Bi-metal foil gas dynamic bearings with bimorph piezoelectric foils

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Abstract. The present paper considers application of bi-metal materials and coatings to provide necessary strength and wear resistance of the surfaces of rigid and elastic gas dynamic bearings. Authors suggest using multi-layer foils with bimorph piezoelectric elements that operate in the generator regime to determine the deformation of elastic elements, and in the actuator regime to form an optimal shape of the surface of the bearing.

1. Introduction

Nowadays, rotor systems are key elements in machinery systems. These systems are subject to a number of mandatory requirements, namely: reduction in size, weight, increased requirements for reliability and energy efficiency indicators, high vibration resistance, etc. The most vulnerable and at the same time, the most important element of the rotary system is the bearing assembly, which is the most loaded during the operation of the device. Rolling-element bearings are standard elements with a developed methodology for selecting the required structural and geometric parameters. Fluid-film bearings in each particular case involve significant preliminary calculations for the choice of bearing type, geometric parameters and lubricant. However, there is a problem associated with the occurrence of situations not envisaged in the design process, which lead to disruptions in the operation of the rotor support assembly and the turbomachinery as a whole. One of the most modern and promising ways to protect parts and assemblies of various mechanisms from the resulting intense wear is the use of antifriction coatings – lubricants similar to paints, but containing fine particles of solid lubricants uniformly distributed in the mixture of binder elements and solvents instead of a coloring pigment. Modern technologies allow the creation of various thin-film coatings to improve the tribological characteristics of friction pairs. Examples of such coatings are wear-resistant and antifriction thin films, which increase the lifetime expectancy of machine parts. Providing durability and wear resistance of thin-film coatings is a complex technical task.

2. Application of antifriction coatings

Modern trends in the development of industrial production are characterized by increased requirements for quality and performance. The development of technology necessitates the creation of materials possessing a complex of properties that provide high strength, corrosion resistance, thermal conductivity, heat resistance, wear resistance, etc. Often, individual metals and alloys cannot provide the required range of properties. Therefore, layered metal compositions have been widely used. Such materials can be manufactured by combining dissimilar metals in a monolithic composition that preserves

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the reliable coupling of the components during further processing and under operating conditions. Such materials include bimetal-layer materials consisting of two or more metals and alloys. The use of layered metal compositions makes it possible to increase the reliability and durability of a large class of parts and equipment. As a result of the cost savings of non-ferrous metals (Ni, Cr, Cu, Mo, Ti, etc.), the cost of manufacturing them is reduced. The use of layered compositions allows for the development of more sophisticated design solutions for the creation of modern machines, instruments and apparatus. Today, bimetals are the most important group of industrial materials with a wide range of properties. The use of bimetals allows significantly increasing the efficiency of production of a wide class of parts and equipment for chemical, oil, agricultural, transport, energy and other machine-building industries. By application, all currently produced bimetals can be subdivided into the following types: corrosion-resistant, antifriction, electrotechnical (conductor and contact), instrumental, wear-resistant, thermobi-metal.

Values such as: roughness, friction coefficient of of rest / slip, hardness - could be determined experimentally using the characteristic equipment (hardness tester, tribometer, profilometer). In a more complicated situation, the definition of the wear resistance value is found. This process is extremely complicated, because it combines a large number of parameters. It is based on the friction force, which in turn is divided into adhesion and deformation components. To evaluate each of the components it is necessary to conduct a large number of different experiments, which in turn makes it difficult to select the coefficients. Simulation of the process is complicated by the influence of varying roughness, temperature, etc. In the process of friction, these quantities change unpredictably, which makes the process of evaluating the wear of thin-film coating difficult. At the moment, studying the wear resistance of thin-film coatings is an important technical task. There are many different domestic and foreign methods of investigation of thin antifriction coatings, which differ significantly from one another (the method of "friction difference", the method of measuring the main momentum and forces, Archard equation). Analysis of the studies showed that there are two ways to determine the wear resistance of thin films (coatings). In the first case, it is necessary to create a mathematical model for the destruction of the coating, by selecting the coefficients with a step-by-step stop of the wear process. In the second case, it is necessary to conduct a direct experiment until complete wear of the coating. The mechanism of action of antifriction coatings is as follows. After polymerization, the binder elements together with the dry lubricants fill the cavities of the microroughness of the surface and increase its supporting area (Figure 1).

