ORIGINAL STUDY

CURRENT PROBLEMS OF EQUIPMENT WEAR IN THE MINING, OIL AND GAS, AND AGRICULTURAL INDUSTRIES

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Abstract. *The article provides an overview of current issues related to equipment wear in the mining, oil and gas, and agricultural industries, and analyses the latest technologies for strengthening and restoring the surfaces of working parts. It examines the main types of mechanical and corrosion wear, typical components subject to premature failure, and the economic consequences of failures. Particular attention is paid to advanced surface treatment methods: laser and plasma hardening, gas-thermal and electric arc spraying, as well as new coatings based on nanomaterials and high-entropy alloys. A comparison of technologies is made based on key parameters (adhesion strength, particle temperature, productivity). The need to introduce multifunctional protective coatings with anti-friction and corrosion-resistant properties to increase the reliability and service life of equipment in aggressive operating conditions is emphasised.*

Keywords: Equipment wear and tear. mining industry, oil and gas industry, agricultural industry, strengthening and restoration technologies, modern coatings.

1. Introduction

The continuous improvement of the performance characteristics of modern machinery and equipment, associated with increased power and productivity, can only be achieved through the corresponding improvement of the operational characteristics of their main components and parts. This problem is most relevant for industries such as mechanical engineering, mining and metallurgy, agriculture, and oil, where equipment operates under difficult conditions of high temperatures and loads, as well as corrosive environments. Therefore, the improvement of surface hardening technologies is an important and relevant task for surface engineering, a new direction in materials science.

The widespread use of coatings for strengthening and restoring industrial parts is often limited by a lack of information about the possibilities and methods of applying coatings, their advantages and disadvantages, the requirements for equipment, and the selection of parts for coating. The feasibility of applying coating technology depends on the degree of complexity of its implementation and the economic efficiency of applying coatings in each industrial field.

Wear and tear of mining and metallurgical equipment parts. Wear and tear of mining and metallurgical complex equipment is a pressing issue that requires careful consideration using scientific and technical approaches based on the application of new technologies and materials for equipment repair, restoration and strengthening of parts at minimal cost. To comprehensively address these issues, it is necessary to analyse the methods currently used to restore parts in production conditions and the possibility of improving the technological and operational properties of equipment using promising materials and technologies. Today, the level of wear and tear of fixed assets in the country's mining industry is 63.8% [1].

The paper [2] presents calculations of global energy consumption due to friction and wear in the mining industry. A wide range of mining equipment used for extraction, transportation and enrichment in underground, open-pit mining and mineral processing was analysed. Total energy consumption in global mining activities, including the extraction of minerals and rocks, is estimated at 6.2% of total global energy consumption. About 40% of the energy consumed in mineral extraction (equivalent to 4.6 EJ annually on a global scale) is used to overcome friction. In addition, 2 EJ is used to repair and replace worn parts, as well as to stockpile and replenish spare parts and equipment needed in case of breakdowns due to wear and tear. The most energy-intensive mining operations are crushing (32%), transportation (24%), ventilation (9%) and digging (8%).

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One of the main problems associated with the short service life of mining and metallurgical equipment parts is intensive wear due to operation in aggressive environments, abrasive and hydroabrasive wear. According to research, more than 50% of the total volume of worn parts in the mining and metallurgical industry are rotating parts (shafts, bushings, bearing rings), and for various technological equipment, their wear is in the range of 0.1-1.5 mm [3]. Fracture, corrosion, wear and deformation are typical types of shaft failure. Among them, the predominant mechanism is fatigue failure, caused primarily by the effects of cyclic loads experienced by shafts during regular operation [4].

Rock crushing is the first mechanical grinding process after drilling and blasting in rock crushing. Equipment used in rock crushing processes, such as armour plates, armour cones, linings, beaters, hammers and hammer blades, is at high risk of premature wear. Premature wear of hammers causes the crushing process to stop after just one week of operation [5].

Drilling operations in quarries are the most labour-intensive process in mineral extraction technology. The most widespread method in open-pit mining (up to 82.5%) is roller cone drilling, with auger drilling accounting for about 17.5%, percussion-rotary drilling for up to 1%, and the remaining 0.8% for thermal and percussion-rope methods [6]. Three main types of drilling tools are used for drilling rock: roller cone bits, percussion drill bits and cutting bits. The ratio of different drilling methods depends on many factors (mining, economic), but mainly on the mining and geological conditions and the strength coefficient of the rock. Depending on geological conditions, the service life of rock-breaking tools can reach several hundred metres or more, and the average mechanical drilling speed is about 20-40 m/h [7]. Areas for improvement of rock-breaking tools include: increasing wear resistance, strength and thermal conductivity and, as a result, performance.

