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Effects of laser cladding and treatment methods on wear resistance in heavy-loaded units

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Abstract

The primary focus of this research is on enhancing wear resistance in heavily loaded friction units, which is critical to extending the service life of machine parts and mechanisms, such as drill bit supports, bearing pads of turbine shafts, and gas turbine blades. These components operate under severe conditions, including high contact pressures, high speeds, and aggressive environments, making lubrication delivery and maintenance challenging. The study explores advancements in wear resistance through the use of nanomaterials such as carbon nanotubes and graphene, additive manufacturing, and various surface treatment techniques such as the creation of oil-retaining microreliefs and the application of solid lubricants and antifriction coatings. These technological innovations have substantially improved the functionality of the components in dry friction units, despite the traditionally shorter service life compared to lubricated systems. The paper details experimental studies on the laser treatment of carbon and alloyed steels, examining structural-phase transformations and the efficiency of laser cladding in enhancing surface properties. Methods for applying solid lubrication to reduce wear and optimize performance in heavily loaded units are discussed, with a focus on laser gas powder cladding. The research demonstrates the potential of laser surface treatment to significantly increase the wear resistance and operational life of machine components, contributing to environmental and economic sustainability in industrial mechanical engineering. Field tests confirm the effectiveness, laser-hardened parts showing significantly improved wear resistance, and reduced production costs, underlining the importance of ongoing research in this area for ensuring the durability and reliability of machinery operating under extreme conditions.

Keywords: Laser processing; Wear resistance; Laser cladding; Heavily loaded friction units

1. Introduction

Wear resistance is the most crucial characteristic of materials, which is largely determining the service life of machine parts and mechanisms. This issue is particularly acute for components operating in heavily loaded friction units, where high contact specific pressures, ultra-high speeds of relative motion, flows of working fluids, the presence of aggressive environments, and the action of cyclically changing temperatures occur [1, 2]. Such conditions are typical for the supports of drill bits, bearing pads of turbine shafts in engine turbocharging systems, blades of gas turbines, etc. A distinctive feature of their operation is the difficulty or even impossibility of lubricating and maintaining the contact zone of the friction units [3].

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Current research and development in the field of improving wear resistance include the development and application of nanomaterials, such as carbon nanotubes and graphene, which possess outstanding antifriction and protective properties. Additive manufacturing, or 3D printing, opens up new possibilities in producing parts with complex shapes and internal structures that cannot be created by traditional methods, thereby significantly increasing their wear resistance [4].

The technological measures developed to date also include creating an oil-retaining regular micro-relief on the contacting surfaces, the use of solid lubricating materials, including those delivered by the rotaprint method, and the application of anti-friction coatings by galvanic, plasma, detonation, and other methods combined with various surface hardening methods (plastic deformation, high-frequency quenching, chemical-thermal treatment (nitriding, chromizing, aluminizing, etc.), have solved many complex technical tasks related to ensuring the operability of various mechanisms [5].

However, despite the achievements, the comparison of the working conditions of heavily loaded dry friction units with the conditions of machines using traditional types of lubrication shows that they are tens and hundreds of times inferior in terms of service life. The main reasons for the low service life of dry friction units are the small volumes of lubricating material and the absence of its circulation in the mechanism.

Laser radiation, due to its high energy saturation and the ability to precisely dose energy into the processed material, allows for local high-speed heating to create areas on the surface with specific structures possessing high dispersity, containing metastable phases, and supersaturated solid solutions. Such structures have a high hardness, 1.5-2 times higher than the hardness achieved by traditional thermal treatment methods [6]. Alongside hard strengthening phases (martensite, carbides, borides, etc.), ductile γ-phases may also be fixed, sometimes in large quantities, up to 30% and more. This is facilitated by the repeatedly observed redistribution in the solid phase of several alloying elements: some, for example, carbon, towards the surface and others, for example, heavy metals, the opposite. It should be noted that this redistribution has an anomalous character and does not fit into the classic representations of the theory of diffusion processes [7]. All mentioned features of structures obtained by laser treatment ensure their high resistance to wear. The wear process is characterized by smoothness, absence of brittle destruction (slipping, cracking), forming a characteristic texture on the friction surfaces, orientated in the direction of sliding [8].

