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Analysis of Operating Conditions for Parts in the Metallurgical and Machine-Building Industries and Justification for the Choice of Protective Coating

Kulikov V.Yu.*, Kvon Sv.S., Issagulov A.Z., Kovalyova T.V., Olzhatayev O.
Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan
*corresponding author

Abstract. Aggressive operating conditions, such as high temperatures, chemical environments, abrasive wear, and corrosion, lead to premature wear and failure of parts in the metallurgical and machine-building industries. To solve this problem, protective coatings are used, but traditional methods (galvanic, chemical treatment) often do not provide sufficient reliability in extreme conditions. One of the most effective solutions is gas thermal spraying, which allows coatings with unique properties such as high hardness, wear resistance, corrosion resistance, and strong adhesion to the substrate to be applied. This article is devoted to the analysis of the operating conditions of parts in aggressive environments and the justification for choosing gas thermal spraying as the optimal protection method. Particular attention is paid to the selection of powder materials, such as WC/Co, Cr_3C_2-NiCr, Cr_2O_3, and Al_2O_3, depending on the type of wear (corrosive, abrasive, adhesive). Various types of gas thermal spraying and their advantages are considered. The correct choice of material and spraying method can significantly increase the service life of equipment, reduce repair costs, and increase overall production efficiency.

Keywords: corrosion, wear, adhesion, hardness, protective coating.

Introduction

Modern industry, particularly the metallurgical and machine-building sectors, faces the problem of premature wear and tear and destruction of machine parts and equipment [1]. The reasons for this are aggressive operating conditions, including exposure to high temperatures, aggressive chemical environments, abrasive wear, corrosion, and erosion [2]. These factors lead to a reduction in the service life of parts, increased repair and replacement costs, and production downtime [3].

This problem is global in nature, causing significant economic damage estimated at billions of dollars annually. According to research, losses associated with corrosion and wear amount to 4-5% of the GDP of developed countries, with a significant share of these losses attributable to industrial equipment [4]. In the context of the metallurgical and machine-building industries, where parts operate under extreme temperatures, high mechanical loads, and aggressive chemical environments, the problem of wear becomes particularly acute [5].

The key types of wear leading to premature failure of parts are corrosion, mechanical (adhesive, abrasive), and fatigue wear [6]. Each of these mechanisms has its own specific characteristics and requires an individual approach to protection.

In the metallurgical and machine-building industries, parts are regularly exposed to aggressive environments. In metallurgical furnaces, casting and heat treatment equipment, parts are exposed to hot gases, melts, and slags [7]. For example, in continuous steel casting plants, parts that come into contact with molten metal are subject to intense corrosion, which reduces their service life to a few weeks [8]. In mechanical engineering, especially in the manufacture of chemical equipment, parts work in contact with solutions of acids, alkalis, salts, and other aggressive reagents [9]. For example, in pumps for pumping sulfuric or nitric acid, in valves and pipelines, corrosion can lead to complete destruction of parts within a few months, creating a threat of accidents [10].

Parts operating in the open air are exposed to atmospheric precipitation, industrial emissions, and salts, and are subject to corrosion and mechanical wear, significantly reducing their service life [11]. According to research [12], even in a temperate climate, the corrosion rate of unprotected steel can reach 0.1-0.2 mm per year, and in aggressive industrial atmospheres, this figure increases several times.

The solution to this problem lies in the use of protective coatings, which significantly extend the service life of parts and increase their reliability [13]. They often have thickness limitations, are brittle, have low adhesion, or are insufficiently resistant to combined effects [14].

Among the many existing coating methods, gas-thermal technologies occupy a special place. Gas-thermal coatings have a unique combination of properties, such as high hardness, wear resistance, corrosion resistance, and adhesion to the substrate [15].