In mining operations, the service life of excavator equipment used in mining and tunnelling projects, as well as in oil and gas drilling, largely depends on the abrasiveness of the soil. In addition, underground mines contain CH4, CO, CO2, H2S, and SO2 in the air, and equipment parts operating in such an environment will be subject to both erosion and corrosion. The performance of tunnel boring machines (TBMs) is greatly affected by the wear of various parts, including disc cutters, expanders, bits, and facing plates [8]. Disc cutters with insert teeth are among the most commonly used cutters in TBMs. It should be noted that most studies focus primarily on the wear mechanisms of conventional disc cutters (dome-shaped and flat cutters). However, the teeth and body of disc cutters actually wear differently. The main mechanisms of wear of carbide teeth are abrasive wear, fatigue wear and adhesive wear, manifested in the form of pits and scratches formed by the penetration of solid rock particles during sliding. In contrast, the main mechanisms of wear on the cutter base are mainly abrasive wear and adhesive wear, characterised by numerous grooves formed as a result of rock particles sliding along the cutter base [9]. An analysis of failed disc cutters revealed that 53% of the alloy teeth failed, with breakage and chipping accounting for the highest proportions - 37% and 15%, respectively, Fig. 1.

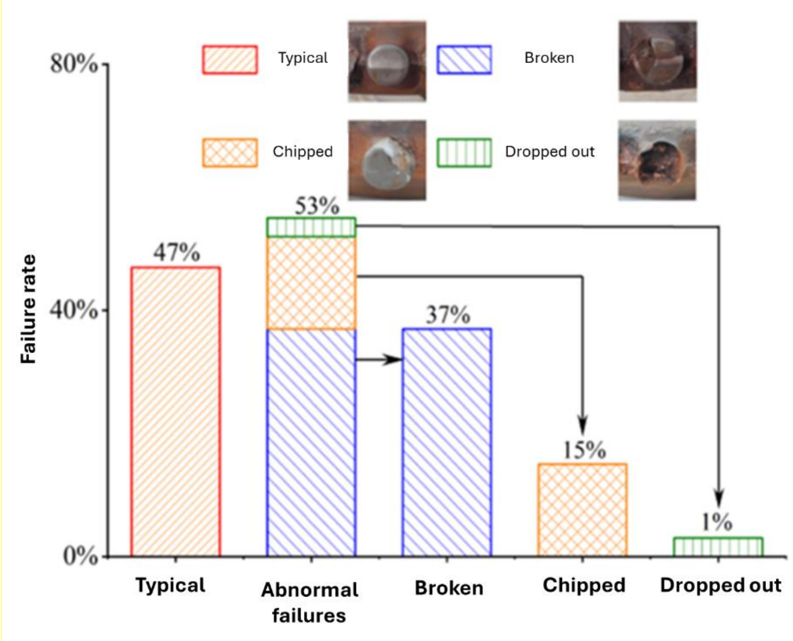

Fig. 1. Statistical distribution of each type of failure of disc cutters [9].

Wear and tear of oil and gas equipment parts. Centrifugal slurry pumps are widely used in various industrial production processes, including agricultural irrigation, deep-sea mining, oil extraction, molten salt energy storage, etc. In deep-sea mining, one of the serious technical problems is the destruction of the flow components of centrifugal slurry pumps due to erosion wear caused by the impact of solid particles [10]. In slurry pumps, the following elements are subject to the most intense wear: the front edge of the impeller blade inlet; the rear edge of the outlet of the impeller discharge surface; the spiral tongue (volute protrusion) of the pump casing, Fig. 2 [11].

