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Introduction

The problem of destruction of parts under the influence of external mechanical loads has long been known. The traditional method of solving this problem is the volumetric modification of products. However, to increase the service life of the product, in most cases, hardening of its surface layers is sufficient, due to the fact that their destruction begins with the surface. This is due to the fact that the most intense plastic deformation occurs in the surface layers, with a depth of grain size [1]. Improvement of properties can be achieved by treating the surface with concentrated energy flows, such as laser radiation, powerful ion beams, plasma flows and jets [2–14]. These types of processing allow modification locally, that is, in those places where destruction occurs during the operation of the product.

The main feature of hardening materials with concentrated energy fluxes, in comparison with the methods of traditional thermal and chemical-thermal treatment, is the nanostructuring of their surface layers. This means a decrease in the scale level of localization of plastic deformation of the surface, which leads to a more uniform distribution of elastic stresses near it under the influence of operational factors. As a result, the probability of nucleation of microcracks in the surface layer leading to failure is significantly reduced. This increases both strength and ductility. This allows us to solve one of the most important problems – ensuring the optimal ratio of surface properties and material volume. In this case, there is no need to use volume-alloyed materials and it becomes possible to a certain extent to solve the important task of mechanical engineering – improving the reliability and durability of large parts in operating conditions.

The application of these surface treatment methods in various industries, for example in the space or aviation, is steadily increasing and becoming comparable with traditional coating methods.

One of the promising methods of external energy exposure, which has a significant effect on the structure, phase composition, physical and mechanical properties of the surface layers of metals and alloys, is multiphase plasma jet treatment. This method allows to obtain high-quality coatings with good adhesion to the substrate and high functional properties. The method allows to apply coatings from the products of explosion of conductors, as well as to form composite coatings significantly superior in their properties to the starting material [15,16], since more durable materials are usually used as the coating material, in this book we consider the coating using the yttrium oxide.

It is known that yttrium is a metal with a number of unique properties, and these properties largely determine its very widespread use in industry today and, probably, even wider application in the future. The tensile strength for undoped pure yttrium is about 300 MPa. A very important quality of both yttrium metal and a number of its alloys is the fact that, being chemically active, when heated in air, yttrium is coated with a film of oxide and nitride protecting it from further oxidation to 1000°C. Promising fields of application for yttrium alloys are the aerospace industry, nuclear technology, and the automotive industry.

The second of the most promising and highly effective methods of surface hardening of products is electron-beam processing [17]. Electron-beam processing provides ultrahigh heating rates (up to 10^6 K/s) of the surface layer to predetermined temperatures and cooling of the surface layer due to heat removal to the bulk of the material at speeds of 10^4–10^9 K/s, resulting in the formation of non-uniform submicron and nanocrystalline structural phase states [18].

This type of processing has wide possibilities of controlling the input energy, low energy reflection coefficients, and a high concentration of energy per unit volume of the material [19]. Electron beam processing has several advantages over other surface modification methods. Compared to high-power ion beams, electron-beam processing is generated with a significantly higher coefficient of efficiency in a pulse-frequency mode at lower accelerating voltages and does not require the creation of special radiation protection. High energy efficiency, high uniformity of energy density over the flow cross section, good susceptibility of pulses and a high repetition rate provide several advantages over the pulsed flow of low-temperature plasma [20–23].

The main advantage of electron beam processing is the combination of virtually complete absorption of electron energy with the possibility of varying the depth of electron penetration into the material, and, accordingly, the dynamics of thermal fields and stress wave parameters [24].

In some cases, a single-component exposure becomes insufficient, and then it is necessary to resort to complex modification (a combination of several methods of energy exposure) [25–27].

In the presented book, all three described methods of energy exposure are considered.

The monograph is concerned with theoretical and experimental research computer simulation of structural phase transformations in Al-11Si-2Cu alloy on different scale levels under electroexplosion alloying, electron beam processing and electron–plasma alloying proceeding at the nanolevel in order to create new materials. Six modes of processing were analyzed for each type of external energy effect and the optimal modes resulting in multiple increase in strength, durometric and tribological characteristics of 100 mm thick surface layer alloy were determined. It was revealed that enormous increase in the physical and mechanical properties of Al–11Si–2Cu alloy under electroexplosion alloying is reached at the expense of creation of a multilayer, multiphase nanocrystal structure formed largely by oxides and silicates of aluminium and yttrium in the surface layer. It was stated that electron beam processing resulted in the formation of a surface whose mechanical characteristics increased significantly the values of the alloy in the cast state which is reached due to the formation of a fine-grained, gradient, cellular structure free from intermetallides. Electron-ion-plasma alloying leads to the cardinal structural transformation of material's surface layer consisting in the formation of a multielemental multiphase layer having a submicrocrystalline structure. Dissolution of silicon inclusions and intermetallides of micron and submicron dimensions characteristic of the cast state alloy takes place.