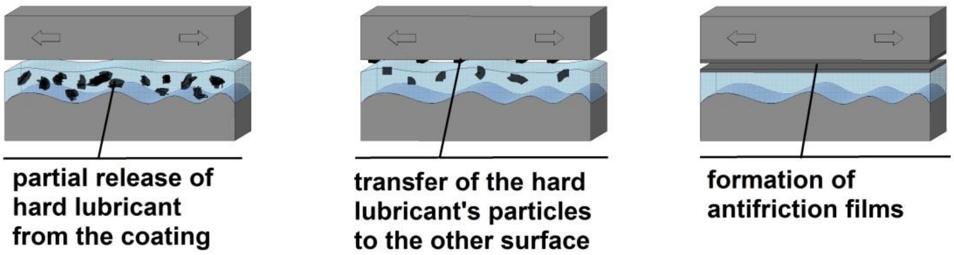

Figure 1. Antifriction coating mechanism.

In the process of friction, some of the lubricating particles are transferred to the conjugate surface. In this case, they are oriented parallel to the direction of motion, forming a smooth and slip protective anti-friction film on both surfaces. Such antifriction coatings are made on the basis of molybdenum disulfide, graphite, polytetrafluoroethylene, as well as compositions of various solids, the content of which, depending on the type of coating, can reach 70%. Dry lubricants in coatings provide the necessary complex of properties. Binders determine its protective properties, chemical resistance and type of curing.

The technological process of preparation depends on the material and condition of the workpiece. Adhesion and lifetime expectancy of antifriction coatings depend largely on the applied technology of preliminary preparation of parts' surfaces. In the Figure 2, a diagram of the dependence of the lifetime expectancy of the coatings on the methods of preliminary preparation of the surface is presented.

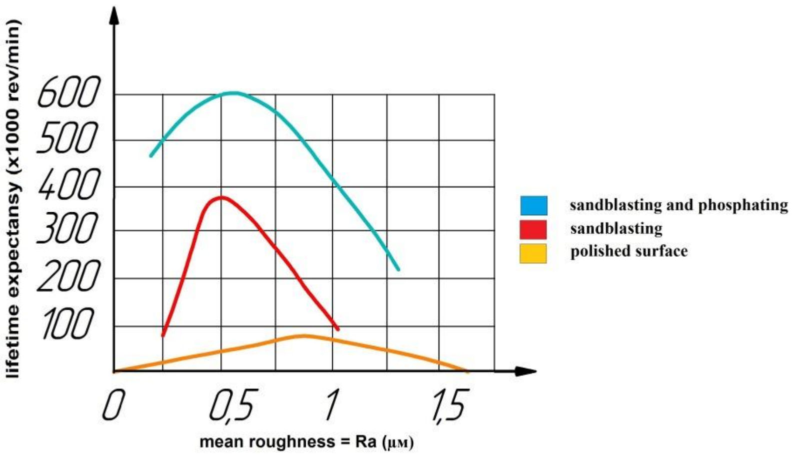

Figure 2. Lifetime expectancy versus methods of preliminary treatment of the surfaces.

