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Wear resistance of plasma coatings formed by combined surface-thermal treatment methods: toward the design of hybrid machine-tool equipment

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ABSTRACT

Introduction. In the context of the increasing demand in the modern machine-tool industry for the development of hybrid machine-tool equipment integrating mechanical and surface-thermal operations, the study of combined technologies for the formation of wear-resistant coatings becomes highly relevant. The integration of fundamentally different processing methods – mechanical shaping and high-energy surface-thermal modification – on a single machine platform represents a promising direction for improving the efficiency and quality of manufacturing processes. Plasma spraying supplemented by high-energy heating with high-frequency currents (*HFC*) or the formation of composite ceramic–metal coatings from mechanical mixtures creates the prerequisites for designing multifunctional hybrid systems that meet the requirements of *Industry 4.0*. However, the comparative effectiveness of various combined coating treatment options under tribological loading has not been sufficiently studied to date. ***The purpose of the present work*** is to conduct a systematic comparative study of the wear resistance of plasma coatings formed under different conditions of combined spraying technology under dry sliding friction , and to formulate recommendations for the design of advanced hybrid machine-tool equipment. **Methods.** Plasma coatings sprayed from *PG-12N-01, PG-S27*, and *PGN-V3K* powders were investigated, as well as coatings subjected to additional high-energy induction remelting and coatings from mechanical mixtures of metal powder and aluminum oxide (Al_2O_3). Spraying was performed with a *PUN-3* plasma torch at optimized conditions. High-energy heating was carried out using a *VChG 6-60/0.44* generator at a frequency of 440 kHz. Wear resistance tests were conducted under continuous dry sliding friction against a *VK8* cemented carbide indenter at a load of 20 N. The wear criterion was the volume loss of the coating material, determined by measuring the wear scar width with a *UIM-21* toolmaker's microscope. The coating microstructure was studied by optical metallography. **Results and discussion.** It was established that remelted nickel coatings of the *PG-12N-01* grade exhibit wear resistance exceeding that of the initial non-remelted coating by 35%. At the same time, remelting of *PG-S27* high-chromium cast iron coatings led to a 20 % decrease in wear resistance due to the formation of an unfavorable dendritic structure. Coatings based on ceramic–metal mechanical mixtures showed the best results: the nickel–ceramic mixture *PG-12N-01* (20 %) + + *15A* (80 %) exceeded the baseline value by 44 %, while the cobalt–ceramic mixture *PGN-V3K* (20 %) + + *15A* (80 %) provided a 30 % increase in wear resistance compared to the initial cobalt alloy coating, with wear practically ceasing after the run-in period. The structure of ceramic–metal coatings is characterized by a uniform distribution of fine oxide ceramic particles in a metallic matrix, which ensures high tribological performance of the composite. The research results form an experimental basis for the design of next-generation hybrid machine-tool equipment integrating mechanical processing and surface-thermal technological operations.

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Introduction

The contemporary development of the machine-tool industry is characterized by a sustained trend toward the creation of multifunctional equipment capable of implementing several fundamentally different technological operations on a single platform [1, 2]. The concept of hybrid machine-tool equipment integrating mechanical and surface-thermal operations meets the current requirements for accuracy, productivity, automation, and adaptability under the conditions of manufacturing digitalization and the *Industry 4.0* paradigm [3, 4]. Given the increasing complexity of workpieces, the growing demand for multifunctional equipment, and the reduction of production cycles, it becomes imperative to incorporate advanced surface-thermal hardening technologies, robotization, and digital control into machine-tool systems [5, 6].

The conventional organization of manufacturing processes, in which surface-thermal hardening and machining operations are performed on separate pieces of equipment located in spatially separated departments, gives rise to significant errors: distortions induced by thermal exposure, workpiece datum and setup errors, and accumulated deviations in dimensional chains [7, 8]. The combined effect of these factors necessitates the assignment of increased inter-operational allowances for finishing, reaching 30–40% of the hardened layer depth [9]. The fragmented application of different processing technologies increases the number of operations, time expenditures, and reduces machining accuracy. Consequently, the development of an integrated approach to the design of hybrid systems that combines modern principles of automation, digital modeling, and process parameter prediction constitutes an important task for enhancing the competitiveness of the domestic machine-tool industry [10–21].

