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Volodymyr Pleskach — Candidate of Technical Sciences, Associate Professor of the Department of Composite Materials, Chemistry and Technologies, Zaporizhzhia Polytechnic National University, Zaporizhia, Ukraine, *e-mail: vmpayzp@gmail.com*, ORCID: 0000-0002-6182-4332

Ivan Akimov — Candidate of Technical Sciences, Associate Professor of the Department of Composite Materials, Chemistry and Technologies, Zaporizhzhia Polytechnic National University, Zaporizhia, Ukraine, *e-mail: akimovi@ukr.net*, ORCID: 0000-0001-6076-0149

Svitlana Kyrylakha — Master's student of the Department of Integrated Welding Technologies and Structural Modeling, Zaporizhia Polytechnic National University, Zaporizhzhia, Ukraine, *e-mail: lanakirilaha@gmail.com*, ORCID: https://orcid.org/0009-0001-5688-5616

PROTECTION OF MACHINE PARTS MADE OF ALUMINUM ALLOYS FROM GAS ABRASIVE WEAR

Purpose. *Analyzing the patterns of gas abrasive wear of the aluminum alloy VD17, applying protective coatings that can provide effective wear resistance, providing recommendations of the optimal type of protective coating.*

Research methods. *The study usedinstallation, the design of which allows changing the parameters of gas-abrasive wear within wide limits, that as best reproduce the wear conditions of machine parts under different operating conditions. The study was conducted on samples of aluminum alloy VD17 with metal protective layers applied by galvanic and chemical methods. The study was conducted using metallographic analysis to identify the structure that provides optimal protection against gas-abrasive wear.*

Results. *Analysis of the nature and magnitude of materials wear was carried out, in the flow of free abrasive depending on the velocity of the abrasive flow and its angle of attack. The degree of reduction in wear of the aluminum alloy VD17 when using chromium and nickel protective coatings was determined. Based on the comparative assessment of the quantitative characteristics of the protective layers, the ability of coatings to reduce wear of the alloy VD17 under the action of a gas abrasive flow was determined.*

Scientific novelty. *The angle of attack corresponding to maximum wear was determined for both the VD17 alloy and the proposed protective chromium and nickel coatings. Based on the analysis of the obtained results, it was revealed how applied metal protective coatings react to gas-abrasive wear depending on the composition and adhesion to the base.*

Practical value. *The results of the work can be used by designers involved in products that operate under conditions of gas-abrasive wear.Based on the obtained dependences of the wear of the materials depending on the angle of attack, it is possible to choose the optimal material and product configuration in such a way that wear is minimal, as well as to choose the optimal type and method of coating application depending on the configuration of the part and production capabilities.*

Key words: *reliability, wear resistance, gas abrasive wear, wear, electroplating chrome plating, chemical nickel plating.*

Introduction

The main concern of any manufacturer to be successful in the market is to ensure the release of reliable products. Reliability is usually understood as the ability of a certain product to perform its functions according to its intended purpose under certain operating conditions [1, 2]. In practice, one of the most important indicators of reliability in operation is durability. It, in turn, is determined by the time that the product will be able to perform its functions until it enters the so-called limit state. The limit state occurs when repair becomes impossible or impractical. Most often, during operation, the long-term operation of a product is affected by various types of wear, which can affect the product daily and constantly. Wear is understood as the process of gradual destruction of the surface of a product, which leads to a change in its size, shape or mass [3].

In the literature on wear, the greatest attention is paid to mechanical wear. Under different operating conditions, it can take different forms. Within the general science of wear – tribology [4, 5], the greatest attention is paid to the study of wear due to sliding or rolling friction [6, 7].

One of the important mechanical types of wear is abrasive wear, and in particular, gas abrasive wear. Nowadays, many structures and products are made of high-strength aluminum alloys. In particular, they are used for the manufacture of fan and compressor blades of aircraft engines. Achieving a long service life of such engines is

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prevented by the relatively rapid wear of aluminum alloys under the influence of air flow with suspended particles of free abrasive (dust, soot, ice particles, etc.). Protection of aluminum parts from gas-abrasive wear will allow not only to increase the engine service life, but also to reduce its mass.