Preparation for the application of antifriction coating begins with degreasing. This technological operation can be carried out with organic low-fat solvents, manually, and also with the help of ultrasonic cleaners. The washing operation is performed several times until all traces of fat are completely removed from the surface. In this case, a new solvent must be used for the next wash. After degreasing the parts are dried in air. Do not touch the treated surfaces with hands. The oxides present on the surface being treated are removed by chemical (etching, anodizing and phosphating) or by mechanical methods (sandblasting, polishing). For pre-treatment of metallic materials, phosphating and sandblasting are particularly well established. A rough, porous surface after preliminary treatment promotes mechanical adhesion to the antifriction coating, thereby achieving a much better adhesion. As a mechanical method for steel, titanium, aluminum, copper, magnesium and their alloys, sandblasting with alumina or cast steel (grain size about 55 microns). This type of preliminary surface preparation is also required for chrome and nickel-plated parts. In addition to removing corrosion, sandblasting makes the surface of the part more rough (Ra from 0.5 to 1.0 μm) and provides better adhesion of the antifriction coating. According to the technology, after completion of work, it is necessary to remove adherent sand particles with dry compressed air, not containing oil. To avoid the risk of corrosion on the surfaces treated in this way, antifriction coating is required in the shortest possible time. It should be taken into account that during sandblasting of parts, their linear dimensions change to 1.3 μm. After sandblasting, it is possible to apply an antifriction coating, however, for a longer service life of the coating, it is recommended to phosphate the part (subject the surface to pickling). For processing parts made of copper and copper alloys, instead of sandblasting, etching with a mixture of two or more acids (sulfuric, phosphoric, nitric, chromic, and hydrochloric) can be used. Etching of stainless steel is made by special solutions of oxalic acid. The immersion time, the concentration of the solution varies depending on the alloy and the state of the surface. After etching, thoroughly clean the parts to remove acid residues. Aluminum and its alloys are processed by electrolytic oxidation (anodizing). Aluminum alloys with a copper content of 0.5% or more, as well as alloys with a total content of dopants in excess of 7.5%, are treated in a solution of sulfuric acid. After treatment with sulfuric acid, the parts must be washed in water, then the surface film must be fixed by immersion in a 5% solution of sodium or potassium dichromate, rinsed and dried. Drying is performed at a temperature of no higher than 102 ° C. Other aluminum alloys and aluminum can be processed in a solution of chromic acid. Chromic acid forms a thin film, which provides protection from corrosion. After treatment with chromic acid, the part must be rinsed in hot water and allowed to air dry. To form a good surface film in acid solutions, it is necessary to use high purity water (with a low content of chlorides and sulfates). After anodizing before applying to the part of the antifriction coating, they must not be touched with bare hands.

Phosphating (Figure 3) is used for iron and steel, but is not suitable for stainless steel, galvanized cast iron and parts with cadmium and galvanic coating. Treatment with manganese phosphate increases the bearing's load capacity and lubricating properties of the coating. Zinc phosphate treatment improves its corrosion resistance. Iron phosphate improves adhesion with antifriction coatings. For phosphating, only those solutions are used that create layers of small crystals. Most of the particles deposited on the surface must be in the range of 3 to 8 μm. This is equivalent to the weight of the applied layer from 5 to 15 g / m^2. After treatment, the phosphate layer should have a smooth, uniform structure and color from gray to black. Spots of phosphating solution and corrosion marks on the surface of parts are not allowed. To avoid corrosion under the influence of moisture contained in the ambient air, antifriction coatings should be applied as soon as possible after phosphating.

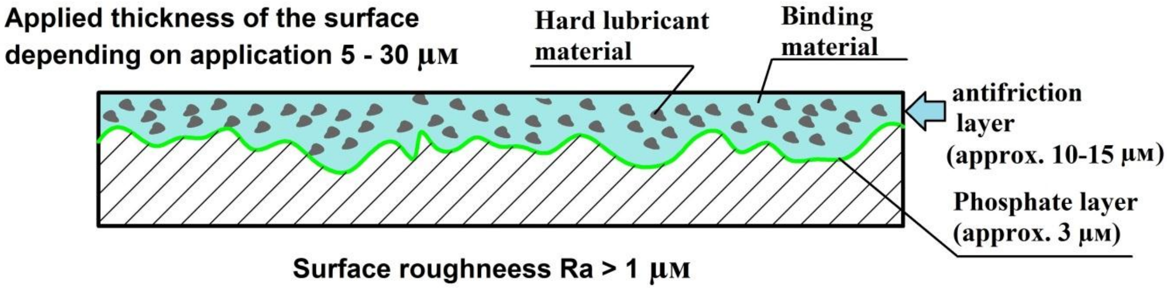

Figure 3. Model of antifriction coating formation.

The most important process is the application of the antifriction layer. Antifriction coatings (Figure 2) are dispersions of selected solid lubricants in solutions of organic or non-organic compounds in solvents or water. After applying and drying, antifriction coatings form a strong bond between the binding agent and solid lubricants. In the case of tribological requirements, the transferred solid materials are transferred to the mating component, a transfer film is formed, which leads to a reduction in the so-called shearing forces and, therefore, leads to a decrease in the friction coefficient. To date, there are a large number of different binders and hard materials with different properties, also based on nanoparticles.

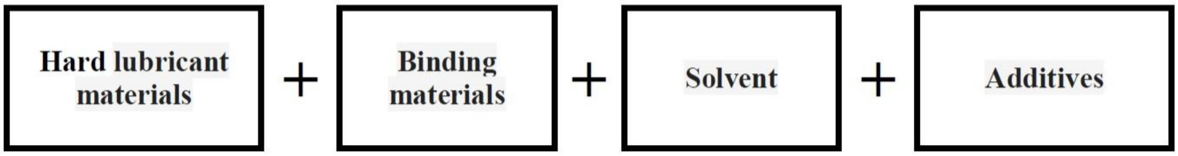

Figure 4. Contents of an antifriction coating.