To ensure the physical and mechanical properties of the coating, it is necessary to select the right material for gas thermal spraying. Powders used for gas thermal spraying can be classified according to their chemical composition and purpose [16]:

1) Powders based on metals and alloys;
2) Powders based on carbides, borides, and nitrides;
3) Powders based on oxides;
4) Composite powders (cermets);

Powders based on metals and alloys are the most extensive group, including materials based on iron, nickel, cobalt, copper, and their alloys. They are used to restore the dimensions of parts, increase wear resistance, and improve corrosion resistance [17]. Powders based on carbides, borides, and nitrides, often referred to as hard alloys, have exceptional hardness and wear resistance. The most common are tungsten and chromium carbides [18]. Oxide-based powders, such as aluminum oxide (Al_2O_3), zirconium dioxide (ZrO_2), and chromium oxide (Cr_2O_3), are used to create coatings with high hardness, wear resistance, and heat resistance [19]. Composite powders are a mixture of a metal matrix and a solid phase (e.g., carbides or oxides). They combine the plasticity of metal and the hardness of ceramics, making them ideal for conditions of abrasive wear and impact loads [20].

The assessment of the operating conditions of parts in the machine-building and metallurgical industries that operate in aggressive environments and the selection of materials for gas thermal spraying are key to improving the reliability, durability, and cost-effectiveness of equipment as a whole.

In this regard, the purpose of this article is to analyze the operating conditions of parts in the metallurgical and machine-building industries that operate in aggressive environments and to justify the use of gas-thermal coating as the most effective and universal solution for their protection. Particular attention will be paid to the selection of optimal chemical compositions for coatings capable of withstanding specific types of aggressive exposure.

1. Working conditions for parts in the metallurgical and machine-building industries

Machine and equipment parts in the metallurgical and machine-building industries are exposed to various aggressive environments, which can be divided into several groups, as shown in Table 1.

Table 1. Aggressive environments and components in the metallurgical and machine-building industries

Environment	Part	Consequence of interaction between a part and its environment
Diluted solutions of nitric acid, solutions of salts with oxidizing properties	Fastening parts, rollers, bushings for machines and vessels (Figure 1a)	Nitric acid causes intense corrosion of most metals, especially carbon and low-alloy steels. Salt solutions cause active corrosion, especially in areas of stress concentration.
Atmospheric precipitation, aqueous solutions of organic acid salts at room temperature, shock loads	Parts with increased plasticity that are subject to impact loads – hydraulic press valves (Figure 1b) Parts that come into contact with atmospheric precipitation – pipes (Figure 1c)	Corrosion is exacerbated by mechanical stresses, leading to corrosion-mechanical wear. These stresses can cause damage to coatings and substrates.
Temperatures up to 1200 °C in air and hydrocarbon atmospheres	Sheet metal parts for furnace rollers (Figure 1d), hangers and supports in boilers, furnace screens (Figure 1e)	Accelerate corrosion processes and can cause thermal destruction of the part surface.
Temperature up to 780°C	Rotors, discs, blades (Figure 1f)	Leads to thermal stresses, which can cause the coating to peel off.
Conditions of abrasive wear	Plungers, rods (Figure 1g), guide rollers, grippers	Destruction of the part's surface
Conditions for adhesive wear	Piston rings (Figure 1 h), hydraulic cylinder rods, plain bearings (Figure 1i), bushings	Scuffing, scratches, micro-welding on the surface of the part

Mating parts of machines and equipment in the metallurgical industry operate under extreme conditions, which leads to the appearance of various surface defects that accelerate wear and tear and can lead to breakdowns. These defects can be classified according to their origin and nature. Abrasive wear caused by the impact of solid particles (dust, dirt, wear products) entering the friction zone. This leads to the formation of scratches, grooves, and scuffs on the surface of parts, which increases friction and temperature. Fatigue wear occurs under the influence of high alternating loads, which leads to the formation of microcracks on the surface [21]. Over time, these cracks grow, and metal particles separate from the surface, forming spalling. The causes of fatigue wear are often defects in the structure of coatings, such as pores, cracks, and oxide films. To prevent this, dense coatings are necessary. Adhesive wear occurs when working without lubrication or when there is a lack of it. In this case, areas of rubbing surfaces adhere at the molecular level and then break down, leading to the formation of deep scratches and grooves.