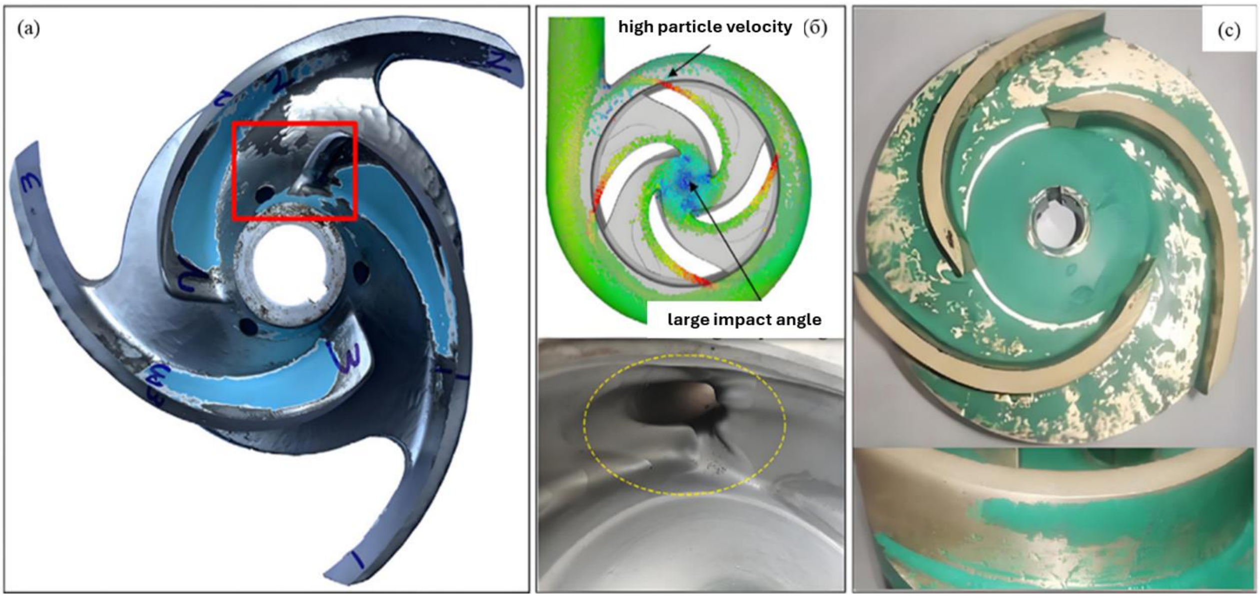

Fig. 2. Distribution of wear on a slurry pump: a) front edge of the blade; b) spiral tongue; c) rear edge of the blade [11].

In the oil and gas industry, the operational reliability and cost-effectiveness of the extraction, transportation and processing of hydrocarbon raw materials are determined by technologically advanced and fail-safe shut-off valves, which are subject to fairly high requirements: ensuring instant localisation of possible accidents, safety of technological systems in a wide range of operating environments, pressures, temperatures, and environmental conditions (seismic impact, humidity, low and high temperatures, etc.). Today, the following main types of shut-off valves have been developed and are widely used: valves, gate valves, butterfly valves and ball valves [12]. Gate valves have a number of advantages over other shut-off devices, including: simplicity of design, small dimensions, favourable cost characteristics and the ability to operate in a wide variety of conditions. During the operation of gate valves, a number of problems arise related to wear and corrosion. More than 50% of gate valve failures are caused by the destruction of sealing surfaces, which is associated with intense corrosion and erosion wear. These processes lead to a loss of tightness, increased repair costs and, in some cases, critical equipment failures. A particularly dangerous situation occurs when the sealing surfaces seize, making it impossible for the shut-off valve to operate at critical moments, such as in emergency situations. The cost of repairing the valve varies from 30-50% of the total cost of repairing the gate valve, which makes this problem important from an economic point of view. Studies have shown that the most vulnerable parts of gate valves are the mating surfaces of the ‘seat’ and “gate” parts, as well as the ‘spindle’. These elements are most susceptible to wear due to constant friction, exposure to aggressive working environments and cyclic loads. As a result, their wear becomes the main cause of valve failures, and it becomes necessary to surface harden the mating surfaces of the ‘seat-gate’s assembly to increase its service life. Based on this, it is important to identify the main factors affecting the reliability of the gate valve and seat, as well as to develop recommendations for improving their reliability under high loads and intensive operation.

One of the key factors determining the stability of fuel and energy resources supply to the regions of our country is the degree of reliability of oil and gas equipment and pipelines. The main factor contributing to the reduction in the reliability of oil and gas equipment and pipelines is the impact on the metal of their inner surface of the hydrocarbon media being pumped and processed, which contain corrosive components. During operation, the throughput capacity of pipelines gradually decreases due to the accumulation of paraffin deposits, increased roughness of the pipe walls as a result of internal corrosion and the accumulation of corrosion products and mechanical impurities. The decrease in throughput capacity leads to a sharp decrease in the efficiency of pipelines and a significant increase in the cost of pumping oil-containing liquids.