Analysis of research and publications

Abrasive wear is one of the most common and destructive types of damage to machine parts during operation. In general, it consists in the fact that abrasive particles - bodies with a hardness significantly higher than the hardness of the metal - under different conditions of interaction with the surface of the part lead to its local destruction. The particles themselves can be very diverse in origin, shape, size and hardness. These can be grains of sand, dust, oxides, intermetallics, metal wear products, etc.

Depending on the interaction of abrasive particles with a metal surface, several types of abrasive wear are distinguished: with the participation of fixed and moving particles, with and without lubrication, impact interaction or under low pressure, with high or low speed of mutual movement, etc. Abrasive wear occurs in sliding bearings for various purposes, in parts of construction, agricultural and mining equipment, etc.

Ukrainian scientists [8] have made a significant contribution to the study of the mechanism of abrasive wear, such as B.I. Kostetsky, I.V. Kragelsky and others, and ways to prevent it.

One of the types of abrasive wear is gas abrasive wear. It consists in process of abrasive particles destroy metal, moving at a greater or lesser speed in a gas stream. Gas abrasive wear occurs in buildings under certain meteorological conditions, helicopter engines over sandy unprepared airfields, etc. The features and basic patterns of gas abrasive wear under various conditions were studied by such scientists as G. Evans,I.V. Kragelsky, I.R. Kleis and others [9].

Today it is known that the intensity of gas abrasive wear depends on the flow velocity V and its angle of attack α.

The dependence of wear on the velocity of the gas-abrasive flow is related to the kinetic energy of the abrasive particle at the moment of impact. Therefore, the intensity of wear depends on both the mass of the particle and the speed of its movement in the second degree. It increases with increasing velocity and flow of the carrier gas, and the size and mass of the abrasive particles. In addition, the hardness and shape of the abrasive particles affect the amount of wear.

The change in wear intensity when the angle of attack of the gas abrasive flow α changes depends on the mechanism of destruction of the surface material. The latter, in turn, depends on the properties of the material being worn.

If a plastic material is destroyed, then at small values of the angle α the particles remove metal by cutting and scratching. With an increase in the angle α to 60° and more, destruction due to repeated plastic deformation begins to prevail. In the surface layer, slag gradually appears and accumulates, and the amount of wear begins to decrease.

When it comes to high-strength brittle materials, at small angles of attack the particles slide along the surface and often cannot scratch it. As the angle α increases, the wear rate gradually increases. The brittle fracture mechanism begins to operate, and with a vertical direction of particle impact it comes into full force. That is, at α = 90° the wear reaches a maximum.

Purpose of work

The task of this work is to analyze the patterns of gas-abrasive wear of aluminum alloys of fan blades and compressors of aircraft engines and to find proposals for protecting them from gas-abrasive wear.

Research material and methodology
Gas abrasive wear testing facility

This study used a gas-abrasive wear test rig that fairly well reproduces the wear conditions that exist in aircraft engines.

Currently, there are no specific standards or special methods for studying gas-abrasive wear of structural materials. Therefore, quite diverse installations are used in the research, the main task of which is to create test conditions that are as close as possible to the operating conditions of the relevant machine parts.

According to literature data, existing test rigs are divided into gravitational, mechanical, and pneumatic, based on the principle of the abrasive flow.

In gravity installations, the speed of abrasive particles is created due to their free fall. In such installations, it is difficult to create a high speed at the moment of impact of particles, but it is possible to calculate it quite accurately at the moment of impact. Most often, such installations are used to assess the stability of various coatings, in particular enamel ones.