Plasma technology is one of the most effective methods for improving the wear resistance of components of technological equipment. A protective layer deposited by plasma spraying is capable of withstanding various types of wear: abrasive, erosive, mechanochemical, and sliding friction wear [22–24]. However, the principal challenge in ensuring the service properties of plasma-sprayed coatings remains the attainment of a structure with stable qualitative characteristics, namely minimal porosity, high cohesive strength, and reliable adhesion to the substrate [25, 26]. In practice, addressing this challenge is complicated by the multifactorial nature of the spraying process, in which the peripheral zones of the plasma jet are heated to a lesser extent than the central region, resulting in incomplete melting of a fraction of the powder particles [27, 28].

Considerable efforts have been directed toward modeling the state of powder particles within the plasma jet and the conditions of their impingement upon the substrate [29–31]. Despite advances in theoretical methods, the complexity of the mathematical apparatus often precludes the determination of process parameters that would guarantee the formation of a dense, low-porosity structure [32, 33]. Nevertheless, it has been experimentally demonstrated that the optimization of spraying parameters exerts a substantial influence on the structural characteristics of coatings. In [34, 35], typical structural variants differing in porosity, particle deformation degree, fraction of unmelted inclusions, and the nature of adhesion to the substrate have been presented.

To achieve a qualitatively new level of coating performance, combined technologies based on supplementary energy input have been developed. Among the most promising approaches are high-energy heating of coatings by high-frequency current (*HEH HFC*) heating of coatings and the formation of composite ceramic–metal coatings from mechanical mixtures [36–38]. The *HEH HFC* method is based on the synergistic utilization of induction heating effects – the skin effect, the proximity effect, and the slot effect – and provides volumetric-surface heating of the deposited layer at specific power densities on the order of 10^8 W/m^2, with a penetration depth of the induced energy commensurate with the coating thickness (up to 1.0 mm) [39, 40]. Spraying coatings from mechanical mixtures of metallic powder and aluminium oxide ceramic (Al_2O_3) enables the formation of composite structures in which the metallic constituent serves as a ductile binder for the hard refractory ceramic particles [41–43].

The aforementioned combined treatment approaches are of fundamental importance from the standpoint of designing advanced hybrid machine-tool equipment. The integration of concentrated energy sources – induction generators, plasma torches, and laser heads – into a unified machine-tool system together with machining modules creates the possibility of implementing a complete manufacturing cycle for hardened components at a single workstation [44, 45]. However, existing methodological approaches frequently fail to account for the multitasking nature of such systems, the complexity of their design at the preliminary research stage, and the need for compliance with the requirements of modularity and structural flexibility [46, 47].

To date, systematic comparative investigations of the wear resistance of coatings obtained under different combined treatment options, conducted under unified tribological loading conditions, have not been performed. Meanwhile, such data are essential for the scientific substantiation of the selection of a specific surface-thermal module in the design of hybrid equipment.

The purpose of the present work is to conduct systematic comparative wear resistance tests of plasma coatings formed under different conditions of combined spraying technology in dry sliding friction, and to perform a structural analysis of the effects of combined treatment on the tribological characteristics of the coatings.

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

– determination of the wear kinetics of plasma coatings deposited from *PG-12N-01*, *PG-S27*, and *PGN-V3K* powders without additional treatment, after high-energy induction remelting, and for coatings from ceramic–metal mechanical mixtures;

– comparative analysis of the wear resistance of coatings obtained under different combined technology options;

– metallographic examination of the coating microstructure to identify the structural factors governing tribological behavior;

– formulation of recommendations for the selection of a rational combined treatment option for application in advanced hybrid machine-tool equipment.

Methods

Materials and equipment for plasma spraying. A *PUN-3* plasma torch with a power output of up to 40 kW was employed as the coating deposition device [44, 48]. Air served as the plasma-forming gas. The experimental setup was equipped with a control system enabling the regulation of the energy parameters of the process (arc current, voltage, and plasma-forming gas flow rate) as well as the kinematic characteristics, including the traverse speed of the plasma torch and the rotational speed of the specimens.

The specimens for spraying were bushings (outer diameter 25 mm, width 12 mm) machined from low-carbon steel grade *St20* (*GOST 1050–2013*). Immediately prior to spraying, all specimens were subjected to grit blasting in a dedicated chamber. Processing under identical conditions produced a surface roughness in the range of ***Rz*** = 70–85 μm, ensuring the requisite quality of the adhesive contact. The thickness of the sprayed layer was maintained within the range of 0.55–0.60 mm.