Depending on the shape, size, weight, quantity and material of the work pieces, as well as surface properties, various methods of applying antifriction coatings are used. When choosing the method of applying antifriction coatings, it is necessary to take into account the requirements for the film, the configuration and location of the coated sliding surfaces. The quantity of the prepared composition is calculated taking into account the viability indicated in the technical documentation for the material and the area that can be covered during this time. Antifriction coatings can be applied by spraying, immersion, brushing, roller coating and screen printing. The final step is to control the thickness of the coating. The thickness of the film has a significant effect on the service life, friction coefficient and anticorrosion properties of antifriction coatings. It should exceed the size of the surface irregularities of the contacting surfaces, making, as a rule, from 5 to 20 microns. The application of a coating on both interfaced surfaces with a relatively thin layer provides a greater load-capacity than a thicker layer on only one surface.

3. Application of bimorph piezoceramic elements in foil gas dynamic bearings

The introduction of monitoring and active control in the rotor-bearing nodes will solve the problem of occurrence of situations unforeseen during the design s of by varying the shape of the radial and axial clearance, as well as by changing the rigidity of the elastic support surface. In addition, active control will expand the scope of sliding bearings. At the same time, active control is realized by various actuating mechanisms, which act on the regulated body by means of an electromagnetic field, mechanical forces, piezoelectric effect. The latter acquires the most popularity today and is realized due to devices called piezoactuators or piezoelectric drives. Such devices have unlimited resolution capabilities, piezoelectric converters convert electrical energy directly to mechanical, they are able to move in the subnanometric range (this property is useful when correcting the gap's geometry between the rotor and the bearing housing), the speed of operation of such actuators is in the microseconds range, existing to date powerful packet actuators are capable of moving 100 tons or more by 250-500 microns with a minimum step of 0.05 - 0.1 μm; and other properties [1].

The developing direction in the field of piezoactuators is the use of combined flexible lamellar elements containing metal layers and piezoceramics. A combination of such elements is called plate-like flexural actuators [2] or bi-morphs. There are two types of bimorphs: parallel and sequential. In the parallel bimorph, the direction of polarization of the plates is the same. This determines the high sensitivity and the ability to use for control the bias voltage, which generates an electric field parallel to the direction of polarization, thus reducing the risk of depolarization. In the sequential bimorph, the polarization direction of the plates is opposite. To avoid depolarization, the maximum electric field is limited to several hundred volts per millimeter of thickness. Bimorph can work in two modes (Figure 5). When using the direct piezoelectric effect, the mechanical energy applied to the bimorph is transformed into electrical energy. The mechanical force causes bending of the bimorph, at the same time compression of one of the constituent plates and expansion of the other occurs, which causes the formation of a charge in the bimorph. Bimorph works in a generator mode. Bimorph, operating in this mode, is used as a flexible sensor. The sensor of the generator type does not require an external power source to operate. Such a sensor is designed to convert dynamic deformations into electrical signals, followed by processing and recording by various devices. The sensor can be used as an independent converter of mechanical deformation into an electrical signal, or be an integral part of a more complex device. The sensor can be connected to a monitoring and control system in two main ways: according to the voltage acquisition scheme or the current acquisition scheme. Bimorph, using the inverse piezoelectric effect - conversion of electrical signals into mechanical forces – is a piezoelectric actuator. The bimorph piezoelectric actuator is a passive non-linear four-terminal network and requires the presence of a power source for excitation. In the sequential bimorph the plates are connected sequentially in relation to the power supply. In this case, the plate with positive polarity is under the influence of positive voltage and, due to the inverse piezoelectric effect, lengthens, then as a plate of negative polarity does not work and prevents this length change, which leads to bending of the bimorph. Since the piezoceramic element has the properties of a capacitor, the energy absorbed by it is released gradually after the voltage is cut off. In order for the bimorph to quickly return to its original state, there are two resistors between the electrodes.

