methods

Investigation of the topography and morphology of the diamond wheel working surface at various stages of its operation – prior to dressing, after electrochemical dressing, and during combined grinding – was performed by scanning electron microscopy (*SEM*). Analysis of the elemental composition of the surface layers was carried out by energy-dispersive X-ray spectroscopy (*EDS*), enabling the determination of chemical element distribution in microvolumes of the investigated regions.



a *b*

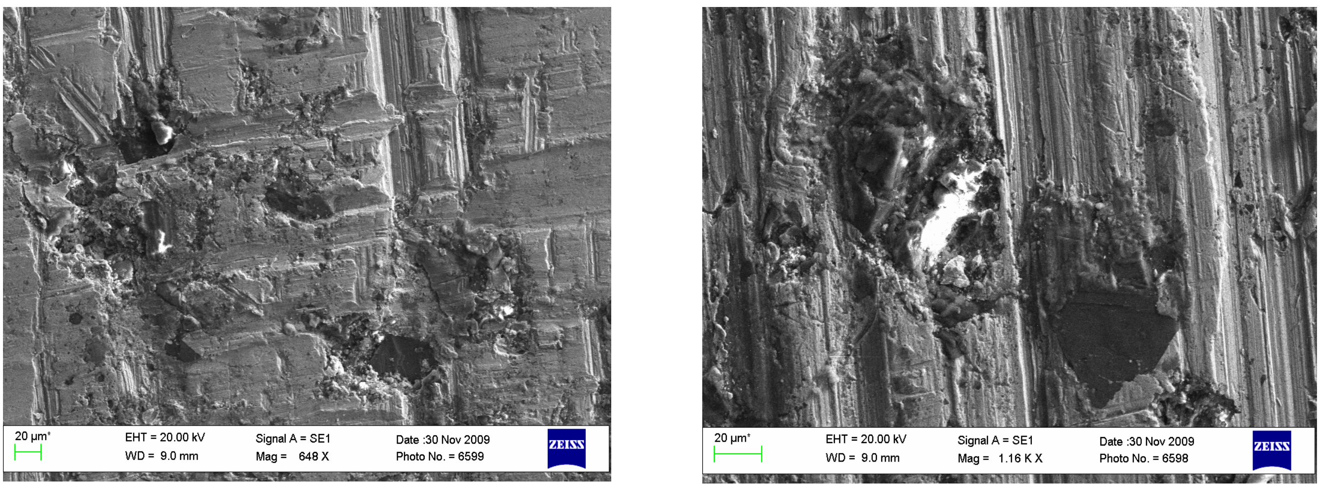
Fig. 2. View of the grinding stand and scheme of the combined method

To identify the nature of the forming oxide films and identify their phase composition, spectral analysis data of the contact surfaces obtained after prolonged grinding at elevated electrical and mechanical parameters were used. Increasing the process parameters during long-term machining was a necessary condition for obtaining pronounced contact boundary layers suitable for instrumental analysis, given that under standard grinding conditions, the contact time of an individual diamond grain with the workpiece material is on the order of 10^{-5}–10^{-7} s, and the dimensions of the forming boundary layers are exceedingly small [17, 39].

Results and Discussion

Condition of the new diamond wheel surface

The working surface of a new diamond wheel, formed during the manufacturing stage, is characterized by an undeveloped structure with minimal exposure of diamond grains (Fig. 3, *a*). The diamond grains are almost entirely embedded within the metal bond matrix, which precludes their effective participation in the microcutting process. Microscopic investigations demonstrated that attempts to grind with a new diamond wheel without preliminary dressing do not yield satisfactory results: the few grains partially protruding above the bond surface are either subject to fracture due to excessive localized loads or operate for a limited duration with a predominantly diffusion-dominated wear mechanism (Fig. 3, *b*). Adjacent to the fractured