In mechanical type installations, the speed of abrasive particles is created due to centrifugal forces. The basis of these installations is a rotor rotating around a vertical axis, through the channels of which abrasive particles are accelerated to the required speed. Several stationary samples are installed around the rotor at one angle or another. During testing, it is relatively easy to establish the parameters of the particles at the moment of impact. However, the installation requires accurate dosing of the abrasive supply. In addition, the test result is negatively affected by the flow of abrasive around the edges of the sample.

In pneumatic installations, the required speed is set to the particles by a stream of air or gas, and a flat sample, moving or stationary, is installed at a certain angle to the gas-abrasive jet flowing from the nozzle. Such installations have the ability to change the wear parameters in a wide range, adapting to the operating conditions of the material being studied. Their disadvantage is that the speed of the particles at the moment of impact may not exactly correspond to the speed of the gas flow. There are also difficulties in creating angles of attack close to zero.

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Nevertheless, today this type of installation is the most common, since they make it relatively easy to reproduce any test conditions that are close to operating conditions: in terms of speed and angle of attack of the gas abrasive flow; type, size and concentration of abrasive particles in the flow; composition and temperature of the gas flow, etc.

In this study, a pneumatic type installation was used. During the research, gas-abrasive wear conditions were created in it, close to the operation of compressor blades and fans of aircraft engines (Fig. 1).

The main element of the installation is a rotor with a diameter of 700 mm, which serves to fix 60 samples simultaneously and give them a circular speed. On the front side of the disk, an annular groove of a special shape is machined for fixing the samples. The samples are installed tightly to each other so that only the surface of the samples is worn during the tests. Using a three-stage pulley, the disk can be given the following rotation speeds: 700, 1500 and 3000 rpm. The rotor with the samples is carefully balanced. To eliminate imbalance when testing samples that differ significantly from each other in mass, samples of the same mass are installed on the rotor at diametrically opposite places around the circumference.

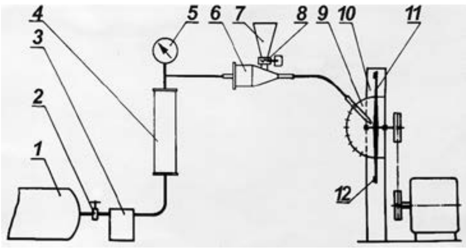

Figure 1. Scheme of the gas abrasion wear test setup:

1 – compressor; 2 – tap; 3 – oil-water separator;
4 – rotameter; 5 – manometer; 6 – mixing chamber;
7 – bunker; 8 – dispenser; 9 – abrasive chamber;
10 – housing; 11 – sample; 12 – rotor

The sample is a flat plate with dimensions of 35×20×2 mm. On the upper edge it has a chamfer that enters the groove of the rotor. The sample is fixed on the rotor with a screw (Fig. 2). To prevent abrasion of the sample when screwing and unscrewing the screw, a conical brass washer is installed between the screw and the sample.

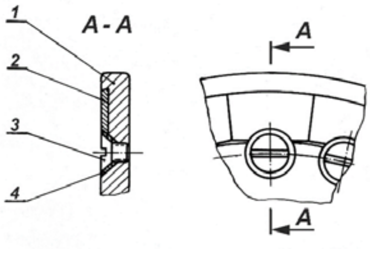

Figure 2. Sample mounting diagram:

1 – rotor; 2 – sample; 3 – screw; 4 – washer

The air flow is created by a compressor. The air supplied to the unit is cleaned in an oil-water separator. The valve sets the volume of spent air necessary to create a given gas flow rate. Its value is determined using a rotameter RS-7.

The unit for feeding abrasive into the gas stream consists of a hopper, a dispenser and a mixing chamber. The dispenser is a profiled screw, which is rotated by an electric motor through a gearbox and thereby ensures continuous feeding of abrasive into the mixing chamber. Using replaceable screws, the concentration of abrasive in the gas stream can be varied within wide limits. In the mixing chamber, a flow velocity sufficient to capture abrasive particles is created. In addition, the abrasive feeding unit provides the possibility of heating the gas stream or introducing additional components (for example, moisture) into it.