The field of application of the results presented in the monograph is research, scientific and technological enterprises involved with modification of light alloy surfaces with the aim of their use in the automobile and aerospace industry.

The book is intended for specialists in the field of physical material science, condensed state physics, metal science and thermal treatment and it may be useful for undergraduate and post-graduate students of the corresponding specialties and directions of training.

The authors are grateful to their colleagues who took an active part in the research and discussion of the results included in the monograph – V.D. Sarychev, S.A. Nevskii. Special thanks are due to the reviewers V.A. Danilov and V.V. Maruv'ev for valuable comments, which were taken into account when preparing the manuscript for publication.

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Analysis of modern methods of surface modification of light metals using external energy sources

1.1. Plasma spraying and electron beam surfacing of wear-resistant coatings

In engineering technologies, to provide the required level of wear resistance of machine parts, plasma spraying of wear-resistant coatings is widely used [28,29]. Among the advantages of the plasma spraying method, one can single out high productivity, good process control, as well as the ability to process parts of various configurations and dimensions.

In the study [30], high-quality Ti/TiBCN coatings were obtained on the surface of 7075 aluminium alloy by laser welding. The coating material was Ti powder (99.5% purity, crystallite size 100–150 μm) and TiBCN powder (98.5% purity, crystallite size 100–150 μm); in the entire series of experiments, the mass of Ti powder did not change, and only the TiBCN content varied (0 wt.%, 5 wt.%, 10 wt.% and 15 wt.%). After coating, the structure was analyzed using scanning electron and transmission microscopy. Microhardness was used as a parameter evaluating the strength characteristics of the resulting coatings. As a result of studies, it was found that the strength characteristics of coatings increase with increasing TiBCN content and reach maximum values at 15 wt.%. Microstructural analysis showed that the cross-sectional structure of the sample, after laser surfacing, is divided into a coating zone, a transition zone, a heat-affected zone and a substrate. Coatings mainly consist of equiaxed grains and white lattice-like crystals, and the transition zone mainly consists of elongated dendrite crystals and white small particles. Q. Wang and his science group [31] studied three different Fe-based powder materials, gray cast iron, high chromium steel, and self-fluxing powders with a high content of chromium and nickel. Coating was carried out by plasma spraying on an Al–Si system alloy substrate. The microstructure, hardness, phase composition, substrate adhesion, and wear resistance of the deposited coatings were studied. The sprayed coatings showed improved wear resistance compared to the original Al–Si alloy in terms of friction coefficient, mass and volume losses. The best integral characteristics were shown by chromium steel coatings. Various wear mechanisms have been identified: a mixture of adhesive and abrasive wear for gray cast iron coatings, oxidative dominant wear for chromium steel coatings, and a mixture of oxidative and fatigue wear for self-fluxing coatings.

Another example of such studies can be found in [32], in which the creation of a high-strength coating consisting of a mixture of aluminium powder with carbon nanotubes on the surface of an aluminium alloy is considered. It was found that, depending on the speed of laser processing, the mechanical characteristics of the final product change. The results showed that the microhardness of the coating was 43% higher than the microhardness of the substrate. The authors attribute such changes in the mechanical characteristics to the diffusion of alloying elements from the substrate into the melt pool, which was formed as a result of laser melting, and it is also worth noting the obvious contribution of carbon nanotubes to the microhardness of the modified layer.

In addition to aluminium, magnesium and alloys based on it are actively used in the modern aerospace and automotive industries, due to its high specific strength and stiffness. However, the low corrosion resistance of magnesium and magnesium alloys significantly limits their widespread use. Magnesium and its alloys can be protected by forming protective surface layers, which can be achieved by plasma spraying, capable of producing metal and / or ceramic coatings. In [33], NiAl10 and NiAl40 plasma coatings on a AZ91 magnesium alloy substrate were obtained using a hybrid plasma spraying system. The results show a significant effect of the preheating temperature of the AZ91 substrate during plasma sputtering on the development of diffusion bonding due to the formation of a sublayer consisting of the Mg3AlNi2, Al12Mg17 phases and Mg and Al solid solutions.

