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Study of the influence of surface treatment on the wear development under quasi-static loading of the levers of a newly designed thrust bearing

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ABSTRACT

Hydrodynamic thrust bearings are generally used to absorb axial forces in machinery, especially where the use of rolling bearings is inappropriate in terms of dimensional constraints, service life, high loads or difficult access during assembly. Misalignment between the stator and the rotor, especially on large rotary machines, can lead to a reduction in the load capacity and damage to the entire device. To eliminate misalignment between stator and rotor (especially in large rotary machines) the thrust bearing with a system of very precise manufactured levers has started to be used.

The article deals with the study of the influence of surface treatment on the development of wear and damage under quasi-static loading of the levers, which are critical parts of a newly designed axial bearing. The presented research has been carried out in two phases. In the first phase, basic samples that represented the types of geometries coming into contact in real conditions of bearing operation were manufactured and experimentally tested. Based on the results obtained at this stage, it was found that electroless nickel-plated samples showed the best results in terms of surface treatment. Due to this, real levers were produced in three sizes, which are estimated to have the potential for the greatest use in turbines, and these were surface treated with electroless nickel plating. In the second phase, the surface integrity and stiffness of the levers were examined. All samples and levers were made of 34CrNiMo6 steel. The evaluation was performed using stereomicroscope and a scanning electron microscope. Based on the results, it could be stated that the integrity of the surface was not significantly violated in any simple sample or lever. Thus, the tests confirmed the suitability of the proposed method of surface treatment of levers and their sufficient rigidity under quasi-static static loading.

Keywords:Lever, Surface treatment, Crack,Wear, Damage, Quasi-static load

1. Introduction

High requirements are currently imposed on modern machines, which concern not only their construction and technological parameters but also their reliability and related diagnostics. The most demanding is using a machine and its tools in unattended mode with continuous operation. Generally, the machines that are subjected to a variety of environmental conditions that contribute to corrosion, erosion, fouling and various temperature-related issues, are all rotary machines such as turbines, compressors, and pumps. Their long-term reliability is a common goal for all plant operators. Achieving it requires an approach that considers a range of contributory factors and makes use of the most appropriate technology and manpower available to them.

Unfortunately, in large rotary machines, due to the deflections of the stator (but also rotor) parts, it is not guaranteed the necessary parallelism of the active surface of the segments with the active surface of the rotor collar. This misalignment is caused by many factors (thermal expansion, shaft deflection, “inaccuracy” in production, etc.). In the best case, it results in a reduction in bearing capacity [1], but it often can lead to bearing damage that influences not only economic efficiency of the whole mechanical system, but mainly its operational reliability and safety. To prevent misalignment between the stator and rotor, especially in large rotary machines, an axial bearing with a system of very precisely manufactured levers have been used, but there is still a challenge to find new, more efficient solutions in terms of the design of a self-equalizing thrust bearing and its components [2].

2. State of the art

If two pieces of rotary equipment are connected, every effort should be made to minimize misalignment of the rotating components. In a turbine machine, there are always concerns that the deflection could lead to a high bearing load (turbine machines). High deflection can result in extremely high loads during ambient starting conditions. Such a high load could result in immediate bearing damage, even if the shafts are finally properly aligned at normal operating temperatures. A proper alignment will reduce bearing, shaft, and clutch failures, bearing and clutch temperatures, vibration, and power consumption. In addition, the good alignment will extend the life of the equipment between scheduled maintenance intervals.

Several researchers have already dealt with misalignment at the rotary machines. Jose M. Bossio [3] described the problem of angular shaft misalignment in motors. The loading system coupled with flexible couplings is analysed in this work. Hariharan and Srinivasan [4] have done experimental studies on a rotor dynamic test apparatus to predict the vibration spectrum for shaft misalignment. A self-designed simplified 3-pin type flexible coupling was used in the experiments. Vibration accelerations were measured using a dual-channel vibration analyser for baseline and the misalignment condition. The rigid and pin type flexible coupling with shaft parallel misalignment is simulated and studied using both experimental investigation and simulation. Both the experiment and simulation results prove that misalignment can be characterized primarily by second harmonics (2X) of the shaft running speed. He also found that by using a new newly designed flexible coupling, the vibration amplitudes caused by the shaft parallel misalignment can be reduced by percentage. Piotrowski [5] described the importance of misalignment phenomenon as Industry worldwide is losing billions of dollars a year due to misalignment of machinery. Vibration analysis of misaligned shafts for different speeds, realized by experimental and numerical approaches, was studied by Rahinj [6] and his colleagues. It has been found that the vibration amplitudes the 2X and 3X are gradually increases with increase in misalignment and rotational speed of shaft.

One of the solutions how to compensate a misalignment between of the active surface of the bearing and the active surface of the rotor collar is using so called self-equalizing thrust bearings.

At least two elements are required for the slide bearing - the bearing itself and the rotor collar. The sliding bearing contains segments to which lubricating oil is supplied. Each segment is a separate carrier part of the bearing. The bearing surfaces (both bearings and shaft collars) are completely separated by an oil film with a thickness of approx. 20-40 |rm. The oil film avoids the risk of contact and therefore abrasion of the bearing surfaces [7].

Self-equalizing thrust pad bearings consist of the following basic parts (Fig. 1):

1. Bearing body/housing,
2. Thrust pad,
3. Self-equalizing element (lever),
4. Nozzle,
5. Floating pressure element.

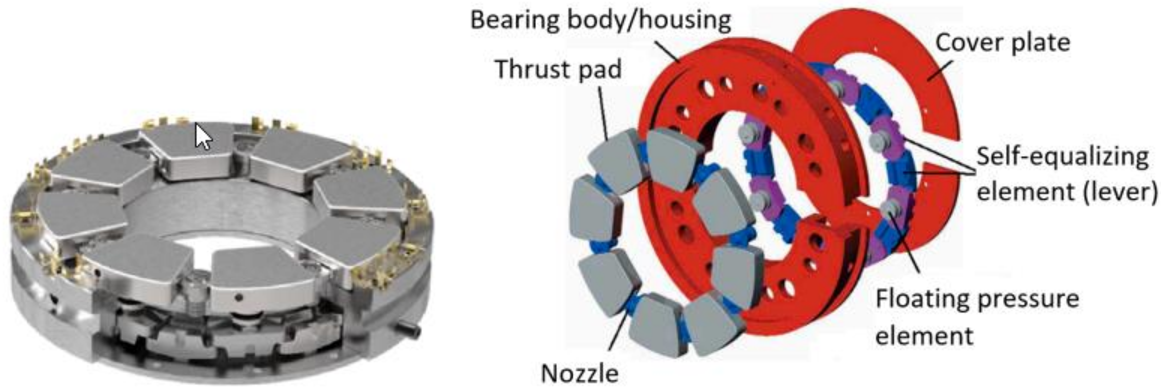

Fig. 1. Self-equalizing bearing with levers.

Fig. 1. Self-equalizing bearing with levers.

For every thrust, the pad is necessary to use 2 levers. It means that for example at 18 pads bearing is necessary to use 36 levers.

There are several basic types of self-equalizing thrust bearings currently used in the market with various types of levers produced from a different material and by a different technology. They are:

(a) The cast levers with ground arm to a specific size (height) that is a standard solution (Fig. 2). A precision casting from martensitic stainless steel for castings is chosen here as the semi-finished product. The whole construction of the lever arm is adapted so that it is possible to use the same lever arm both at the top and at the bottom. The contact surfaces of the lower and upper lever arms are in the pairs of planar shape. There are at least two machined surfaces on the lever arm - the swing point is ground, and the technological base needed to grind this swing point is milled [8,9].

(b) A cast lever that is ground to a specific size (height) with inserted cylinders (so-called cylinder solution, Fig. 3) was developed from the original “standard” design, where between the modified levers from the standard design is inserted a ground cylinder made of stainless chrome-molybdenum steel with an ultimate strength of up to 1300 MPa and yield strength up to 900 MPa. This cylinder mediates the rolling bond between the levers and thus the passive resistance between the levers is significantly reduced which results in a better load transfer between the individual levers [10,11].
(c) Levers of a complex in shape (Fig. 4) cast from cast steel are designed for high series. As a semi-finished product, a precision casting from martensitic stainless steel is chosen for castings with a yield strength of up to 1100 MPa and a yield strength of up to 1000 MPa [12]. Due to the easy assembly, the whole structure of the lever is adapted so that it is possible to use the same lever at the top and at the bottom, i. e. the upper and lower levers are identical.
(d) Simply shaped levers made of stainless chrome-molybdenum steel made by machining from bars or sheet metal [13] are more suitable from the point of view of overall easier machinability with strict tolerances, however, from the point of view of kinematics and a certain (non-negligible) resistance which arises when tilting the surfaces of the levers, it no longer seems to be a suitable solution. The movement of the levers is considerably limited in this construction due to the grooves that fix the individual levers [14], as it is shown in Fig. 5.
(e) A completely machined lever arm from a bar semi-finished product (so-called low-profile solution). The shape of the lower lever arm is different from the upper one (Fig. 6). The movement of the levers in this construction is different from previous constructions. There is no component for pressure distribution, but the upper lever arm and the “false” pressure distribution part (cylinder) form one part, which performs only a linear movement. On the other hand, the lower lever arm rolls slightly, but due to the fixation of the lever arm by the pin, the friction between the lower lever arm and the cover plate takes place [15]. The contact surfaces of the lower and upper lever arms are in pairs Cylinder/Plane and Cylinder/Plane, where the contact surfaces rub against each other due to the movement of the upper lever arm, which is only linear. The semi-finished product here is sheet metal or rod made of stainless chrome-molybdenum steel with a ultimate strength of up to 1300 MPa and a yield strength of up to 900 MPa [16].

In the case of the thrust bearing, the most critical part is a system of very precise manufactured levers, which are in the close contacts each to other, so they have to be not only properly designed from the geometrical point of view, but the important role plays also a quality of the functional surfaces of these levers [17,18].