Additional reserves of laser processing, in terms of increasing the wear resistance of friction units, include the targeted change in the chemical composition of local areas of surface layers of parts through laser microalloying or cladding, as well as controlling the sizes and placement of these areas on the contacting surfaces. These innovative approaches allow for not only increasing wear resistance, but also optimizing other working characteristics of parts.

This work is dedicated to further study of the potential of laser surface treatment technology to enhance the wear resistance of parts in heavily loaded friction units, which continues to be a relevant issue in industrial mechanical engineering production.

The environmental and economic benefits of increasing the wear resistance of components are becoming increasingly apparent. Reducing waste, decreasing the need for frequent replacement of parts, and saving resources contribute to the sustainable development of the industry. In this context, ongoing research and development of new materials and technologies play a key role in ensuring the longevity and reliability of machine units under extreme loads.

2. Research Methods

Experimental studies were conducted to examine the characteristics of structural phase transformations occurring in carbon and alloyed steels during laser treatment, as well as to establish the patterns of the laser cladding process. Samples made from steel C45 and 14NiCrMo13-4 with different initial structures measuring 40x40x5 mm were processed by CO_2 laser radiation on a technological complex equipped with beam parameter control devices, a system for metering and delivering cladding powder, and a four-axis CNC table. To increase the absorptive capacity, samples were preliminarily subjected to chemical oxidation.

On some of the samples, coatings made from a Nickel based surfacing powders, a stainless steel-based alloy X12CrNiTi18-9, and bronze CuSn10Pb10-C were applied using the method of laser injection gas-powder cladding. Chemical compositions of the materials used presented in Tables 1 and 2. The cladding powder was fed into the beam trail at a 45° angle using the carrier gas. The experimental settings are detailed in Table 3.

Table 1 Chemical composition of materials

Material	**C**	**Si**	**Mn**	**Ni**	**P**	**S**	**Cr**	**Mo**
Steel C45	0.43–0.5	Max 0.4	0.5–0.8	Max 0.004	Max 0.0045	Max 0.045	Max 0.4	Max 0.1
14NiCrMo13-4	0.11–0.17	Max 0.4	0.3-0.6	3–3.5	Max 0.0025	Max 0.0035	0.8–1.1	0.2–0.3
X12CrNiTi18-9	Up to 0.12	Up to 0.8	Up to 2	11–13	Up to 0.0035	Up to 0.02	17–19	Up to 0.3
CuSn10Pb10	–	Max 0.01	Max 0.2	Max 2	Max 0.1	Max 0.1	-	-

Table 2 Chemical composition of bronze alloy

	Fe	**Si**	**Mn**	**Ni**	**P**	**S**
CuSn10Pb10	Max 0.25	Max 0.01	Max 0.2	Max 2	Max 0.1	Max 0.1
	Al	Cu	Pb	Zn	Sb	Sn
	Max 0.01	78-82	8-11	Max 2	Max 0.5	9-11

Table 3 Laser experimental settings

Power, kW	1.2
Speed *V*, m/min	0.5–2
Laser spot diameter *d*, mm	2 – 5
Powder consumption, g/s	0.1- 0.5

After laser processing, the samples, like the actual parts, were subjected to metallographic and durometric studies, during which the structure, microhardness, and dimensional characteristics of the laser heating zones and clad layers were examined. The samples were ground and polished. The equipment for macroscopic and microscopic examination was chosen according to ISO/TR 16060:2003 [9]. Macroscopic and microscopic examination of the laser-treated samples followed the ISO 17639:2003 standards [10]. Metallographic examination of the steel and laser treated layer, as well as analysis of the geometry and dimensions of the laser treated layer, were performed using an optical microscope equipped with a video camera, at various magnifications (up to × 1000). The hardness was assessed using the Vickers method with a squared tetrahedral pyramid, under a load of 9.807 N, according to EN ISO 6507-1 [11].

After analyzing the results, actual parts (journal bearings of roller-cone drill bits and turbine thrust bearings) were processed under selected regimes and subjected to real-world tests.

Current directions in the field of laser processing include the use of lasers with variable wavelengths, which allows for finer tuning of heating and cooling processes, adapting them to specific tasks of processing different types of steel. This opens up new opportunities to improve the quality of the clad layers and reduce the internal stresses that arise during cooling [12].