In order to avoid the consequences of surface damage to parts operating in aggressive environments, protective coatings must be used. One promising direction for applying protective coatings is gas thermal spraying. Gas thermal spraying is a process of heating, dispersing, and transferring condensed particles of the sprayed material by a gas or plasma flow to form a layer of the desired material on the substrate [22].

Fig. 1. – Effects of aggressive environments on parts in the metallurgical and machine-building industries

The following types of gas-thermal spraying are most commonly used to increase the wear resistance of parts: high-velocity oxygen fuel (HVOF) spraying / high-velocity (supersonic) spraying (HVAF); plasma spraying, detonation spraying [23].

There are several methods of gas-flame spraying, depending on the energy that acts on the sprayed material (Figure 2).

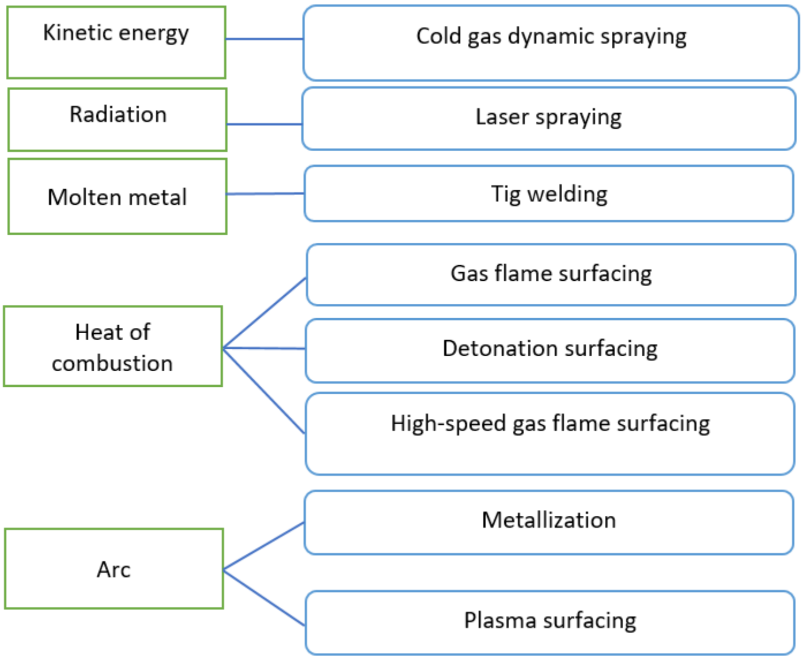

Fig. 2. – Classification of gas-thermal spraying methods based on the energy source

The use of gas-thermal coating application has a number of significant advantages [24]:

1) Gas-thermal methods allow coatings to be applied from a wide range of materials: metals, alloys, cermets. This makes it possible to select the optimal coating composition for any aggressive environment and operating conditions;

2) During gas thermal spraying, coating particles in a plastic state collide with the substrate at high speed, forming a strong mechanical bond and, in some cases, a diffusion bond;

3) Gas-thermal coatings can have a thickness ranging from tens of microns to several millimeters, which allows for the creation of reliable protection against corrosion wear;

4) During the spraying process, the substrate temperature usually does not exceed 150-250 °C, which eliminates thermal deformation, structural changes, and softening of the part;

5) Gas thermal spraying can be used not only to protect new parts, but also to restore worn ones, which significantly reduces repair costs.

6) Many gas thermal processes are more environmentally friendly than galvanic processes, as they do not use toxic chemicals.

2. Materials for improving the wear resistance of parts in the metallurgical and machine-building industries

The choice of powder for gas thermal coating depends on the service properties of the part (relative wear resistance, friction coefficient, heat resistance, corrosion resistance, heat resistance, contact endurance).

Taking into account the types of wear during the operation of parts in the metallurgical and machine-building industries, materials for gas thermal spraying can be classified (Table 2).

