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Improvement of Operational Parameters for Precision Rolling Bearings by Cleaning Working Surfaces from Micro Pollution of Various Nature

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Abstract. In manufacturing high-precision rolling bearings for aviation and urban machinery, the key tasks are to reduce the cost of production of such products, increase their efficiency and resource, and ensure their reuse after performing appropriate repair work. The results of many years of research show that these tasks can be successfully solved by cleaning the working surfaces of the parts of such precision tribonodes by non-contact pulse methods, particularly by using variable electromagnetic fields. The article describes the process of deep cleaning the working surfaces of parts of various high-precision ball bearings (from overall to miniature). During this cleaning, ferromagnetic and other impurities in the form of micro-, sub-micro- and nanoparticles were removed on a developed stand that can be used on an industrial scale. Further studies of cleaned bearings showed improved operational parameters such as reduced noise and vibration and the degree of magnetization. To achieve the specified results, appropriate cleaning methods were developed and tested.

Keywords: miniature ball bearings, nanopollution particles, vibration speed, vibration acceleration, pulse-magnetic-turbulent cleaning, ultrasonic method.

1 Introduction

The performance, reliability, and resource of modern land and aviation equipment, technological machines, and various devices and equipment depend on the accuracy and quality of bearing assemblies and rolling bearings. In addition, with a high accuracy class of bearings, their final cleaning operations at manufacturing enterprises do not always ensure the declared quality. First, precise bearings of small sizes (including miniature ones) used in aircraft engineering and instrument-making fall into this problem. One of the ways to increase it is to increase the efficiency of removing production micro-, sub-micro- and nanoparticles caused by new bearings and operational parts, one of such types of nature [1, 2]. Along with rolling bearings, this approach is appropriate for precision parts of complex shapes, which are widely used in mechanical systems of aviation, space technology, the machine-building industry in general and engine-building industries. As in mechanical processinare while ensuring the necessary accuracy of various types of parts and the quality of processed surfaces [3-5], effective cleaning of such micro metal products is not always ensured, which in the process of work worsens the occurrence of various types of unwanted noises and vibrations [6, 7], accelerates the initial surface wear and affects its naturey [8, 9].

Traditional cleaning methods are used to remove industrial contaminants from the working surfaces of machine parts and mechanisms. Today's most effective methods are based on ultrasonic waves, which cause cavitation in the liquid. This makes it possible to destroy the integrity of the pollution film and destroy them from the place of deposition in the zone of action of the flow of this medium. However, even such highly effective methods do not allow for the qualitative removal of micro- and nano-ferromagnetic particles of damage from bearing surfaces. The one-vector nature of the action of activating and destructive pollution fields and forces, the static nature of the cleaning object, and its design features lead to the creation of certain areas of shading of working surfaces by structural elements. Based on this, the nature of micro- and nano-particle damage and the mechanisms of their retention by fairly massive ferromagnetic parts of ball bearings [10] are not sufficiently studied. However, appropriate practical monitoring and diagnostic possibilities are offered [11], which facilitates the collection of statistical data. Modern lubrication systems of aircraft engines include dozens and two ball bearings of an open type, the lubrication of which is implemented by circulating the lubricating fluid.

The requirements for the latter are extremely high. The size of the contamination particles must be less than 3 μm, which meets the requirements of the 12th class according to the international purity classification for aviation lubricants. No less responsibility should be applied to plastic lubricants, which fasten bearings [12].

It is evident that during the assembly of, for example, a gas turbine engine, all parts, including non-dismountable ball bearings, must be subjected to pre-operational preparation, which aims to diagnose and maximally remove existing contaminants of various natures and sizes. Therefore, the problem of highly effective cleaning of ball bearings, working surfaces of precision spools, and distributors, which are part of the corresponding units and systems of precision devices, especially in aircraft engine construction, remains relevant not only during repairs but also during the manufacture and assembly of new units and nodes of gas turbine engines.

2 Literature Review

A thorough literature analysis shows that during the production and operation of machines and mechanisms, on the working surfaces and between the parts of the friction nodes, small particles of dirt are collected and accumulated, sticking to the edges of the seals, which can be separated from the liquid mechanically or with the help of force fields. In the first case, various filters are widely used for filtering working fluids. In the second, pollution particles are removed from fluids by gravitational, centrifugal, magnetic, electric, and other fields.

It is known that the deposition of small particles smaller than 10 μm in a gravitational field can last several days, even with a small height of the liquid column. м of particles by tens and hundreds of thousands of times, carrying out a controlled filtration process. The results of experiments on removing micro-pollution from the working surfaces of miniature bearings show the weak effectiveness of these methods concerning micro-, sub-micro- and nano-sized pollution particles.

Currently, in addition to traditional methods of cleaning parts, such as cleaning with alkaline aqueous solvents [15], various solutions and compositions that allow cleaning of its parts and ball bearings without disassembling the mechanism before the scheduled replacement of lubricant [16], new technologies for cleaning surfaces from mechanical burrs are being created, hydraulic methods, as well as using ultrasound [17].

Today's most common and effective methods are based on ultrasonic waves, which cause cavitation in the liquid. Nevertheless, even such highly effective methods sometimes fail to remove sub-micro dirt from ball bearings. The reason for this is the single-vector nature of the action of fields and forces that activate and destroy pollution, as well as the static nature of the cleaning object and its design features. This contributes to the formation of particular zones of shading of the working surfaces by structural elements and leads to the fact that it is challenging to clean ball bearings without detailed disassembly effectively, and when using non-disassemble ones, it is impossible.

