Modern methods of applying ceramic coatings to titanium alloys: prospects and technological solutions

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This study focuses on the analysis of modern technologies for applying ceramic coatings to titanium alloys to enhance their performance characteristics, particularly for aerospace applications. The article examines key methods and technologies, such as plasma spraying, micro-arc oxidation, electron beam processing, as well as combined and multilayer coatings. Special attention is given to the parameters of plasma spraying that influence the quality and durability of coatings. The research methodology includes theoretical analysis, experimental studies, and comparative evaluation of various coating application technologies, along with the systematization of optimal parameters that improve the operational properties of titanium alloys. The prospects of applying these technologies in extreme loads and aggressive environments are also considered. The results show that plasma spraying, micro-arc oxidation, and combined treatment methods significantly improve the corrosion resistance, wear resistance, and thermal stability of titanium alloys. The greatest effect is achieved by optimizing the spraying parameters, such as plasma temperature, powder feed rate, and substrate distance, which enable the formation of coatings with minimal porosity and high adhesion. In conclusion, the study highlights the importance of modern coating technologies in enhancing the performance characteristics of titanium alloys in critical industries such as aerospace, medical, and energy sectors. Further research should focus on overcoming technological limitations, reducing costs, and adapting methods to industry-specific requirements.

Key words: Titanium alloys, ceramic coatings, combined coatings, plasma spraying, micro-arc oxidation, electron beam treatment, spraying parameters, extreme loads, aerospace industry.

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Introduction

Titanium began to be widely used in the second half of the 20th century, especially in the aerospace and defence industries. In the USSR, the titanium industry developed rapidly from the 1950s onwards, when the first industrial production of titanium alloys was established. By the 1980s, the USSR had become one of the world leaders in titanium production, using it for aviation, space programmes and shipbuilding. However, after the collapse of the USSR, the industry experienced a crisis due to the breakdown of production links. In the 1990s, the consolidation of titanium enterprises began. Today, titanium remains a strategically important material for the aerospace, medical and energy industries [1]. It is actively used in the manufacture of structural elements for aircraft, implants, surgical instruments and equipment operated under high loads, temperatures and aggressive environments. However, the use of titanium alloys in extreme conditions requires additional surface protection, which makes it relevant to study coating methods such as plasma spraying, electron beam processing and micro-arc oxidation.

This work aims to analyse modern technologies for applying ceramic coatings to titanium alloys, evaluate their respective advantages and limitations, and optimise parameters to enhance performance characteristics within the aerospace industry. Particular attention is paid to plasma spraying and the impact of its key parameters on coating quality.

1. The use of titanium alloys in various industries

Due to their unique properties, titanium alloys are widely used in virtually all areas of industry. High strength combined with low weight, corrosion resistance, biocompatibility and resistance to extreme temperatures make them a versatile material for solving complex problems. This is the rationale behind the development of the titanium industry.

The growth in titanium consumption in the aerospace industry demonstrates its strategic importance for modern aircraft construction and space technology. The increase in the share of this sector from 40% in 2007 [2] to 56% in 2020 [3] is due to the development of aviation technology, increased requirements for lightness and strength of structures, and the expansion of space programmes. Titanium remains an indispensable material for the production of aircraft, rockets and satellites due to its corrosion resistance, heat resistance and high specific strength. The shift in demand towards aviation confirms global trends towards increased air traffic, the development of more economical and environmentally friendly aircraft, and active space exploration.

The main areas of application for titanium alloys include the manufacture of aircraft and rocket structural elements, such as frames, cladding, fasteners, and engine components capable of withstanding significant thermal loads. Titanium composites with added reinforcing fibres, such as SiC, are used to increase strength and reduce weight, making them ideal for creating lightweight and durable parts for aircraft and spacecraft.

Titanium alloys play an important role in the modern aviation industry due to their combination of low density, high strength and corrosion resistance, which allows them to be used effectively in the construction of compressors and fans for aircraft gas turbine engines (GTEs) operating at temperatures of up to 700–800 °C. Particular attention is paid to the development of intermetallic titanium materials based on $Ti - Al - Nb - X$ systems with improved heat resistance properties, which expands their scope of application in aviation engine construction [4].

One promising area is the use of recycled titanium waste, due to the high cost of titanium, its importance in the manufacture of aircraft parts, and the need to reduce raw material consumption without compromising quality. Thanks to modern processing methods, such as EBM and VAR technologies, secondary titanium alloys are used in the production of aviation and space components, including engine parts, frames, and fasteners. Thus, the processing of titanium waste not only reduces production costs, but also ensures that products meet the high quality standards required in the aerospace industry [5].

In the aerospace industry, ceramic coatings are important for protecting parts from high temperatures, corrosion and wear. Particular attention is paid to heat-resistant coatings, which are used on gas turbine engine components to ensure durability and resistance to thermal shock loads. High-strength non-oxide ceramics, such as silicon nitride and zirconium dioxide, are used in engine components (e. g., bearings and bushings) where high wear resistance and thermal stability are required. Such materials help to increase the service life of equipment and reduce operating costs [6].