On the basis of prior studies [35, 48, 49], three grades of standard wear-resistant powders with a particle size fraction of 50–100 μm were selected for the experiments. The chemical composition of the powders is given in Table 1.

On the basis of previously conducted research [35, 49], the following optimized plasma spraying parameters were established: arc current 140–160 A at a voltage of 140 V; plasma-forming gas flow rate

Table 1

Chemical composition of powder materials for plasma spraying

Powder grade	*C*,%	*Cr*,%	*Ni*,%	*Si*,%	*Fe*,%	*B*,%	*W*,%	*Al*,%	*Co*,%
PG-12N-01	0.3–0.6	8–14	balance	1.2–3.2	2–5	1.7–2.8	–	0.8	–
PG-S27	3.3–4.5	25–28	1.5–2	1–2	balance	–	0.2–0.4	–	–
PGN-V3K	1–1.3	28–32	0.5–2	2–2.7	2	–	4–5	–	balance

18–22 L/min; spraying distance 110–125 mm; specimen rotational speed 50 min^{-1}; linear feed rate of the plasma torch 300 mm/min. The layer thickness per pass was 0.2 mm.

High-energy heating by high-frequency currents. For the combined treatment of coatings by the *HEH HFC* method, a setup equipped with a *VChG 6-60/0.44* generator operating at a frequency of 440 kHz was used [39, 40]. The setup was fitted with a loop inductor incorporating an *N87*-grade ferrite magnetic core, which provided electromagnetic field concentration and energy release to a depth of 0.6–0.8 mm – sufficient for through-heating of the entire sprayed layer. The induction treatment parameters were as follows: specific power density (3.1–3.2)×10^8 W/m^2 at a relative traverse speed of the specimen and inductor of 70–75 mm/s. These parameters ensure volumetric-surface heating of the coating to a temperature sufficient for the remelting of metallic powders, while maintaining high processing productivity.

Formation of coatings from ceramic–metal mixtures. To obtain composite coatings, a technique involving the preparation of mechanical mixtures with a predetermined component ratio was employed [41–43]. Fused alumina grade *15A* with a grit size of 20–28 µm (Al_2O_3) was used as the hard ceramic fraction. Mixing was performed in a dedicated ball mill until a uniform distribution of the components was achieved. On the basis of prior investigations [48, 49], it was established that the optimal composition comprises 20 wt.% metallic powder and 80 wt.% ceramic. Two mechanical mixtures were prepared: *PG-12N-01* (20%) + *15A* (80%) and *PGN-V3K* (20%) + *15A* (80%). Spraying of these mixtures required an adjustment of the parameters toward increased plasma jet energy: arc current 160–165 A at a voltage of 140 V; gas flow rate 16–18 L/min; spraying distance 110 mm.

Wear resistance testing. Coatings obtained under different treatment conditions were subjected to comparative tribological tests. The design of the testing rig implemented a continuous dry sliding friction scheme in the absence of lubrication (Fig. 1). A *VK8* cemented carbide indenter with a diameter of 30 mm was used as the counterbody. Test parameters were as follows: indenter rotational speed 1,500 rpm; normal load on the friction pair 20 N.

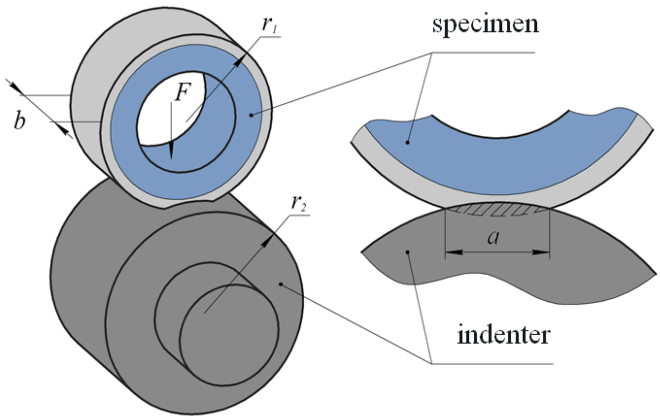

Fig. 1. Scheme of wear resistance testing:
1 – specimen with coating; **2** – cemented carbide indenter;
F – load; ***n*** – rotational velocity