There are ways and methods [18, 19] that realize the forced mutual movement of the structural elements of the bearing when creating ultrasonic vibrations in a constant flow of washing liquid. Forced contact rotation or movement reduces the time of action of the liquid on the working surfaces, and a complex mechanical drive can become a source of additional contamination. All these charges lead to the insignificant efficiency of such devices.

The most extensive are the theoretical and experimental ones, which reveal the malfunction of rolling bearings at the initial stage of their operation by analyzing the fluctuation of the amplitude of vibration signals [20] using the so-called performance indicators [21, 22] or using the methods of investigating bearing defects by electrical methods based on resonance [23]. However, such methods are more adapted to laboratory research and are very complex and not consistently effective for practical use and an actual increase in durability and service life of high-precision rolling bearings.

Almost all types of precision ball bearings design a small cross-section of gaps between elements, thin channels of the complex primary profile, and mutual overlap of working surfaces due to design features forming a unique set of problems, the solution of which requires a special approach.

3 Research Methodology

In modern tribotechnics, a special place is occupied by the problems of precise mechanics, in connection with which the requirements for their functionality, in addition to the standard requirements for the quality of wear resistance and anti-friction, are constantly increasing: in terms of noise level – in particular underwater, aviation and land systems and complexes; by the level of vibrations and noise – in highly sensitive electromechanical systems. At the same time, all rolling tribosystems are constantly being asked to increase their service life. Taking into account the experience of previous studies obtained in the course of scientific and research work, the team of authors developed a method and stand for cleaning the contacting surfaces of friction nodes, which is based on the idea of excitation and removal of micro- and submicron-ferromagnetic particles by acting on them by pulsed variable magnetic fields, which remove them from the surfaces, move them, pulling them on themselves and keeping them in the zone of the fields of most significant stress. This method has been implemented in the technological process of cleaning aviation non-dismantling ball bearings of gas turbine engines at leading enterprises of the world level: "Ivchenko-PROGRES ZMKB", OJSC "Motor Sich" (Zaporizhia), and repair plant "Motor" (Lutsk), as it has been repeatedly proven in industrial conditions, that the method of non-contact cleaning of the surfaces of rolling tribosystems with a source of pulsed magnetic-turbulent fields is the most effective in comparison with traditional mechanical and ultrasonic methods and gives a positive economic effect from its use.

Using the developed method and stand for pre-operational preparation of bearings (Figure 1), the mechanism of holding ferromagnetic micro- and submicron-particles on the surfaces of ferromagnetic parts by magnetic fields at the boundary of the domain grains was determined for the first time. The existing methods of cleaning the working surfaces of parts: ultrasonic, cavitation, and pulsating hydraulic are not effective enough because they do not consider the fundamentally different retention mechanisms of removing magnetically susceptible microparticles.

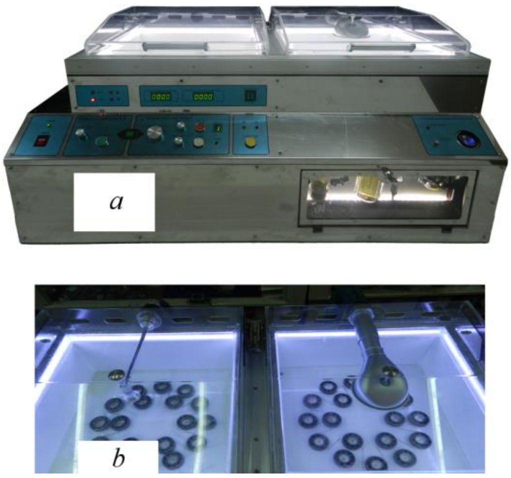


Figure 1 – Stand for pre-operational preparation of bearings: a – appearance of the stand; b – a chamber for cleaning and drying the ball bearings

Considering the high cost of special aviation bearings (from 100 USD to 15 000 USD) and their relatively high service life compared to the inter-repair service life of gas turbine engines (10–15 times), it is economically feasible to use them repeatedly, subject to appropriate pre-operational preparation with control of specific quality indicators, for example, by the general level of vibrations.

At the first stage of the study of the influence of micro- and nano-pollution on the performance and service life of miniature sliding ball bearings, modernized laboratory devices for determining the general level of vibration (Figure 2) are used as the primary operating characteristics of sliding bearings.