The design of a new self-equalizing thrust bearing is an extensive research, which the authors have been dealing with for a long time and which includes several partial studies from several areas such as design and simulation, technology, tribology, and others. The specific goal of the presented research, that according to the authors best knowledge has not been done by any researcher yet, is to investigate the influence of surface treatment on the development of wear under quasi-static loading of levers of a newly designed axial bearing made of steel EN/DIN 34CrNiMo6. To find the most appropriate solution in terms of geometry, surface finish and surface integrity, two types of contact pairs of surfaces Cylinder/Cylinder and Cylinder/Plane were studied in two phases. The partial goal of the research in the first phase was to compare the behaviour of selected surface treatments and to monitor their response to quasi-static loads under loads of five sizes, from nominal to extreme loads. Another goal in this pha se was to evaluate the adhesion of coatings using a stereomicroscope and a scanning electron microscope. The second phase was focused on assessing the suitability of the selected surface treatment together with verification of the stiffness of the levers. The obtained results will make it possible in the final phase to find the optimal variant of the bearing, which will perform its function more efficiently, more reliably and safer when it is put into operation in large rotary machines.

3. Lever design of a newly developed self-equalizing thrust bearing

The aim of the set of levers is to distribute the load evenly over the entire circumference of the bearing. The evenly distributed load is then transferred to the bearing housing and subsequently to the machine frame. The lever system must be designed and manufactured so that it can transfer the pressure/force exerted on the lower part of the bearing to the upper part of the bearing, i. e. that the axial bearing segments are always in contact with the shaft collar.

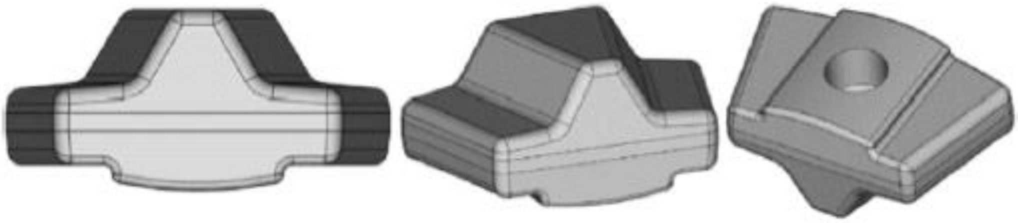

Fig. 2. A standard lever.

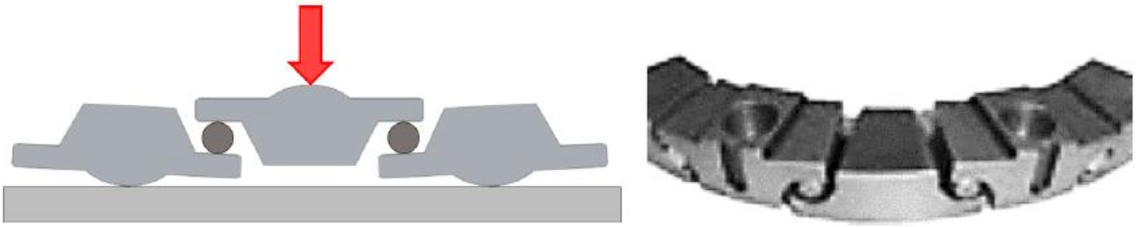

Fig. 3. Levers with inserted cylinders [8].

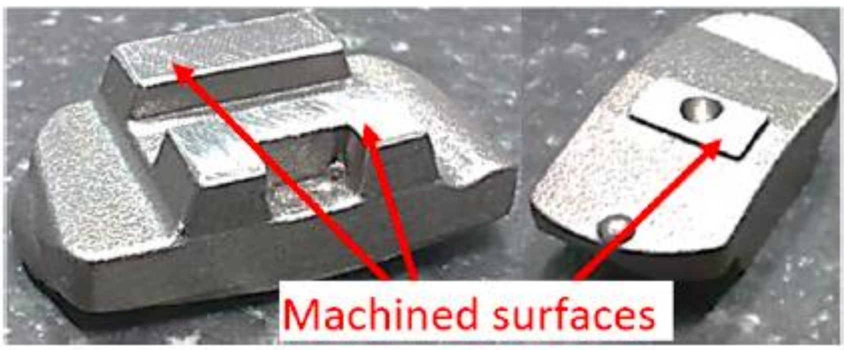

Fig. 4. A detailed view at machined surfaces of a complex lever.

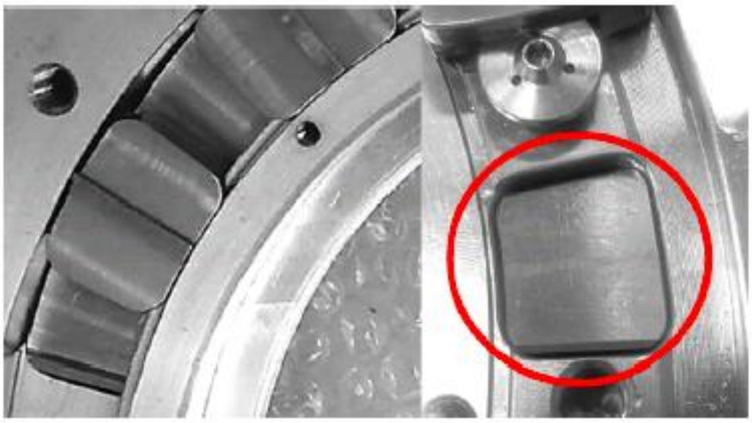

Fig. 5. A detailed view on the levers fixed by means of grooves in the bearing body.

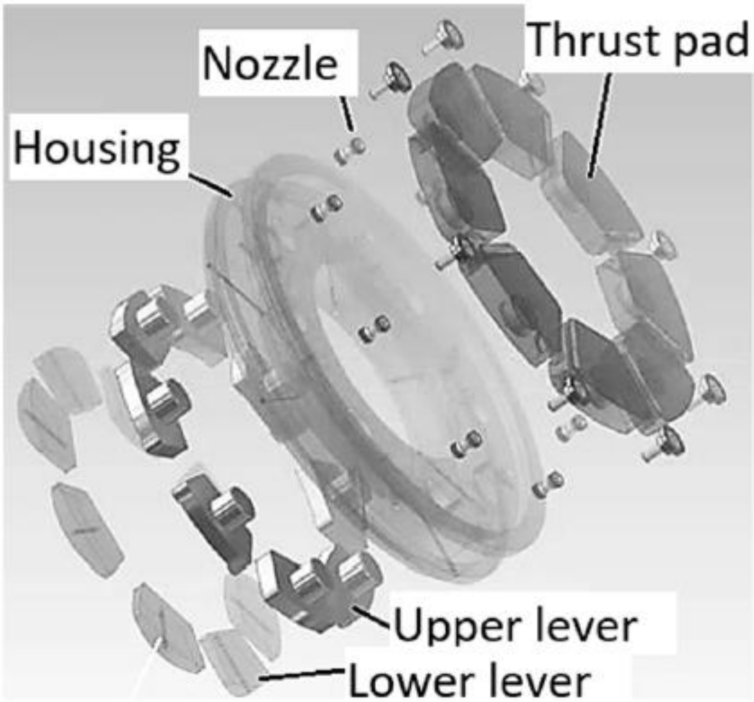

Fig. 6. Thrust bearing with the low-profile levers [15].

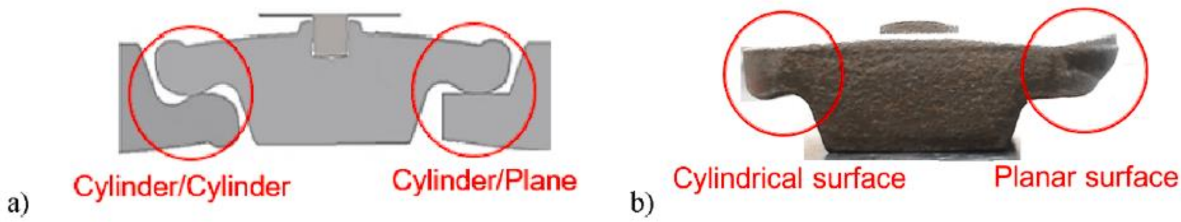

Fig. 7. Investigated variants of contact surfaces of the levers [19].

The functionality of the bearing and its ability to transfer loads and compensate for misalignment is greatly affected by the geometry of the levers at the areas of contact. Kinematic and numerical analysis (which are not the subject of this study) pointed to the most suitable variants of contact pairs for the investigation that are namely (Fig. 7) [19]

(a) “Cylinder/Cylinder”,

(b) “Cylinder/Plane”.

During operation, the bearing is loaded in various ways, which take place simultaneously (static, friction and micro-friction, dynamically - frequency, random or rolling), which in practice causes different types of wear [20].

In addition, the basic shape-dimensional and material properties of the contact parts, their interconnection, and the reaction between them must be considered in the contact processes. These interactions can be material, physical, chemical, etc. Therefore, a few influences need to be considered: [21,22]

- number of bodies participating in the contact process,
- macro-geometry and microgeometry of contact bodies,
- physical, chemical, and mechanical properties of the bodies forming the overall system,
- characteristic type of deformation between individual bodies,
- type and speed of relative movement.

Finally, the accuracy of the individual levers is very important, but also the overall accuracy of the levers in the assembly (in the dimensional chain). According to the initial calculations and drawings in 2D sketches and 3D models, the height of the levers (in the case of an assembly with 36 levers) must be within a tolerance of 0.025 mm. The whole set of levers is extremely sensitive and any deviation from the nominal size of the rocker in the range of more than 0.025 mm leads to a malfunction of the whole set. This places very high demands on production and assembly [23].

A misalignment and its consequences are reflected in the fact that the difference in measured temperatures between the upper and lower segments can be up to 60 °C and on the lower segment can reach up to 125 °C. This temperature of 125 °C is then already limited for the bearing metal and causes degradation of the bearing metal. It can lead to the so-called fatigue cracking (Fig. 8) caused by longterm “overheating” of the bearing or dynamic stress [14,24].