The integral wear characteristic was the volume loss of the coating material ***V***, determined by the formula:

$$\Delta V = \left(\frac{\pi r_1^2 \arcsin \dfrac{a}{2r_1} + \pi r_2^2 \arcsin \dfrac{a}{2r_2}}{180^{\circ}} - \frac{a}{2}\left(\sqrt{r_1^2 - \frac{a^2}{4}} + \sqrt{r_2^2 - \frac{a^2}{4}} \right) \right) b,$$

where $\boldsymbol{r_1}$ is the radius of the coated bushing (mm); $\boldsymbol{r_2}$ is the radius of the cemented carbide indenter (mm); ***b*** is the bushing width (mm); ***a*** is the wear scar width (mm).

The wear scar width ***a*** was measured using a *UIM-21* toolmaker's microscope with a graduation of 1 µm. Each data point on the wear curves was determined as the arithmetic mean of three replicate tests at a given cycle, thereby ensuring the statistical reliability of the results.

Metallographic examination. The microstructure of the coatings was studied on transverse cross-sections prepared by standard metallographic techniques involving sequential grinding and polishing. Observations were performed on an optical metallographic microscope at magnifications from 100× to 500×.

Results and Discussion

Wear kinetics of the coatings. The investigations conducted yielded a comprehensive picture of the wear intensity of the coatings as a function of the sliding distance under different combined treatment conditions. Fig. 2 presents the volume wear kinetics curves for all coating variants examined.

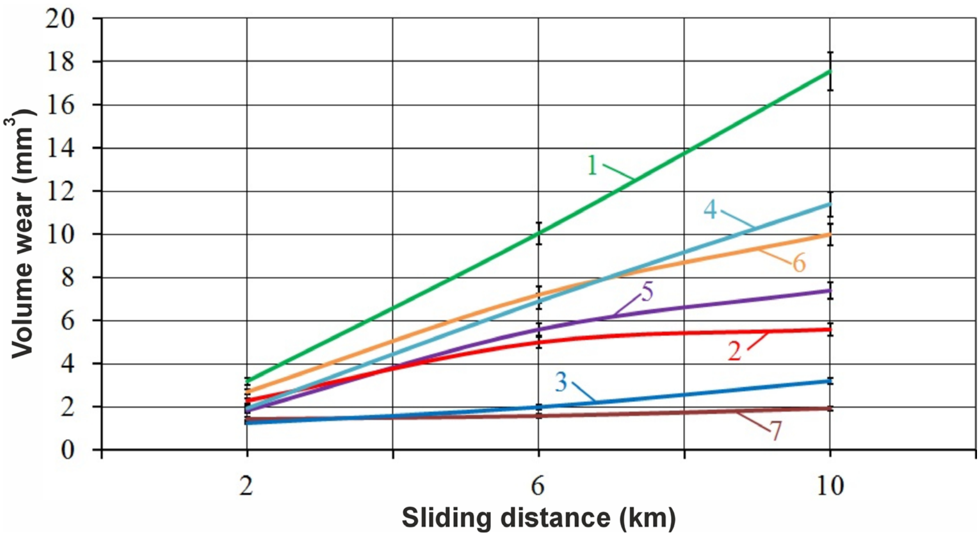

Fig. 2. Wear kinetics of specimens with plasma coatings:
1 – *PG-12N-01*; 2 – *PG-S27*; 3 – *PGN-V3K*; 4 – *PG-12N-01* (with *HFC* remelting);
5 – *PG-S27* (with *HFC* remelting); 6 – *PG-12N-01* (20%) + *15A* (80%);
7 – *PGN-V3K* (20%) + *15A* (80%)

Analysis of the obtained data reveals a number of characteristic patterns. Among the standard (untreated) coatings, the nickel coating *PG-12N-01* (curve **1**) exhibits the lowest wear resistance, which is attributable to the relatively low hardness of the nickel matrix compared to the other materials investigated. The coating from the high-chromium alloyed cast iron *PG-S27* (curve **2**) occupies an intermediate position; its wear resistance is governed by the presence of chromium carbides in the microstructure, which confer enhanced resistance to abrasive action. The highest resistance to degradation among the standard coatings is demonstrated by the cobalt-based powder *PGN-V3K* (curve **3**), which is associated with a favorable combination of high hardness imparted by chromium-tungsten carbides and the ductility of the cobalt matrix.