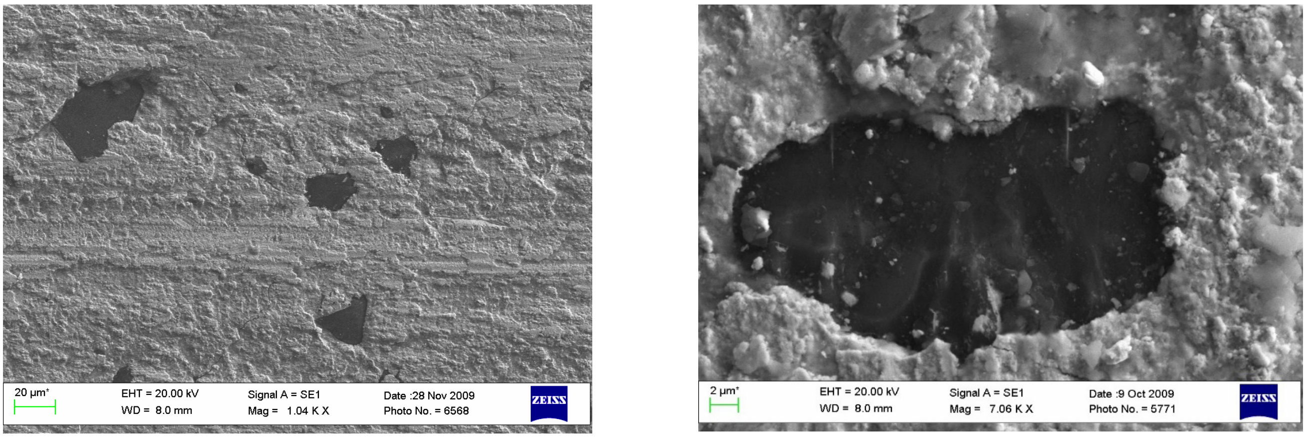
a *b*

Fig. 3. Surface of a new diamond wheel *AC6 125/100 M1 – 100%:*

a – general view; *b* – area with a fractured diamond grain and a grain below the bond level grain in the center of the image, a diamond grain is observed that is situated below the wheel surface and not involved in the cutting process. The elevated contact temperatures and friction forces associated with this type of interaction, as a rule, lead to thermal damage of the workpiece. This observation confirms the fundamental necessity of forming a working surface profile of the wheel before its operation.

Loss of cutting ability due to loading

During grinding of composite materials under conditions that do not provide electrochemical dressing, the working surface of the diamond wheel undergoes intensive loading. The loading process encompasses several interrelated mechanisms: mechanical adhesion of workpiece material microparticles in the intergranular spaces, adhesive seizure at elevated contact temperatures and pressures, and chemical interaction between the components of the workpiece material and the bond [26, 27]. Microscopic images of the loaded wheel surface (Fig. 4, *a*, *b*) demonstrate the formation of a continuous layer of adhered material in which the diamond grains are situated below the surface and completely lose their cutting function.



a *b*

Fig. 4. Wheel surface covered with a loaded (clogged) layer:
a – general view; *b* – detail view

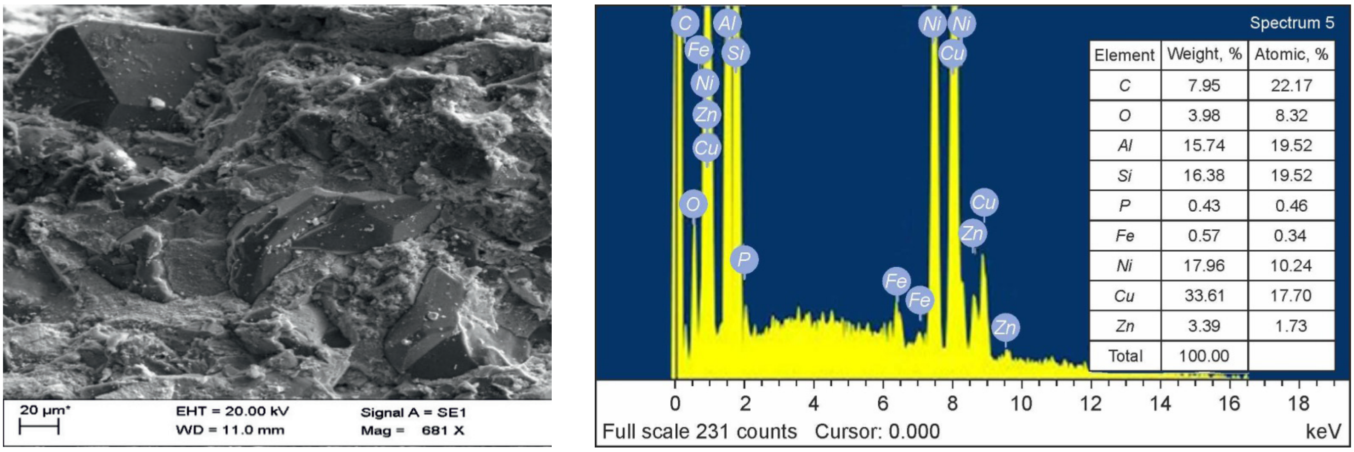
The loaded (clogged) layer exhibits low thermal conductivity compared to diamond grains, which further worsening the temperature conditions in the contact zone. The resulting temperature rise intensifies adhesion-diffusion processes and accelerates the loss of wheel performance, establishing a positive feedback loop in the tool degradation cycle. This problem is typical when machining any high-strength and difficult-to-machine materials and represents one of the principal technological limitations of conventional diamond grinding [28, 40].