3. Analysis of laser treated surface

To manufacture components of heavily loaded friction assemblies operating in aggressive environments, low-carbon case-hardenable alloy steels, such as type 14NiCrMo13-4, are used. Initially, after normalization, the structure of this steel comprises irregularly shaped ferrite grains of various orientations and unevenly distributed carbides. Small areas of pearlite are located between the grains (Fig.1a). Laser treatment of the steel in the delivery condition after normalization, carburization, and high-frequency induction hardening results in the formation of reinforced layers in the surface layer, significantly differing in structural-phase composition and microhardness distribution (Fig.2). Laser treatment of steel after normalization leads to the formation of two distinctive zones of phase transformations. On the surface there lies a quenching zone made of solid solution. Traces of its crystalline structure are only detected after multiple polishing and etching processes. The microstructure is austenitic-carbide in nature. Carbides form a fine-meshed network, elongated in the direction of heat dissipation. In the lower part of this zone lies a layer whose structure consists of needle-like martensite and residual austenite. The austenite appears as triangles located between martensite plates. The second zone also has a martensite structure with austenite. However, the martensite needles become smaller. At the boundary with the base metal, the needle-like nature of the martensite is almost invisible, and troostitic formations are present, following the pattern of the original austenitic grains. The microhardness varies unevenly in depth, ranging from 4.6 to 6 GPa.

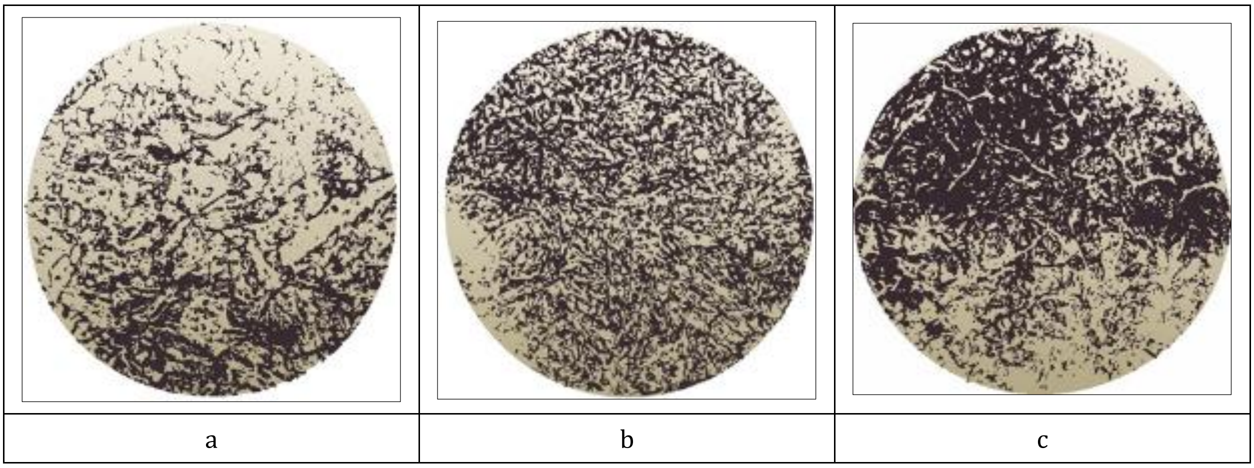

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Figure 1 14NiCrMo13-4 microstructure: (a) before laser treatment; (b) transferring zone; (c) treated zone