However, in addition to the aerospace industry, titanium is used in a wide range of industries. In the industrial market, titanium is one of the most significant sectors, covering a wide range of applications, namely: marine technology, chemical and oil & gas industries, energy, desalination, heat exchangers and the aerospace industry. The titanium industry is more dependent on the state of the aircraft manufacturing industry than manufacturers of other materials. The introduction of lockdown measures in most countries in 2020–2021 led to a sharp decline in passenger traffic, which subsequently exacerbated the situation with orders for new aircraft. The development of industrial applications for titanium is largely influenced by fluctuations in raw material prices [7].

Titanium is used to manufacture cylinders, containers, shells, cladding, bulkheads, stringers, beams and other parts and components for new equipment. Promising areas for the development of high-strength titanium alloys include improving alloying, enhancing strengthening mechanisms, and developing new processing methods. The development of complex alloying theory is aimed at complicating macro- and micro-alloying complexes to improve performance characteristics. The main focus is on solid solution and dispersion strengthening, since intermetallic compounds (with chromium, iron, copper, nickel, aluminium) reduce plasticity and crack resistance.

Research is also being conducted on the creation of alloys with maximum strengthening of α- and β-phases, and the development of high-speed and gradient hardening methods that improve mechanical properties and reduce energy consumption by 2–3 times. An important area of research is the creation of layered composite materials (CM) that provide high strength (up to 2500–2900 MPa) at a cost that is 20–30% lower than that of β-alloys.

Particular attention is paid to CM with an aluminium interlayer between layers of titanium alloys, which prevents the formation of brittle phases and improves operational properties. Eight- and multi-component ($\alpha + \beta$) alloys are being developed, as well as nanostructured shells that are resistant to biaxial tension. These innovations significantly increase the strength, durability and reliability of titanium in structural applications [8].

Titanium implants made of porous titanium and its alloys are widely used to replace bone defects due to their high biocompatibility, strength, and ability to osseointegrate. Modern technologies, including 3D printing and surface modification, improve bone tissue ingrowth and reduce the risk of inflammation. A porous structure with optimal pore size promotes better vascularisation and bone regeneration [9].

The generalised diagram of titanium applications (outside the aerospace industry) shown in **Fig. 1** clearly demonstrates its role in various industries, emphasising its importance as a strategic material for future technologies.

Foreign studies also indicate the widespread use of titanium in a wide range of industries. Titanium alloys are widely used in biomedicine due to their unique combination of mechanical strength, corrosion resistance and biocompatibility. Their low elastic modulus makes them ideal for medical implants, including orthopaedic prostheses, dental and maxillofacial structures [10, 11]. Moving on to the oil and gas industry, it is worth noting the use of titanium alloys in downhole tubulars, where their corrosion resistance ensures long-term operation in aggressive environments.

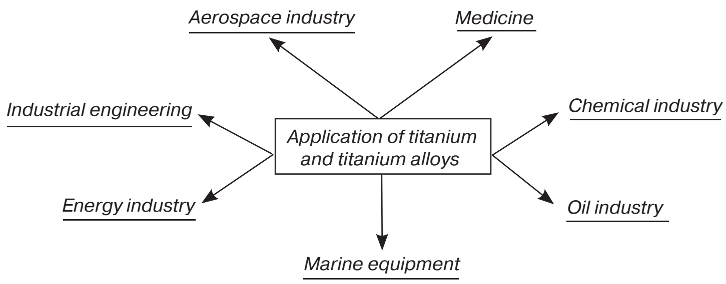

Fig. 1. The scope of application of titanium and its alloys

In the transport sector, the advantages of titanium alloys are realised through a reduction in component weight. In the motorcycle and automotive industries, they are used to manufacture exhaust systems, engine valves and connecting rods, with more economical Ti – Al – Fe alloys being used alongside the classic Ti – 6Al – 4V [13]. Titanium alloys are particularly important in car suspension systems and other structural elements, where their high strength and excellent corrosion resistance ensure reliability and durability when operating in difficult road conditions. However, due to its high cost, the use of titanium in the automotive industry is mainly concentrated in sports and specialised models, where weight reduction and improved performance are important [14].

Marine applications of titanium alloys, such as propeller shafts and ship hulls, are based on their exceptional resistance to corrosion in seawater [15]. Titanium alloys are used in construction to reinforce and restore stone and brick structures due to their strength, corrosion resistance and durability. Their low density and resistance to aggressive environments make titanium structures advantageous despite their high initial cost [16, 17].

However, titanium alloys are used most widely in the aerospace industry. Their high strength-to-weight ratio makes them indispensable for airframe, landing gear and power unit structures [18]. The Ti – 6Al – 4V alloy is widely used in jet engines for manufacturing turbine blades and discs, due to its combination of high strength, corrosion resistance, and the ability to withstand extreme temperatures that exceed the limits of aluminium alloys [19]. Titanium fasteners reduce weight while maintaining strength, and are even used in heat shields for satellites and rockets [20, 21]. Modern high-strength titanium alloys combine strength, ductility and heat resistance thanks to special thermomechanical treatments and microstructure control. This allows them to be used in critical spacecraft components [22].