Continuous electrochemical dressing: formation of the cutting relief

To address the loading (clogging) problem, continuous electrochemical dressing of the diamond wheel was employed in this study, implemented simultaneously with the grinding process. The physical essence of the method consists in the selective anodic dissolution of the metal bond components of the wheel in an electrolyte medium under the action of an electric current applied between the wheel (anode) and the dressing cathode (Fig. 1, *a*, *b*).

It was established that under the action of the electric current, the bond elements with relatively low electrochemical potential – primarily aluminum, copper, and zinc - dissolve most intensively as a result of anodic processes. This selective dissolution leads to a gradual exposure of diamond grains previously covered by the bond layer. Fig. 5, *a* presents the surface of the diamond wheel after electrochemical dressing. Spectral analysis of the surface (Fig. 5, *b*) confirms the preferential removal of the aforementioned metals from the near-surface layer of the bond.

As evident from Fig. 5, *a*, after electrochemical dressing the wheel surface is distinguished by a pronounced, well-developed relief. The diamond grains are firmly retained in the bond matrix and protrude



a *b*

Fig. 5. Surface of the diamond wheel after dressing and its spectral analysis:
a – surface topography; *b* – *EDS* spectrum

substantially above its surface. At the periphery of the grains, depressions – intergranular cavities – are formed, which serve several important functions: ensuring electrolyte access to the zone of anodic reactions, removal of electrochemical reaction products and detached fragments of the workpiece material, and creation of conditions for effective cooling of the cutting zone. Such a surface topography of the wheel provides optimal conditions for mechanical microcutting: each exposed grain functions as an individual cutter with a defined geometry and depth of penetration, thereby ensuring a stable and predictable cutting ability of the tool [32, 33].

The rational electrochemical dressing parameters are determined by the balance between the intensity of bond dissolution (required for grain exposure) and the preservation of the bond retaining capacity (required to prevent premature grain pull-out). It was experimentally established that the optimal dressing current density depends on the properties of the workpiece material and may vary within the range from 0.1 to 0.6 A/cm^2. For the machining of high-strength ZrB_2-based composites, values in the upper portion of this range (0.4–0.6 A/cm^2) are recommended, owing to the elevated loading intensity characteristic of these materials.

Combined electro-diamond grinding with anodic dissolution of the stock allowance

A fundamental feature of the developed technology is the use of additional electrochemical anodic dissolution of the stock removal allowance from the workpiece surface, performed simultaneously with mechanical grinding and continuous wheel dressing. The physical essence of this action consists in the preliminary weakening of the workpiece surface layer in the zone of impending contact with the diamond grains: anodic dissolution disrupts interatomic bonds in the crystal lattice of the material, forms a modified layer with reduced mechanical properties, and creates conditions for a significant reduction in cutting forces [9, 34].

As a result, a qualitatively new technological process is implemented: a diamond wheel, possessing high cutting properties due to continuous dressing, removes the anodically weakened layer with minimal cutting forces and contact temperatures, without causing deformation damage to the surface layer of the workpiece. The schematic of the combined method and a general view of the modernized stand are presented in Fig. 2. Essentially, in this technology the first cutting action is performed by an electric current, which weakens the stock removal allowance, and the second action is performed by a diamond grinding wheel, which performs the final removal of the modified layer.