It is worth noting that the technological tasks of Kazakhstan's oil and gas industry enterprises, presented on the official platforms of the Samgau Centre for Scientific and Technological Initiatives Fund [13] and the National Academy of Sciences under the President of the Republic of Kazakhstan [14], are also related to improving the efficiency of oil and gas pipelines: optimising existing methods of combating complications and introducing advanced technologies to minimise the impact of negative factors in hydrocarbon production, while searching for solutions (Task No. 16 of the Samgau Centre for Scientific and Technological Initiatives); studying the conditions for the formation of salt deposits on the inner walls of production pipelines at the field and methods of combating their formation (Task No. 24 of the Samgau

Scientific and Technical Information Centre); cleaning paraffin deposits in the wellbore and pipelines (Task No. 13 of the National Academy of Sciences of Kazakhstan).

The main reasons for the formation of salt, paraffin, bitumen and hydrate deposits on the internal surfaces of production pipelines and oil heating furnace coils are the characteristics of the composition of the oil being extracted. This includes a high content of mineral salts, paraffin and asphaltene-resinous substances, as well as the presence of free water and gas. For example, when the temperature and pressure decrease during oil transportation, paraffin crystallises, which reduces the efficiency of pipelines and increases operating costs [15]. Low temperatures, pressure changes, uneven flow and stagnant zones also contribute to the formation of deposits. The evaporation of formation water and an increase in its salinity due to a decrease in temperature and pressure lead to the precipitation of salts (e.g., NaCl, $CaCO_3$) in the wellbore, which causes the formation of salt deposits. To prevent these phenomena, it is recommended to use salt deposit inhibitors, depressant and stabilising additives, maintain a temperature above the paraffin precipitation point, use gas and water drainage systems, and regularly clean pipelines using mechanical and chemical methods [16-17]. These measures increase the efficiency of equipment and reduce the negative impact on the operational performance of oil and gas pipelines.

The efficiency of oil and gas pipelines can be improved by using polymer coatings that prevent the formation of paraffin deposits in pipelines. Polymer coatings are widely used in extreme conditions, including deep-water pipelines, due to their high resistance to mechanical stress, chemical exposure and thermal changes. In [18], there is a proposal to use various polymer coatings with low surface energy applied to the pipeline to improve anti-fouling properties and reduce paraffin deposits. The results of the influence of eight coatings, including polyvinylidene fluoride (PVDF), silicone rubber, methyl acrylate-styrene copolymer (MAS), polyurethane (PU) and epoxy resin (EP), on flow resistance and paraffin deposition prevention using a rotational viscometer and the cold spot method. The most effective coating was S1 (silicone rubber vulcanisation at room temperature), which demonstrated the maximum reduction in flow resistance (21.7%) at a temperature of 26.0 °C and the most effective prevention of paraffin deposits (74.7%). Minimal deposits are observed on pipes coated with ethylene tetrafluoroethylene (ETFE), which is due to their smooth surface and low surface interaction energy [19].

Current research is focused on developing bio-inspired materials and multifunctional coatings that improve mechanical properties and provide reliable protection for pipelines in challenging operating conditions [20-21]. The authors of [22] presented the development of a superhydrophobic coating made of fluorinated silica (F-SiO2) Polydimethylsiloxane (PDMS) with high corrosion resistance, which was obtained by two-stage spraying. The highlight of this work was the formation of a microstructure that can create air pockets to form an air layer at the apparent solid-liquid interface. As a result, the coatings demonstrated a high ability to resist the effects of corrosion. In [23], multifunctional superamphiphobic coatings were presented using a simple spraying method. Highly fluorinated Palygorskite SiO2 (Pal SiO2-F) composite fillers were produced by in-situ growth of SiO2 on the surface of palygorskite and its chemical modification. These fillers were integrated into polyethersulfone (PES) and poly (vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP), which allowed the formation of unique micro-/nano-hierarchical structures with multiple papillary elements and intertwined networks. A stable air film was formed on the surface of the PES-PVDF-HFP/SiO2-F coating thanks to the chemical inertness and high adhesion of the polymers, as well as carefully designed structures. This air film was used as an anti-adhesion layer and an effective thermal barrier, which gave the coating pronounced anti-adhesion properties in the crude oil system.