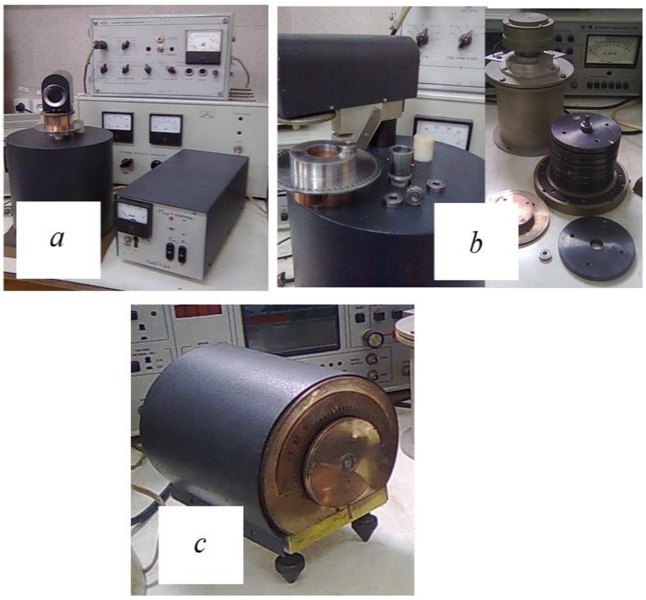


Figure 2 – The appearance of the laboratory stands for the assessment of the general level of vibration of the general level of vibrations: a – the stand for vibration and noise studies; b – rolling device; c – a device for measuring the moment of friction

The laboratory complex allows for assessing vibration speed, acceleration, and friction moment in rolling tribosystems. The set of loading disks and mandrels, included in its composition, significantly expands the nomenclature of the investigated bearings.

The following requirements were established experimentally: the total vibration level of the bearings should not exceed 67 dB, and the friction moment at a rotation frequency of 1500 rpm and a radial load of 200 g should not exceed 0.23 N·mm.

After the preparatory work, the bearings are positioned in the appropriate order and undergo the pre-operational preparation operation, which includes cleaning and checking the vibration characteristics on the pre-operational preparation stand (Figure 1).

4 Results

4.1 Study of vibration characteristics

Since the general vibration level is a dynamic quantity with a relatively high level of oscillations, several experimental studies showed that vibration stabilization occurs after one minute of bearing operation at a normal load (Figure 3).

Notably, most researchers show vibrations in bearings as non-linear and non-stationary characteristics [24, 25].

Vibroacoustic characteristics were evaluated in the delivery state by the manufacturer and after cleaning and replacing the lubricant with a new one in 0.25 g for each ball bearing.

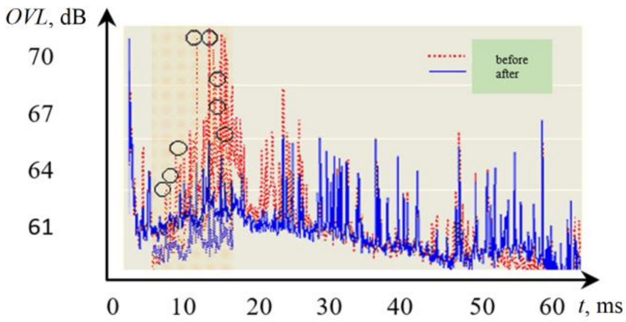


Figure 3 – Oscillograms of the general vibration level of ball bearings and their extremes (marked with a circle) before and after cleaning

Based on the results of measuring the friction moment and the general level of vibrations, the graphs shown in (Figures 4, 5) were drawn, which reveal the effect of cleaning and replacing the lubricant on the change in the MT friction moment and the average value of the overall vibration level (OVL).

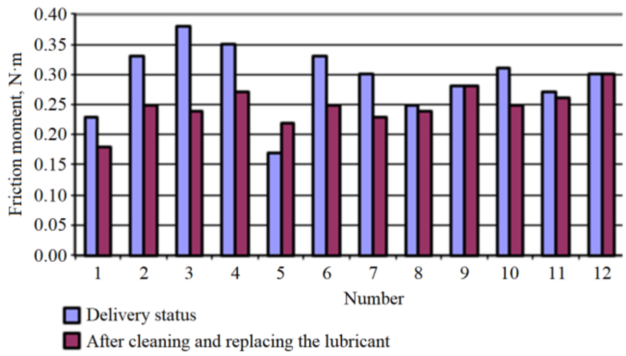


Figure 4 – The graph of the change in the friction moment of the MT after cleaning and applying a new lubricant

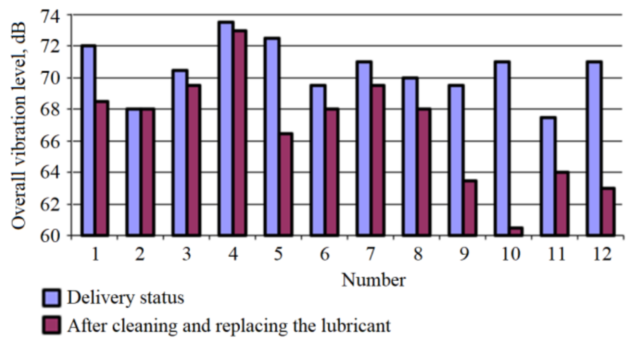


Figure 5 – Graph of the effect of cleaning and replacing the lubricant on the average value of the overall vibration level

The studies showed the effectiveness of the modernized laboratory complex and the possibility of conducting a comparative assessment of the vibroacoustic characteristics of precision rolling tribosystems before and after their cleaning.

The research results showed the objectivity of quality control of ball bearings by the general level of vibrations, which in its case, allows for developing new methods and devices for cleaning model rolling bearings and withstanding a comparative assessment of their effectiveness.

The main feature of non-dismountable miniature rolling bearings used in various precision mechanical systems of aviation, space, and other special equipment is their overall dimensions, the diameter of which is less than 25 mm, which is orders of magnitude smaller than the diameters of gas turbine engine bearings. Such dimensions of the cleaning objects required more in-depth research into the cleaning processes to determine the optimal parameters of the alternating magnetic field sources for effective removal of ferromagnetic and other particles of contamination from the rolling surface.