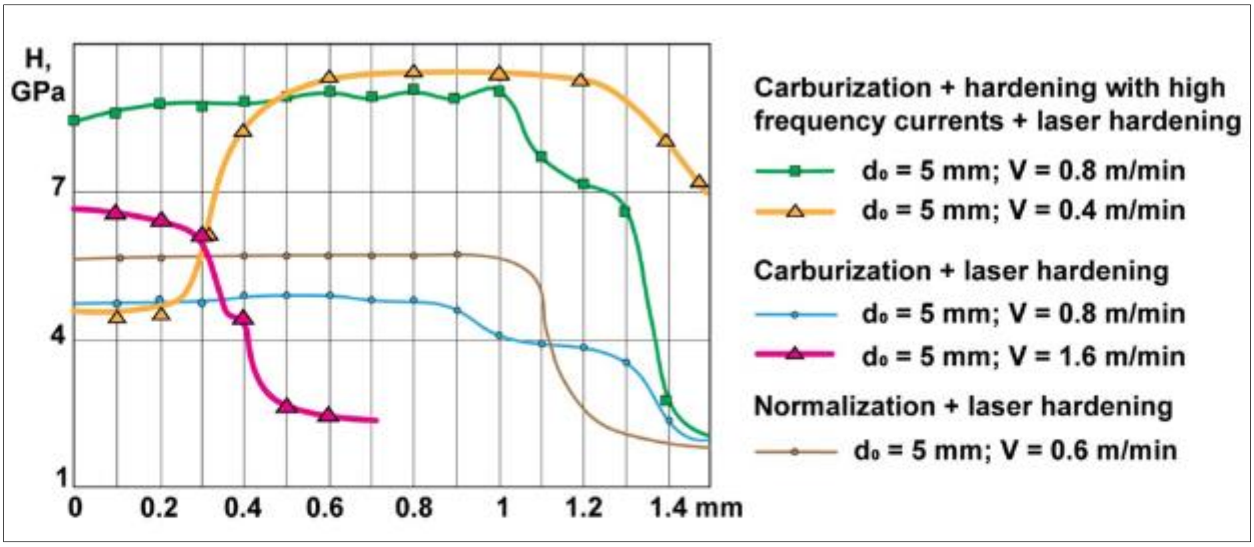

Figure 2 Distribution of microhardness along the depth of the laser heating zone in 14NiCrMo13-4 steel

Laser processing of steel after carburization under conditions (P=1200W, d_0=5mm, V=0.2 - 0.6m/min), which cause surface micro-melting, leads to the formation of an amorphous martensitic structure at the surface with a small amount of spheroidized carbide particles. Below lies a layer of coarse-needled martensite with a fine-meshed network of cementite-type carbides, oriented in the direction of heat dissipation. The microhardness of the structure ranges from 4.2-4.5 GPa. At processing speeds of 0.8-1.6 m/min, structural-phase transformations occur in the solid phase. The dispersion of the structure increases, enhancing its microhardness to 5.1-6.5 GPa. In carburized and quenched steel after laser processing, a martensitic-austenitic structure with free carbides in the form of globules is formed. Below the "white layer" lies a hypereutectoid quenched zone. Its microstructure consists of martensite and cementite-type carbides in a network form (Fig.1b). The nature of the structure and its microhardness, particularly its depth distribution, strongly depend on the laser heating time. There is a rather narrow range of processing speeds (0.8-1.2m/min) at which the structure of the hardened layer has a uniform depth and sufficiently high microhardness (7.5-

9 GPa). In other cases, as with low speeds (0.2-0.6 m/min) and high speeds (1.4-1.8 m/min), the characteristic is a comparatively low surface hardness of 4.5-5.5 GPa up to a depth of 0.2-0.3 mm, and greater - 9-10.5 GPa in depth.

Analysis of the results showed that laser processing under optimal conditions of steel 14NiCrMo13-4, previously subjected to carburization and high-frequency induction hardening, allows for the formation of a reinforced layer up to 1.3 mm deep on the surface, capable by its structure and hardness of providing the necessary load-bearing capacity to components of heavily loaded friction assemblies.

4. Method for organizing solid lubrication of heavily loaded friction units

To ensure high wear resistance, in addition to good load-bearing capacity, friction surfaces must possess high anti-friction properties. For the friction units under consideration, such properties can be significantly enhanced by the use of solid lubrication. To organize this, it is proposed to create uniformly distributed depressions on one of the friction surfaces, having various shapes in plan view but necessarily having a closed contour. In these depressions, solid antifriction material is placed. During the operation of such a unit, under the action of the loading force, the walls of the depressions elastically deform, leading to a reduction in their volume. The anti-friction material filling these closed depressions is extruded into the contact area, fills the micro gaps, and thereby provides forced lubrication.

Depending on the operating conditions of the friction unit, it is suggested to use under laser gas-powder cladding process (Fig. 3) - bronze CuSn10Pb10-C (for high sliding speeds at low loads) or a composite, consisting of an CuSn10Pb10-C bronze matrix (80%) with particles X12CrNiTi18-9 (20%) embedded (for large loading forces, comparatively low sliding speeds).