Table1 shows the various applications of titanium materials in the aerospace industry, highlighting their advantages over aluminium alloys in terms of higher strength, which leads to weight savings [23].

Analysis of the data in **Table 1** demonstrates the widespread use of titanium materials in various aerospace components, which is due to their superior performance characteristics compared to aluminium alloys. The use of commercially pure titanium in airframe structures (floors, window frames) and hydraulic systems (tubes) provides an optimal combination of strength and corrosion resistance. High-strength Ti – 6Al – 4V and Ti – 10V – 2Fe – 3Al alloys are used in critical chassis components, demonstrating outstanding mechanical properties while significantly reducing the weight of the structure.

2. Ceramic coatings

2.1. Technologies for producing ceramic coatings

Current research in the field of metal coatings, including titanium alloys, focuses on enhancing their performance characteristics. Ceramic and metal composite coatings are important in this regard, as they provide heat, wear and corrosion resistance in various operating conditions.

Non-polymer composite materials are indispensable in space technology due to their ability to withstand extreme temperatures, radiation and mechanical loads throughout spaceflight. Ceramic composites (CCs), with their exceptional heat resistance properties, are employed in heat shielding systems, fairings, and combustion chambers to provide protection at hypersonic speeds. Meanwhile, metal composites (MCCs), which offer high rigidity and dimensional stability, are employed in load-bearing structures, landing gear and antenna systems.

Current research focuses on enhancing production technologies for these materials, including 3D printing, to enable the creation of more intricate and economical designs. Particular attention is being paid to developing new hybrid solutions and methods of protection against oxidation. A promising area is the creation

Table 1
Areas of application for titanium materials in the aerospace industry

Commercially pure titanium	Frame construction	Floors
Ti – 6Al – 4V		Window frames
Ti – 10V – 2Fe – 3Al; Ti-6-6-2		Landing gear
Ti – 3Al – 2.5V		Hydraulic piping
Ti – 15V – 3Cr – 3Sn – 3Al		Coil springs
Ti – 6Al – 4V; Ti-6-2-4-2S	Gas turbine engine	Compressor disc
		Compressor blades
		Fan blades and disks
Ti – 35V – 15Cr		Compressor stator
TIMETAL21S		Propulsive nozzle assembly

of large-scale elements with highly reproducible characteristics, which could open up new opportunities for their use in space programmes [24].

A number of recent studies have confirmed the practical implementation of these approaches, showing that micro-arc oxidation (MAO), also known as plasma electrolytic oxidation (PEO), can be used effectively to modify the surface of titanium alloys, thereby improving their corrosion resistance, biocompatibility, and mechanical properties. For instance, treating commercially pure titanium in an electrolyte containing calcium and phosphates forms coatings containing calcium phosphate compounds, increasing the surface's bioactivity and reducing the corrosion current density by over 15 times compared to untreated titanium [25]. Additionally, modifying the titanium surface using PEO with zinc ions results in porous coatings that enhance the adhesion, proliferation, and differentiation of mesenchymal stem cells, while also increasing the material's corrosion resistance [26]. PEO treatment of titanium using various electrolytes has also been found to produce coatings with a thickness of 12–20 μm and a porous morphology. These coatings exhibit good biocompatibility and reduce tendon adhesion, which is particularly important in orthopaedic applications [27].

In addition, recent studies have focused on the role of additives and conditions that affect the morphology and functionality of PEO coatings. Recent work has shown that modifying the electrolyte at the PEO of titanium can significantly improve the properties of the resulting coatings. For example, the addition of nitrilotriacetic acid (NTA) to the electrolyte promotes the formation of more uniform and dense oxide layers, which leads to increased corrosion resistance and biocompatibility of the coatings, as well as a reduction in the level of metal ionisation in physiological solutions [28]. In addition, the use of sodium aluminate-based electrolytes allows coatings containing α- and γ-Al_2O_3 phases to be obtained, which have high hardness (up to 49 GPa) and improved adhesion, which significantly increases the wear resistance and corrosion resistance of titanium [29]. It has also been established that the use of PEO with different current modes and electrolyte compositions allows the formation of nanocrystalline TiO_2 coatings with a predominance of the rutile phase, which demonstrate improved tribological properties, including a reduction in the friction coefficient and increased wear resistance [30].

In [31], ceramic coatings obtained by electric spark machining (ESM) of titanium alloy VT3-1 and steel X12MF using Ti – Zr – C electrodes were studied. The coatings, with a thickness of 10–18 μm, demonstrated 100% uniformity, microhardness up to 11.8 GPa, and consisted of (Ti,Zr)C carbides and solid solutions based on Ti/Fe. The optimal mode (0.06 J) provided high adhesion and wear resistance, which is promising for high-load applications.

Study [32] demonstrated the effectiveness of ESM with SHS electrodes (Ti0.8Cr0.2C – Ni – Fe) for applying wear-resistant coatings to P6M5 steel. The hardness of the coatings (10.6–13.5 GPa) was 5–7 times higher than that of the original material and the wear resistance increased sevenfold. The best coating structure was achieved at an energy of 0.3 J without the macrodrops characteristic of high-energy modes (1.0 J). This method showed promise for tooling applications.