Through numerous experimental studies carried out on the developed stand for pre-operational preparation of rolling bearings (Figure 1), using a modernized set of instruments for determining the general level of vibrations (Figure 2), the dependence of the amplitude and frequency of rotation of an alternating pulsed magnetic field on the distance to it in the environment was determined aviation gas This made it possible to determine and adjust the working location of the pulsed magnetic field source in such a way that with one-sided positioning for a magnetic field with an amplitude of 20 mm, effective cleaning will be for bearings with a ring height of up to 15 mm.

With two-way positioning, effective cleaning will be for an experimental ball bearing with a ring height of up to 30 mm when switching from one side to the other. Simultaneously, the magnetic field strength for effectively cleaning bearings from ferromagnetic particles at half the width of the bearing should be at least 0.1 mT. Testing showed that the most effective removal of microparticles of ferromagnetic and other nature from all surfaces of a non-dismantling rolling bearing occurs when the amplitude of the magnetic induction of the moving S/N field is 0.35–0.45 mT and at a constant speed of rotation. Measurements were made using an EM 4305 Tesla meter.

It was experimentally determined that the minimum time for cleaning the bearings within the determined optimal amplitude of magnetic induction and the frequency of rotation of the variable magnetic field source is 2 minutes (one minute on each positioning side). The possibility of positioning rolling bearings in up to 100 pieces has been revealed. At the same time, the amplitude of the magnetic induction of the source of the alternating magnetic field was 150 mT, and the rotation frequency of the S/N field was maintained at the level of 1800 pulses per minute, which is within the range of the frequency that ensures contactless rotation of the bearing and the critical frequency. The critical frequency of rotation of the magnetic field source is when the washing liquid flows in the middle of the rolling path, and when it exceeds the frequency, the liquid is pushed away from the bearing by centrifugal forces.

4.2 Investigation of the nature of contamination of rolling bearings

Ball bearings No. 4-1080096 were used for the research. They passed all stages of industrial cleaning and were provided by the manufacturer in hermetically sealed packaging. After deconservation, the bearings were installed on the appropriate bearings at the bottom of the chamber of the cleaning stand, and under the conditions of optimal amplitude and frequency of the alternating magnetic field, they were subjected to cleaning for 1-2 minutes. During the cleaning process, impurities of various natures (metal particles of various sizes and lint) accumulated on the bottom of the chamber, which had a characteristic shine and moved opposite to the movement of alternating magnetic fields. It was visually observed that most of these particles carried out a rolling motion, which indicates the occurrence of a magnetic moment in microparticles, which is created by the difference in the intensity of the magnetic field in the lowest (contact) and highest areas of the pollution particles.

After cleaning a batch of 4-1080096 bearings in 10 pieces in the TS-1 washing liquid, it was filtered through a fine filter element, and the selected microparticles were subjected to fractographic analysis. With the help of electron microscopy and X-ray spectral analysis, the average size and composition of impurities removed from experimental miniature ball bearings was established (Figure 6).

Studies have shown that the most significant number of pollution particles recorded on filter elements had a size of up to 5 μm, while particles larger than 50 μm were observed much less often. Especially many of the smallest particles, less than 1 μm, were recorded (Figure 6).