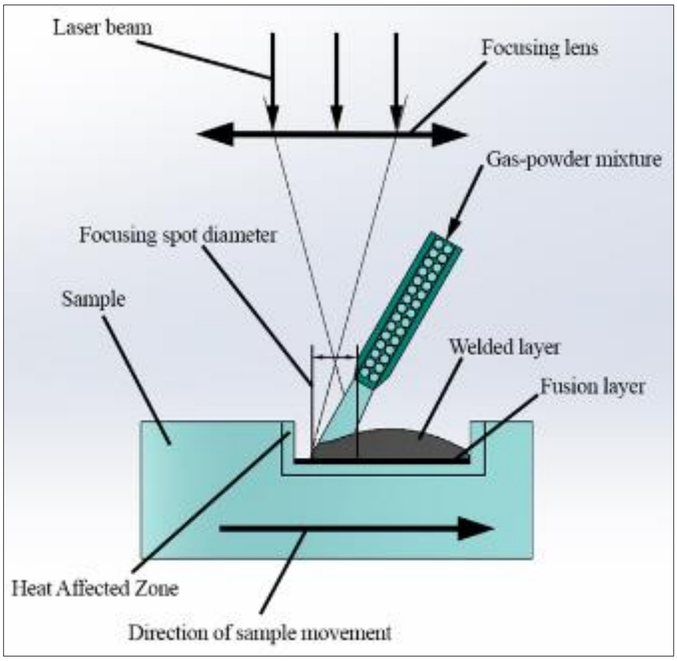

Figure 3 Laser gas-powder cladding scheme

For placing these anti-friction materials in the depressions, laser gas powder cladding is considered suitable. In this method, powdered cladding material is fed into the molten surface layer of the depression part, which moves according to a specific law, in the beam's trail by a stream of transporting gas. Subsequent grinding of the allowance ensures the necessary dimensions and surface quality.

The advantages of the proposed method of applying anti-friction materials include: high selectivity and productivity of the process, the ability to organize various compositions by using a complex of different powder materials, and high adhesion strength of the clad layer with the base material due to the presence of a metallurgical bond between them.

The use of laser radiation for cladding also addresses another important issue – hardening the surface layers of the groove's walls and bottom as a result of the autotempering of the steel base. As a result, the plastic anti-friction material will be between the parts during operation, whose contacting surfaces have high hardness.

The process of laser gas powder cladding was studied to establish the patterns of changes in the dimensions and properties of the clad layers depending on the processing parameters. Figure 4 shows the dependencies reflecting the effect of processing speed V, powder expenditure G, and focal spot diameter d_0 on the thickness of the clad layer. The presented data were obtained during the cladding of bronze CuSn10Pb10-C. The bronze in the form of a powder with a dispersion of 60-80 µm was supplied at a 45° angle in the trail of focused CO_2 laser radiation. The focal spot diameter was 3.5 mm, and the radiation power was 1.2 kW. The depth of the bronze fusion zone with the steel substrate was 30-80 µm. As a substrate, carbon steel (0.45%C) was used. Figure 5 shows the distribution of microhardness through the depth of the clad layer. As can be inferred from this dependency, directly on the surface lies a bronze layer with a thickness of 0.4 mm, below – a layer of bronze alloy with the base steel, which is indicated by the gradually increasing hardness.

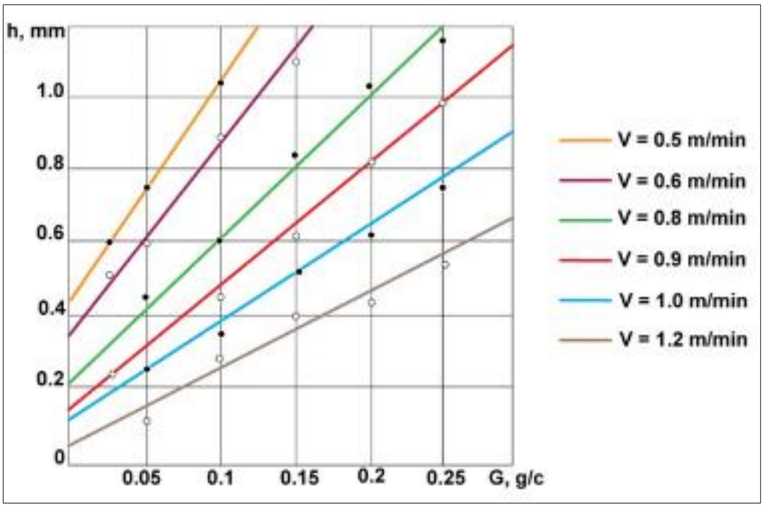

Figure 4 Dependence of layer thickness (h) obtained by laser cladding on speed (V) and powder consumption (G)