Effect of high-energy induction remelting. Additional treatment by the *HEH HFC* method exerted a non-uniform influence on the wear resistance of coatings deposited from different materials. Remelting of the nickel coatings *PG-12N-01* (curve **4**) led to a pronounced reduction in wear intensity: in terms of the final volumetric wear values, the relative improvement in wear resistance was approximately 35%. This effect is a logical consequence of the formation of a continuous, pore-free cast structure that eliminates stress concentrators and zones of weakened interparticle bonding within the sprayed layer. The result obtained is consistent with the findings of [39, 40], in which it was shown that induction remelting of nickel-based self-fluxing alloys leads to the elimination of porosity and the formation of a continuous structure analogous to a cast one.

A fundamentally different situation was observed upon remelting of coatings from the high-chromium cast iron *PG-S27* (curve **5**). Instead of the anticipated improvement, a 20% decrease in wear resistance relative to the baseline variant was recorded. The wear resistance of the remelted specimens begins to decline well before the maximum sliding distance is reached. This adverse effect is attributable to the specific nature of structural transformations occurring during the solidification of high-chromium cast iron from the liquid state. The dendritic structure that forms upon remelting, with a non-uniform distribution of the carbide phase, possesses a reduced resistance to wear compared to the original dispersed structure of the as-sprayed coating [50]. Furthermore, possible overheating of the material during high-energy heating, leading to a deterioration of the physicomechanical properties, cannot be excluded. It should be emphasized that prior experiments involving the remelting of *PGN-V3K* coatings also yielded negative results owing to the formation of a non-uniform structure, which indicates the limited applicability of the *HEH HFC* method to coatings based on highly alloyed systems [40].

Thus, although *HEH HFC* technology provides a substantial enhancement in the wear resistance of nickel coatings, in practice it is exceedingly difficult to guarantee consistent quality of the remelted layer across a broad spectrum of materials. This conclusion is of fundamental significance for the design of hybrid machine-tool equipment, in which the induction heating module must deliver a predictable and reproducible outcome irrespective of the material being processed.

Wear resistance of ceramic–metal coatings. The experimental investigations convincingly demonstrated that the incorporation of aluminium oxide ceramic into the coating composition yields the most significant and consistent improvement in wear resistance. The nickel–ceramic mixture *PG-12N-01* (20%) + *15A* (80%) (curve **6**) exhibited a wear resistance exceeding the baseline nickel variant by 44% and surpassing the result obtained on the remelted coatings by 11%. This finding indicates that the formation of a composite structure incorporating inclusions of high-hardness ceramic constitutes a more effective means of improving wear resistance than thermal modification of a single-component coating.

The cobalt–ceramic mixture PGN-V3K (20%) + 15A (80%) (curve **7**) exhibited the best performance among all the investigated variants. The enhancement in wear resistance relative to the initial cobalt coating amounted to 30%. A characteristic feature of the wear kinetics of this coating is the virtual cessation of volumetric wear upon completion of the brief running-in period of the friction pair. The linear character of the wear curve with a slope approaching zero suggests that the service life of the cobalt–ceramic coatings substantially exceeds the sliding distance established in the present experimental investigations. This circumstance points to the potentially high durability of such coatings in the industrial operation of components subjected to dry sliding friction conditions.

The summarized data on the comparative wear resistance of the investigated coatings are presented in Table 2.

Table 2

Comparative wear resistance of plasma coatings under different combined treatment conditions

Group	Coating variant	Change in wear resistance relative to the base variant,%*
1	*PG-12N-01* (base)	0 (reference 1)
	PG-12N-01 + *HFC* remelting	+35
	PG-12N-01 (20%) + *15A* (80%)	+44
2	*PG-S27* (base)	0 (reference 2)
	PG-S27 + *HFC* remelting	−20
3	*PGN-V3K* (base)	0 (reference 3)
	PGN-V3K (20%) + *15A* (80%)	+30

* Note: relative to the base coating within the respective group.

Metallographic analysis. To elucidate the identified tribological behavior patterns, a structural analysis of the coatings formed under different combined treatment conditions was performed.