In the abrasive chamber, the actual wear of the samples occurs with a gas-abrasive flow with specified parameters. Structurally, it is a flat box, the end part of which includes the edge of the disk with the samples. On its semicircular wall, there are cut holes for a pipe with a replaceable nozzle, from which the flow of abrasive particles is directed to the samples. The cut holes allow the nozzle to be installed in nine fixed positions (every 15°) at an angle relative to the plane of the disk at the same distance from the theoretical point of contact of the abrasive with the sample.

The shape and dimensions of the nozzle outlet ensure that abrasive particles only hit the samples and eliminate wear of the rotor and sample mounting parts. Due to the sufficiently small size of the nozzle outlet and the small distance between it and the sample surface, there is no significant dispersion of the collision parameters of individual abrasive particles in the flow during testing.

At the moment of interaction of abrasive particles and the sample, two types of motions act on them: the circular velocity of the sample and the velocity of particles with the gas flow. Therefore, the actual velocity of particles at the moment of collision was found by geometric addition of the vectors of the corresponding motions (Fig. 3).

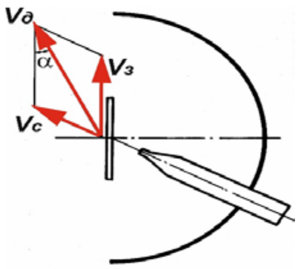

Figure 3. Diagram of the velocities of abrasive particles relative to the sample:

Vs – sample velocity; Vs – jet velocity of the gas abrasive flow;
Vd – actual collision velocity; α – angle of attack

The circular velocity of the point in the center of the sample was taken as the sample velocity Vc. The deviation of the velocities of the extreme points of the sample from the one adopted in the calculations does not exceed 3%. The

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jet velocity of the gas abrasive flow Vc was calculated according to the laws of gas dynamics using the readings of the air volume flow rate by the rotameter and the pressure in the flow by the manometer (Fig. 1). The angle of attack α was calculated according to the data of the velocity triangle.

Research methodology

According to the characteristics of the air flow in the compressors of most aircraft engines [10], the speed of the gas-abrasive flow during the tests varied from 95 to 280 m/s. The installation allows you to change the angle of attack of the abrasive flow from 20 to 860.

For the tests, quartz sand with a particle size of 100...200 microns was used. The sieved and prepared sand for testing was dried in a drying cabinet at a temperature of 120 °C before loading into the batcher and weighed with an accuracy of 0.1 g. At all test speeds, a constant sand concentration in the flow was maintained: 20 g/m^3.

The used sand was not reused because after contact with the samples, the sand particles are crushed, their shape, size, edge sharpness, etc. change. Therefore, the wear results when using fresh and used sand will be different.

In each test mode, 4...6 samples of the same type were simultaneously examined. The samples were weighed before and after the test on an analytical balance with an accuracy of 0.1 mg. The difference in the mass of the sample before and after the test determined the mass wear of the sample. But in order to compare the results of tests of different durations carried out on samples made of materials that differ significantly in density, the obtained mass wear, depending on the density of the tested material, was converted into volumetric and measured in mm3 of the sample material removed from 1 sm^2 of the outer surface of the sample at a consumption of 1 kg of abrasive during the test (mm^3/ sm^{2}kg).

Aluminum alloy VD17

The basis for the research was the aluminum deformed alloy VD17 of the aluminum-copper-magnesium system, which has the following chemical composition: aluminum – the base, copper – 2.6...3.2%, magnesium – 2.0...2.4%, manganese – 0.45...0.70%, iron and silicon – up to 0.3% each.

Alloy VD17 is duralumin with increased heat resistance; it is usually subjected to hardening and natural aging. At room temperature, it has a tensile strength of up to 500 MPa and a relative elongation of 10%, and is characterized by high fatigue strength and fracture toughness.