Formation of oxide films and their functional role

Under simultaneous operation of the two electrical circuits - the dressing circuit and the anodic etching circuit – complex electrochemical processes occur on the surface of the diamond wheel, leading to the formation of oxide films on the bond elements and lateral surfaces of the diamond grains. Fig. 6 presents a view of the wheel surface after combined electro-diamond machining of zirconium diboride. Diamond

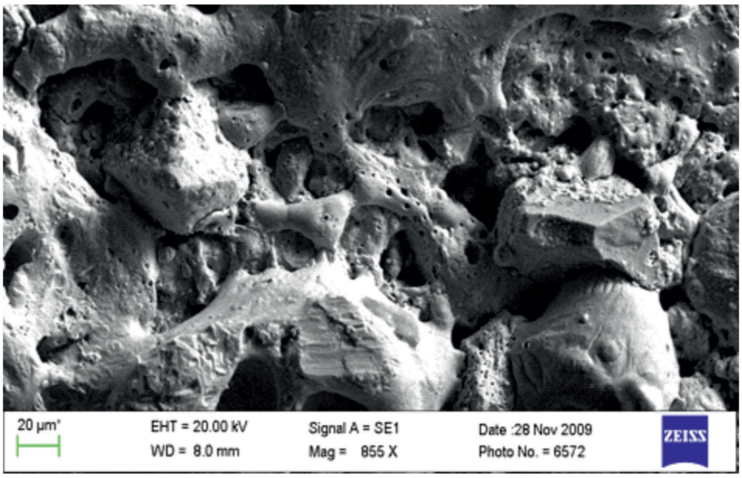


Fig. 6. View of the wheel surface after combined electro-diamond processing of zirconium diboride

grains protruding above the bond are clearly visible, with their lateral surfaces covered by a film formed as a result of electrochemical reactions between the wheel bond and the electrolyte in the presence of oxygen.

The nature of the forming films is determined by the composition of the metal bond and the conditions of the electrochemical process. The metals constituting the bond of diamond wheels - copper (*Cu*), aluminum (*Al*), nickel (*Ni*), zinc (*Zn*), and tin (*Sn*) – are capable of forming oxides of various stoichiometric compositions upon anodic oxidation in the presence of oxygen: Cu_2O and CuO, Al_2O_3, NiO, ZnO, and SnO_2 [41, 42]. The combination of these oxides forms a continuous multicomponent layer on the bond surface and adjacent areas of the diamond grains, possessing a number of functionally significant properties.

The most important of these properties is the ability of oxide films to act as solid lubricants in the grinding zone. Copper and zinc oxides are characterized by a low coefficient of friction when sliding against the surfaces of high-strength ceramics, which contributes to a reduction in the frictional component of cutting forces [43, 44]. Aluminum oxide (Al_2O_3), possessing high hardness and chemical inertness, forms a stable protective barrier that prevents direct contact between the metal bond and the workpiece material, thereby reducing the intensity of adhesive seizure and diffusion wear [45, 46]. Thus, the oxide films perform a dual function: they reduce friction in the contact zone and protect the diamond grains from premature wear, thereby increasing the tool service life.

Analysis of contact boundary processes

One of the fundamental difficulties in the experimental study of contact processes during grinding is the extremely short duration of interaction between an individual diamond grain and the workpiece material – on the order of 10^{-5}–10^{-7} s [17, 47]. The boundary layers in which mass transfer, adhesive seizure, and phase transformation processes develop have characteristic dimensions at the nanometer and submicrometer scales. Detection and identification of such layers by experimental means on the investigated specimens presents a considerable methodological challenge. Even the application of high-resolution methods – scanning electron microscopy, X-ray diffraction, and chemical analysis – requires samples with more pronounced contact boundary layers, which is achievable only through prolonged machining at elevated parameters [39, 48].

For this reason, a portion of the experiments in this study was conducted under prolonged grinding with diamond wheels at elevated mechanical and electrical parameters. This approach made it possible to form layers on contact surfaces suitable for instrumental analysis and to obtain reliable information on the composition and structure of boundary formations. Analysis of the obtained data confirms that during combined electro-diamond grinding, processes of both oxidative and adhesion-diffusion character proceed on the contact surfaces, the cumulative action of which determines the cutting ability of the wheel, its wear resistance, and the quality of the generated workpiece surface [21, 22, 49].