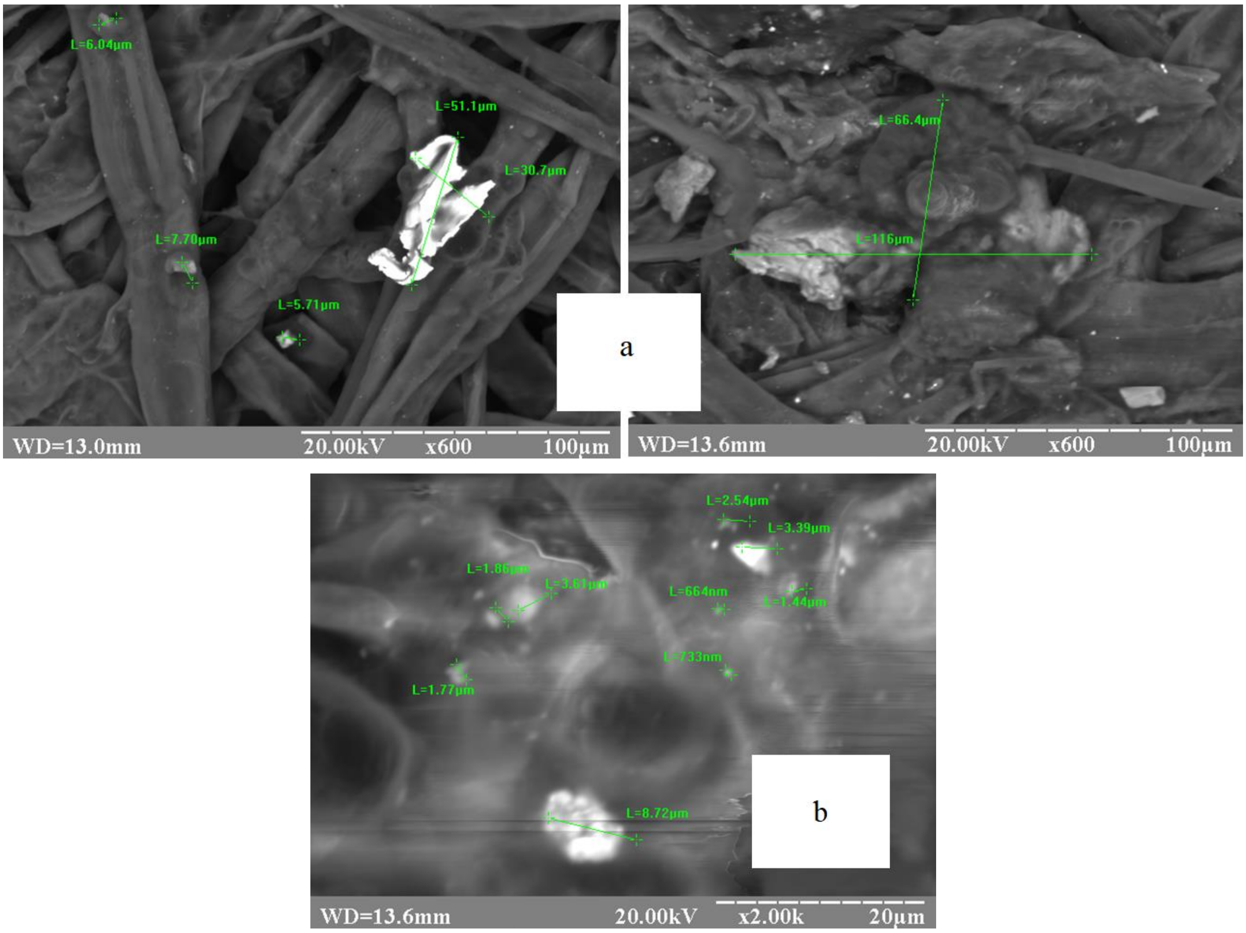


Figure 6 – Samples of contaminants that were removed from new bearings: a – large fragments of metal shavings; b – small particles of pollution of various nature

4.3 Research of the chemical composition of rolling bearing contaminants

The chemical composition of most metal contamination particles is close to steel 1.3505 (EU), some of which had a composition characteristic of bronze and brass, which collectively indicates the nature of micro-contamination of rolling bearings, closely related to their production. That is the very atmosphere of bearing production, which is permeated with micrometallic dust during the production of each part (grinding, polishing, stamping, and cutting) at all stages of assembly and assembly of bearings, brings to their surface micro- and nanoparticles that are naturally produced in bearings. Among this group, there are those whose composition coincides with the composition of the materials from which the structural elements are directly made (steel 1.3505 (EU) of the rolling elements and the bracket, bronze, or brass of the separator) and those that are not directly related to the design of rolling tribosystems, which were subject to research. The extracted non-ferromagnetic pollution particles (Figure 7) are mainly represented by abrasive materials, such as carbide and silicon oxide (they have a characteristic crystal appearance). A significant part of non-metallic contamination is composed of fragments of polymerized fuel and lubricant materials, which may be the remains of preservation material.

Research on the chemical composition of contaminants (Figure 7) showed that most are ferromagnetic metal fragments in the form of metal particles and shavings.