When designing the levers for new self-equalizing thrust bearing within the authors research, it was, therefore, necessary to find the most suitable way of surface treatment, which together with the appropriate geometry would ensure the resistance of the bearing to wear with the best possible efficiency of production in terms of economic, time and process. There are several ways in which it is possible to improve the surface properties (mechanical, tribological, contact, etc.) of components such as e. g. surface hardening technology; laser hardening; cementation; nitriding; electroless nickel plating; rolling, grinding; sandblasting; thermal spraying and others [25,26].

To decide which surface treatment methods should be used in the research of the newly designed self-aligning bearing, preliminary experiments were performed and a report [27] was prepared to evaluate the available techniques in terms of hardness, depth of surface reinforcement or need to use a finishing operation. on the machine. After a basic analysis and synthesis of knowledge, the samples were made in the initial research from three materials: [28]

- Non-alloy heat-treated steel (C45),
- Chrome-nickel-molybdenum heat-treated steel (34CrNiMo6), and
- Chrome-molybdenum heat-treated steel (42CrMo4).

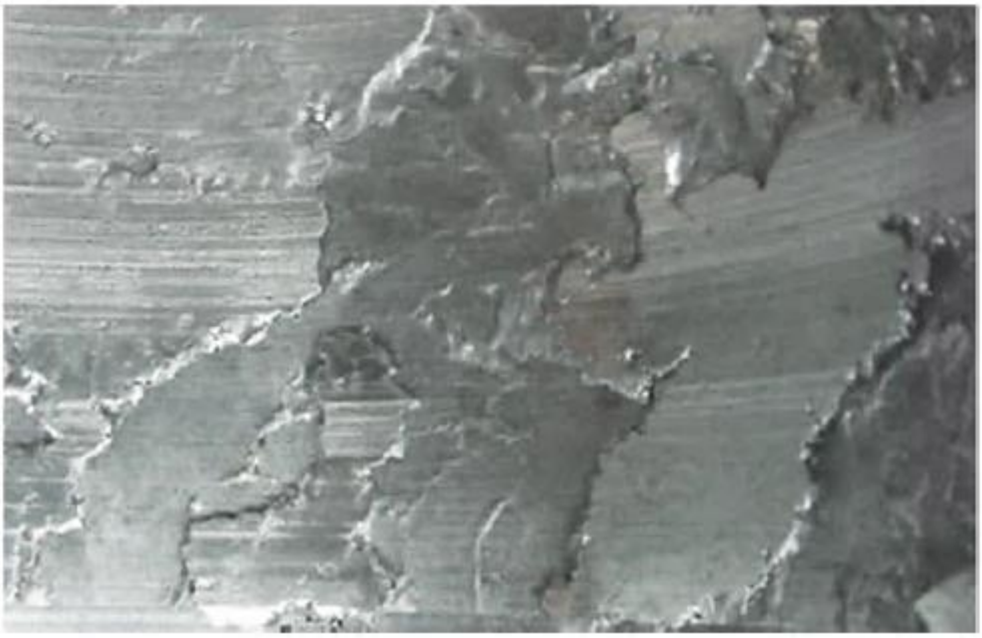

Fig. 8. Fatigue cracks - caused by long-term “overheating” of the bearing or dynamic stress [24].

All three basic materials have been basically refined to achieve high strength. As a result, however, it was shown that the only usable variant for further investigation was chromium-nickel-molybdenum heat-treated steel (DIN 34CrNiMo6 steel) to avoid the failures and damages during the bearing operation [29]. Chemical composition of DIN 34CrNiMo6 steel is in Table 1.

Nitriding and electroless nickel plating were chosen for this steel for further research into possible surface hardening due to its excellent tribological properties. Nitriding was chosen due to the uniform thickness of the formed layer without the need for further processing [31]. Similarly, like nitriding, electroless nickel plating can only be used after final finishing without the risk of large dimensional changes to the product [32]. The technique of surface treatment by tumbling seemed to be an alternative to the actual running of the levers during operation. Here, there are also no significant dimensional changes. There is only an adjustment of the roughness and there is a presumption that there could be a slight improvement in the tribological properties of the product [33].

Other surface reinforcement or surface treatment technologies did not meet some of the requirements and were therefore not considered further. Therefore, based on the extensive preliminary research [19] carried out on 108 simplified samples in the shape of cylinders and a planar surface, which corresponded to the contact pairs of the lever “Cylinder/Cylinder” and “Cylinder/Plane”, the following surface treatment technologies were selected:

(1) nitriding,

(2) electroless nickel plating, and

(3) tumbling.

4. Materials and methods

Since several aspects have been investigated in the design of the self-aligning bearing, it would not be economical to produce them directly in the final shape to determine the effect of the surface treatment on the behaviour of the levers. So, the authors decided to make the research in two phases:

1) In the first phase the simple basic samples, representing Cylinder/Cylinder and Cylinder/Plane contact pairs were experimentally tested under a quasistatic load.
2) In the second phase - Base on the results of the previous phase, only the levers with the most suitable surface treatment were produced and experimentally tested under quasi-static loading, in which the suitability of the surface treatment together with the stiffness of the levers was verified.

4.1. The 1st phase - Quasi-static test of the basic samples

In view of the existing solutions presented above in Section 2 and considering the numerical analysis (which was carried out but not the subject of this article), it was found that the most suitable lever geometry at the point of contact to ensure the self-aligning function of the bearing is flat or cylindrical.

For basic testing of the influence of lever surface treatment on their behaviour under quasi-static loading, therefore, two basic types of experimental samples of EN/DIN 34CrNiMo6 steel were designed and produced. The first type of the samples was in the cylinder shape of a 12 mm diameter and a 25 mm length, the second type was in a shape of a plate of 25 x 25 mm, which correlated with the size of a lever for a reference bearing with 18 pads. Totally 108 samples were produced, the number of which was designed based on a “custom plan”, in which, as in the central composition plan, orthogonality and rotation were fully preserved [34]. Static tests were performed for two pairs of contact surfaces Cylinder/Cylinder and Cylinder/Plane (Fig. 9), which were the same surface roughness and with the same surface treatment.

The axes in the pair Cylinder/Cylinder (Fig. 9a) were rotated by 15° relative to each another to achieve a point contact between the samples and thus to achieve a simulation of the probable load during the operation of the levers in the turbine, when assembling the levers with this type of contact surfaces. In the Cylinder/Plane (Fig. 9b) arrangement, a “line contact” was achieved, which was created by placing the cylinder against the plate, whereby the load was distributed over a larger area.

Cylindrical specimens were made by turning with the following machining factors:

- cutting speed: vc = 120 mmin~1
- cutting depth ap = 0.5 mm
- coolant Blasocut BC35 Kombi 5% + 95% water
- feeds per revolution f = 0.08; 0.12; 0.16; 0.2; 0.24 mm
- Cutting inserts roughing: ISCAR CCMT 09 T304-SM, finishing: ISCAR DCMT 11 T304-F3P (slightly worn VB = 30-40 |im)

Table 1 Chemical composition [30].

Chemical composition [30].

Component	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al
(wt.%)	0.34	0.793	0.282	0.0196	0.0052	1.72	1.55	0.221	0.0092	0.193	0.0194

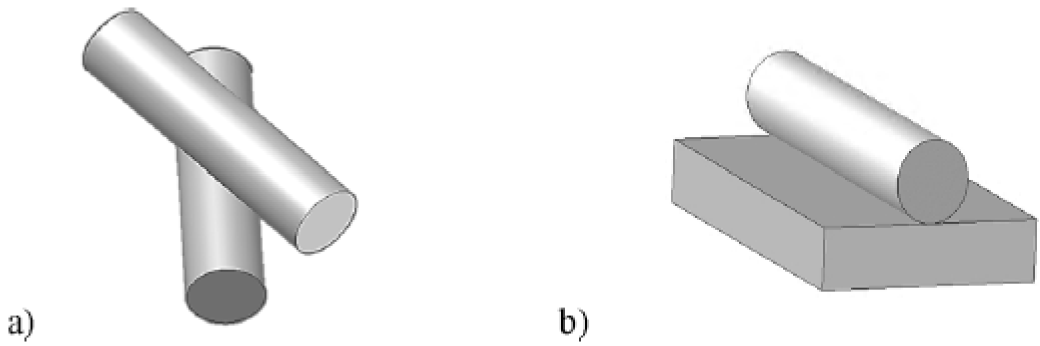

Fig. 9. The basic samples with contact surfaces (a) Cylinder/Cylinder, (b) Cylinder/Plane.

All samples were subsequently heat-treated after turning according to the recommendations for this material for refinement. The quenching was carried out in oil from a temperature of 830-860 °C and during tempering the temperatures ranged from 630 to 660 °C [35]. The hardness of the base material was 330 HB. After heat-treatment, the samples were divided into three basic groups. The first group consisted of samples without further surface treatment, the samples treated with electroless nickel plating were in the second group and in the third group were the samples with nitriding surface treatment.

Tumbling on an OTEC DF3 machine was also used as surface strengthening for half of the samples. After several tests, the following tumbling parameters were set up for tumbling:

- Tumbling type: Towed
- Rotor speed: 40 rpm
- Rotation bracket: 90 rpm
- Immersion depth: 420 mm
- Lift: Not used
- Medium: H4/400
- Total tumbling time: 6 min (3 min CW + 3 min CCW)

In Table 2 is summary of parameters for the testing samples production and their processing.

The measuring instrument assembly for the quasi-static test was manufactured at the University of West Bohemia in Pilsen (Czech Republic) and is shown in Fig. 10.

The setting of the boundary conditions for the static test was based on the assignment when the magnitude of the static load acting on the thrust bearing was 180 kN. If the self-equalizing mechanism of the bearing worked perfectly, a force of 5 kN (~500 kg) would act on the individual lever arms [36]. Due to the fact that passive forces occur in the self-equalizing mechanism and due to the geometry of the levers, it is clear that some of the lever arms will be subjected to a force many times greater than the nominal 500 kg. Therefore, the following load sizes were selected for the static test:

- 500 kg (nominal load),
- 1000 kg (overload),
- 2000 kg (heavy overload),

- 5000 kg (extreme overload => self-equalizing mechanism does not work).

The samples were loaded, pushing them against each other, while the load lasted 10 s.

The magnitude of the load was measured with a strain gauge. The imprints were evaluated using NIKON stereomicroscope and the surface contact was evaluated by a Philips XL30ESEM scanning electron microscope.