Potentiodynamic measurements showed a twelve-fold increase in the polarization resistance (930 W cm^2) of the NiAl10 coating compared to the initial alloy AZ91, the NiAl40 coating showed an almost twofold increase in polarization resistance (112 W cm^2). Long-term corrosion tests showed a significant positive effect of the sublayer formed from the eutectic structure of the Al12Mg17 phase with a solid solution of magnesium and aluminium on the corrosion resistance of NiAl40 plasma coatings.

In [34], the authors studied coatings formed on VT6 titanium alloy by plasma spraying of alumina powder, grade 25AF230 and subsequent microarc oxidation (MAO) at different current densities. The current density during MAO influenced the morphology of the coating and the average size of the structural elements of the coating. Open porosity in the form of open pores, as well as cracks, decreased from 50.3 ± 4.5% to 10.3 ± 1.5%. As a result of subsequent oxidation, the microhardness increased by 80–115 HV2 depending on the current density. Microarc oxidation also allows the formation of structural elements in the form of pores and crystals from 15–150 μm in size on the surface of the deposited alumina coatings.

Non-vacuum electron beam surfacing is an effective method for obtaining corrosion-resistant coatings of the Ti–Ta–Nb system formed on plates of technically pure titanium grade VT1-0 [35]. As a result, it was found by optical and scanning electron microscopy that the coating has a complex structure formed as a result of nonequilibrium cooling of the melt. A number of characteristic zones can be distinguished in the coating structure: 1. zone of deposited metal; 2. base metal zone; 3. transition zone. In the coating structure at different scale levels, traces of the dendritic structure, grain and subgrain boundaries, and hardened areas with a needle structure can be distinguished. The corrosion resistance of the obtained coating significantly exceeds the corrosion resistance of the VT1-0 alloy ≈ 6 times.

The authors of [36] proposed a technology for the formation of multilayer corrosion-resistant tantalum-containing coatings by the method of non-vacuum electron beam surfacing on the surface of workpieces made of technically pure VT1-0 titanium. The technology allows forming defect-free coatings up to 4.5 mm thick. Multilayer coatings have a complex gradient structure, both in the cross section of the deposited layer and in the cross section of the composition as a whole. The formation of tantalum-containing coatings on titanium leads to hardening of the material, which is confirmed by the results of durometric studies. An increase in the strength characteristics of surface-alloyed layers has a negative effect on the level of impact toughness of the material, which decreases by 35–45% compared with technically pure titanium. The level of corrosion resistance of two-, three-, and four-layer coatings in boiling 68% nitric acid is two orders of magnitude higher than the level of corrosion resistance of technically pure titanium in a similar medium and is only 6–7 times lower than that of pure tantalum.

The use of aluminium alloys in friction units is a promising task in mechanical engineering. Aluminium alloys have advantages over many structural materials: ease of processing, low density, acceptable strength characteristics. However, their low resistance to mechanical wear does not allow them to be applied without surface modification. In [37], the issues of increasing the wear resistance of the drive variator disks of a combine harvester made of AK9 aluminium alloy by applying a plasma coating were considered. For the experiment, samples were made of cast iron SCh18-36 and aluminium alloy AK9. A plasma coating of PN85Y15 powder 0.5...0.7 mm thick was applied to samples from AK9 aluminium alloy. To determine the comparative wear resistance of the samples, an accelerated test method was used, in which a flat sample is abraded with a reference disk with the abrasive fed into the friction zone. As a result of the tests, the PN85Yu15 plasma coating on AK9 aluminium alloy is 3.7 times superior in wear resistance to SCh18-36 cast iron.

A known method of chemical-thermal hardening of the surface of titanium alloys and products [38] includes heating the surface of the product in a nitrogen environment, the heating is carried out by a concentrated heat source with a power density of 10^3–10^4 W/ cm^2, current 80–150 A and the speed of the source relative to the product of 0.005–0.01 m/s The concentrated heat source was an electric arc or a plasma jet. The result: increased wear resistance and corrosion resistance of parts made of titanium alloys.