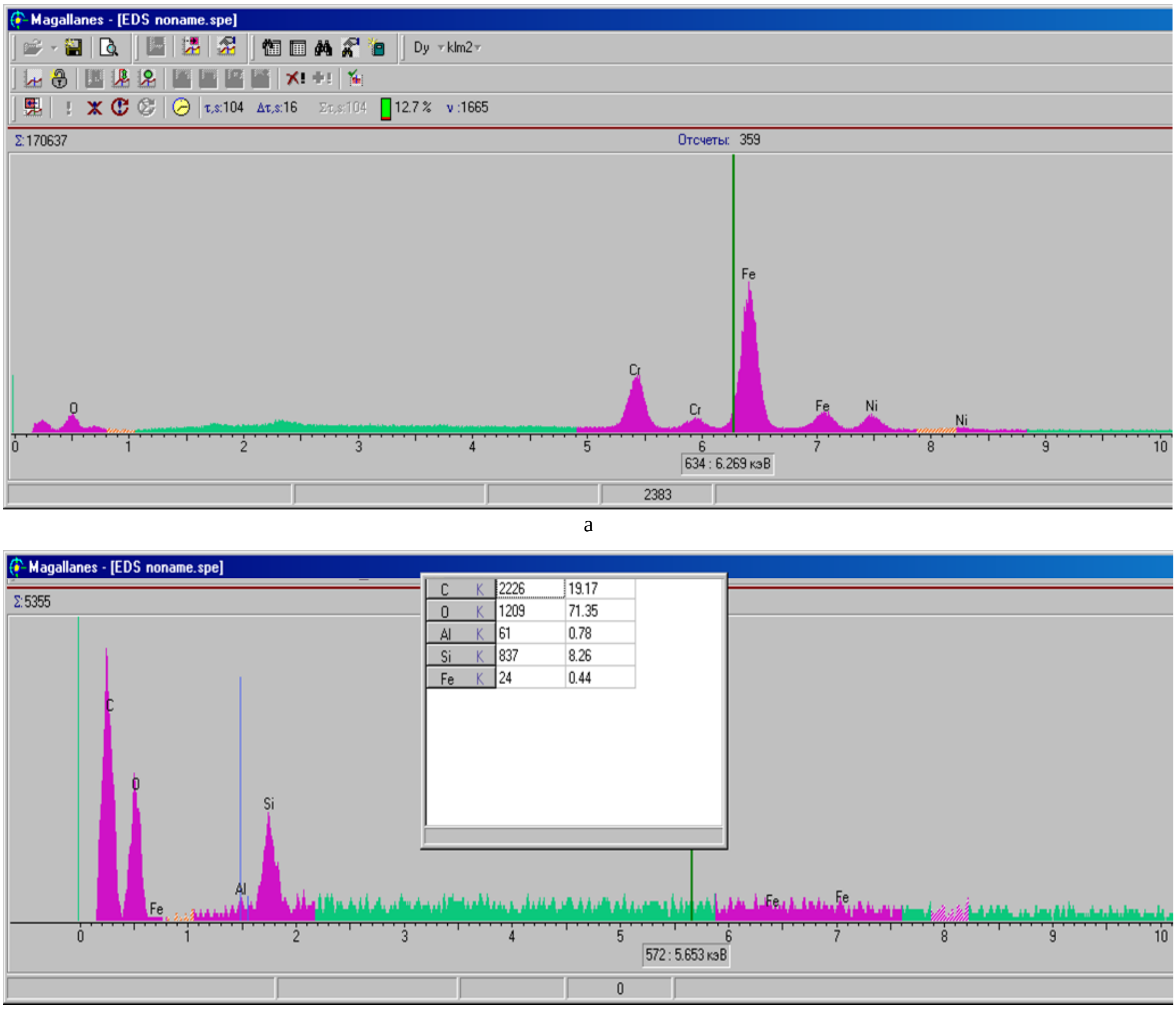


Figure 7 – Spectra of the chemical composition of metallic (a) and non-metallic (b) contaminants removed from the new bearings under study

4.4 Study of geometric parameters of contamination of rolling bearings

A careful study of the geometrical parameters of the removed microparticles is called on the REM-106I electron microscope about their asymmetric shape, which is characterized by the presence of the maximum and minimum size of each particle.

The dependence of the size of the removed particles of pollution fixed on the filter elements *R*, considering their type, is indicated in Figure 8.

The nature of the distribution is the same for ferromagnetic and non-ferromagnetic particles (the main part is less than 5 μm). It can be seen from the graphs that when the size of the removed impurities decreases, their number increases many times, especially for sizes smaller than 3 μm.

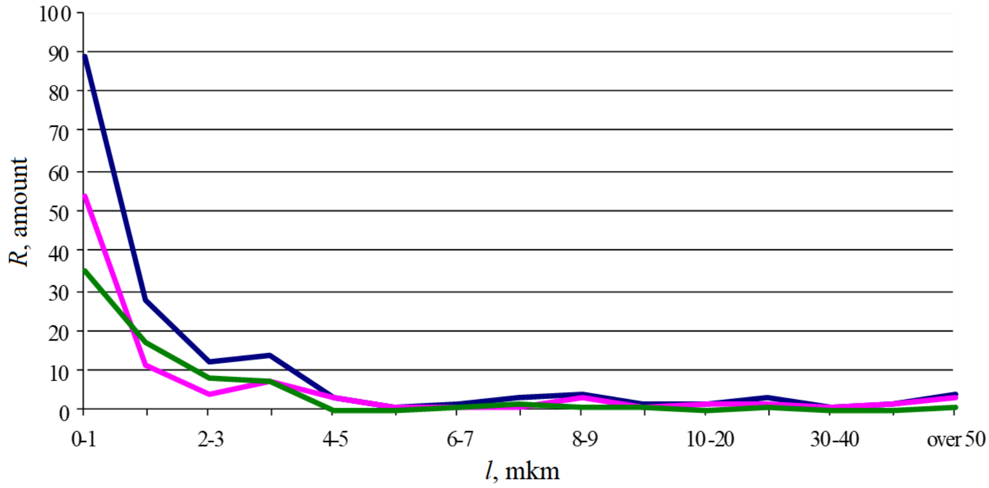


Figure 8 – Graph of dependence of the number of removed pollutants *R* on their type and maximum linear size *l*: 1 – total number of pollutants; 2 – pollution of ferromagnetic nature; 3 – pollution of a non-ferromagnetic nature

4.5 Approval of the method of cleaning non-dismountable rolling bearings

Using numerous experimental studies, as well as observations of the processes of removing ferromagnetic micropollutants on the stand created for non-contact magnetic-turbulent cleaning of ball bearings in assembly (Figure 1), a generalized method of non-contact cleaning of miniature ball bearings in assembly was developed and tested, which consists of the following.

De-preservation of both new and used ball bearings. This happens by immersing them in desiccators filled with TS-1 aviation fuel, where they are kept for 1-2 h. Previously, by repeatedly rotating the free ring of the bearing in different directions, the maximum removal of preservative oil from the working surfaces of the experimental bearing was achieved.

Depending on the standard size of the ball bearing, a template with inserts with the corresponding diameter of the inner ring is selected (Figure 9). After that, the bottom of the cleaning chamber, the safety gasket, and all surfaces of the template with the bearings are thoroughly wiped with alcohol and positioned accordingly on the working surface of the cleaning chamber.