Another important task for Kazakhstan's oil and gas industry is to increase the service life of pump and compressor pipes (Task No. 15 of the National Academy of Sciences of Kazakhstan). The service life of pump and compressor pipes (PCP) is currently reduced to two months, which causes significant economic losses. Frequent well shutdowns are associated with PCP leaks caused by deformation of drill pipes during drilling and constant mechanical contact between the pipe and the wellbore walls and equipment, leading to accelerated wear of the coating, defects and the occurrence of pitting, crevice and underfilm corrosion. High mechanical stresses and constant friction cause premature wear even of the most wear-resistant epoxy coatings. Stress corrosion occurs, which in turn leads to corrosion fatigue cracking and failure of the drill pipe. To solve this problem, a Kazakhstani company planned to conduct pilot industrial tests (PIT) in 2024 using an internal polymer coating to protect tubing from corrosion and equipping threaded connections with stemer. The success of the PILT will be assessed according to the following criteria: uninterrupted operation of the subsea pumping equipment without tubing leaks during the tests and preservation of the integrity of the internal coating and threaded connections. An alternative solution is to inject corrosion inhibitors directly into the wellhead of the subsea pumping equipment, which also helps to increase the service life of the tubing. This problem is relevant for work in aggressive environments and directly affects the economic efficiency of production.

An analysis of scientific works aimed at solving these problems has been carried out, and an overview of existing methods for their implementation has been formulated. Work [24] considers the use of a nanoparticle anti-friction coating (NPAF) as an alternative to traditional copper coatings for oil casing couplings. Copper coatings are highly resistant to scuffing, but their use is limited due to economic and environmental constraints. The NPAF anti-friction coating was manufactured using nanoparticles of polytetrafluoroethylene (nano-PTFE), polyacrylic resin, and a high-concentration ethanol colloid of nanocopper. The nano-copper colloid, with a solid particle concentration of 14–20% and an average particle size of about 95 nm, was obtained by liquid-phase reduction. The NPAF coating was successfully applied to the surfaces of threaded couplings of oil casing pipes, where it demonstrated a significant reduction in friction and wear. The authors noted that NPAF coatings are a promising solution for improving the performance of threaded connections of oil casing pipes under difficult operating conditions.

The authors of [25] proposed a different way to improve the performance characteristics of threaded connections in petroleum drilling tools (PDT) using an anti-friction coating based on nanocopper (NaCU-AFC). The coating was made of nanocopper and an epoxy resin-based binder. Experimental results showed that the use of NaCU-AFC reduces torque by 35.66% and significantly increases resistance to galling, which extends the service life of PDT. Tightening analysis also demonstrated an increase in the average number of tightening cycles to 2.5, which is 76.05% more than in the control group. The NaCU-AFC coating showed a significant improvement in the anti-friction properties and scuffing resistance of PDT threaded connections, indicating its high potential for use in oil drilling. However, additional research is needed to confirm the practicality and reliability of the coating, including studies of its chemical resistance and durability.

Thus, based on an analysis of the scientific literature, it can be said that among the innovative approaches, the use of superhydrophilic/underwater superoleophobic coatings stands out, which demonstrate anti-adhesion properties in an aqueous environment, significantly increasing the effectiveness of combating wax deposits. However, it has been noted that such coatings are mechanically fragile and susceptible to damage in aggressive environments, which limits their practical application in the harsh conditions of oil production. Thus, a durable and multifunctional superamphiphobic coating can be developed and may become an excellent option for coatings with anti-adhesive and anti-fouling properties, with enormous potential for application in the petrochemical industry and other harsh conditions.

Wear and tear of agricultural machinery parts. The efficiency of agricultural production is largely determined by the level of technical support and the use of high-quality agricultural machinery. Repair and maintenance account for a significant share of costs, amounting to 12% or more of the cost of agricultural products [26]. According to Energyprom.kz data from 2 April 2020, the development of the agricultural machinery manufacturing industry is a pressing issue in Kazakhstan. Despite the growth in production and the efforts of manufacturers, according to data from the Statistics Committee of the Ministry of National Economy of the Republic of Kazakhstan for 2019, Kazakh companies covered only 12.8% of the demand for tractors for agriculture and forestry, and in the segment of ploughs and disc harrows, Kazakh companies covered only 3.5% of the demand for these devices [27]. The average wear and tear of the entire fleet of agricultural machinery in the Republic of Kazakhstan reached 76%.