Table 2. Materials for gas thermal spraying for a specific type of wear

Type of wear	Material for gas thermal spraying
Corrosion wear	Co-, Ni-alloys or Cr_2O_3 and Al_2O_3 impregnated oxide/ceramic coatings
Abrasive wear	WC/Co and mixture NiCrBSi + WC/Co
Adhesive wear	Mo + NiCrBSi

Corrosion wear is successfully countered by:
1) Cermets:
– tungsten carbide (WC-Co 88-12, WC-Co-Cr 86-10-4);
– chromium carbide (Cr_3C_2-NiCr 75-25);
2) Metal oxides (Cr_2O_3, Al_2O_3).
The hardness of typical wear-resistant coatings is shown in Figure 3.

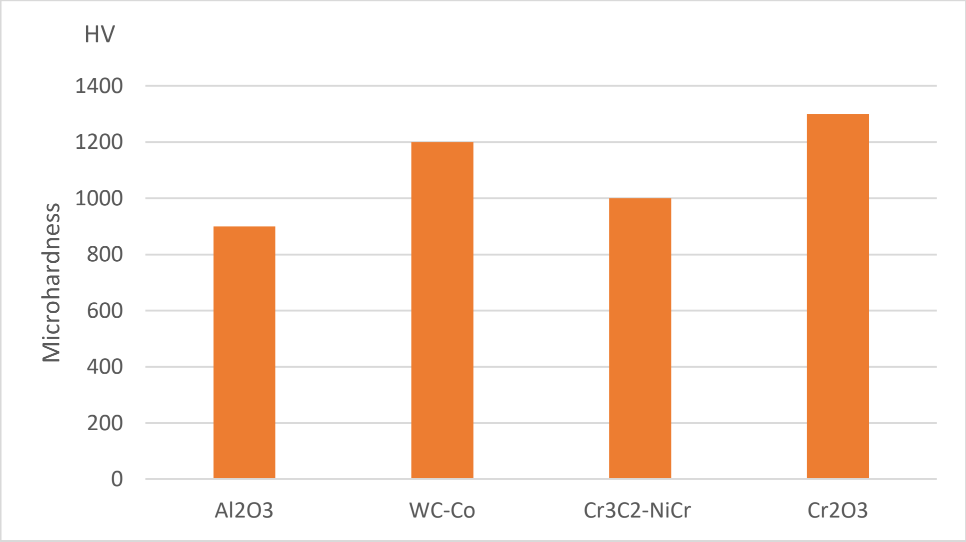

Fig. 3. – Hardness of wear-resistant coatings

Aluminum oxide (Al_2O_3) is a very hard but brittle material. Aluminum oxide spraying creates coatings with high hardness and excellent dielectric properties [25]. The coating has good wear resistance to abrasion. Aluminum oxide coatings are used on parts operating under abrasive wear conditions where high impact strength is not required. It is used for insulating coatings on pump shafts where electrical insulation and wear resistance are required. In metallurgy, it is used on guide rollers operating at high temperatures.

Tungsten carbide in a cobalt matrix (WC-Co) is the most well-known and widely used cermet for gas thermal spraying [26]. Tungsten carbide (WC) particles provide exceptional hardness and wear resistance, while the cobalt matrix (Co) binds them together, providing the necessary ductility and strength. The ratio of WC to Co can vary (e.g., WC-12Co, WC-17Co) depending on the required properties. WC-Co coatings are used to protect against abrasive wear and erosion. They are applied to rods, pump sleeves, plungers, seals, and wear surfaces in the metallurgical industry (e.g., guide rollers, grippers). The coating has high compressive strength and excellent erosion resistance.

The main advantage of Cr_3C_2-NiCr lies in the synergy (complementary action) of its components [27]. Cr_3C_2 provides exceptional hardness and wear resistance. NiCr (the binding matrix) provides ductility, adhesion strength, as well as corrosion and heat resistance. The coating is applied to ball valves, valve seats, and pump impellers to increase their wear resistance in aggressive environments. Cr_3C_2-NiCr coating is also applied to shafts operating under conditions of friction and wear, such as pressure rollers in the metallurgical industry. As a replacement for hard chrome, Cr_3C_2-NiCr coating is applied to hydraulic cylinder rods. This provides high wear resistance, corrosion protection, and better environmental performance compared to chrome plating.