All ball bearings to be cleaned are checked for free rotation of the outer rings before installation on the corresponding bearings by turning them easily by hand. If the free ring does not rotate or periodically jams, this bearing is re-immersed in the TS-1 aviation gas environment.

After installing the bearings on the housing, the cleaning chamber is closed with a lid.

Selection of the number and duration of cycles of reverse rotation of the bearings is performed by the operator as follows. The cycle duration and their number are set on the control panel (experimentally established and recommended cleaning duration of 1-3 minutes in each direction and 3-5 cycles).

The mode switch of the experimental model of the non-contact magnetic-turbulent cleaning of rolling surfaces of ball bearings assembly is set to the “Automatic” position, after which the “Start” button is pressed.

After cleaning according to the selected program, the ball bearings are turned over, the cover is closed, and the bearings are cleaned according to the selected program.

At the end of the cleaning procedure, the substrate and bearings are carefully removed from the cleaning chamber and installed in the demagnetization and pre-drying chamber, and the lid is closed.

The “Demagnetization” button is pressed on the control panel, which occurs in the automatic mode of operation.

After the preliminary drying and demagnetization procedure, all bearing surfaces are lyophilized with a working fluid (e.g., IPM-10 oil) by injecting the working fluid into the rolling path of the ball bearing. After that, the bearing is packed in a polyethylene hermetic bag and transferred to this state for cleaning efficiency evaluation according to their operational vibroacoustic parameters.

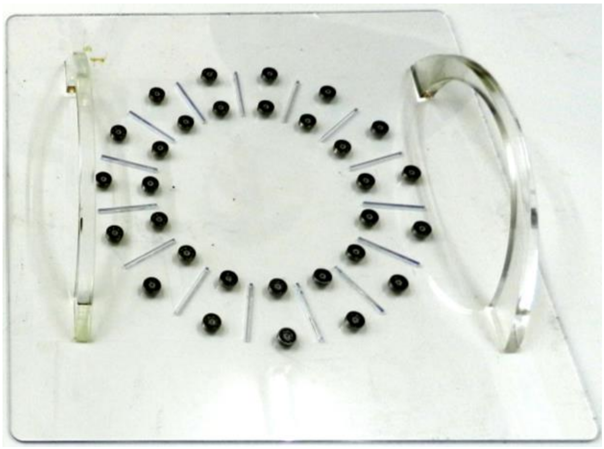


Figure 9 – Designed and manufactured prototype of a pad with bearings for positioning ball bearings

All microparticles removed from the rolling path of the experimental non-dismantling ball bearings during cleaning according to the developed method of non-contact pulse-magnetic-turbulent cleaning at the stand for pre-operational preparation of bearings were subject to examination with a scanning electron microscope REM-106I.

The results of measurement and research of non-dismantling bearings of the 1st category after each stage of technological action and research of removed microparticles.

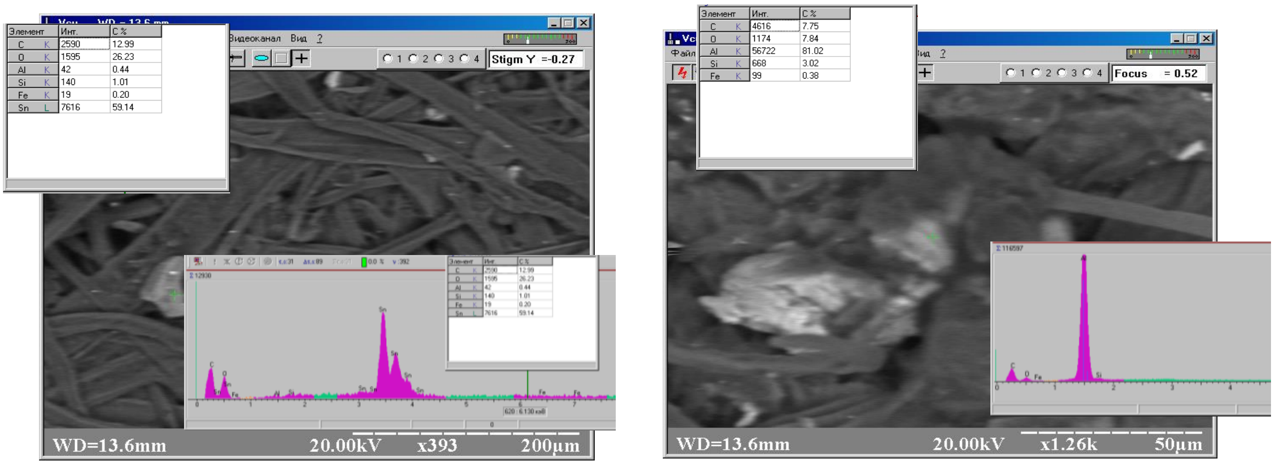
After removing the preservative grease of unpacked ball bearings in the environment of TS-1 aviation gas, the average values are vibration acceleration of 5.2 m/s^2 and vibration speed of 3.4 m/s^2.

After cleaning the ball bearings according to the technology used at the customer's enterprise, their vibration characteristics improved: vibration acceleration – 3.1 m/s^2; vibration speed – 1.8 m/s^2.