Duralumin VD17 is used in many branches of engineering. It is used to make truck bodies, building structures, parts in the refrigeration and food industries, etc. In aircraft construction, it is used to make propeller blades, compressors and engine fans operating at temperatures up to 250°C, frames, control rods, etc. [11–13].

Metal protective coatings

Based on the analysis of literary sources, metal protective coatings were selected to protect the VD17 aluminum alloy: electroplating chrome plating and chemical nickel plating.

For electroplating, a standard electrolyte is usually used, which contains: 250 g/l CrO_3, 2.5 g/l H2SO4 at t = 45...55°C and current density i_k = 20...60 A/dm^2.

Temperature and current density significantly affect the current output and properties of cathode chromium deposits. Depending on these parameters, the chromium deposit varies from pale milky and soft to shiny and hard. Different types of coatings are obtained at high current densities and different temperatures. At relatively low temperatures, matte coatings are obtained, and with increasing temperature at constant current density, shiny coatings are obtained.

The following parameters were chosen for chromium plating of the samples: electrolyte containing 300 g/l CrO3, 2.5 g/l H2SO4, current density ik = 45…50 A/dm2, and at a temperature of t = 45...500 °C, matte coatings were obtained, and at a temperature of t = 50...65°C, shiny ones were obtained [14, 15]. The microstructure of the electroplated chromium coating on the VD17 alloy is shown in Fig. 4.

One of the main advantages of chemical nickel plating is the ability to obtain a uniform coating layer on parts of any complex configuration (including compressor blades). Chemically deposited nickel has certain advantages: the surface of the coating is shiny, its hardness is higher than that of electrolytic nickel deposits, the coating does not reduce fatigue strength.

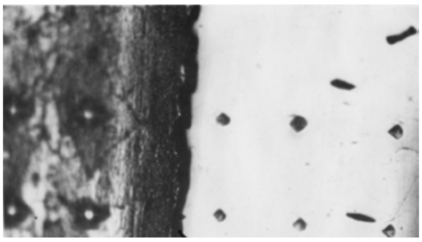

Figure 4. Microstructure of electroplated chromium coating on VD17 alloy

For chemical nickel plating of aluminum alloys, alkaline solutions (pH = 8...10) are used due to more favorable conditions for the process on the surface of light alloys [16]. Nickel plating of samples was carried out in a solution of the following composition: nickel chloride (II) $NiCl_2$ – 21 g/l; sodium hypophosphate – 24 g/l; sodium citrate – 45 g/l; ammonium chloride NH_4Cl – 30 g/l; ammonium hydroxide NH4OH – 50 g/l at an acidity of pH = 8.5...9.5 and a temperature of 75...800 °C. The process lasted 6...8 hours with regular adjustment of the acidity of the solution using ammonium hydroxide.

The resulting coating, 40...60 microns thick, is actually a solid solution of phosphate in nickel with small inclusions of phosphides. Chemical analysis showed that the precipitate contains 96...97 % nickel and 3...4 % phosphorus.

Nickel-plated samples were divided into two groups. The samples of the first group were annealed at a temperature of 2300 °C for 45 min. in order to improve the adhesion of the coating to the base. The samples of the second group, in addition to similar annealing, were subjected to hardening and aging according to the regime usual for the VD17 alloy (Fig. 5).

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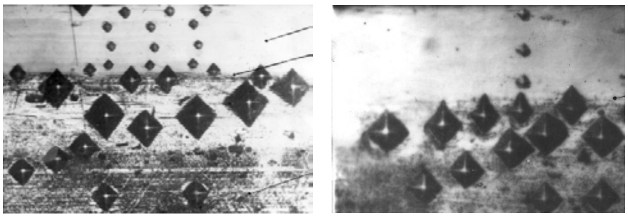

a *b*

Figure 5. Microstructure of nickel coatings processed in the first mode (*a*) and in the second mode (*b*)

Research results

The study showed that the main influence on the wear rate of a structural material under the action of a gas abrasive flow is the velocity of the abrasive flow and the angle at which the abrasive flow acts on the surface of the material. The dependence of the wear rate on the angle of attack for all the studied materials was typical for plastic materials: with an increase in the angle of attack, wear increases and, having reached a maximum, smoothly decreases (Fig. 6).