Fig. 3 presents a representative metallographic micrograph of the microstructure of the nickel plasma coating *PG-12N-01* without additional treatment. It is clearly evident that the application of optimized spraying parameters resulted in a uniform lamellar structure with low porosity and a minimal content of unmelted and undeformed particles. The level of wear resistance is determined not only by the hardness of the powder material but also by the strength of cohesive bonds between the deformed particles. The character of the transitional boundary between the coating and the substrate indicates a minimal number of discontinuity regions, which guarantees high adhesive bond strength. An analogous uniform structure is observed for the *PG-S27* and *PGN-V3K* coatings.

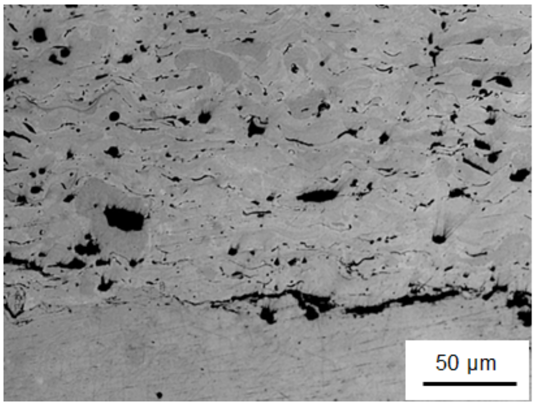

Fig. 3. Microstructure of the as-sprayed nickel plasma coating *PG-12N-01*

Fig. 4 presents the microstructure of the remelted nickel coating *PG-12N-01* after *HEH HFC*. The micrograph clearly shows that upon induction remelting the porosity is virtually completely eliminated and a continuous cast structure is formed. The absence of interparticle boundaries and pores ensures enhanced cohesive strength, which accounts for the observed 35% increase in wear resistance. It should be noted, however, that upon remelting of *PG-S27* high-chromium cast iron coatings, a coarse dendritic structure with a non-uniform distribution of the carbide phase was formed, which possesses a reduced resistance to contact loading. This circumstance explains the adverse effect of remelting on the cast iron coatings and attests to the limitations of the *HEH HFC* method with respect to ensuring a universal improvement in wear resistance.

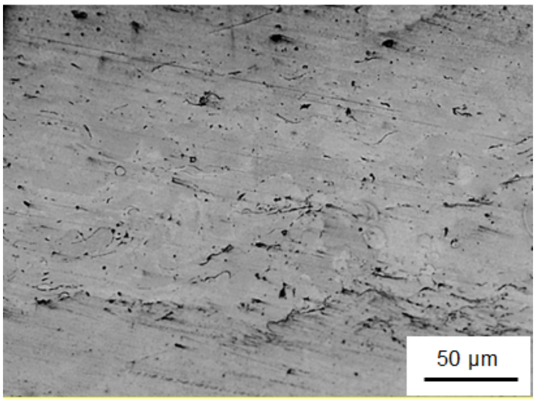

Fig. 4. Microstructure of the remelted nickel coating *PG-12N-01* after *HFC* remelting: uniformly fused cast structure

Fig. 5 presents a micrograph of the coating structure deposited from the nickel–ceramic mixture *PG-12N-01* (20%) + *15A* (80%). The resulting composite incorporates fine oxide ceramic (Al_2O_3) particles uniformly distributed within the nickel coating matrix. An analogous structure is formed upon spraying of the cobalt–ceramic mixture *PGN-V3K* (20%) + *15A* (80%). Although residual pores and partially melted particles are present in the sprayed layer, the composite coatings demonstrate the best tribological performance among all the investigated variants. The dominant role in ensuring high wear resistance is played by the considerable hardness of the aluminium oxide particles (HV ≈ 2,000–2,300), which, in conjunction with the strength and ductility of the metallic binder, provides resistance of the composite to contact loading.