After cleaning the ball bearings according to the developed method of cleaning non-dismountable ball bearings on the stand for pre-operational preparation of bearings, their vibration characteristics improved significantly: vibration acceleration – 1.7 m/s^2; vibration speed – 1.1 m/s^2.

It is important to note that after applying the method of non-contact pulse-magnetic-turbulent cleaning of non-dismountable ball bearings on the created prototype of the stand at the operating rotation speed of the inner rings of 1800 min^{-1}, the level of vibration (vibration speed) decreased by 40–45 %.

Results of studies of the chemical composition of the extracted microparticles of pollution are presented in Figure 10.



a b

Figure 10 – Results of studies of the chemical composition of the extracted microparticles of pollution: a – 200 µm; b – 50 µm

5 Discussion

The study of the size and chemical composition of microparticles removed in the process of non-contact cleaning of non-dismountable ball bearings of the 1st category on the stand showed that microparticles were separated from the rolling path: 30–50 µm in size – 8 %; 10–30 µm – 12 %; 5–10 µm – 50 %, the rest (30 %) – particles up to 5 µm in size.

X-ray spectral analysis of remote microparticles after using the method of non-contact pulse-magnetic-turbulent cleaning of non-dismantling ball bearings on the created test sample of the stand showed that 80 % of the remote particles have a ferromagnetic ferrocarbon nature and contained on the boundaries of the domain structure of the surfaces of the bearing parts (Figure 10).

It is worth noting that about 5 % of the removed solid microparticles are metal-ceramic conglomerates, characteristic of the wear process of the abrasive processing tool during the finishing of surfaces in the conditions of bearing production. These particles are the most dangerous for ball bearings during operation and especially for all friction pairs of oil systems.

A comparative evaluation of the cleaning of non-disassembled small rolling bearings on the pre-operational preparation stand with new parameters of the pulse variable magnetic field source, which takes into account the features of the standard dimensions according to the developed method in laboratory conditions, showed high efficiency compared to the known ones, as contamination from the working surfaces of the rolling elements was removed after their previous cleaning on the most effective special ultrasonic equipment. The vibration level decreased by 10–27 % on average and on some ball bearings – by 40–65 %.

The criterion for the effectiveness of cleaning model rolling bearings based on the overall vibration level was the presence of a sufficiently large amount of dirt removed from newly preserved ball bearings produced by AFG and SKF, as well as from those that were in use after their preliminary cleaning by ultrasonic methods on modern equipment.

After cleaning the ball bearings according to the technology used at specialized enterprises using their special ultrasonic equipment, the developed method removed enough microparticles smaller than 10 µm. However, the ultrasonic cleaning method has become widely used in various industries due to its ability to activate impurities. The occurrence of cavitation processes under the action of ultrasonic waves in liquids allows the breaking of the integrity and adhesion of the most complex and robust contaminants [26-28].

Therefore, ultrasonic is widely used in machine building, precision manufacturing, instrument making, radio electronics, and medicine [29, 30].

After analyzing the comparative tests results, it can be noted that the complexity of the structure and the static, especially of prairie ball bearings, are significant obstacles when cleaning by the ultrasonic method, considering many zones shielded from the access of ultrasonic waves, as well as the magnetic component of retention of impurities of a ferromagnetic nature on the working surfaces of the ball bearing. Therefore, when applied, this method does not work effectively enough when cleaning miniature ball bearings in an assembly. However, it can be used with our developed pulsed magnetic-turbulent cleaning method, having previously selected power of the combined pulsed-magnetic source.

6 Conclusions

A method of researching the main operating parameters of non-dismountable ball bearings by vibroacoustic characteristics and their cleaning from microparticles of ferromagnetic and other nature has been developed.

It was established that with one-sided positioning for a magnetic field with an amplitude of 20 mm, effective cleaning would be for bearings with a ring height of up to 15 mm. With double-sided positioning, when moving the bearing from one side to the other, effective cleaning will be for bearings with a ring height of up to 30 mm.

The optimal values of the amplitude of the moving magnetic field at a constant speed for the most effective removal of microparticles of ferromagnetic and other nature from all surfaces of a non-separable rolling bearing are 0.35–0.45 mT.

The criterion for the effectiveness of the developed method of cleaning model rolling bearings in terms of the general level of vibration is the presence of a sufficiently large amount of dirt removed from newly preserved ball bearings manufactured by AFG and SKF, as well as from those that were in use after their preliminary cleaning by ultrasonic methods on modern equipment.

Based on the results of the experimental tests, the optimal rotation frequency of the source of the magnetic S/N field for ball bearings with an outer ring diameter of up to 25 mm was determined, which is within 1800 pulses per minute.

The minimum time for cleaning bearings of various standard sizes when ensuring the determined optimal values of the amplitude of tension and frequency of rotation S/N of the magnetic field is up to 2 minutes.

The principal possibility of using the effect of non-contact magnetic-turbulent cleaning of the surfaces of miniature rolling ball bearings when cleaning them with standard sizes up to 30 mm has been experimentally proven.

The method of non-contact magnetic-turbulent cleaning of rolling surfaces of miniature ball bearings was developed and tested.

Joint comparative tests of the developed method of pulse-magnetic-turbulent non-contact cleaning of non-disassemble ball bearings on the bench in the laboratory showed its high efficiency: the level of vibration decreased on average by 10–27 %, and on some ball bearings – by 40–65 %.

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