In agricultural machinery, abrasive wear is probably the most significant cause of mechanical damage to equipment components that come into contact with abrasive bodies. Abrasive wear critically affects production planning, soil cultivation quality, and energy consumption in the soil cultivation process each time an action is performed, so determining the wear losses of soil cultivation implements is important [28]. During the operation of soil cultivation machines and units, working surfaces are subject to uneven wear, which reduces the service life of parts and increases the cost of their replacement and renewal. The working parts of soil cultivation equipment, such as ploughshares, wear out particularly quickly, with their service life varying between 5 and 20 hectares, depending on soil and climatic conditions [29]. Ploughshares made of L53 and 65G steel lose about 40-60% of their service life on heavy soils if hardened coatings are not used. The total service life of mower cutting segments when working in fields that meet the agricultural requirements for harvesting should be 3.5 hectares/unit on average. [30]. The working parts of other soil cultivation machines also have a limited service life: discs of hullers and disc harrows from 5 to 25 hectares, cultivator tines from 5 to 15 hectares [31].

Against the backdrop of the above statistics, there is a technological need to increase the production capacity of repair and technical enterprises by introducing new technological processes for strengthening agricultural machinery parts. Such approaches will significantly increase the durability and wear resistance of parts and reduce overall operating costs.

2. Materials used to strengthen parts operating under conditions of wear

Modern approaches to reducing friction and wear include the use of innovative materials with improved strength and wear resistance characteristics, advanced surface treatment methods, highly effective coatings, advanced lubricants and additives. In the mining industry, hammers were made of high-chromium cast iron, especially in the production of mineral fillers. Numerous studies confirm that high chromium white cast iron (HCWCI) is an indispensable material in conditions where excellent resistance to abrasive, erosive and impact wear is required [32-33]. High chromium white cast iron is a suitable material for functional components of crushing machines, which are widely used in mineral processing to increase wear resistance and extend equipment life at lower production costs. Such wear resistance characteristics of high-chromium cast iron (C-Cr-Fe) are due to the presence of a hard eutectic carbide of the M7C3 type embedded in the austenitic matrix, which after heat treatment can be completely or partially transformed into a martensitic matrix [34].

The priority direction in the development of drilling equipment is the improvement of rock-breaking tools. Many achievements in this area are associated with the use of modern superhard materials, the creation of new composite materials, and the development of drilling tool designs with combined armament. The cutter of a rock-breaking tool (such as PDC-polycrystalline diamond cutters) is obtained by sintering polycrystalline diamond powder on a substrate under very high temperatures and pressures (HTHP high-temperature, high-pressure method). In [35], it is reported that the introduction of graphene under unchanged conditions of sintering PDC cutters leads to an improvement in electrical conductivity by approximately 42 times, an increase in thermal conductivity by 60%, and an improvement in the hardness and wear resistance of the cutter by 75% and 33%, respectively.

For the extraction of hard rock, the cutting head of tunnel boring machines is mainly equipped with a set of disc cutters and bits with carbide tips. The main body of the tools is made of inexpensive grades of steel. Hard alloys or cemented carbides are a metal-ceramic composite material widely used in various industries. As a composite material, they consist of a hard phase, usually WC, and a plastic and durable binder phase. Since its introduction, cobalt Co has established itself as the most common binder phase metal due to its excellent properties [36]. Although alternative binder elements such as Ni and Fe have long been studied alongside Co, Co remains the preferred choice due to its superior properties: high hardness, impact toughness, lower sintering temperature, and excellent wettability of WC grains compared to other metals. However, in recent years, the partial or complete replacement of Co has become an important part of hard alloy research. Since Co is considered an essential raw material that plays a key role in battery technology, which has gained worldwide recognition thanks to the production of electric vehicles and portable computers, this has led to a steady increase in Co prices in recent years [37].

2.1 Main technologies for strengthening parts operating under wear conditions

Laser hardening is gradually becoming one of the most common methods of surface hardening in modern mechanical engineering. The laser hardening process is very efficient, as the phase transformation of hardening is completed within one second. In addition, deformation after laser hardening is very limited, which guarantees the dimensional accuracy of the processed parts. Furthermore, the environmentally friendly laser hardening process also allows for the processing of complex shapes, including thin-walled and hollow structures. In their work, Zhenyu Chen et al. (2023) showed that by optimising the parameters of the laser process, it is possible to significantly improve the hardness and wear resistance of QT700-2 malleable cast iron [38]. Of great interest is the hardening of hard alloys based on tungsten carbide cobalt WC-Co by laser radiation, after which the microhardness of the surface layer increases by 10-14 GPa [39]. In the work of Tomohisa Kanazawa et al. (2023), it was shown that after laser hardening, the durability of the gear increased 3.8 times compared to untreated gears [38]. In [39], laser cladding technology was used to obtain FZNCr-60A nickel alloy coatings on the surface of balancing plates of slurry pumps used in underground mining, made of 1045 steel (analogous to structural steel 45). Currently, laser cladding is widely used in the repair of machine parts due to its advantages, such as lower dilution rate, small heat-affected zone, and good metallurgical bond between the coating and the substrate [40].