The mechanism of enhanced wear resistance of the ceramic–metal coatings can be explained as follows. High-hardness ceramic particles, being uniformly distributed within a ductile metallic matrix, bear the primary share of the contact load, thereby impeding micro-cutting and plastic deformation of the surface layer. The metallic binder, enveloping the ceramic particles, ensures their retention within the coating structure and prevents brittle fracture. This behavioral model is consistent

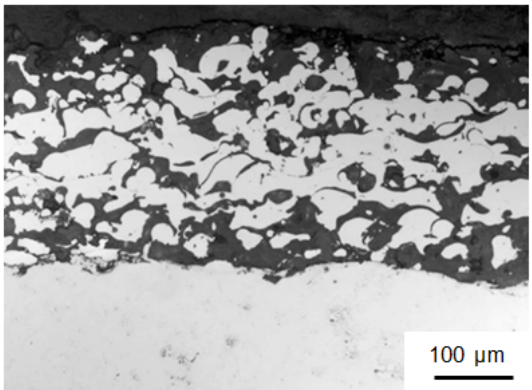

Fig. 5. Microstructure of the nickel–ceramic coating from the mixture *PG-12N-01* (20 %) + + *15A* (80 %): uniform distribution of oxide ceramic particles in the metal matrix

with established concepts regarding the performance of composite materials of the “ceramic–metallic binder” type, as expounded in [41, 48, 49].

Discussion of results in the context of hybrid equipment design. The experimental results obtained bear direct applied significance for the development of theoretical foundations and conceptual approaches to the design of hybrid machine-tool equipment integrating mechanical and surface-thermal technological operations. The identified patterns permit the formulation of a number of scientifically substantiated recommendations.

First, the ambiguity of the results of high-energy induction remelting (a positive effect for nickel coatings and a negative one for high-chromium cast iron coatings) points to the necessity of incorporating an intelligent control system for the surface-thermal treatment parameters into the hybrid equipment, one that adapts to the properties of the material being processed. This requirement is fully consistent with the *Industry 4.0* concept, which envisions the deployment of sensor-based monitoring systems and adaptive control algorithms [5, 6, 51, 52].

Second, the superiority of ceramic–metal coatings over all other investigated variants provides evidence for the expediency of integrating a plasma spraying module for composite mixtures into a hybrid machine-tool system. The ability to form coatings with a rational balance of hardness and ductility renders this technology particularly promising for the hardening of components operating under complex loading conditions (a combination of sliding friction and dynamic impact loads) [42, 43].

Third, the results of the metallographic analysis confirm the critical role of process parameter optimization, which dictates elevated requirements for the control systems of hybrid equipment in terms of ensuring the precise and reproducible metering of energy parameters for both plasma spraying and supplementary thermal treatment.

It should be noted that a representative example of components for which the technology under development has direct practical significance are elements of production equipment for the manufacture of rail switch tie plates, which operate under conditions of dry metal-on-metal sliding friction at high contact loads [48].

Conclusions

Based on the systematic comparative testing of plasma coatings formed under different combined treatment conditions in dry sliding friction, the following findings have been established.

High-energy induction remelting by the *HEH HFC* method provides a substantial improvement in the wear resistance of nickel coatings of *PG-12N-01* grade (by 35%) owing to the formation of a continuous, pore-free cast structure; however, for coatings deposited from *PG-S27* high-chromium cast iron, this treatment leads to a 20% decrease in wear resistance as a result of the formation of an unfavorable dendritic structure.

Coatings from ceramic–metal mechanical mixtures demonstrate the best tribological performance among all the investigated variants: the nickel–ceramic mixture exceeds the baseline nickel coating by 44%, while the cobalt–ceramic mixture provides a 30% increase in the wear resistance of the cobalt coating, with volumetric wear virtually ceasing after the running-in period.

Structural analysis confirmed that the high wear resistance of the ceramic–metal coatings is attributable to the uniform distribution of fine, high-hardness aluminium oxide particles within a ductile metallic matrix, which ensures effective resistance to contact loading.

The research results form an experimental basis for the design of next-generation hybrid machine-tool equipment integrating mechanical and surface-thermal operations. The ambiguity of the induction remelting effects points to the necessity of developing adaptive control systems for the parameters of the surface-thermal module, while the superiority of ceramic–metal coatings substantiates the expediency of incorporating a plasma spraying module for composite mixtures into advanced hybrid systems.

The virtually unlimited possibilities for varying the composition of ceramic–metal mixtures create prerequisites for the formation of coatings with an optimal balance of hardness and ductility, ensuring the service life of components under both dry sliding friction and dynamic impact loading conditions.

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Conflicts of Interest

The authors declare no conflict of interest.