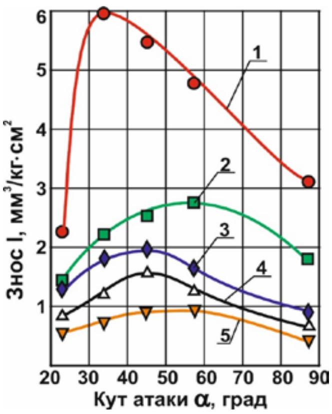

Figure 6. Dependence of wear of VD17 alloy and coatings on the angle of attack at a gas abrasive flow velocity of 95 m/s:

1 – VD17 alloy, 2 – nickel coating, h/t 1,
3 – nickel coating, h/t 2; 4 – matte chrome coating,
5 – shiny chrome coating

The angle of attack of the flow α, which corresponds to the maximum wear, depends on the mechanical properties of the material of the samples. The smallest angle of attack is for the VD17 alloy. The angles of maximum wear of the coatings are somewhat larger, being in approximately the same range. This is due to the increase in the hardness of the worn material.

Also, with increasing gas-abrasive flow velocity, a shift of the wear maximum towards larger angles of attack is observed. In this case, the greater the hardness of the worn material and the greater the abrasive flow velocity, the less clearly the maximum on the wear-angle of attack curve is manifested (Fig. 7).

Discussion

There is a noticeable difference in the wear of the aluminum alloy and nickel and chromium coatings. This is due to the significantly different physical and mechanical properties of the coating metals and aluminum. At the same time, the study showed a sufficiently high quality of adhesion of such different metal coatings to the aluminum surface.

The angle α, which corresponds to the maximum wear at a certain flow rate, is different for all materials. The smallest angle α of maximum wear is for the aluminum alloy VD17. With increasing material hardness, the maximum shifts towards larger angles. The same shift is observed with increasing gas abrasive flow rate. In this case, the greater the hardness of the material being worn and the greater the flow rate, the less clearly the maximum appears on the wear-angle of attack curve.

As for the quantitative characteristics, the degree of wear reduction of metal coatings depends on the hardness of the corresponding coating, and the order of the wear curves is preserved at all angles of attack and velocities of the gas abrasive flow.

The protective properties of nickel coatings are quite stable at all speeds: nickel coating heat-treated according to the first mode increases wear resistance by 2.3...2.7 times, and heat-treated according to the second mode - by 3...4 times. The difference between the wear of both nickel coatings is 15...35%.

The difference in maximum wear of chrome coatings is 40...60 %. The effectiveness of protection of aluminum alloy by chrome coatings increases with increasing abrasive flow rate. Shiny chrome coating increases the wear resistance of VD17 alloy by 6.5...9.0 times, matte – by 4...7 times.

The intensity of wear growth of nickel coatings with increasing flow velocity is somewhat higher than that of chromium coatings. The most sensitive to the increase in abrasive flow velocity is alloy VD17.

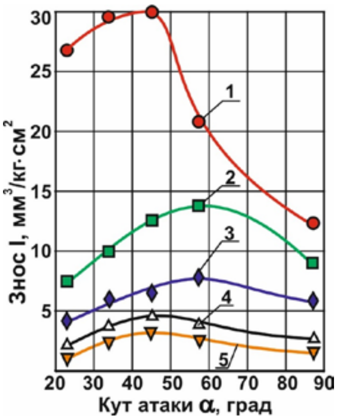

Figure 7. Dependence of wear of VD17 alloy and coatings on the angle of attack at a gas abrasive flow velocity of 280 m/s

1 – VD17 alloy, 2 – nickel coating, h/t 1, 3 – nickel coating, h/t 2, 4 – chrome matte coating, 5 – chrome shiny coating

Conclusions

1. A detailed analysis of the regularities of gas abrasive wear of the VD17 alloy was carried out.

2. To increase the wear resistance of the VD17 alloy,

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galvanic chromium and chemical nickel coatings were proposed and the patterns of their wear in a gas-abrasive flow were studied.