After every load, the width of imprints was measured, as it is shown in Fig. 11, and the development of wear was documented and processed in the form of graphs.

If real levers should be used for bearings production, it is first necessary to investigate the dangerous situation, in which the coating is partially delaminated, thus creating a large fragment of the coating which splits off the surface. This can clog the nozzle or damage the sliding surface of the bearing, leading to a very dangerous and costly accident. Therefore, the strength of the coating was subsequently examined using a Philips XL30ESEM scanning electron microscope.

Table 2 Summary of parameters for the testing samples production

Shape	Feed f (mm)	Surface roughness Ra (μm)	Cutting speed v_c (mmin^{-1})	Cutting depth a_p (mm)	Heat-treated for refinement	Surface treatment	Tumbling
Cylinder/ Plane	0.08	0.6	120	0.5	all samples	Electroless nickel plating/ Nitriding	half of the samples
	0.12	1					
	0.16	2					
	0.20	3					
	0.24	4.5					

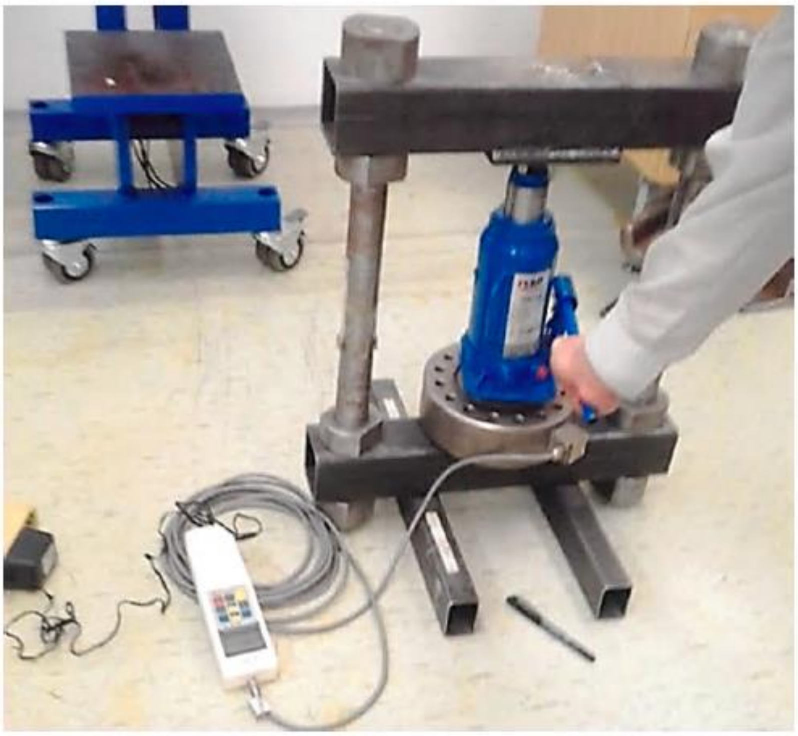

Fig. 10. Measuring set for quasi-static test of the samples.

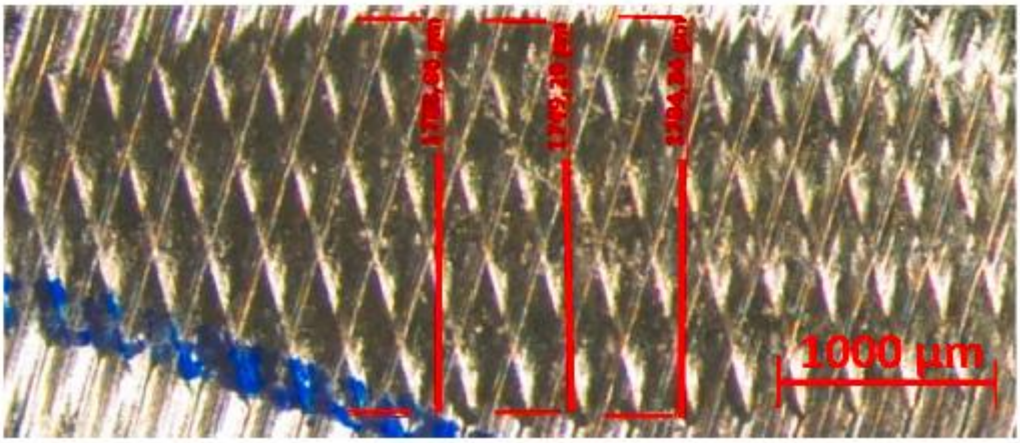

Fig. 11. Imprint wear measuring, Sample no. 11, load 2 t.

For compression quasi-static tests, three sizes of levers were selected, which according to current experience have the potential to be used the most in turbines. The levers were marked as “small”, “medium” and “large”. For each size, the lever without a hole (lower variant in the bearing) and with a hole (an upper variant of the lever) was made.

The levers were manufactured using the DMU 40eVo linear milling centre. The machining strategies were chosen so that the workpiece was machined in two steps of fixing. Special clamping jigs for the first and second clamping positions have also been adapted to this strategy. The final height of the lever arm was measured with a probe with an accuracy of 0.1 µm. The resulting accuracy (when the clamping error was considered) was in the range of ±0.01 mm. Process of the lever machining, the lever after machining from one side and machined lever are shown in Fig. 12.

The static load of bearings is usually known from the manufacturer of the equipment (turbines, turbochargers) and it is possible to calculate it or also experimentally verify, whether the lever arm (or lever arm surface) can carry out this static load. For safety reasons, the levers were tested only for a maximum load of 20 t. Fig. 13 shows the setting of the lever during testing. The lever arms were supported on both sides on hardened cylinders. Since, in this case, the lever arm had a cylindrical contact area (“A”) on one side and contact area (“B”) on the other plane, therefore, both contact pairs - Cylinder/Plane and Cylinder/Cylinder - could be statically test at once.

Fig. 12. (a) Process of the lever machining; (b) the lever after machining from one side; (c) machined lever.

After loading, all levers were visually inspected and the state of wear was documented on both arms of the lever, i. e. with cylindrical and planar geometry. This was done using a NIKON stereoscopic microscope. Subsequently, each lever in both areas arms was also checked on a scanning electron microscope.

5. Results and discussions

5.1. The 1st phase - Quasi-static test of the basic samples

5.1.1. Contact pair cylinder/cylinder

The development of wear for the Cylinder/Cylinder contact pairs is shown in the graphs in Fig. 14, which show the dependences of the wear on the load force for different surface treatments of the samples without and with tumbling treatment. In the case of nitrided samples, it was not possible to acceptably measure the dimension of the resulting trace after loading 0.5 t and 1 t.

It is clear from the graphs below that wear development at individual surface treatments differ, however at the load 5 t, the biggest wear appears at the samples only heat-treated without tumbling, as it was suspected. The trend of wear development is steeper at the nickel-plated samples in comparison with nitrided samples. Tumbling is a benefit for the surface treatment when the surface is stripped of “tops” of roughness after this technology. Therefore, the stress can be distributed over a larger area and in the case of static load, less wear will occur.

The examples of the imprints made by means NIKON stereomicroscope for the samples with a contact pair Cylinder/Cylinder for different surface treatments are presented in Fig. 15 and the topography was evaluated by scanning electron microscope.

Significant differences were found between the surfaces when testing the Cylinder/Cylinder assembly. Fig. 15 documents the development of damage all type of samples. The surface protrusions, which are the remnants of machining, are retained even under a load of 5 t. It is probably a combination of factors of surface strengthening of these protrusions and distribution of the load over the area [37].

The nitride layer in the static test showed good results at lower loads, i. e. up to 1 t, when the imprints were not practically measurable. This layer is very hard and durable, but on the other hand very brittle. Imprints with a load of 1 t have already shown cracks visible by means of a stereomicroscope, see Fig. 16. For imprints with a load of 2 and 5 t, large cracks are visible, which delimit the imprint. These cracks are interconnected and form a stepped transition between the unaffected coating (or the relatively unaffected) and compact centre of the imprint. The detail of a crack at the border of the imprint is shown in Fig. 16a, and detail of a delaminated layer in the middle of the imprint is shown in Fig. 16b.

It has been observed that the nitriding layer is fragmented into considerably large pieces. Cracks of beam and radial types have been visible here, which were also visible when examined with a stereomicroscope at 10x magnification, as it is shown in Fig. 17a. The effort of the layer to peel off is visible in the middle of the imprint in Fig. 17b. These fragments were in the order of tens of micrometre. Due to the oil film thickness of the bearing, which is in the range of 25-40 |rm, this value is already critical. To be able to use this nitride coating in the real operation, it would be necessary to guarantee that it will not be a point local load, but the load will be spread over a larger area. Even under these conditions, however, there is a danger that these coatings will not be able to withstand sudden overloads, which may occur especially in the case of a start-up or non-standard run-down of the power plant.

In the case of nickel-plated samples, relatively low hardness and high plasticity of the layer is evident compared to nitrided samples. The widths of the formed imprints have similar dimensions compared to the imprints formed in the uncoated samples, which were only refined.

Fig. 18 documents imprints in nickel-plated samples and shows a network of cracks on which the coating is fragmented (Fig. 18a). However, delamination is not visible even at the edge piling up after plastic deformation (Fig. 18b).

5.1.2. Contact pair cylinder/plane

The development of wear with the load increasing for the Cylinder/Plane contact pairs is shown in the graphs in Fig. 19. It can be seen from the graphs below that the static wear of the Cylinder/Surface assembly was orders of magnitude lower in all cases, with the nitrided surface having the advantage at low loads that greater damage (no cracks) occurs at very high loads (2 t).

The examples of imprints documented at plates of Cylinder/Plane contact pair when they were loaded by 5 t are in Fig. 20. From the imprints in the Fig. 20a-c below, a certain benefit of tumbling is still evident, when the surface is deprived of “peaks” of roughness after this technology. Therefore, the stress can be distributed over a larger area and in the case of a static load, less wear will occur.

Fig. 13. Lever set-up during the pressure testing.