In [33], a multilayer Cr/CrC coating on γ-TiAl alloy was developed using the double glow plasma surface alloying (DGP) method. Two-stage processing (chromium plating + cementation at 1050–1100 °C) resulted in a 35-micron coating with a gradient structure. The coating demonstrated exceptional characteristics: a friction coefficient of 0.2 (2.2–2.8 times better than the base material) and increased oxidation resistance (2.3 times less mass gain at 830 °C), which is associated with the formation of protective layers of Cr_2O_3 and carbides.

An analysis of modern technologies for forming coatings on titanium alloys has shown the high efficiency of plasma electrolytic oxidation (PEO), electric spark alloying (ESA) and double glow plasma surface alloying (DGP) methods. PEO allows coatings with adjustable properties — from biocompatibility to wear resistance — to be obtained by selecting the electrolyte and processing mode. ESA produces dense carbide layers with high hardness and adhesion, suitable for friction units. DGP provides the creation of multilayer structures with excellent oxidation resistance. These technologies open up broad prospects for the use of titanium in medicine, aviation, mechanical engineering, and other knowledge-intensive industries.

2.2. Technologies for applying ceramic coatings to titanium

Titanium and its alloys are widely used in various industries due to their properties. However, to expand the functional capabilities and improve the performance characteristics of titanium in extreme conditions, specialised coatings must be applied.

Analysis of research shows that modern coating methods for titanium can significantly improve its performance properties. The use of composite materials increases mechanical strength and heat resistance, electric spark treatment (ESA) with various electrodes forms coatings with high hardness and wear resistance, and ceramic coatings provide resistance to friction at high speeds. In the future, further development of coatings will be linked to the optimisation of ESA methods, the introduction of new composite materials and the improvement of tribological characteristics, which will expand their application in aviation, space and industry.

A study [34] proposes an innovative method for creating multilayer ceramic coatings based on calcium phosphates, combining solutions for both areas. The TiCaO adhesion layer, similar to that used in aviation alloys, provides strong adhesion, while the upper layers (hydroxyapatite and octacalcium phosphate) prevent corrosion and increase bioactivity, demonstrating the synergy between thermal protection and biomedical technologies.

Moving on to medical implants, work [35] focuses on optimising bioactive coatings for the Ti – 6Al – 4V alloy. Combined treatment (sandblasting + oxidation) and layer-by-layer application of glass-ceramic followed by annealing allow obtaining a coating with needle-like fluorapatite crystals, high adhesion and the ability to stimulate hydroxyapatite growth in vitro. This approach solves the problem of integrating ceramics with a titanium base, which is critical for the durability of implants.

In the context of extreme conditions, such as vacuum, study [36] reveals the limitations of magnetron sputtering of MoS_2-based solid lubricant coatings (SLCs). Despite their low friction coefficient (0.02–0.07), their service life is 2.5–3.6 times shorter than that of analogues obtained by the suspension method. Pretreatment of the substrate plate (chromium plating, nickel plating) and the use of a ceramic base increase wear resistance, emphasizing the importance of adapting technologies to specific operational requirements.

A study of the tribological properties of ceramic coatings on titanium during dry sliding on steel over a wide range of speeds (0.1–47 m/s) showed that at low speeds, moderate wear occurs, which becomes catastrophic at 3–4 m/s. However, with a further increase in speed (6–47 m/s), wear is significantly reduced, indicating the formation of a zone of virtually "wearlessness" friction.

Analysis of worn surfaces showed that at low speeds, an abrasive mechanism with a grooved relief dominates, while at 3–6 m/s, areas of coating delamination are observed. At high speeds, the surface becomes smoother, and phase transformations lead to a change in the coating structure: first, a partial martensitic transformation occurs, then its intensity decreases due to the increase in temperature in the friction zone, which contributes to the stabilization of the ceramic layer.

The addition of aluminum oxide (Al_2O_3) to the ceramic coating improves its wear resistance, reduces the wear rate, and slows down phase transformations. At high friction speeds, a protective layer of metal transfer forms on the surface, which further increases the tribological resistance of the coating on titanium [37].

Modern developments in the field of plasma electrolytic oxidation (PEO) are aimed at improving the properties of coatings on titanium alloys, including wear resistance, corrosion resistance, heat resistance, electrical insulation, and biocompatibility. Biocompatibility is achieved by adding calcium ions and phosphates, while decorative properties are achieved by introducing vanadates and vanadium fluorides. To increase hardness and wear resistance, sodium hydroxide, aluminate, and sodium silicate are added to the electrolyte. Corrosion resistance is improved by reducing porosity with the addition of metallic and non-metallic powders, as well as by adjusting process parameters. Technologies developed, for example, at the Central research institute of structural materials "PROMETEY", make it possible to obtain coatings with high microhardness (780 HV), low friction coefficient (0.06), and no porosity, which significantly expands their application. [38].