In industry, plasma hardening is most widely used for strengthening parts of agricultural machinery, chemical, petrochemical, metallurgical and other production equipment. An analysis of the results of industrial use of plasma hardening technology has shown that the average operational durability of heat-treated rolls per campaign increases by 20-60%, the average operating time in terms of the amount of rolled metal increases by 30-100%, and the specific consumption (in tonnes per tonne of rolled metal) decreases by 20-50% [43]. Currently, plasma hardening is used in production to harden large-sized equipment parts, such as hot rolling rolls, locomotive wheel tyres, railway wheel sets, trolley wheels, and crane wheels. Hardening small and thin-walled parts with plasma hardening is not always effective due to the difficulty of achieving the cooling rate required for hardening. In exceptional cases, spray or flow cooling may be used.

Due to its technological simplicity and accessibility, combined with high quality of the restored surface, the gas-flame spraying method is widely used for hardening and restoring various machine and equipment parts. Gas flame spraying is widely used to restore parts of agricultural machinery, pump and compressor equipment, covers and shafts of electric motors, etc. This method is most commonly used in the repair of agricultural and automotive equipment, for surfacing drill bits and quickly wearing parts of mining equipment. Gas-flame spraying is primarily suitable for restoring parts that are not subject to significant dynamic loads. Such parts include body parts of tractors and automobiles, where the mounting seats are subject to wear (sockets of the block for main bearing inserts; sockets of gearbox crankcases; support flanges, cylinder sleeve seating belts; the surface of the lower connecting rod head, etc.). A significant range of products includes shafts made of cast iron, 45 steel, alloy steels, with worn seating areas (gearbox shafts, machine running gear, etc.). Gas-flame spraying is not very effective when processing small parts. This is due to the high consumption rate of filler material.

An analysis of modern technologies for restoring worn surfaces shows that in practice there is a need to restore surfaces worn to a thickness of up to 2 mm, giving them wear-resistant properties when subjected to friction using oils. There are a number of modern technologies and methods for restoring worn friction surfaces, which require special equipment and expensive materials. Along with this, the electric arc spraying process stands out as advantageous. Practically the only disadvantage of coatings applied by electric arc spraying is their low adhesive strength, especially when applying coatings thicker than 3 mm, which is a consequence of high internal residual stresses, different elasticity modules, and linear expansion coefficients of the base metal and coating. One option for increasing the adhesive strength of the bond, as discussed in the literature, is to apply an intermediate plastic layer. In [41], it is reported that electric arc spraying technology has been introduced at OAO Azovstal MK Azovstal" to restore worn parts of metallurgical equipment, such as continuous casting machine roller necks, hydraulic cylinder pistons, etc. Due to their porosity and ability to retain lubricant, the sprayed coatings have shown improved performance, which has reduced the downtime of the repaired equipment.

Currently, supersonic gas-flame spraying methods (HVOF, HVAF) are becoming increasingly widespread. The velocity of the heated gas jet at the burner nozzle reaches 1700-2700 m/s, which allows for the creation of unique coatings with a bond strength of up to 100 MPa [35]. The porosity of the coating is 0.5% and is similar in its characteristics to coatings obtained by detonation spraying. In the work of Payank Patel et al. (2024) studied the potential of high-entropy AlCoCrFeMo alloys for new-generation tribological interfaces obtained by three methods, namely low-pressure cold spraying (LPCS), flame spraying (FS) and high-velocity oxygen-fuel spraying (HVOF) [35]. HVOF coatings showed higher hardness values compared to FS and LPCS coatings, which can be explained by their fine-grained microstructure, lower porosity and oxide inclusions compared to the other two coatings. A number of studies [38-39] have concluded that the HVAF method is effective for producing carbide-based coatings (WC-17Co, Cr3C2), since the use of compressed air results in a lower spraying temperature and, consequently, less carbide decomposition.