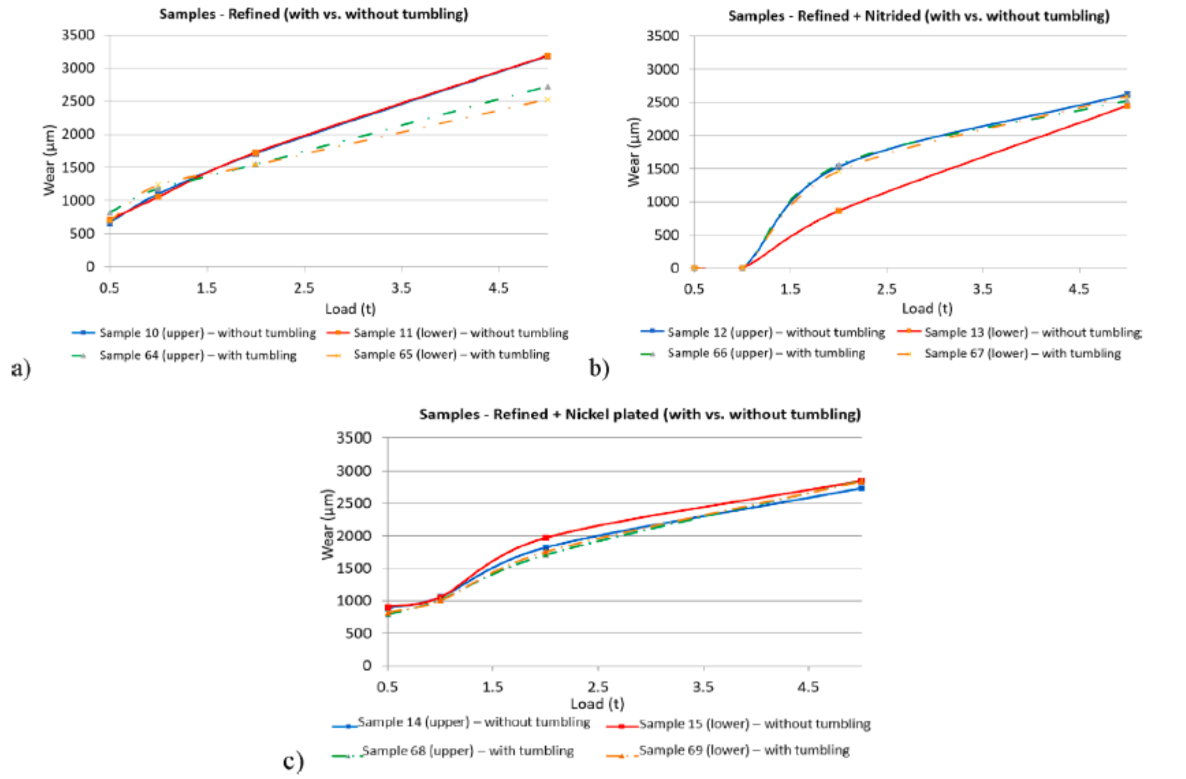

Fig. 14. Wear development for the samples with the Cylinder/Cylinder contact pair, (a) samples only refined, (b) refined + nitrided samples, (c)refined + nickel plated samples.

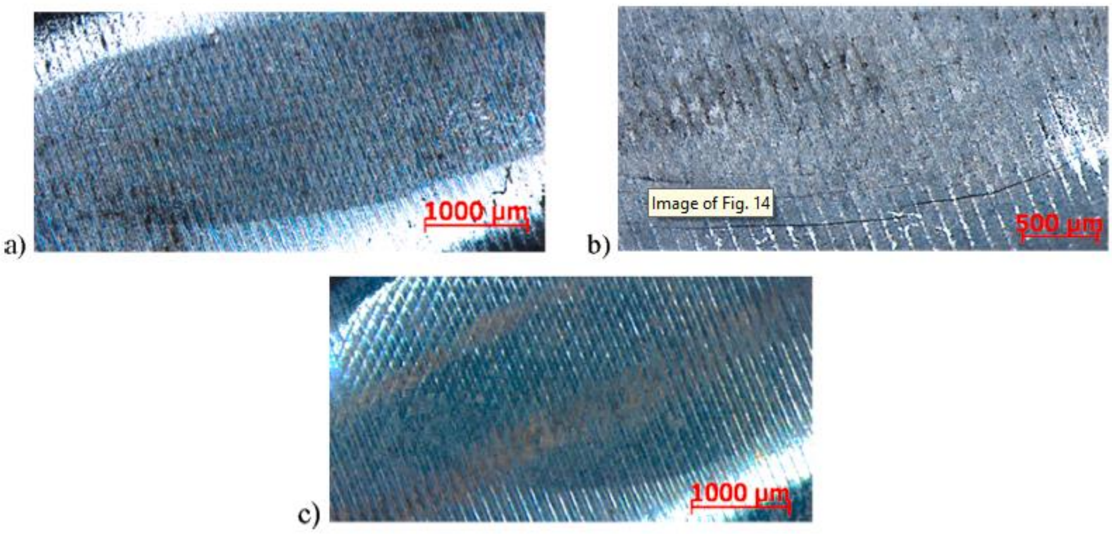

Fig. 15. The imprints of the samples with a contact pair Cylinder/Cylinder, (a) Sample No. 11, only heat-treated, 2 t load, (b) Sample No. 66, nitrided, 2 t load, (c) Sample No. 15, nickel-plated, 2 t load.

The topographies with a detailed view of the samples in contact pairs of the Cylinder/Plane with different surface treatments are shown in Figs. 21-24 separately for the cylinder and for the plate. No cracks in the nitrided layer were found on the cylinder or on the plate in the images of the nitrided sample. It can be stated that the nitrided layer also withstood a high load (overload) of 5 t.

In the case of nickel-plated specimens, there are visible cracks that accompany the plastic deformation, which occurs when the cylinder is pressed into the plate. At the same time, even this already considerable load (5 t) was obviously not enough to cause the massive destruction that was observed on the Cylinder/Cylinder contact pairs. However, for efficient weight distribution, it will be necessary to ensure a sufficiently high-quality assembling so that the line contact does not pass into point contact.

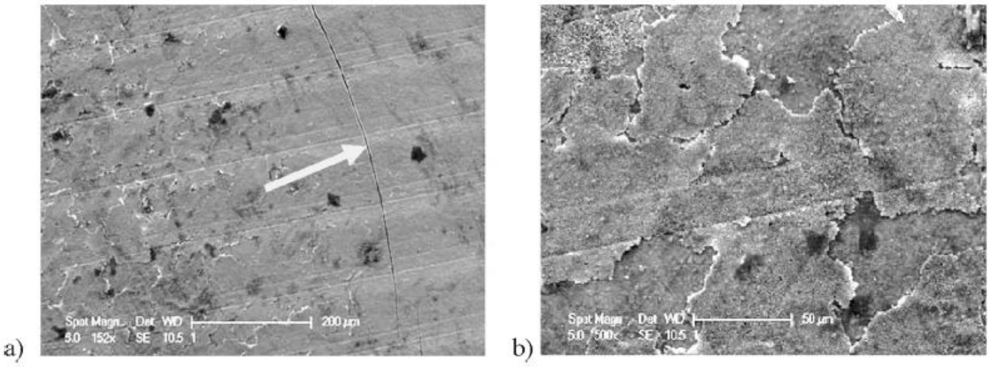

Fig. 16. Sample No. 67 - nitrided, (a) detail of a crack at the border of the imprint (b) detail of a delaminated layer in the middle of the imprint.

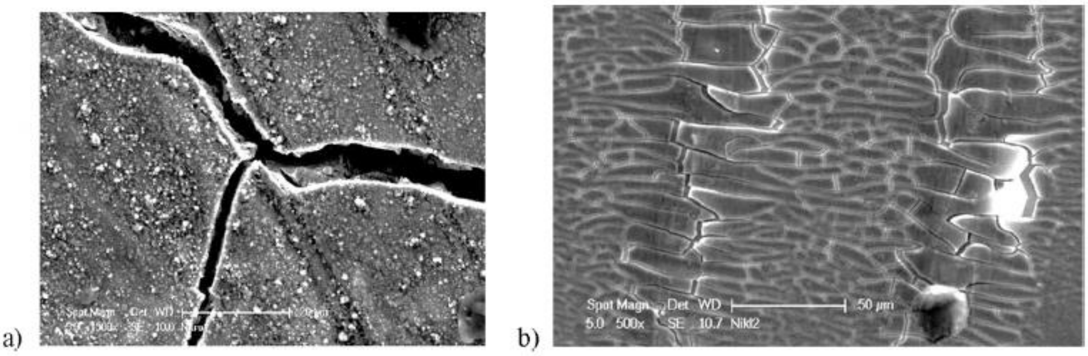

Fig. 17. Samples with nitrided layer, (a) radial crack, (b) the effort of the layer to peel off.

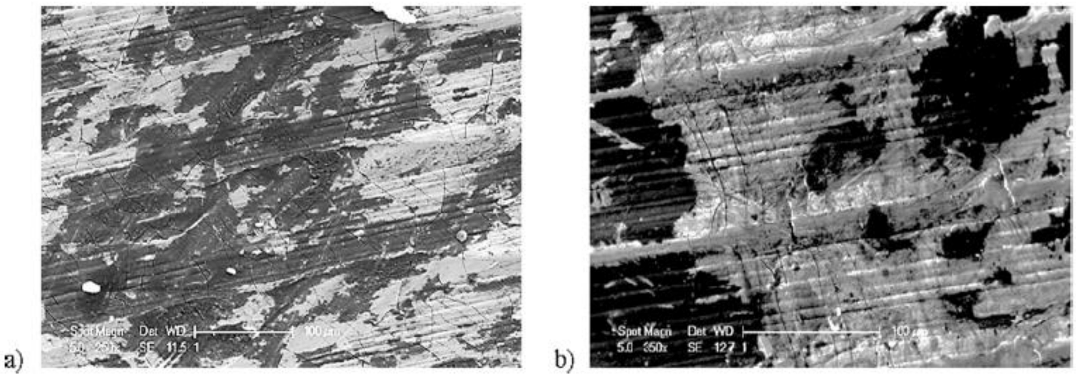

Fig. 18. Sample No.15 - nickel-plated, (a) 0.5 t load, (b) 1 t load.