In [39], the combined effect of ultrasonic rolling (USR) and TiZrN/TiZr ceramic coating on the fatigue strength of Ti – 6Al – 4V alloy was studied. The treatment was carried out using a WC/Co ball tool (diameter 14 mm) at a frequency of 20 kHz, static pressure of 600 N, and feed rate of 0.05–0.10 mm/rev. This created a surface layer with residual compressive stresses of up to 814 MPa, which improved the adhesion of the multilayer coating (23 μm) applied by arc plasma spraying. Without USR, the coating reduced fatigue life by 77.7% due to the brittleness of the ceramic. However, complex treatment (USR + coating) increased the service life of the samples by 100 times at a load of 550 MPa. The key factor was the formation of a layer with residual stresses 600 μm deep, which suppressed cracks [39].

Modern methods of applying coatings to titanium, such as composite materials, electric spark treatment, ceramic and multifunctional layers, significantly increase its mechanical strength, wear resistance, thermal stability, and biocompatibility. Key achievements include combined technologies (sandblasting + oxidation, ultrasonic rolling + plasma coating), the creation of protective layers with residual stresses, and the use of additives (Al_2O_3, Ca/P ions) to stabilize the structure and reduce wear. An important aspect is the adaptation of methods to operating conditions: the formation of "wear-free" friction zones at high speeds, the optimization of solid lubricant coatings for vacuum, and the synergy of biomedical and thermal protection solutions. Prospects are associated with the development of multilayer systems, reduction of porosity, and integration of substrate plate pretreatment, which expands the application of titanium alloys in aviation, medicine, and industry.

3. Problems with the exploitation and treatment of titanium alloys, and ways to solve them

Titanium alloys are in demand in aviation and space exploration due to their strength and corrosion resistance, but their exploitation and treatment are associated with a number of problems. Aggressive environments, high temperatures, and mechanical loads accelerate wear and reduce the durability of parts. In addition, mechanical and additive processing of titanium is complicated by its low thermal conductivity and high viscosity, which leads to overheating of tools and residual stresses.

The main problem with the Ti – 6Al – 4V titanium alloy is the compromise between strength and ductility: increasing strength usually reduces ductility. In study [40], this problem was solved by cryogenic rolling followed by short-term vacuum annealing. Cryogenic rolling increased the tensile strength to 1241 MPa but reduced the elongation to 3.2%. After annealing at 973 K for 5 minutes, the alloy retained high strength (1126 MPa) and significantly improved ductility (elongation 10.9%), achieving a record static viscosity of 12.000 MPa·%. This was made possible by partial recrystallization, the formation of a fine-grained structure, and the suppression of grain growth by the β phase. The method proved to be energy efficient and suitable for industrial application.

In aerospace applications, where alloys are exposed to aggressive environments (e. g., fuels, chemical reagents, and atmospheric conditions), additional corrosion protection is required. Studies have shown that preserving the oxide film on the surface of titanium plays a key role in ensuring its durability, which makes the development of anti-corrosion treatment technologies relevant for the aerospace industry.

The micro-arc oxidation (MAO) method has proven to be the most effective for increasing the corrosion resistance of titanium alloys used in aviation and space exploration. Experiments have shown that treatment in a silicate-alkaline electrolyte ($KOH + Na_2SiO_3$) results in the formation of a thick, wear-resistant coating capable of withstanding aggressive environments, including fuel mixtures and atmospheric exposure at high altitudes. In addition, such coatings are resistant to abrasive destruction, which is especially important for parts subject to friction and impact, such as engine components, fuel systems, and external structures.

Optimizing the MAO process for the aerospace industry increases component service life and reduces maintenance costs. For example, a coating formed at a current density of 40 A/dm2 in a silicate-alkaline electrolyte showed minimal mass loss under aggressive testing conditions, confirming its suitability for use in extreme conditions. This makes the MAO method an important tool for improving the reliability and safety of aviation and space technology [41].

Relatively low surface hardness and insufficient wear resistance significantly limit their use in friction units and other critical structures operating under conditions of intense mechanical stress. The solution to this problem was found in surface boronizing technology, which allows for a significant improvement in the tribological characteristics of titanium alloys [42].

The variety of existing technological solutions in the field of titanium alloy boronizing reflects the constant search for optimal treatment methods. Gas boronizing, carried out in an atmosphere of boron-containing compounds at elevated temperatures, provides precise control of the composition and thickness of the formed layer by regulating the parameters of the gas environment [43]. An alternative method of boronizing in salt melts is characterized by high productivity and uniformity of coating, which is especially important for the treatment of parts with complex geometric shapes [44]. A special class of methods is represented by laser pulse boronizing, which combines local impact with minimal thermal deformation of the treated part, opening up new possibilities for the treatment of precision products [45].

An analysis of the technological and economic aspects of various boron coating methods allows us to identify traditional boron coating as the most demanded industrial solution. The key advantages of this method are the exceptional simplicity of the technological process, which does not require complex and expensive equipment, as well as the possibility of forming dense, non-porous coatings with controlled thickness and composition [46]. An important factor in the popularity of the method is its economic efficiency — the use of inexpensive boron-containing reagents and standard thermal equipment makes the process accessible to a wide range of enterprises.