The Cr_2O_3 coating is a hard, dense, and chemically inert ceramic. It is this coating that determines the key properties of the coating [28]. The Cr_2O_3-based coating has high microhardness, which makes it extremely resistant to abrasive wear and erosion. This property is its main advantage. The coating has natural lubricating (tribological) properties, which reduces friction between mating surfaces. This is especially important in conditions of dry friction or insufficient lubrication. Chromium oxide is a stable compound and does not react with most chemically aggressive environments, providing excellent corrosion resistance. Cr_2O_3 is also stable at high temperatures and does not lose its properties, allowing the coating to be used in conditions where metals can soften or oxidize. This coating is applied to protect parts from abrasive wear and corrosion, especially when pumping aggressive liquids (for example, for pump rods and plungers in the chemical industry or at treatment plants).

To protect against high-temperature corrosion, the schemes shown in Figures 4 and 5 are used.

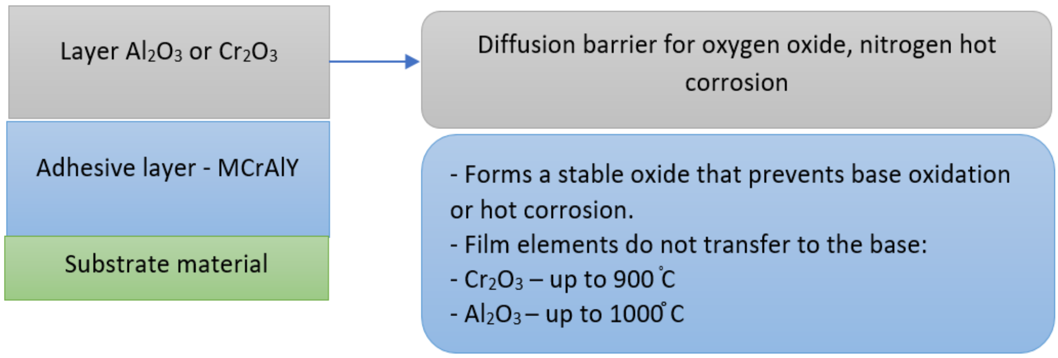

Fig. 4. - Corrosion coatings operating at temperatures up to 1000 °C

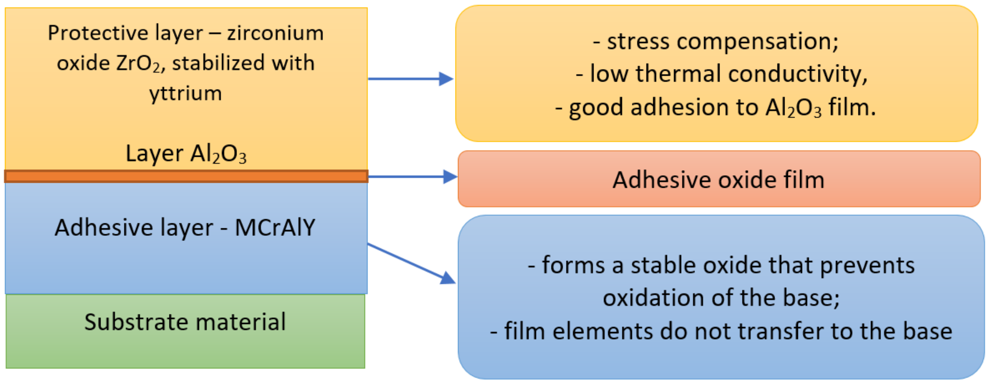

Fig. 5. - Thermal barrier coatings for turbine blades (up to 1,200 °C)

To increase wear resistance, WC/Co or NiCrBSi+WC/Co mixtures are used in cases where the part is subject to abrasive wear [29]. At the same time, to achieve high and uniform hardness, as well as a homogeneous and dense coating structure, it is best to use high-velocity oxy-fuel spraying (HVOF/HVAF) for mating surfaces.