Previous tests have shown that nickel-plated samples with tumbling, and partially also nitrided samples, show the best results in terms of the amount of damage created.

5.2. The 2nd phase - Static test of real levers

Since the nickel-plated surfaces showed the best of all variants of surface treatment, the final experimental verification of tribological properties was started, for already real levers surface-treated with nickel plating. Due to the shape complexity of the levers, a frequency test was not considered and only a static test was performed [38,39]. The aim of the test was to determine whether there was any development of damage to the surface layer under quasi-static loading.

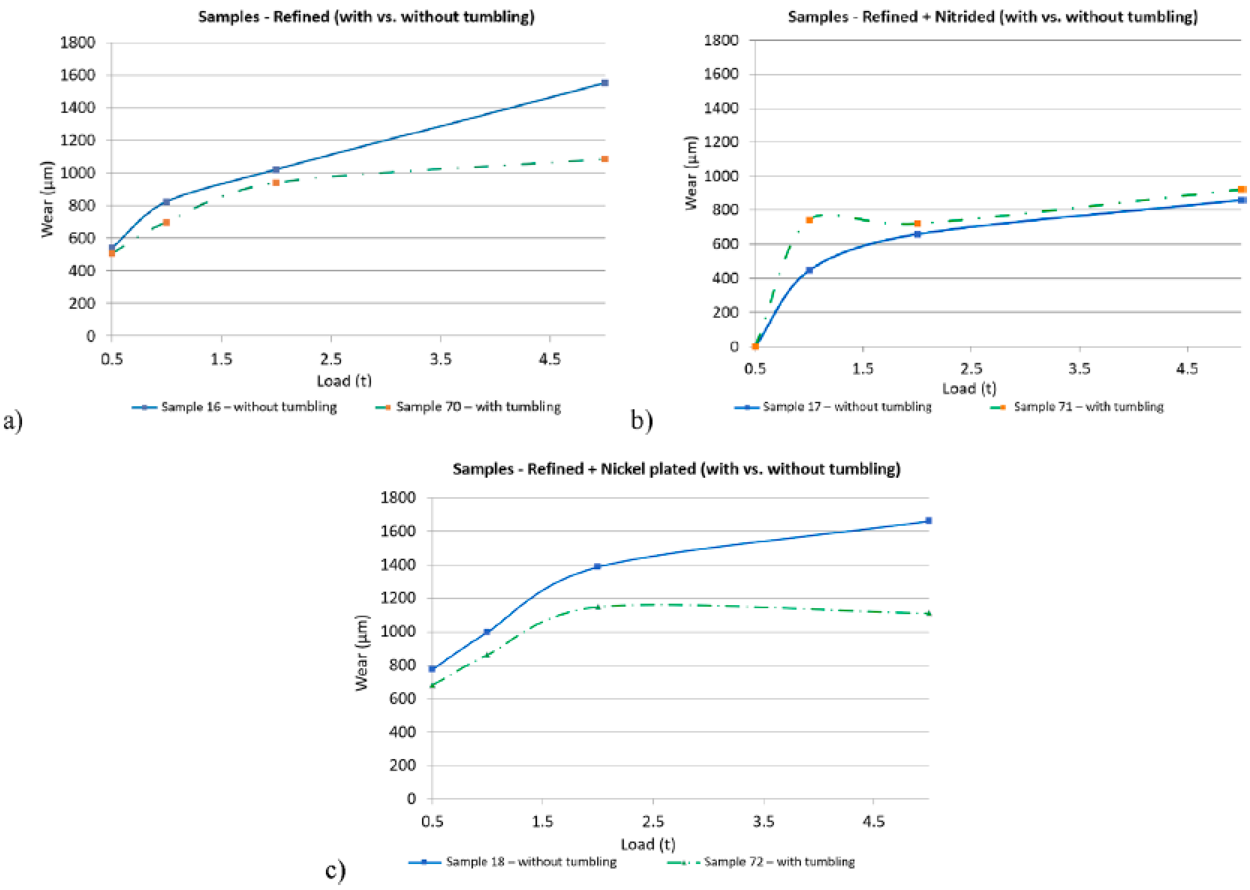

Fig. 19. Wear development for the samples with the Cylinder/Plane contact pair, (a) samples only refined, (b) refined + nitrided samples, (c) refined + nickel plated samples.

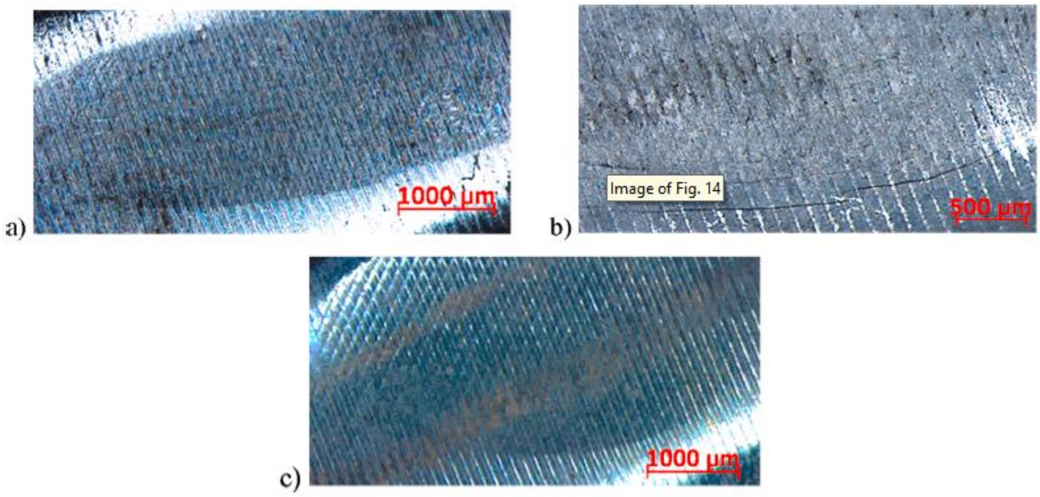

Fig. 20. The imprints of the samples with a contact pair Cylinder/Plane, (a) Sample No. 16 - Plate, only heat-treated, 5 t load, (b) Sample No. 17 -Plate, nitrided, 5 t load, (c) Sample No. 18 - Plate, nickel-plated.

As was mentioned in Section 4.2, three sizes of levers were selected and manufactured for compression quasi-static tests.

From the graph below (Fig. 25) it is evident that in the medium and large variants the stiffnesses are very similar, although the levers are quite different in size. The medium and large levers returned to their original shape after the end of the load (which was also verified on the granite slab), which means that the deformation of all levers was in the range of elastic deformations.

The smallest levers were no longer as rigid as the larger variants, and at about 150-160 kN plastic deformation had already occurred, as shown in Fig. 26. Then the test was interrupted because the lever arms slipped out of the jaws (documented by vertical line down in the graph in Fig. 26). However, it needs to be stated that the nominal load on the whole bearing in real practice, where the smallest variants of levers are used, is a maximum of~130 kN. It is <11 kN per lever arm, so the safety factor is more than 10 times higher.

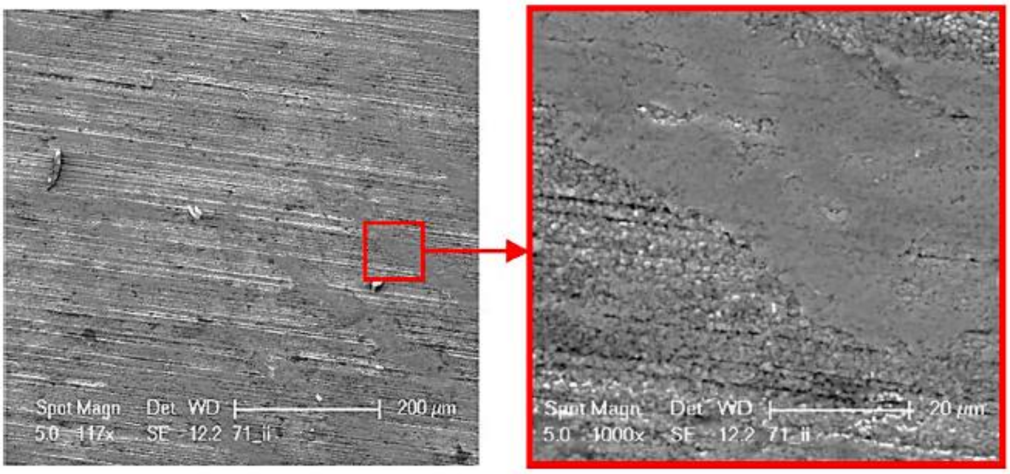

Fig. 21. Sample No. 71 Plate, nitrided, 5 t load.

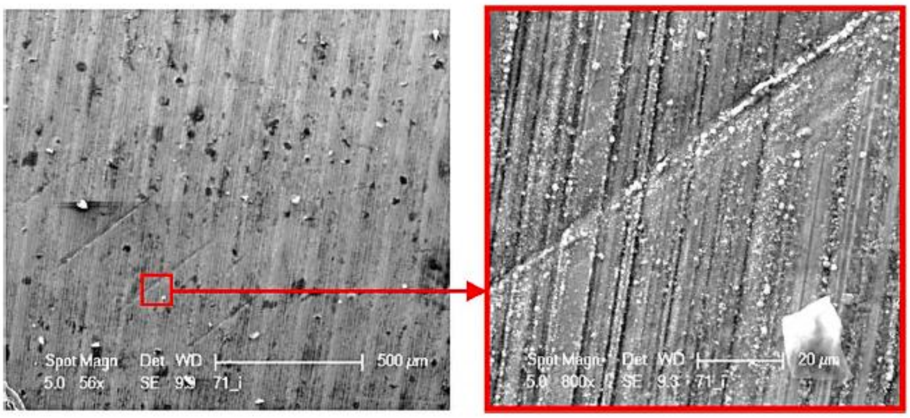

Fig. 22. Sample No. 71 Cylinder, nitrided, 5 t load.