The advantage of the electric arc spraying (metallisation) method is the high productivity of the process and the possibility of significantly reducing the time required for spraying. For example, at a current of up to 700 A, a steel coating can be sprayed at a rate of 30-35 kg/h, which is several times higher than the productivity of gas-flame spraying. Electric arc spraying is used to restore the following parts: engine crankshafts, brake drums, brake discs, clutch discs, cylinder heads, engine connecting rods, cylinder liners, rotor shafts and electric motor starters, cylinder blocks, etc. Metallisation is used to apply an anti-friction layer of lead and aluminium, zinc and aluminium, or bronze to bushings and bearings. Recently, electric arc spraying has come to be used in several industries as the most suitable and effective method of protecting high-performance equipment, such as boiler tubes, from corrosion, thanks to its economic benefits in terms of maintenance and production [38]. The widespread introduction of the electric arc metallisation process is hampered by the lack of systematic solutions to prevent the burnout of alloying elements from the metal and reduce the oxide content in the coating. Royanov V.A. et al. (2019) proposed using a pulsed air supply by introducing an additional element into the spray head of the arc metalliser in order to reduce the oxidative effect of the air spray jet on the liquid metal of the electrode ends [41]. Thus, despite the extensive research carried out on electric arc spraying, some problems remain unresolved, such as the speed and oxidation of dispersed metal in a heterophase flow, etc.

In fact, air plasma spraying is a diffusion metallisation process that allows for the effective formation of protective coatings and the restoration of worn parts of metal products. Plasma spraying has a number of advantages over gas-flame and arc spraying: it allows coatings to be applied from a wide range of materials; the use of inert gases that do not contain oxygen in plasmatrons helps to reduce the oxidation of the sprayed material and the surface of the part; coatings obtained by plasma spraying are superior in physical and mechanical properties to coatings obtained by gas-flame and arc spraying. Plasma spraying has a high energy density, and particles can reach high temperatures and speeds, which allows many refractory materials to be melted [39-40]. The authors of [41], after searching the Web of Science database for keywords related to plasma spraying and analysing articles published on this topic over the past 20 years, report that air-plasma spraying is mainly used to obtain wear-resistant coatings.

Table 1 presents a structured comparative analysis of modern strengthening technologies that are actively used in industrial production to increase the wear resistance and durability of parts and structures. These data allow us to assess the suitability of technologies for various industries and propose optimal solutions for specific operating conditions.

Table 1. Characteristics of surface treatment and coating technologies.

Technology	Particle velocity of material, m/s	Plant capacity, kg/h	Spray material utilisation ratio	Adhesion strength to substrate, MPa	Temperature of material particles, °C	Reference
1	2	3	4	5	6	7
Detonation spraying	350-1000	0,1-6	0,3-0,6	up to 200	up to 3000	[54-55]
High-velocity air-fuel spraying (HVAF)	300-600	5-10	0,6-0,8	50-100	up to 1500	[56]
High-velocity oxygen fuel spraying (HVOF)	400-900	5-20	0,5-0,7	80-150	up to 2000	[57]
Plasma spraying	50-400	0,5-8	0,7-0,9	up to 60	up to 4000	[58]
Gas flame spraying	до 300	До 2	-	up to 30	2500	[59]
Laser cladding	-	0,5-12	0,8-0,95	100-200	up to 3000	[60]
Plasma powder cladding	-	До 25	85	80-300	up to 2000	[61]
Physical vapour deposition (PVD)	-	1-10	-	30-60	200 - 500	[62]
Magnetron spraying	200	300	30–50	50–100	500–800	[63]

Thus, the development and implementation of resource-saving technologies for the restoration and strengthening of equipment parts is one of the pressing issues that has not yet been fully resolved for the Kazakh market. The widespread use of wear-resistant coatings for strengthening and restoring parts in industry is often limited by a lack of information about the possibilities and methods of applying coatings, their advantages and disadvantages.

3. Conclusion

An analysis of current equipment wear problems in key industries has shown that increasing the service life and reliability of machines is only possible with a comprehensive approach to the selection of materials and surface hardening technologies. The parts most susceptible to wear are those operating under intense mechanical, abrasive and corrosive loads: shafts, sealing elements, ploughshares, discs, cutting tools and pump working parts. Among the effective methods of restoration and protection, the most promising are laser and plasma treatment technologies, electric arc and detonation spraying, HVOF/HVAF methods, as well as the use of innovative coatings based on nanocomposites, high-entropy alloys and polymer matrices. Their correct application can significantly increase the service life of components and assemblies, reduce maintenance costs and equipment downtime. In the context of growing demands for reliability and economic efficiency, the integration of resource-saving strengthening technologies, taking into account the specific operating conditions and economic factors of a particular industry, is becoming a key area of development.

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Conflict of interest

The authors declare no conflict of interest.

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