A method is described in [39] for the manufacture of a catalytic composite coating, which comprises producing a catalytically active layer by plasma spraying. Before applying the catalytically active layer, an adhesive layer is applied by spraying a powder composition containing, wt.%: aluminium 3–10, aluminium hydroxide the rest, and the subsequent catalytically active layer is applied by a powder composition containing, wt.%: aluminium 3–5, chromium 2–5, tungsten oxide 0.8–1.2, oxides of cerium, lanthanum, neodymium in the amount of 1.8–2.2, copper oxide 2–3, aluminium hydroxide, the rest. Then, using an ion-plasma method with two evaporators, an activator layer is applied containing, wt.%: copper oxide 27-34, chromium oxide 66–73. The powder composition is applied at a distance of 15–50 mm from the substrate. The thickness of the catalytically active layer is set in the range of 30–100 µm, the thickness of the third layer of activator is set in the range of 4–6 µm.

A method [40] of hardening a cutting tool, including the deposition of a multilayer coating of the Ti–Al system is available. The cutting tool is placed in the working chamber on the table, the activation of its surface before deposition of the multilayer intermetallic coating of the Ti–Al system is carried out by heating and cleaning the surface using a plasma source of a filament cathode and electric arc evaporators. A multilayer coating is applied while simultaneously spraying two single-component cathodes of Al and Ti and rotating the table around its axis with TiAlN and TiAl layer-by-layer, with argon used for sputtering titanium–aluminium and nitrogen for sputtering titanium aluminium nitride as a working gas. Gas change is carried out using a gas flow regulator, while layer-by-layer coatings are sprayed in a single cycle with alternating deposition of TiAlN and TiAl layers, which are repeated at least 10 times, while the table rotational speed is 10 rpm, the thickness of each layer is from 5...50 nm with a total coating thickness of up to 5 µm, in which TiAl3, Ti3Al intermetallic phases are formed, in the pure form of Ti and Al.

The method described in [41] is used for producing a coating based on complex nitrides, in which a substrate is placed in a vacuum chamber of a facility equipped with magnetron sprays, electric arc evaporators and a resistive heater, the surface of the substrate is cleaned in a glow discharge when the surface is contactless heated by a resistive heater to 100°C and ion cleaning by an electric arc evaporator in an inert gas medium when the surface is heated to a temperature of 300...350°C, then a lower layer of titanium and alternating layers of nitride are applied to the substrate in a mixture of inert gas and nitrogen.

In the method [42] for treating a TiC–Mo system with a multiphase plasma jet of a composite wear-resistant coating on a friction surface, a titanium carbide powder sample is placed between two layers of molybdenum foil, an electric explosion of the foil is carried out with the formation of a pulsed multiphase plasma jet, and its friction surface is melted with a specific energy flux of 3.5...4.5 GW/m^2 and sputtering on a fused layer of plasma jet components with subsequent self-hardening and the formation of composition coating containing titanium carbide and molybdenum.

A method has been developed [43] for depositing heat-resistant and wear-resistant coatings based on titanium aluminides on titanium and titanium alloys, including conducting electric arc welding with a non-consumable electrode in inert shielding gases using a filler wire. An aluminium wire is used as a filler wire, and surfacing is carried out in modes that provide a deposited layer with an aluminium content of 5–25%.

A known method [44] is the deposition of alloys based on titanium–copper intermetallic compounds on titanium and titanium alloys, including arc welding by a non-consumable electrode in inert shielding gases using a filler wire. The filler wire is made of copper or copper alloys, and surfacing is carried out in modes that provide a deposited layer with a copper content of 5–40%.