Laser cladding (direct energy deposition) increases the wear resistance and hardness of surfaces by forming composite layers with a metallurgical bond. Local melting of the powder and base followed by rapid cooling creates a dense, fine-grained structure that improves strength [47]. The method allows combining dissimilar materials and is characterized by high purity and controllability. Hybrid approaches are promising, for example, the combination of laser texturing with thermal oxidation: studies have revealed a 17-micron gradient oxide layer with variable oxygen content, which increases hardness and elastic modulus. Tests have shown that combined processing reduces wear rates significantly compared to individual methods and the original alloy, confirming its effectiveness for strengthening titanium parts under extreme loads [48].

The high viscosity and low thermal conductivity of titanium cause overheating and wear of cutting tools, vibrations, and dust detonation, complicating treatment [49]. Even with hard-alloy tools and CNC, accuracy problems remain due to thermal deformation and vibrations. Post-processing of thin-walled parts with internal cavities obtained by selective laser melting is particularly difficult: mechanical methods are limited by small allowances, complex profiles, and the risk of warping due to residual stresses in the surface layer. An alternative is chemical polishing of the BT6 alloy, which eliminates micro-relief and laser processing defects. It increases corrosion resistance and mechanical properties and allows the depth of processing to be controlled without damaging thin structures [50].

Combined treatment of VT6 alloy (electro-explosive alloying of titanium foil with boron carbide + electron beam irradiation) improved the composition and structure of the surface layer. The electron beam leveled the surface, creating a multilayer submicron nanostructure up to 30 μm thick with uniform distribution of elements. Ultra-rapid cooling formed needle-like structures (1–10 μm), increasing the strength and wear resistance of the material [51].

After analyzing all the sources presented, it was found that titanium alloys, such as Ti – 6Al – 4V, play a key role in the aviation and space industries due to their excellent mechanical and corrosion properties. However, the use of these materials is associated with a number of problems, including aggressive environments, high temperatures, and mechanical loads, which accelerate wear and reduce the durability of components. In addition, the processing of titanium is complicated by its low thermal conductivity and high viscosity, which leads to overheating of tools and the formation of residual stresses.

Despite its widespread use in industry, VT20 titanium alloy has a limited service life. To improve it, a combined thermomechanical treatment combining thermal cycling and static-pulse effects has been proposed. Studies have shown that this method significantly improves performance characteristics: reduction in grain size and roughness, increase in hardness, reduction in friction coefficient and volumetric wear. The strengthening mechanism includes heating-cooling cycles and short-term deformation pulses. The results confirm the effectiveness of combined treatment in increasing the wear resistance and durability of VT20, opening up new prospects for its use in critical structures [52].

Based on the sources studied, various methods aimed at solving these problems were identified. After comparing them, we compiled a table that helps to clearly see the advantages of each approach **(Table 2)**.

These technologies significantly improve the performance characteristics of titanium alloys and open up new opportunities for their application in various industries.

4. Coating application

4.1 Parameters of plasma spraying of powder coatings

In the process of powder coating by plasma spraying, an important aspect is the preparation of the surface to which the coating will be applied, which includes mechanical and chemical treatment to improve the adhesion of the coating to the substrate. To achieve optimal results, the surface must be clean and roug — this can be achieved by sandblasting or chemical etching. The recommended coating thickness varies depending on the application and operating conditions, but is typically between 50 and 500 microns. Thinner coatings can be used in cases where high precision and minimum weight are important, while thicker coatings provide better protection against wear and corrosion.

Plasma temperature, powder feed rate, and distance between the nozzle and substrate play a key role in the spraying process, and optimizing these parameters allows for uniform powder distribution and improved mechanical properties of the resulting coating. However, it is important to note that too high a temperature can lead to overheating of the substrate, and too low a temperature can lead to insufficient powder sintering [53].

A number of criteria have been developed to assess the quality of abrasive blasting surface preparation. The main ones include the degree of surface roughness, measured using various methods (such as profilometry), and the presence of contaminants or scale. Abrasive blasting helps to create optimal roughness, which improves the adhesion of the sprayed coating to the substrate. Effective surface preparation is a determining factor in achieving high bond strength and coating durability. The recommended coating thickness can range from 50 to 500 microns, depending on the specific application, desired strength, and operating conditions (for example, thicker coatings are preferable for protection against significant wear and corrosion, while thinner layers can be used for components requiring high precision).

The optimum temperature significantly affects the quality of the sprayed powder and the adhesion of the coating — it allows the powder to sinter effectively, but can lead to overheating of the substrate. The powder feed rate affects the number and speed of particles reaching the surface, but too high a speed can lead to coating defects, and the correct distance between the nozzle and the substrate allows a balance to be achieved between the thermal and mechanical effects on the coating, which is undoubtedly important for its quality [54].