To avoid adhesive wear, it is necessary to prevent metallurgical interaction between surfaces, which leads to micro-welding. For example, in engine cylinders, this is achieved using a special porous coating. It is applied using plasma spraying (a mixture of molybdenum and NiCrBSi), and the pores retain the lubricant. Ni-Cr-B-Si is a self-fluxing powder widely used for spraying and melting [30]. The nickel base provides good corrosion resistance and strength. Chromium (Cr) increases corrosion and erosion resistance, while boron (B) and silicon (Si) lower the melting point and promote the formation of a glassy phase during melting, which ensures a dense and non-porous coating.

The use of specialized powder materials in gas thermal spraying technology opens up wide opportunities for improving the wear resistance, corrosion resistance, and strength of parts in the machine-building and metallurgical industries. The right choice of material, taking into account the operating conditions of the part and the required properties of the coating, can significantly extend the service life of equipment, reduce repair costs, and increase overall production efficiency. Each material has its own area of application, from metal-ceramic powders that provide exceptional hardness to ceramic materials that create heat-shielding barriers.

In summary, in order to select the optimal material for gas thermal coating, it is necessary to know:

- the operating conditions of the part - abrasive wear, erosion, corrosion, impact loads, high temperatures;
- the required properties of the coating - hardness, strength, corrosion resistance, thermal insulation properties;
- the spraying method - high-velocity oxygen fuel (HVOF) spraying, plasma spraying, detonation spraying, etc.

This makes gas-thermal coating a versatile and indispensable tool in modern industry.

Conclusion

Parts used in the machine-building and metallurgical industries are subjected to intense aggressive influences, such as high temperatures, abrasive wear, and corrosion, which leads to their rapid wear and destruction. Traditional protection methods, such as electroplating, do not always cope with extreme conditions, as they have limitations in terms of thickness, brittleness, and low adhesion. In this regard, gas thermal spraying has proven itself to be a highly effective and versatile method for protecting and restoring parts.

A key aspect of the success of gas thermal spraying is the correct choice of powder material. Materials intended for spraying are divided into several groups: metals and alloys, carbides, borides, nitrides, oxides, and composite powders (cermets). For example, Co- and Ni-alloys, as well as ceramic coatings based on chromium oxides and aluminum oxide, are used for parts subject to corrosion wear.

Under conditions of abrasive wear, carbide-based materials such as WC/Co and their mixtures with NiCrBSi show the best results. To protect against adhesive wear, which causes micro-welding and scoring, coatings based on molybdenum and NiCrBSi are used.

Gas thermal spraying technology has a number of advantages, including the ability to create a strong mechanical and diffusion bond between the coating and the substrate, no thermal deformation of the part due to low heating temperatures, and the ability to apply coatings of varying thicknesses. This makes gas thermal spraying a versatile tool that can not only protect new parts but also effectively restore worn ones. In general, a thorough analysis of operating conditions, the correct choice of powder material and spraying method (e.g., HVOF for high-velocity spraying or plasma spraying for porous coatings) can significantly increase the durability and reliability of equipment, reduce maintenance costs, and increase overall production efficiency.

The next area of research will be the selection of the composition ratio of powders for gas-thermal spraying with damping properties using the high-speed gas-flame spraying method.

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Information of the authors

Kulikov Vitaly Yuryevich, c.t.s., professor, Abylkas Saginov Karaganda Technical University
e-mail: v.kulikov@ktu.edu.kz

Kvon Svetlana Sergeevna, c.t.s., professor, Abylkas Saginov Karaganda Technical University
e-mail: s.kvon@ktu.edu.kz

Issagulov Aristotel Zeinullinovich, d.t.s., professor, Abylkas Saginov Karaganda Technical University
e-mail: a.isagulov@ktu.edu.kz

Kovaleva Tatyana Viktorovna, PhD, tutor, Abylkas Saginov Karaganda Technical University
e-mail: t.kovalyova@ktu.edu.kz

Olzhatayev Olzhas Kanatovich, doctoral student, Abylkas Saginov Karaganda Technical University
e-mail: olzhasmailru7@gmail.com