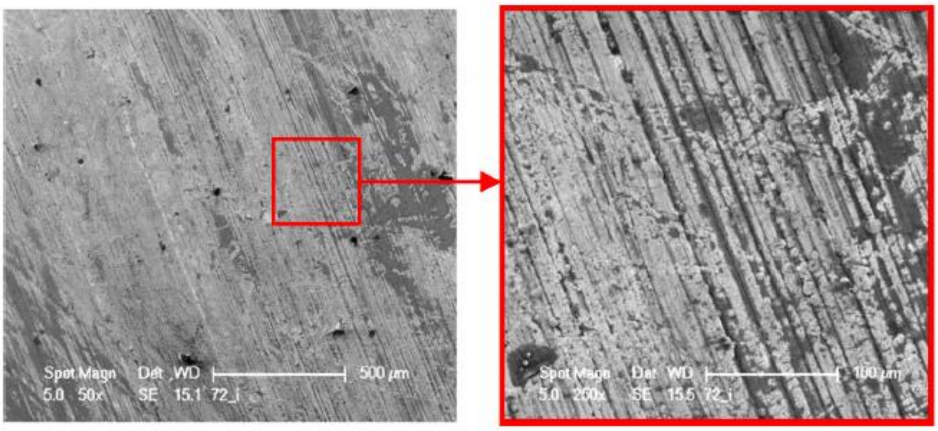

Fig. 23. Sample No. 72 Plate, nickel-plated, 2 t load.

Prior to the static test, areas A and B were marked on the levers (Fig. 27), which were documented on a scanning electron microscope. For all lever arms, these indicated areas have been retained, i. e. the cylindrical contact area is labelled “A”, the planar contact area is labelled B.

Minor defects were found in most levers, but subsequent analysis of the surface using a scanning electron microscope showed that the integrity of the surface is not significantly compromised in the observed defects. These were rather related to the surface reflective layers.

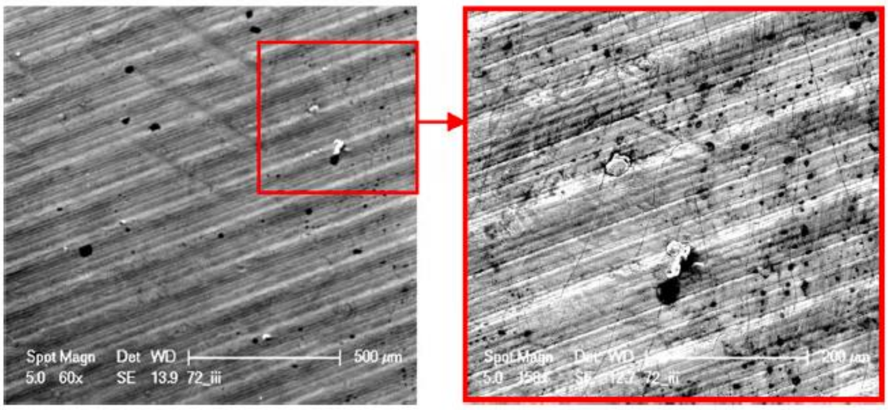

Fig. 24. Sample No. 72 Cylinder, nickel-plated, 2 t load.

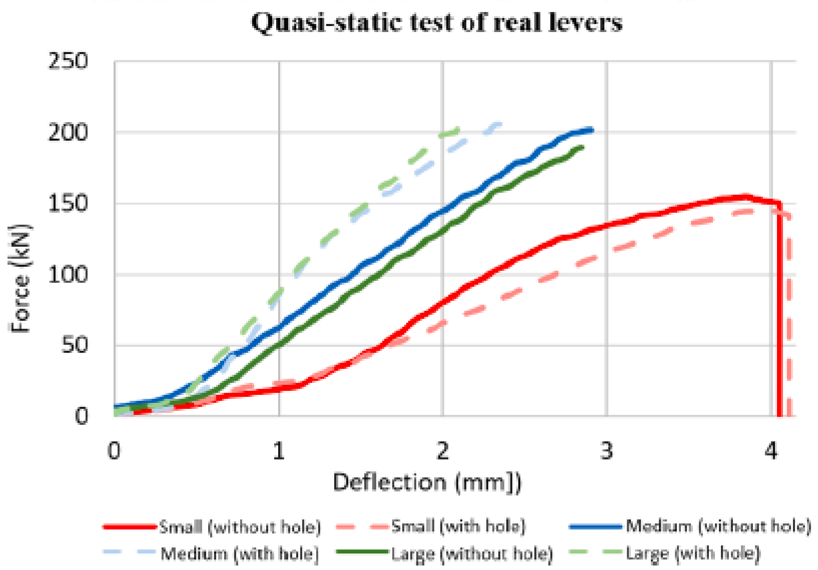

Fig. 25. Deflection development for all levers.

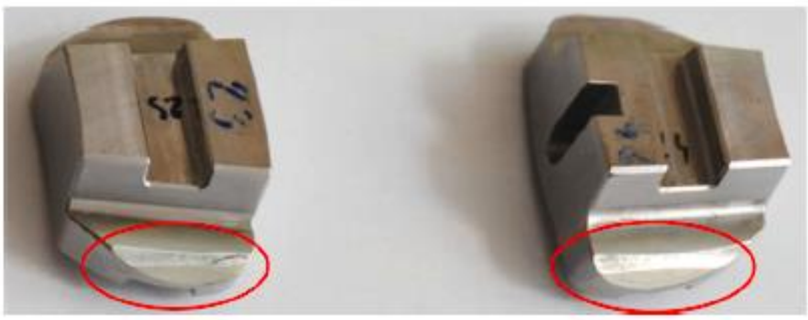

Fig. 26. Deformed small levers.

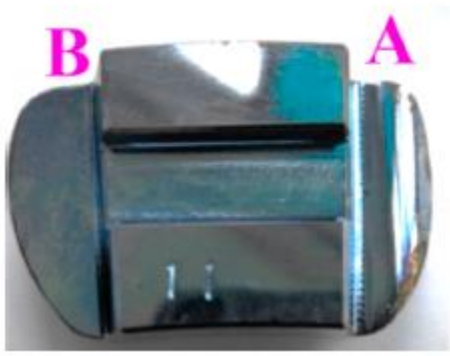

Fig. 27. A lever treated by electroless nickel plating before test.

The following Fig. 28a-c show some surface defects in selected lever at both arms, A and B.

As follows from the monitored lever, it was not possible to specify the actual condition of the surface only based on visual inspection (although when magnification by means of a stereomicroscope was performed). In all cases, when defects were detected by visual inspection using a stereomicroscope, these defects were refuted by subsequent observation with a scanning electron microscope. Only impurities that appeared as defects when visually observed were present on the surface of the levers. In some cases, these were surface defects, the cause of which was the surface treatment technology. These defects were more visible in the levers, which were not treated by tumbling.

Finally, it can be stated that no defects were found on any lever (at any surface roughness) after static loading, over more, no damage of the lever from the stiffness point of view was not observed and found out.

The stiffness of the levers seems to be also sufficient. With the smallest variant, the difference is more than 10 times, and with larger levers, it is not even detectable. The measurement was stopped after reaching 200 kN when the levers were still in the range of elastic deformations. The effect of the hole on the overall stiffness of the lever arm was not significant, which confirms the potential to use of the levers for both positions in the bearing, upper and lower.

6. Conclusions

One of the most important parts used in large rotary machines, such as turbines or compressors, is bearings. A critical part of the bearing is the lever, which transmits the load and compensates for the misalignment of the axes caused by various causes. After specifying the material and shape of the levers, preliminary research was performed focused on the surface treatment of the levers.

Based on this, the behaviour of two contact pairs Cylinder/Cylinder and Cylinder/Plane surface treated in several ways (nitriding, nickel plating, tumbling, and non-processing) under quasi-static loading was investigated within the presented research.

Since several aspects have been investigated in the design of the self-aligning bearing, it would not be economical to produce them directly in the final shape to determine the effect of the surface treatment on the behaviour of the lever arms. So, the authors decided to make the research in two phases.

The results of the simple-shaped samples that represented contact pairs between the levers pointed on the best properties electroless nickel plated samples. Based on that, the real levers were made, and their surfaces were treated by electroless nickel plating and the adhesion of surface layer, along with lever stiffness were investigated in this phase.

The results obtained in the research can be summarized in the following way:

- At the samples without surface treatment (only heat treated) - surface protrusions, which are the remnants of machining, are retained even under a load of 5 t.
- The nitrided layer is very hard and resistant to load, but on the other hand very brittle while large cracks were visible at loads of 2 and 5 t.

- Tumbling is a benefit for the overall surface treatment when the surface is stripped of “tops” of roughness after this technology. Therefore, the stress can be distributed over a larger area and in the case of static load, less wear will occur.
- The results of a quasi-static test of real levers showed that the designed levers of all three tested sizes are sufficiently rigid.
- Only impurities that appeared as defects when visually observed were present on the surface of the levers. In some cases, these were surface defects, the cause of which was the surface treatment technology. These defects were more visible in the levers, which was not treated by tumbling.