The main methods of surface preparation in the plasma spraying process may include: cleaning (remov-

Table 2
Comparative table of titanium alloys treatment methods

Treatment method	Advantages	Application	Ref.
Cryogenic rolling + vacuum annealing	Increased strength and ductility, highest viscosity	Improvement of mechanical properties	[40]
Micro-arc oxidation (MAO)	Improved corrosion resistance and wear resistance	Protection against aggressive environments	[41]
Boronizing	Improvement of tribological characteristics	Increased wear resistance	[42–46]
Laser cladding	Increased wear resistance, creation of composite layers	Surface hardening	[47]
Combined processing	Reduced wear rate, increased hardness and elastic modulus	Machining titanium parts under extreme conditions	[48]
Chemical polishing	Increased corrosion resistance, improved mechanical properties	Processing of thin-walled parts	[49]
Electro-explosive alloying + electron beam irradiation	Increased strength and wear resistance, improved composition and structure	Surface treatment with submicron nanostructure	[51]
Combined thermomechanical treatment (TCT + SPT)	Reduction in grain size and roughness, increase in hardness, reduction in friction coefficient and volumetric wear	Increased wear resistance and durability of titanium alloys	[52]

ing contaminants, oils, and rust from the surface of the part); grinding or sandblasting, i.e., creating roughness on the surface to improve coating adhesion; degreasing. The recommended coating thickness depends on the specific application and material characteristics. Typically, the thickness can vary from several tens to hundreds of microns, depending on the required performance properties and operating conditions of the part.

The melting point and thermal conductivity of the material affect the spraying process and adhesion. The temperature at which the coating is applied can significantly influence the properties of the final coating. Rapid or slow cooling can lead to different microstructural changes in the coating [55].

Surface preparation includes: cleaning; roughening; degreasing. The recommended coating thickness depends on the specific application and desired performance characteristics. Typically, the coating thickness can vary from 50 to 300 microns, depending on the type of material and operating conditions.

The melting temperature of the materials influences the choice of sputtering modes and the properties of the final coating; thermal conductivity determines how quickly heat will be transferred from the plasma to the substrate and coating; the cooling rate affects the microstructure and mechanical properties of the resulting coating; the substrate temperature is important for preventing thermal damage and ensuring optimal adhesion [56].

The use of an alternating magnetic field during laser spraying of powdered cobalt alloys containing niobium (Nb) forms dense, hard coatings with high wear and corrosion resistance. Nb promotes the formation of the NbB ceramic phase, which increases crack resistance. The magnetic field reduces thermal stresses through negative thermal deformation, reducing the risk of defects. The optimal Nb content, together with the magnetic effect, improves the mechanical properties and durability of the coatings, making them promising for highly loaded protective surfaces [57].

In study [58], WC-10Co4Cr coatings were developed using high-speed plasma spraying, and the resulting coatings were analyzed. For this purpose, *X*-ray diffraction and scanning electron microscopy techniques were used. As a result, data on the phase composition, microstructure, and mechanical properties of the coatings were obtained. It was found that the coatings have high hardness and good adhesion to the substrate, which makes them promising for use in various industries, including mechanical engineering, as well as wear protection.

Ceramics are an important class of materials due to their high temperature resistance, rigidity, and corrosion resistance. In gas turbine engines, ceramic coatings applied by plasma spraying protect the blades from high temperatures. The top layer of stabilized zirconia oxide ceramics compacts during exploitation, reducing its heat-shielding properties, and a diffusion zone with carbide phases forms underneath it, which can reduce the strength and durability of the coating [59].

Plasma spraying of powder coatings is a multi-stage process, the success of which depends on careful control of many parameters. The review considered the key aspects affecting the quality and properties of coatings: surface preparation, material selection, spraying mode control, and thermal process management. Based on the analysis of all the parameters considered and their influence on the spraying process, a process map is proposed that systematizes the optimal values of key parameters (**Fig. 2**).

4.2. Methods for improving the operational properties of materials using various processing technologies

Basic research on electron beam treatment (EBT) focuses on steels, titanium and aluminum alloys, while nickel and copper alloys have not been studied sufficiently. An analysis of works published between 2013 and 2023 identified the following areas:

- EBT with/without heat treatment;
- EPT after electro-explosive alloying;
- EPT of deposited layers and additive alloys.

Although EPT modes have been optimized for many materials, the limited study of nickel and copper restricts the application of the method [60].

Electrolytic plasma boriding in aqueous electrolytes increases the hardness (up to 2000 HV), wear and corrosion resistance of steels and titanium alloys. Key parameters: polarity of the part, type of current, electrolyte composition, hydrodynamics. For titanium, it is important to control the vapor-gas shell with boron potential. The method allows boronizing to be combined with hardening, which is effective for critical parts in mechanical engineering and the aerospace industry [61].

Plasma-assisted arc coating increases the fatigue life of the AK5M2 aluminum alloy used in aviation and automotive engineering. The method combines plasma treatment with arc welding, improving strength and crack resistance under cyclic loads. Tests have confirmed an increase in fatigue strength, which expands the possibilities for using the alloy in critical structures [62].

Electrolytic-plasma saturation of titanium and alloys with light elements (C, N, O) increases their corrosion resistance and wear resistance. The method combines electrolytic and plasma effects to form hardened layers. Tests have shown an increase in hardness, strength, and resistance to aggressive environments, which expands the application of the material in the aerospace and medical industries [63].