1.2. High-intensity electron and powerful ion beams, laser radiation

The literature has written in detail about the flaws of the surface properties of aluminium alloys, which seriously limit their further application in many fields [45]. The main problem is the low resistance to localized effects, in particular pitting corrosion, caused by the destruction of an oxide film exposed to the atmosphere, fresh or salt water, and other electrolytes. To overcome this drawback and increase the stability of the oxide film, surface alloying of aluminium with such transition metals as Mo, Cr, W, and Ta is performed [46, 47]. But since the solubility of these components in aluminium is less than 1 at.% various methods of exposure to concentrated energy flows are used, one of which is a pulsed electron beam. Irradiation by a pulsed electron beam gives rise to huge inhomogeneities in the distribution of temperature fields in the surface layers of the material and leads to ultrafast melting, mixing, and high-speed crystallization. In [48], surface alloying with molybdenum of an aluminium alloy by a high-current electron beam was investigated. As a result, it was found that, after irradiation, an Al5Mo phase with a acicular structure appeared in the doping layer. Numerous structural defects have been discovered, such as craters, various cracks, dislocation loops, and dislocation walls. Studies of various irradiation regimes showed that with an increase in the number of pulses, the density and size of the craters formed on the irradiated surface decreased significantly, and a large increase in corrosion resistance was also observed. The international scientific team investigated the influence of the electron beam scanning speed on the surface of the Al–3Ti–1Sc aluminium alloy [49]. Experimental studies were carried out in a vacuum chamber in five modes, differing in surface scanning speeds. Five passes were made at speeds of 3, 8, 12, 15 and 20 mm/s. The research results showed that the cooling rate, which is a function of the scanning speed of the electron beam, plays a key role in determining the microstructure of the Al–3Ti–1Sc alloy. At a slow scanning speed of 3 mm/s, an accelerating voltage of 50 kV and a beam current of 30 μA, the primary phases Al3(Ti, Sc, Fe) with a tetragonal lattice are still formed in the re-solidified melt, but they are much smaller in size (most of them are smaller than 2 μm) than the primary phases Al3(Ti, Sc) (~100 μm). When the scanning speed is increased to 20 mm/s, the primary Al3(Ti, Sc) phases are completely suppressed, and the newly solidified melt has a homogenized structure. It is also worth noting that the microhardness of the layer formed after scanning exceeds the microhardness of the initial alloy by 48%.

In recent years, numerous methods have been applied to modify the microstructure of aluminium alloys by laser surface hardening in order to increase their mechanical properties [50, 51]. This is an innovative hardening technology, which allows introducing high-amplitude compressive stresses and grinding the microstructure in the surface layers of the processed materials, which leads to an increase in mechanical properties [52]. In [53], the effect of laser processing on the microstructure and mechanical properties of the 2024-T351 aluminium alloy was studied; laser processing was performed at room and cryogenic (from –196°C to –130°C) temperatures. The research results showed that the surface microhardness, residual compressive stresses, and tensile strength of the laser-treated sample increased by 22.84%, 36.81%, and 11.88%, respectively. The authors also note that the use of laser processing in the cryogenic temperature region further increases the mechanical properties of the material, so the relative elongation, when tested for tensile testing, increased by 7.51% compared with the sample subjected to laser processing at room temperature. The authors explain these results of mechanical tests by the fact that the use of cryogenic temperatures during the process can effectively suppress slip and annihilation of dislocations, which leads to an increase in their density, thereby contributing to grain refinement and an increase in the mechanical characteristics of 2024-T351 aluminium alloy. As already mentioned, aluminium and its alloys are widely used in almost all areas of modern industry, including those where there are problems of cavitation wear of parts. Cavitation erosion is a phenomenon of destruction of the surface of a part, arising as a result of the rapid formation, growth and collapse of bubbles in liquids due to strong pressure fluctuations [54]. Shock waves repeatedly hit the surface of the part, which leads to the formation of pits, plastic deformation, strain hardening, the appearance and propagation of cracks, and ultimately the mass removal of the surface material. Z. Tong and the rest. [55] investigated the effect of laser shock hardening on the cavitation-erosion properties of AA5083 aluminium alloy. It was found that impact laser treatment leads to the formation of a fine-grained structure on the surface of the AA5083 alloy. The high density of the dislocation structure induced by laser impact treatment leads to an increase not only in strength but also in the ductility of the material. Along with the strength characteristics, cavitation-erosion resistance is also increased by 2.13 times compared with the untreated sample. The authors attribute these effects to thinning of grains and an increase in the density of dislocations during laser processing. A detailed analysis of the mechanical properties and microstructural evolution of a 2A14 aluminium alloy subjected to multiple laser impact hardening (LIH) was performed [56]. When analyzing the mechanical properties, tensile tests and the results of microhardness measurements were used, and the characteristics of the microstructure were studied out using scanning electron microscopy and transmission electron microscopy. Experimental results showed that the strength characteristics of 2A14 aluminium alloy improve with an increase in the number of impact laser processing cycles. After 3 cycles, the tensile strength and surface microhardness reached 525 MPa and 262 HV, respectively, which is 20.69% and 72.37% compared with the untreated sample. In addition, a high density of dislocation structures was found in the surface layer of the sample; this explains the serious increase in mechanical characteristics.