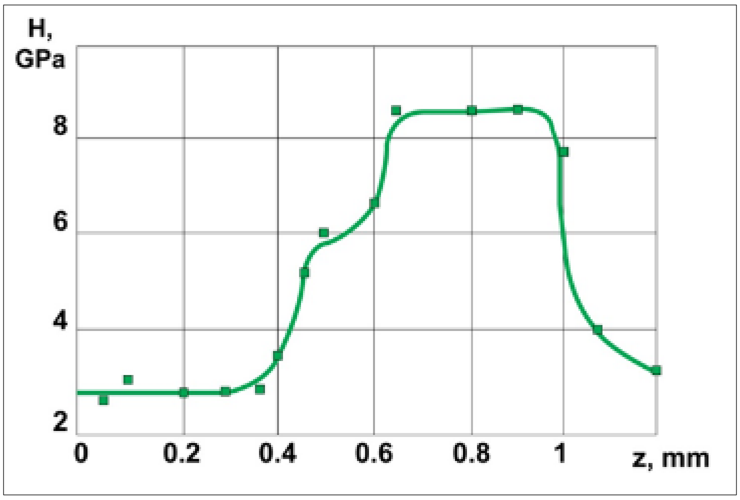

Figure 5 Distribution of microhardness (H) along the depth of the deposited layer of CuSn10Pb10 bronze on Steel C45

Below this is a small transition layer, a quenching zone of the steel in solid condition with a microhardness of 8-8.5 GPa and the original steel structure. Figure 6 presents microphotographs that illustrate the microstructures of the mentioned layers.

In the process of laser gas powder cladding, a layer of bronze fills the special closed-contour depression on the steel surface. In the microphotograph taken directly from the ground surface, (Fig.6a) non-melted particles of bronze powder can be seen, embedded in the crystallized melt, which in the lower layers has a sufficiently uniform structure (Fig.6b). The bronze layer is firmly connected to the substrate, because of the presence of its fusion layer with steel. The structure of the transition layer is shown in Fig.6c. Below the base melt zone there lies a thermal influence zone, part of which was heated above the AC3 point. This facilitated the process of austenitization and subsequent formation, as a result of autotempering, of a highly dispersed martensitic structure with high microhardness.