3. The influence of the physical and mechanical properties of coatings on resistance to gas abrasive wear was analyzed.

4. Based on the comparative evaluation of the quantitative wear characteristics of protective coatings, it can be concluded that both coatings can be used to protect machine parts made of VD17 alloy from gas-abrasive wear. The choice depends both on the conditions of interaction of the part with the flow and on the possibility of applying a high-quality galvanic or chemical coating to the part.

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ЗАХИСТ ДЕТАЛЕЙ МАШИН З АЛЮМІНІЄВИХ СПЛАВІВ ВІД ГАЗОАБРАЗИВНОГО ЗНОШУВАННЯ

Володимир Плескач — канд. техн. наук, доцент кафедри композиційних матеріалів, хімії та технологій, Національний університет «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: vmpayzp@gmail.com*, ORCID: 0000-0002-6182-4332

Іван Акімов — канд. техн. наук, доцент кафедри композиційних матеріалів, хімії та технологій, Національний університет «Запорізька політехніка», «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: akimovi@ukr.net*, ORCID: 0000-0001-6076-0149

Світлана Кирилаха — магістрант кафедри інтегрованих технологій зварювання та моделювання конструкцій, Національний університет «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: lanakirilaha@gmail.com*, ORCID: 0009-0001-5688-5616

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Мета роботи. *Полягає в аналізі закономірностей газоабразивного зношування алюмінієвого сплаву ВД17, у знаходженні захисних покриттів, які можуть забезпечити ефективне зменшення зносу, та надання рекомендацій щодо оптимального типу захисного покриття.*

Методи дослідження. *При дослідженні використовувалася установка, конструкція якої дозволяє змінювати параметри газоабразивного зношування у широких межах, які б якнайкраще відтворювали умови зношування деталей машин за різних умов експлуатації. Дослідженню піддавалися зразки з алюмінієвого сплаву ВД17 і металеві захисні шари, нанесені на нього гальванічиним і хімічним способами. Дослідження проводилося із застосуванням металографічного аналізу з метою виявлення структури, яка забезпечує оптимальний захист від газоабразивного зношування.*

Отримані результати. *У ході роботи проведений аналіз характеру і величини зносу матеріалів, що досліджувалися, у потоці вільного абразиву залежно від швидкості абразивного потоку і його кута атаки. Визначено ступінь зменшення зносу алюмінієвого сплаву ВД17 при використанні хромового і нікелевого захисних покриттів. На підставі порівняльного оцінювання кількісних характеристик захисних шарів визначено можливості цих покриттів зменшити знос сплаву ВД17 при дії газоабразивного потоку.*

Наукова новизна. *Визначена величина кутів атаки, які відповідають максимальному зношуванню, як для сплаву ВД17, так і для запропонованих захисних хромового і нікелевого покриттів. На підставі аналізу отриманих результатів виявлено, як реагують використані металеві захисні покриття на газоабразивне зношування залежно від складу і зчеплення з основою.*

Практична цінність. *Результати роботи можуть бути використані конструкторами, що займаються виробами, які працюють в умовах газоабразивного зношування. На підставі отриманих залежностей зносу матеріалів, що досліджувалися, від кута атаки є можливість обрати оптимальні матеріал і конфігурацію виробу таким чином, щоб зношування було мінімальним, а також обрати оптимальний вид і спосіб нанесення покриття залежно від конфігурації деталі та виробничих можливостей.*

Ключові слова: *надійність, зносостійкість, газоабразивне зношування, знос, гальванічне хромування, хімічне нікелювання.*

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