Laser heat treatment refers to modern methods of increasing the physicomechanical properties of the surface of machine parts. Compared with other sources of heating, the laser beam has a number of significant advantages, such as significant radiation power, exposure locality, a small heat-affected zone, the ability to process the surface of parts in hard-to-reach places and a high degree of automation of the processing process. New opportunities open up in the process of applying laser irradiation, when a combination of a high level of operational properties with the ductility of the product base is ensured. In this regard, the aim of research [57–59] is to study the physicomechanical properties of the surface layer of titanium samples after exposure to continuous laser radiation and to identify the optimal parameters of heat treatment, leading to a significant increase in microhardness and the formation of stable structures. Samples of technically pure titanium VT1-0 were processed, processed according to the scheme: pretreatment + annealing + continuous exposure to laser radiation. As a result, it was shown that the maximum value of Knupp microhardness occurs at the maximum speed of the laser beam V_{las} = 5 mm/s and is 900 NK compared to the initial value of 450 NK, which is explained by a significant cooling rate. However, such a regime leads to the formation of unstable, nonequilibrium structures, which was confirmed using x-ray phase structural analysis. Thus, from the point of view of increasing microhardness (Knupp microhardness increases to 850 units) and obtaining a calm structure, the regime with a laser beam velocity V_{las} = 4 mm/s is the result. Due to the increased strength characteristics, corrosion resistance, high biocompatibility, low thermal conductivity, titanium, zirconium and alloys based on them are widely used in chemical, machine-building, instrument-making, medical equipment and other industries both in Russia and abroad. However, the main disadvantage of titanium and zirconium are the low mechanical properties of the surface, for example, endurance under conditions of exposure to the product of periodic loads. In this regard, the aim of [60] was to study the process and comparative analysis of the effect of laser hardening of titanium alloy VT6 and zirconium grade E110 on the strength characteristics of their surface. It was found that pulsed laser radiation increases the microhardness of the treated surface of titanium samples to 14 ± 0.1 GPa and zirconium to 19 ± 0.1 GPa, as well as to the formation of a hardened surface layer with a thickness of up to 55 μm for titanium samples and a thickness of up to 30 μm for zirconium samples.

Currently, there is a growing interest in the use of aluminium alloys as a material for cylinder blocks and parts of the connecting rod and piston group of gasoline and diesel internal combustion engines. Compared to the traditionally used gray cast iron cylinder blocks, aluminium alloy blocks have a number of advantages: in addition to their low specific gravity, they have a high specific elastic modulus and good thermal conductivity, which provides significant unloading of thermally loaded zones. Due to the lower mass of the cylinder blocks and the parts of the connecting rod and piston group, the consumption of fuel and, accordingly, the emission of harmful substances are reduced. The authors of [61] studied the microstructure, microhardness, surface roughness, and chemical composition of cast aluminium alloy AK7ch after surface laser heat treatment using new absorbent coatings based on dextrin of compositions 1 (aqueous solution of dextrin + Na_2O $(SiO_2)n$) and 2 (aqueous dextrin solution + ZnO). Laser thermal treatment of the surface of the samples with deposited absorbent coatings with surface melting was carried out on a CO_2 laser with a radiation wavelength of λ = 10.6 µm with a radiation power of P = 5.0 kW and a diameter of a laser spot on the surface d = 7 mm and a fiber optic laser LS-10 continuous operation with a radiation wavelength λ = 1.070 µm with a radiation power of P = 5.0 kW and a laser spot diameter on the surface d = 6 mm. It has been established that the use of absorbing coatings based on dextrin leads to the formation of melted layers of considerable depth on the surface of the AK7ch aluminium alloy, when processing compositions 1 and 2 with a CO_2 laser, the depth of the fusion zone is 1.16 and 0.80 mm, respectively, and when processing using a fiber optic laser, respectively, 0.75 and 0.55 mm In this case, depending on the coating composition, the depth of the reflow zone during processing by radiation of a CO_2 laser is 1.45-1.55 times greater than when processing by radiation of a fiber-optic laser, i.e., coatings of both compositions are more effective when processing an aluminium alloy by the radiation of CO_2 laser. As a result of laser heat treatment, a substantial refinement of the structure and some hardening of the AK7ch alloy in the reflow zone occur. In this case, the size of α-Al dendritic cells decreases from 50–190 µm to 5.0–11.5 µm, the size of silicon crystals decreases from 5–30 µm to 0.5–2.0 µm, and the microhardness increases by 1.11 –1.22 times compared with the microhardness of the alloy in the initial cast state (90 HV0.025). The composition of the absorbing coating does not significantly affect the structure and microhardness of the AK7ch alloy after laser treatment. The study of the surface topography showed that when processing with a CO_2 laser, the surface roughness of the reflow zone is 3.60 (for coating composition 1) and 5.90 µm (for coating composition 2), respectively, and when processing with a fiber laser 1.03 and 3.90 µm. Moreover, depending on the coating composition, the surface roughness of the reflow zone during processing with a CO_2 laser is 1.5–3.5 times higher than when processing with a fiber optic laser, which is caused by more intense melt vibrations due to an increase in the penetration depth when processing with using a CO_2 laser.