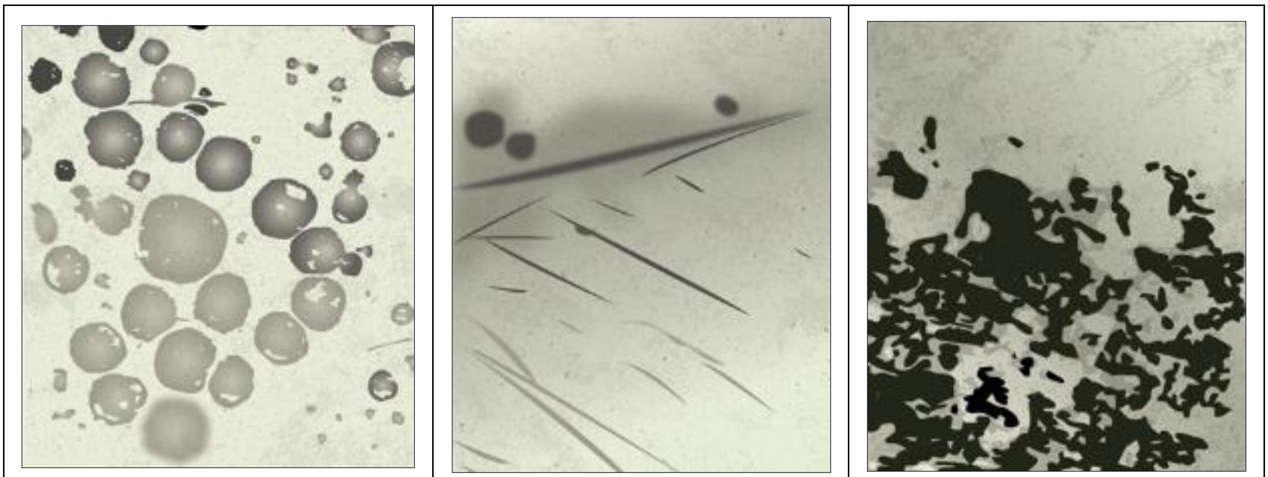

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Figure 6 Microstructures of various zones of the deposited bronze layer on steel: (a) on the surface, (b) below the surface, (c) transition layer

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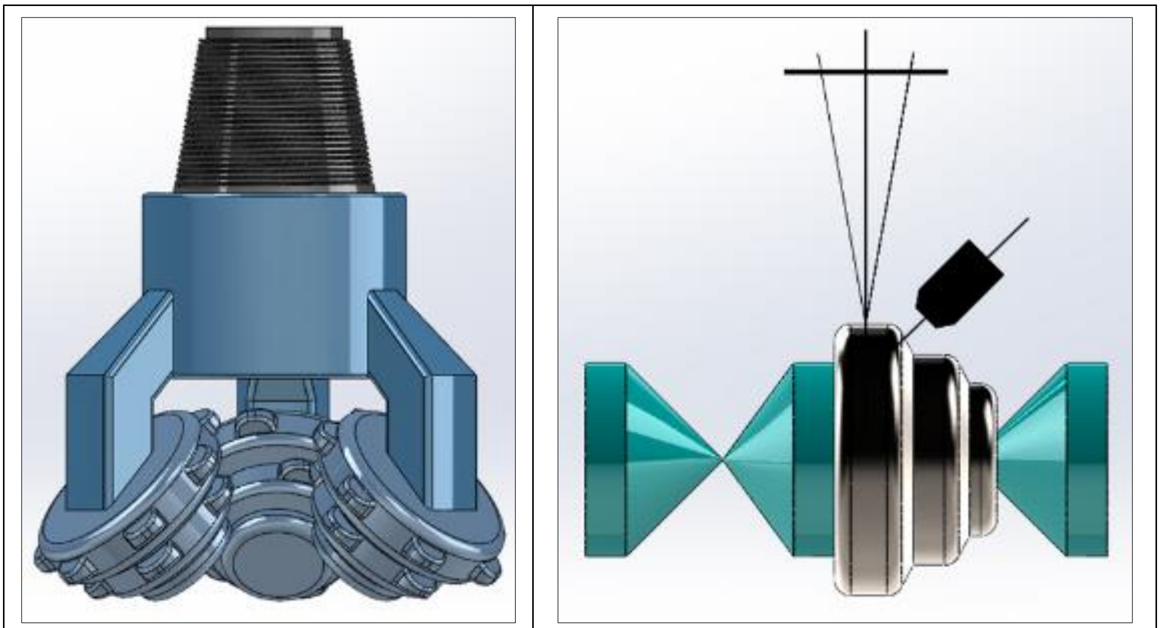
5. Application of the obtained research results in industry



a b

Figure 7 Heavy duty bit (a) and diagram of laser gas-powder cladding of bronze (b)

In well drilling for geological exploration, special bits widely used as tools that break the rock and form its borehole (Fig. 7). It consists of a body comprising three brackets welded together. In the trunnions of these brackets, forming a sliding bearing, three rock-destructive discs are positioned. The brackets and discs are made from 14NiCrMo13-4. To enhance wear resistance, this steel is carburized and subjected to quenching with high-frequency currents. The discs are equipped with special inserts made of hard alloy. The drill bit is a principal element of technological equipment that limits the productivity and cost of drilling. This is due to its low durability, caused by the extreme working conditions of the sliding friction node (high specific pressures, the action of aggressive abrasive-bearing fluid supplied under high pressure, absence of lubrication).

The trunnions of the brackets, previously cemented and hardened by high-frequency induction, were subjected to laser hardening under optimal conditions. On the trunnions of certain brackets, special recesses were made, which were filled with bronze using the laser gas powder cladding method (Fig. 7b).