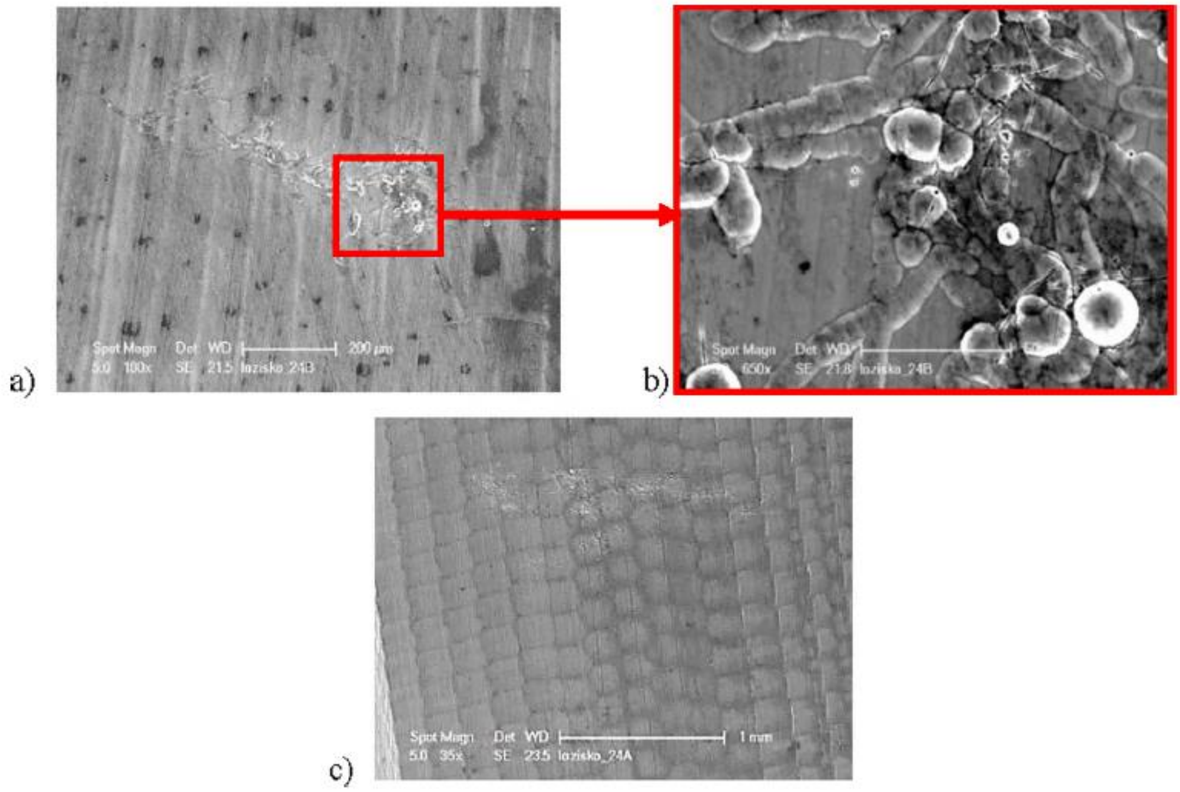

Fig. 28. Surface defects on the lever num. 31; (a) area B; (b) detailed view on the defects in area B; (c) area A.

Finally, it can be stated that no defects were found on any lever (at any surface roughness) after static loading, over more, no damage of the lever from the stiffness point of view was not observed and found out. It led to that the nickel-plated levers have been manufactured and they were used to produce the self-equalizing bearing which was tested at 3 various devices: experimental turbine DOOSAN Skoda Power TG 10, experimental gear stand built by Howden CKD Compressors + GTW BEARINGS, and experimental compressor set Darina IV Howden CKD Compressors. The bearings have fulfilled all the requirements and now they are implemented in real practice.

References

[1] Martsinkovsky, et al., Designing Thrust Sliding Bearings of High Bearing Capacity, in: 13th International Scientific and Engineering Conference, Sumy, Ukraine, 2011.

[2] T. Sedmak, E. Veg, Failure prevention of rotating equipment by vibrodiagnostics, Struct. Integrity Life 12 (2) (2012) 99-104.

[3] J.M. Bossio, G.R. Bossio, C.H. De Angelo, Angular misalignment in induction motors with flexible coupling, industrial electronics, in: IECON '09, 35th Annual Conference of IEEE, 2009.

[4] V. Hariharan, P.S.S. Srinivasan, Vibration analysis of parallel misaligned shaft with ball bearing system" Songklanakarin, J. Sci. Technol. 33 (1) (2011) 61-68.

[5] J. Piotrowski, Shaft Alignment Handbook, 3rd ed., M. Dekker, Inc. New York, U.S.A., 2006.

[6] S.D. Rahinj, et al., Vibration analysis of misaligned shafts international, J. Res. Appl. Sci. Eng. Technol. (IJRASET) 7/IV (2019).

[7] N. Milovanovic, Structural integrity and life assessment of rotating equipment, Eng. Fail. Anal. (2020), https://doi.org/10.1016/j.engfailanal.2020.104561.

[8] P. Avrampos, G. Vosniakos, Coverage in planar surface polishing by trochoidal tool paths, Int. J. Int. Des. Manuf. (IJIDeM) (2017), https://doi.org/10.1007/ s12008-017-0420-1.

[9] L.A. Branagan, Survey of damage investigation of babbitted industrial bearings, Lubricants 3 (2) (2015) 91-112.

[10] Kingsbury, Equalize Your Additional Misalignment, 2011. [Online]. Available: http://www.kingsbury.com/pin-type-leveling-plates.shtml.

[11] I. Pavlenko et al., Application of Artificial Neural Network for Identification of Bearing Stiffness Characteristics in Rotor Dynamics Analysis, Advances in Design, Simulation and Manufacturing, 2018, pp. 325-335.

[12] Waukesha, Catalog - Modular Tilting Pad Thrust Bearings - Compact Equalized - CQ Brochure, 2009.

[13] John Crane, Catalog - Tilting pad thrust bearings, 2015.

[14] M. Urban, T. Skopecek, J. Dolejs, 2015, Measurement of the thrust bearings with self-equalizign elements and the fixtures desing for the specification of their maximal deflection, in: Proceedigns of the Manufacturing Technology Conference, Pilsen, Czech Republic.

[15] Kingsbury, Catalog - Low profile equalizing LEG bearings, 2016.

[16] C.M. Ettles, R.T. Knox, J.H. Ferguson, D. Horner, Test results for PTFE-faced thrust pads, with direct comparison against Babbitt-faced pads and correlation with analysis, Trans. ASME 125 (2003) 814-823.

[17] F.I. Stratogiannis, et al., Optimization of the manufacturing strategy, machining conditions, and finishing of a radial impeller, Machines 8 (1) (2019) 1, https:// doi.org/10.3390/machines8010001.

[18] M.E. Abd El-Azim, M.M. Ghoneim, A.M. Nasreldin, S. Soliman, Effect of various heat treatments on microstructure and mechanical properties of 34CrNiMo6 steel, Zeitschrift fur Metallkunde 88 (1997) 502-507.

[19] M. Urban, K. Monkova, Research of tribological properties of 34CrNiMo6 steel in the production of a newly designed self-equalizing thrust bearing, Metals 10 (2020) 84.

[20] G.A. Pantazopoulos, A short review on fracture mechanisms of mechanical components operated under industrial process conditions: fractographic analysis and selected prevention strategies, Metals 9 (2) (2019) 148.

[21] M. Puskaric, Z. Car, N. Bulic, Magnetic bearing control system based on PI and PID controllers, Technical Gazette 25 (1) (2018) 136-140.

[22] A. Borghi, E. Gualtieri, D. Marchetto, L. Moretti, S. Valeri, Tribological effects of surface texturing on nitriding steel for high-performance engine applications, Wear 265 (2008) 1046-1051.

[23] A.I. Toulfatzis, et al., Final heat treatment as a possible solution for the improvement of machinability of pb-free brass alloys, Metals 8 (2018) 575.

[24] Pioneer motor bearing, Bearing damage - Flip Chart, 2007.

[25] S. Zhu, P. Huang, Influence mechanism of morphological parameters on tribological behaviors based on bearing ratio curve, Tribol. Int. 10 (2017) 10-18.

[26] D. Liu, Q. Zhang, Z. Qin, Q. Luo, Z. Wu, L. Liu, Tribological performance of surfaces enhanced by texturing and nitrogen implantation, Appl. Surf. Sci. 363 (2016) 161-167.

[27] A. Polasek, Design and machining technology verification of the key components of a self-equalizing trust bearing, Diploma thesis. Faculty of Mechanical Engineering, West Bohemia University in Pilsen, Czech Republic, 2016.

[28] A. Vazdirvanidis, et al., Failure analysis of a hardened and tempered structural steel (42CrMo4) bar for automotive applications, Eng. Fail. Anal. 16 (2009) 1033-1038.

[29] J. Cochet, S. Thuillier, T. Loulou, N. Decultot, P. Carre, P.Y. Manach, Heat treatment of 34CrNiMo6 steel used for mooringshackles, Int. J. Adv. Manuf. Technol. 91 (2017) 2329-2346.

[30] N. Popescu, M. Cojocaru, V. Mihailov, Experimental studies on bulk tempering of 34CrNiMo6 steel, Surf. Eng. Appl. Electrochem. 48 (2012) 28-34.

[31] T. Polcar, N.M.G. Parreira, R. Novak, Friction and wear behaviour of CrN coating at temperatures up to 500, Surf. Coat. Technol. 19 (10/11) (2007) 5228-5235.

[32] M. Mihalikova, K. Zgodavova, A. Liskova, Testing of microalloyed steel quality under creep conditions for a new intended use, Adv. Mater. Sci. Eng. 2017 (2) (2017) 1-7.

[33] A. Kuduzovic, et al., Investigations into the delayed fracture susceptibility of 34CrNiMo6 steel, and the opportunities for its application in ultra-high-strength bolts and fasteners, Mater. Sci. Eng. 590 (2014) 66-73.

[34] K.R. Kiran, B. Nanohar, S. Divakar, A central composite rotatable design analysis of lipase catalyzed synthesis of lauroyl lactic acid at bench-scale level, Elsevier Enzyme Microbial Technol. 29 (2-3) (2001) 122-128.

[35] P. Pastucha, V. Majstorovic, M. Kucera, P. Beno, S. Krile, Study of cutting tool durability at a short-term discontinuous turning test, Lect. Notes Mech. Eng. (2019) 493-501.

[36] G. Vukelic, et al., Failure investigation of a crane gear damage, Eng. Fail. Anal. 115 (2020) 104613.

[37] B. Matesa, et al., The influence of heat treatment by annealing on clad plates residual stresses, Metallurgy 50 (4) (2011) 227-230.

[38] S. Baragetti, Fracture surfaces of Ti-6Al-4V specimens under quasi-static loading in inert and aggressive environments, Eng. Fail. Anal. (2019).

[39] Z. Miskovic, et al., Analysis and prediction of vibrations of ball bearings contaminated by open pit coal mine debris particles, Technical Gazette 24 (6) (2017) 1941-1950.