The team of authors [62] used scanning electron microscopy, X-ray microanalysis, and optical metallography to study changes in the morphology, elemental composition, and microstructure of the surface layers of aluminium dodecaboride AlB12 subjected to high-power ion beam treatment. Under the influence of a superpower flow of particles, the surface layer of the irradiated material substantially changes its structural phase state and a new surface relief is formed. The topography of the surface of aluminium dodecaboride modified by a powerful pulsed beam of carbon ions is determined by the dose and density of the carbon ion flux power. The treated surface consists of two unequal areas irradiated by ion flows with different power densities. Most of the surface is irradiated with a more powerful stream and has a fused structure with numerous holes of various diameters, a smaller part consists of islands of tens of micrometers in size and contains precipitates of partially oxidized aluminium. It was established that the action of a powerful pulsed ion beam of an irradiated AlB12 surface leads to the formation of boron carbide.

V.S. Kovivchak et al. [63] analyzed the changes in the surface morphology of polycrystalline metals (magnesium, zinc and aluminium) upon repeated exposure to a powerful nanosecond ion beam with a current density of 50 to 150 A/cm^2. Thus, the effect of MIP on magnesium, zinc, and aluminium leads to the formation of regular structures, spheroidal ridges on ridges, and disk-shaped microparticles on their surface. The parameters of the observed morphological changes are determined by the ion beam current density, the number of irradiation pulses, and the type of material. The spatial parameters of the emerging relief are determined, which for the studied metals are in the range of 8–40 μm. The size of the particles formed during the formation of such a relief is from 0.1 to 1.5 μm. The appearance of regular structures is associated with excitation of capillary waves on the melt surface.

The method of laser hardening of the surface of parts [64], including heating the surface of the part with a laser beam using a scanner. The surface of the part is heated by a continuous laser while moving the beam along the normal to the vector of its movement with a beam oscillation frequency of 10 ÷ 200 Hz, oscillation amplitude $A = (2 \div 100)d$ and with a radiation energy density of 20 ÷ 26 W s /mm^2, where d is beam diameter on the surface of the part.

A known method [65] of laser hardening of the neck of the crankshaft is available. The method includes the relative movement of the surface of the workpiece and the laser source to ensure sequential projection of the laser spot on different parts of the processed surface area. The energy distribution of the effective laser spot is adapted in such a way that on a more heat-sensitive sub-section, such as a portion adjacent to the opening of the oil channel, it is different than on a less heat-sensitive sub-section to prevent overheating of the indicated more heat-sensitive sub-section.

There is a method [66] for obtaining a structured porous coating on titanium, which involves treating a titanium surface in an argon medium by moving a laser beam along it and simultaneously supplying titanium carbide powder to the irradiation zone, followed by acid etching by immersion in nitric acid for 3–5 days, washing and drying at a temperature of 50–100°C. In this invention, laser radiation with a power of not more than 300 W is used, the laser beam is moved on the surface at a speed of at least 20 mm/s, while using titanium carbide powder of a fraction of 80–100 μm

A method of producing [67] a multilayer modified surface of a titanium plate includes laser surface treatment of the plate sides, processing being carried out on both sides of the plate alternately with a 5 kW multi-channel diode laser. The reinforcing tracks in the form of a grid are applied by means of laser radiation paths along the same track, and inert gas is simultaneously supplied to the laser radiation affected area. The uniformity of the structure, hardness and depth of the hardened layer of the titanium plate is ensured.

A method [68] to obtain a coating of microstructured titanium carbide on the surface of titanium products is available. Titanium articles are placed in a reaction medium using a saturated hydrocarbon, and the surface of the article is treated with femtosecond laser radiation in the near infrared region of the spectrum with a pulsed power density of 10^{17} W/m^2 and 10% overlap of the laser exposure areas.