Modern methods of surface treatment of materials show great potential for improving the operational properties of alloys, but require consideration of material characteristics and technological limitations. Electron beam treatment is effective for steels, titanium, and aluminum alloys, but requires further research for nickel and copper alloys. Electrolytic plasma boronizing increases the hardness and corrosion resistance of materials, and combining it with hardening makes it advantageous for aerospace and machine-building parts. Plasma-assisted arc deposition

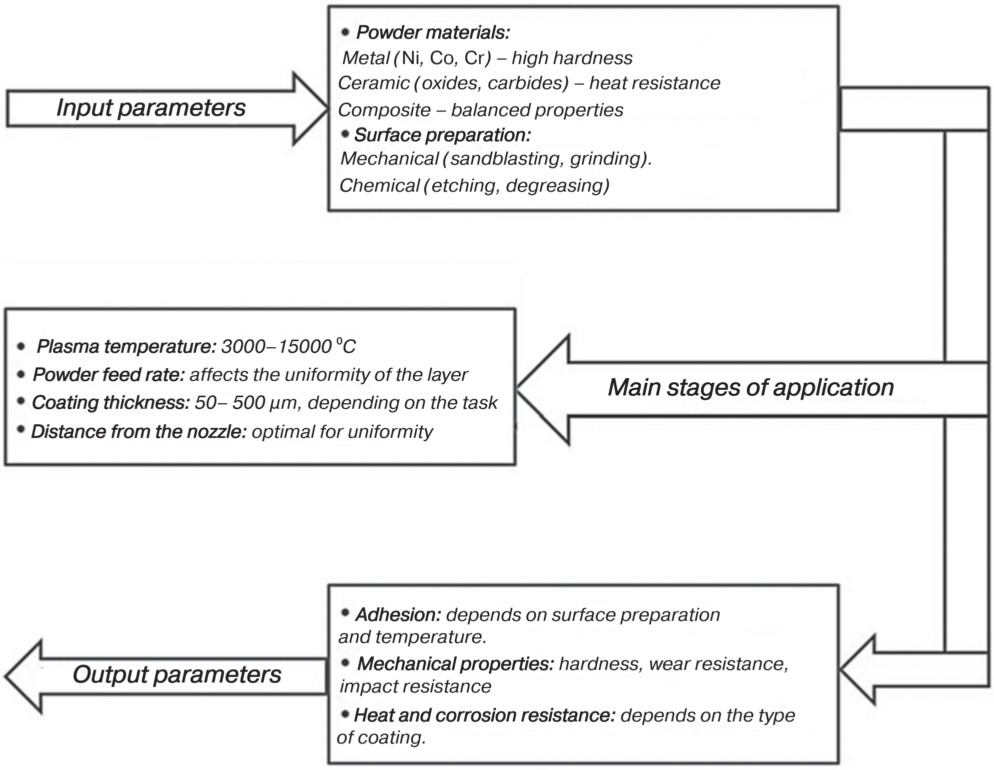

Fig. 2. Parameters for optimal plasma spraying of ceramic coatings

increases the fatigue life of AK5M2 aluminum alloy, and electrolytic plasma saturation of titanium improves its corrosion resistance.

Prospects include the development of hybrid methods, filling gaps in research for nickel and copper alloys, and optimizing treatment parameters for specific conditions. These methods increase the durability and reliability of materials, but require a balance between complexity, cost, and target characteristics when implemented in industry.

Conclusions

Titanium alloys, with their unique combination of strength, lightness, corrosion resistance, and biocompatibility, remain a strategically important material for the aerospace, medical, energy, and other high-tech industries. Their use in extreme operating conditions, such as high temperatures, aggressive environments, and mechanical loads, requires the development of effective surface protection methods. Modern technologies for applying ceramic and composite coatings, including plasma spraying, microarc oxidation, MAO (also known as plasma electrolytic oxidation, PEO), electron beam treatment, and boronizing, demonstrate significant potential in solving these problems.

As a result of the study, the following can be noted:

Plasma spraying stands out for its flexibility and versatility, allowing coatings with specified properties (heat resistance, wear resistance, electrical insulation) to be created. Optimization of parameters such as plasma temperature, powder feed rate, and distance to the substrate ensures high adhesion and minimal porosity. For example, coatings based on yttria-stabilized zirconia (YSZ) have shown improved tribological characteristics, which is critical for turbine engines.

Micro-arc oxidation has proven effective in improving the corrosion resistance of titanium alloys, especially in aggressive environments. Treatment in silicate-alkaline electrolytes forms dense oxide layers that are resistant to abrasive wear and chemical attack.

Combined methods, such as ultrasonic rolling followed by plasma coating, demonstrate a synergistic effect. They not only improve mechanical properties (e.g., increase fatigue life by a factor of 100), but also reduce the risk of coating delamination due to the formation of residual compressive stresses.

Boronizing and laser cladding significantly increase the hardness and wear resistance of surfaces. For example, cryogenic rolling with vacuum annealing of Ti – 6Al – 4V alloy made it possible to achieve record static viscosity (12,000 MPa·%) while maintaining strength and plasticity.

Modern coating technologies for titanium alloys open up new opportunities for improving the reliability and durability of critical components in the aerospace, medical, and energy industries. Further research should focus on eliminating technological limitations, reducing costs, and adapting methods to specific industrial tasks. Successful implementation of these areas will strengthen the leadership of titanium alloys as the material of the future for extreme operating conditions.

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