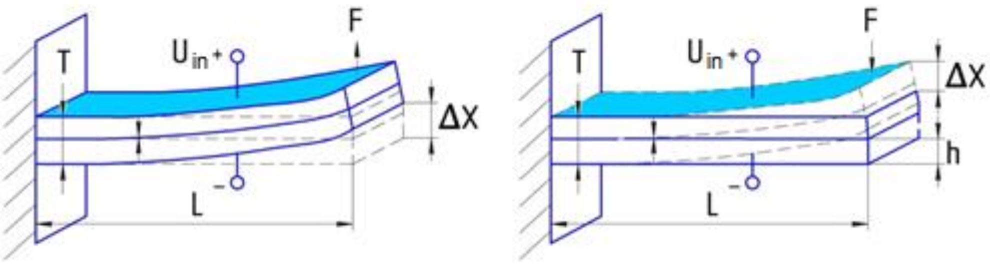

Figure 5. Operating modes of a piezoelectric bimorph.

Based on the piezoelectric effect in 1992, Tsumaki Nobuo proposed the construction of a foil gas dynamic bearing with bimorph piezoelectric foils (Figure 6), which operate in the generator mode, based on direct piezoelectric effect. The presented design is a foil gas dynamic bearing with a control system and allows recording of signals generated from deformation of piezoelectric bimorph elements. Determination of permissible deformations allows adjusting the structure to prevent an emergency situation, as well as continuously tracking the state of the elastic surface.

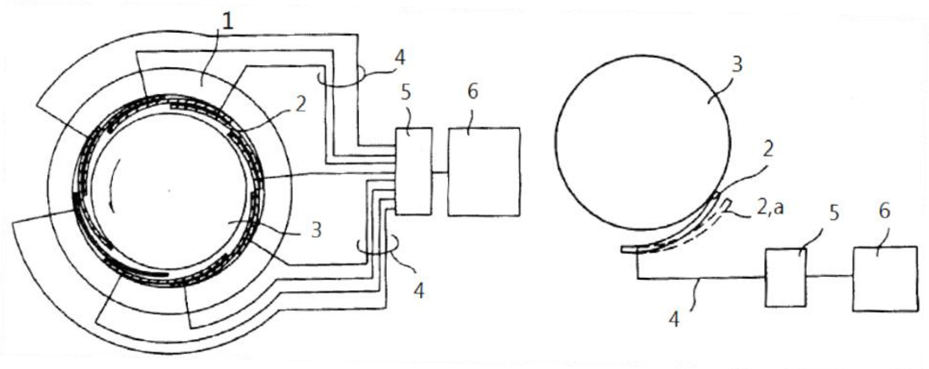

Figure 6. Foil gas dynamic bearing with bimorphs, patent JPH № 0454309: 1 – bearing's housing, 2 – bimorph piezoelement in the initial state, 2,a - bimorph piezoelement in a generator mode under the influence of gas dynamic pressure, 3 – rotor, 4 – wire connections, 5 – ADC, 6 – controller.

As is known from NASA reports, as well as scientific works of scientists in the field of petal gas-dynamic bearings, the most dangerous for this type of bearings are the periods of starting and stopping, when the friction interaction of the shaft surface and elastic elements occurs. To ensure the strength and durability of the surface of elastic piezoelectric elements, it is necessary to cover with wear-resistant antifriction coatings. In general, the separately taken elastic element will represent a multilayered structure (Figure 7), in the middle of which it is necessary to lay an elastic base, to increase the rigidity and fatigue strength of the bimorph piezoelectric element. The piezoceramic plates placed on opposite surfaces of the elastic base must have a different sign connection, as shown in the Figure 5. On top of the piezoceramic elements are covered with a layer of antifriction wear-resistant material.

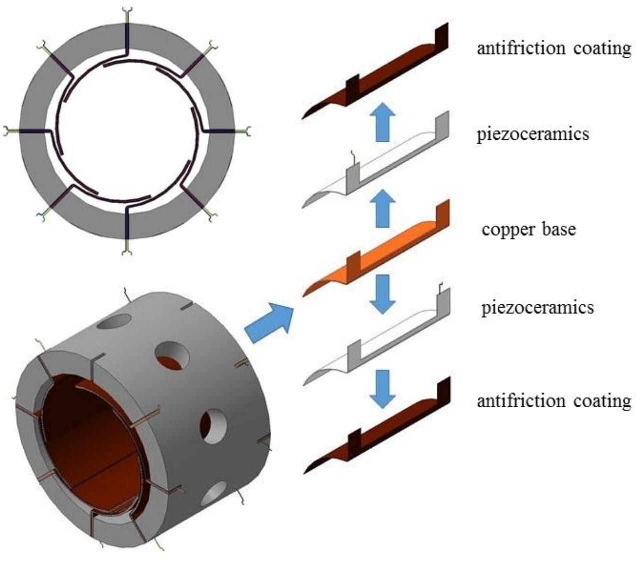

Figure 7. Design of a foil gas dynamic bearing with bimorphs.