A method [69] of surface hardening of metals by changing the level of heat exposure on the treated surface, including local hardening by a scanning laser beam is available. The essence of the method is that the laser beam is polarized into a strip with a variable radiation intensity and scanned along this strip. The degree of polarization is set according to the accepted conditions of heat exposure, taking into account the fixed scanning speed, and the isothermal holding stages of the treated area at various temperature levels are successively implemented, and the temperature is changed at optimal speeds for the hardened metal. A method has been developed [70] for laser heat treatment of complex spatial surfaces of large-sized parts, including the action of a continuous laser beam focused in a light spot on the surface of the part and the application of parallel hardening tracks with overlapping by moving the light spot with a constant linear speed. The application of parallel hardening tracks on vertical or inclined surfaces is carried out by a beam directed to the workpiece at an angle of 0.5–5° from the perpendicular to the specified surface upward in the workpiece plane and when the process gas is supplied under pressure with a nozzle providing crystallization of the molten metal and balancing the gravity of a drop of melt. The application of parallel hardening tracks is carried out alternately in different hardening strips, spaced from each other at a distance sufficient for the tracks to cool at the set processing speeds. The application of parallel hardening tracks is carried out by a laser unit equipped with a coordinate laser head.

1.3. High-dose ion implantation

Ion implantation is a low-temperature process by which the components of one element are accelerated into the solid surface of the plate, thereby changing its physical, chemical or electrical properties. This method is used in the manufacture of semiconductor devices and in the decoration of metals, as well as in materials science studies. Ion beam technologies use monoenergetic and polyenergetic ion beams of various chemical elements. Ion energy, flux (beam current), fluence (integral flux) are the main parameters of the ion beam, which are determined by the goals and objectives of the processing. Usually, beams with ion energies of up to 100 keV and fluences of up to 10^{18} cm^{-2} are used to modify materials, and for surface alloying by ion mixing, with fluences of up to 10^{17} cm^{-2}.

Studies are ongoing on the effect of ion implantation by nitrogen ions on the corrosive behavior of AA7075 aluminium alloy. Implantation of nitrogen, at 2×10^{17}N · cm^{-2} and an energy of 50 keV, promotes the formation of an AlN layer that increases the corrosion resistance of the aluminium alloy, as evidenced by corrosion tests. Further studies showed that over time, the value of corrosion resistance is restored to its original value. Implanted and non-implanted alloys show similar electrochemical parameters after 20 h immersion in an electrolyte solution. However, microscopic examination shows less corrosion damage to implanted samples after 72 h of immersion. Thus, it can be argued that the long-term effect of corrosion resistance depends only on the heat treatment conditions of AA7075 alloys [71]. A scientific team led by O. Girk [72] is studying the physical and mechanical characteristics of aluminium alloy 2024 and titanium alloy Ti–6Al–4V after irradiation with fluxes of helium ions (He) and argon (Ar). Structural analysis by scanning electron microscopy showed that a cone-shaped structure forms on the surface of the materials under study, everywhere, except for the case of Ti–6Al–4V irradiation with He ions. The main factors contributing to the formation of such structures are relaxation of surface stresses and activated surface mobility of atoms. Elemental analysis shows that after irradiation with an ion beam does not change the chemical composition of the target. The study using a confocal microscope showed that the average roughness of the irradiated surface after irradiation with an Ar ion beam is higher than that of an He ion beam and higher on samples of alloy 2024 compared to Ti–6Al–4V alloy. The authors explain this result by the fact that the growth of surface structures is more related to the surface diffusion of atoms and not to their place in the atomic lattice as a result of collisions with a target [73].

The formation of chemical and phase composition, atomic structure, surface topography, mechanical and operational properties of surface layers of metal materials by ion implantation is one of the areas of modern science and technology [74]. Ion implantation allows you to increase the operational characteristics of the protected parts through surface alloying by an amount from several to tens of micrometers. Despite studies in this direction, the processes of formation of these layers, the structural mechanisms of their implementation, and the nature of the change in various properties of metals and alloys as a result of ion irradiation are still not clarified.

A widely used material in the aviation and rocket and space industry is titanium and alloys based on it, due to its unique physical and mechanical properties. The scientific group led by D.A. Alexandrov studied the hardening VT6 titanium alloy by ion implantation with nitrogen and ion saturation of the surface in the plasma of an aluminium alloy. The results of mechanical tests showed that the microhardness of the surface layers of the VT6 alloy increased by 1.5 times, compared with the starting material, and an increase in resistance to abrasive wear by more than 4 times was also observed. Structural analysis of the processed samples suggests that