Prospects for integration into hybrid machine tool equipment

The obtained results are of direct significance for the design of next-generation hybrid machine tool equipment integrating mechanical and electrochemical (surface-thermal) technological operations on a single machine platform. The developed technology of combined electro-diamond grinding demonstrates all the key characteristics required of the technological processes of hybrid equipment within the framework of the *Industry 4.0* concept: multifunctionality (simultaneous grinding, dressing, and electrochemical weakening), controllability (the possibility of independent regulation of electrical and mechanical parameters), adaptability (the possibility of parameter adjustment for various workpiece materials), and modularity (the electrochemical subsystem is integrated into a standard machine tool system as a functional module) [2, 5, 6].

In the context of developing hybrid metalworking systems, *CEDG* technology may be considered as one of the basic technological modules to be integrated into machine tool equipment alongside surface-thermal treatment modules (induction heating, laser hardening), positioning and workholding modules, and digital control and monitoring modules [3, 7]. The modernized *PP-600F* machine used in this study essentially constitutes a prototype of a hybrid machine tool system implementing the principle of integration of heterogeneous actions. Further development of this approach envisages the creation of full-scale hybrid machine tool complexes with digital twins, adaptive control systems based on machine learning methods, and integration into production ecosystems (*MES*/*ERP*) [4, 8, 50].

It is important to emphasize that the necessity of developing a comprehensive approach to the design of hybrid systems – one that unifies modern principles of automation, digital modeling, and process parameter prediction – is driven not only by technical but also by economic factors. The fragmented use of disparate machining technologies leads to an increase in the number of operations, time expenditure, workholding errors, and consequently, a decrease in accuracy and an increase in production costs [7, 37]. The integration of operations on a single machine platform enables a substantial reduction in the production cycle, minimization of interoperational allowances, and assurance of consistently high machining quality, which constitutes a key competitive advantage of hybrid equipment [38, 50].

Conclusion

1. The topography of the working surface of a new *AC6 125/100 M1 – 100%* diamond wheel on a metal bond is studied. It is established that at the manufacturing stage the wheel surface is characterized by an undeveloped structure with minimal exposure of diamond grains, which precludes its direct use without preliminary dressing. Attempts to grind with a new wheel result in the fracture of individual grains and thermal damage to the workpiece.

2. The regularities of the cutting relief formation on the working surface of the diamond wheel under continuous electrochemical dressing are established. It is shown that upon anodic dissolution of the metal bond components (*Al*, *Cu*, *Zn*) in a nitrite-nitrate electrolyte, a stable surface topography with exposed diamond grains and intergranular cavities is formed, providing the conditions for a stable self-sharpening mode. It is determined that the rational dressing current density values range from 0.1 to 0.6 A/cm^2 depending on the properties of the workpiece material.

3. It is shown that under the simultaneous operation of the electrochemical dressing and workpiece anodic etching circuits, multicomponent oxide films (Cu_2O, CuO, Al_2O_3, ZnO) form on the surfaces of the diamond grains and bond elements, functioning as solid lubricants. The oxide films reduce the frictional component of cutting forces, prevent adhesive seizure, and protect the diamond grains from premature diffusion wear.

4. It is demonstrated that the implementation of additional electrochemical weakening of the stock removal allowance at a current density of 15–30 A/cm^2 ensures the formation of a modified surface layer of the workpiece with reduced mechanical properties, which enables grinding of the ZrB_2-based composite with minimal cutting forces and contact temperatures without deformation damage to the machined surface.

5. The results of the study form a technological basis for the design of hybrid machine tool equipment integrating mechanical and electrochemical actions on a single machine platform. The developed technology of combined electro-diamond grinding with continuous electrochemical dressing and anodic dissolution of the stock allowance satisfies the key requirements of hybrid metalworking systems – modularity, controllability, adaptability, and compatibility with digital control principles – thereby confirming its promise as a basic technological module for the creation of next-generation hybrid equipment.

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Conflicts of Interest

The authors declare no conflict of interest.