According to the multi-layered bearing concept presented above, the technological process of manufacturing was developed, the results of which are shown in Figure 8. The central base of the petal can be made of various materials (copper, beryllium bronze, stainless steel). The base increases the mechanical strength of the bimorph, but reduces the amount of movement. In our case, the petals were made of copper (a). To protect the copper surface of the petal from corrosion and external exposure to the environment, a nickel-based coating was used, then the surface was coated with a special lacquer which is an electrical insulator, and also protects against humidity and other influences, which increases the lifetime expectancy b). Using the gluing method, apply a layer of piezoceramics on each side of the petal (c). The thickness of the adhesive layer is 10 - 15 μm. For gluing, epoxy or acrylic glue is used. The elasticity of the adhesive compound usually eliminates the appearance of vibration fatigue during prolonged operation. Electrodes made of lead or nickel are applied to the piezoceramic plate, and the thickness of the layer is 6-10 μm [3].

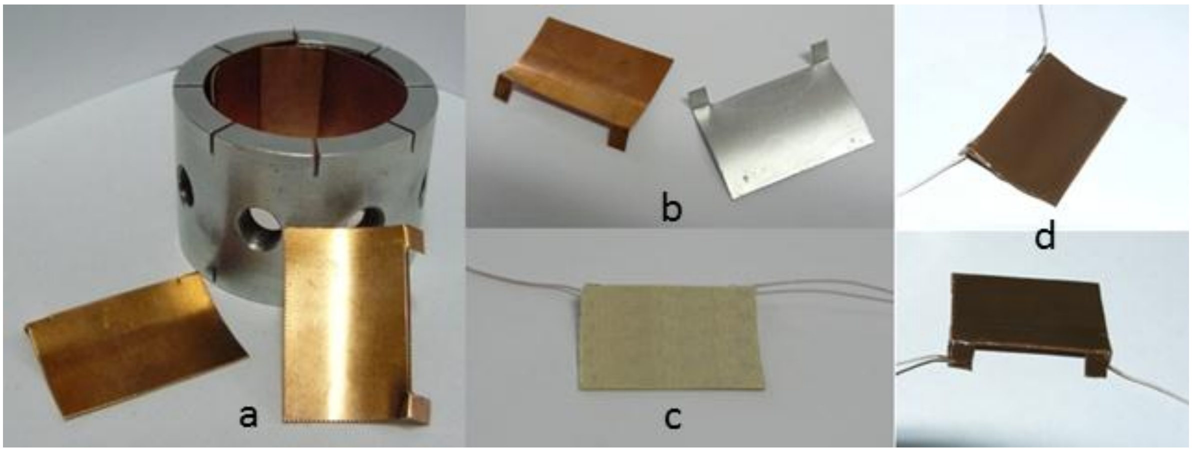

Figure 8. Foil gas dynamic bearing with bimorphs.

After applying the electrodes, the plate is polarized in a strong permanent electric field and acquires piezoelectric properties. Layered technology increases flexibility and allows increasing the degree of deflection of the actuator. In the final stage, antifriction coatings are applied to the surface of the petals using conventional staining techniques, such as spraying, screen printing, dipping, brushing. After coating and drying, the solvent evaporates and the binders polymerize and ensure reliable adhesion to the substrate (d). The choice of a particular method of applying antifriction coatings depends on the geometry of the parts to be coated and the desired result in terms of uniformity and durability of the coatings.

Conclusions

The ways of prevention of emergency situations presented in the article are based on the use of bimetallic coatings, as well as intelligent technologies based on the piezoelectric effect. This approach leads to the emergence of a new class of mechatronic elastic-damper supports with an increased service life and a minimum accident rate. Active monitoring in the most loaded rotor-support nodes will allow to constantly monitor the signature of vibration, to provide real-time information about the deformation of each individual elastic element, which also has a significant scientific interest.

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