After the cladding, the trunnions of the brackets were ground to achieve the required dimensions and surface roughness. Discs with inserts were installed on the trunnions of the hardened and clad brackets. Brackets with discs were assembled in sets of three, welded together to form the drill bit. Standard drill bits and those produced using new technologies, including the process of spark alloying and laser hardening, underwent field testing. Table 4 presents the test results. As can be seen from these results, the application of laser hardening is the most effective. It allows increasing the wear resistance of drill bits and extending the service life of a single bit by 30-60%. It is expected that expanding the test base, the number of alternative technologies, including the application of laser cladding, will improve the obtained result, reducing labor intensity and cost of drilling.

The application of bronze anti-friction coatings was tested on thrust pads of the turbocharger system of a heavy-duty diesel engine.

On the end surfaces of the thrust pad, made of carbon steel C45, concentric annular grooves were made, which were filled with bronze CuSn10Pb10-C using the laser gas powder cladding method.

After cladding, the end surfaces of the thrust pads were machined to size, and special oil-retaining grooves were made.

Bench tests of thrust pads, manufactured using the new technology with the application of laser cladding, revealed a two-fold increase in wear resistance while simultaneously reducing the cost of the product.

Table 4 Test results of heavy duty bits hardened by various methods

Characteristics of earth rock	**Heavy duty bits type**	**Tested heavy duty bits, pcs**	**Drilled, m**	**Penetration per heavy duty bit, m**	**% to comparison base**
Granite	Mass production	11	132.5	12.0	100
	Electric spark strengthening	10	133.4	13.3	110.8
	Laser treatment	10	146.5	14.7	122.5
Albite	Mass production	10	84.9	8.5	100
	Electric spark strengthening	10	110.3	11.0	129.4
	Laser treatment	10	134.9	13.5	158.7

6. Conclusion

The overarching conclusion from this comprehensive research highlights the critical importance of wear resistance in materials, particularly for parts operating under extreme conditions such as heavy loads, high speeds, and corrosive environments. These conditions are predominant in parts such as drill bit supports, turbine shaft bearing pads, and gas turbine blades, where conventional lubrication methods fail due to harsh operational circumstances.

A significant focus of the study is the application of laser technology in surface treatment, specifically through laser cladding and hardening processes. These techniques have demonstrated a profound impact on the wear resistance of materials by altering their microstructure, leading to increased hardness and the formation of beneficial phases without compromising the material's ductility. The research presents detailed experimental findings on the effects of laser treatment on various steel types, showcasing improvements in structural-phase characteristics and enhanced wear resistance.

The introduction of solid lubrication methods, particularly through laser gas powder cladding, represents a novel approach to improving antifriction properties. This method not only enhances wear resistance but also contributes to the optimization of load-bearing capabilities of heavily loaded friction units.

Industry applications, particularly in drilling and turbocharger systems, have validated the effectiveness of these advanced technologies. Field tests demonstrate that laser-treated components exhibit significantly better performance, leading to reduced downtime, maintenance costs, and overall improvements in operational efficiency.

Laser hardening of low-carbon alloyed steels such as 14NiCrMo13-4 is advisable to be carried out after carburization and high-frequency induction quenching. This results in a hardened layer depth of 1-1.3 mm and a microhardness of 7.5-9 GPa.

Laser hardening of components in heavily loaded friction units, such as trunnions of drill bits, ensures an increase in the tool's operational life by 30-60%.

Laser cladding of antifriction materials such as bronze onto steel components aids in the formation of a layer of quenched steel with high microhardness of 8-8.5 GPa under the plastic coating.

The proposed method of forced solid lubrication, involving the creation of special depressions with a closed contour on the contacting surface and filling them with anti-friction material such as bronze using laser cladding, is an effective means of increasing the operational life of heavily loaded friction units.

The study not only reaffirms the critical role of wear resistance in the longevity and reliability of mechanical components, but also showcases the potential of laser processing and surface engineering as pivotal technologies for the future of industrial mechanical engineering. These advances not only promise to extend the service life of components under extreme conditions but also align with sustainability goals by reducing waste and resource consumption. The ongoing research and development in these areas are essential for meeting the demanding requirements of modern mechanical systems and ensuring their sustainable operation in the face of challenging industrial environments.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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