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Water Lubricated Sintered Bronze Journal Bearings - Theoretical and Experimental Research

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ABSTRACT

Recent years have witnessed growing interest in hydrodynamic water lubricated journal bearings. At the present time, water lubricated bearings are widely used in various branches of technology. Well known constructions made from rubber, polymers or composite materials are apply in shipbuilding and hydropower industry.

Various types of water lubricated sliding bearings have been tested at the Technical University of Gdańsk - stiff composite bearings, ceramic, and elastic polymer ones. It was unequivocally determined that a properly designed hydrodynamic water lubricated journal bearing may function under hydrodynamic regime in the conditions of typical loads and speeds found in practical applications.

In this paper, the authors present an attempt at researching the possibility of more extensive use of other stiff bush bearings, represented by bronze bush bearings. The aim of the research was to investigate stiff metal bearings, as solutions offering theoretically greater load bearing capacity than comparable elastic bearings and capable of replacing typical polymer and rubber bearings in certain applications.

Based on the conducted research, it can be concluded that bronze bearings may constitute an interesting alternative to non metallic bearings. Although they require hardened journal surface, they nevertheless offer a greater load bearing capacity, durability and lower movement resistance levels. These bearings are particularly attractive for use with journals of relatively small diameters working under heavy loads.

KEYWORDS: hydrodynamic bearings, water lubricated bearings, marine bearings

INTRODUCTION

Recent years have witnessed growing interest in hydrodynamic water lubricated journal bearings. At the present time, water lubricated bearings are widely used in various branches of technology. Well known constructions made from rubber [1,2,3] polymers [4,5,6] or composite materials [7] are common in shipbuilding industry. Rubber and polymer bearings are employed in pumps, [8], as are ceramic ones [9,10] and bearings made from various sinters [11]. Polymer and rubber bearings are found in water turbines, while ceramic ones are currently undergoing testing and implementation phase [12].

All water lubricated journal bearings may be divided into two basic groups - stiff bearings which do not experience significant bush deformation due to hydrodynamic pressure and elastic bush bearings. The stiff bearing group should include all the constructions with the module of elasticity lower than 3000 MPa, that is all types of bronze and ceramic bearings, as well as majority of composite bearings based on epoxy resins. Remaining bearings - rubber, polymer, foil etc. belong to the elastic bearing group.

ORIGIN AND PURPOSE

Various types of water lubricated sliding bearings have been tested at the Technical University of Gdańsk - stiff composite bearings [13,14,15], as well as ceramic [16], and elastic polymer ones [17,18,19]. It was unequivocally determined that a properly designed hydrodynamic water lubricated journal bearing may function under hydrodynamic regime in the conditions of typical loads and speeds found in practical applications. Unfortunately, low viscosity of the lubrication liquid, that is water, as well as lack of the effect of increasing viscosity as a function of pressure [20,21], result in the fact, that despite the possibility of full hydrodynamic lubrication, the minimum water film thickness is very small and usually does not exceed a few hundredths of a millimeter.

Both the research by the authors, as well as the findings of relevant literature, point out that elastic, polymer bush bearings have lower hydrodynamic capacity than comparable stiff bearings (made of composite materials) and at the same load values operate with lower film thickness [22]. This stems from local deformation of bush surface under the influence of pressure generated in the lubricating film. As a result of the created deformation, the shape of bearing interspace changes in the area of increased pressure. Such surface deformations may reach the theoretical minimum value of bearing interspace thickness. It is for this reason that significant limiting of the value of the forming hydrodynamic pressure takes place in the bearing, which has influence on its load capacity. Typical results of calculated pressure distribution in water lubricating film, as well as of bush deformation are presented in the diagrams below (Fig. 1 and Fig.2). The calculations employed the theory of hydrodynamic lubrication. The isothermal model was selected due to its being valid for water. Bush deformation was calculated using the finite element method. The values of sliding pressure and speed were typical for a stern tube bearing of a marine propeller shaft.

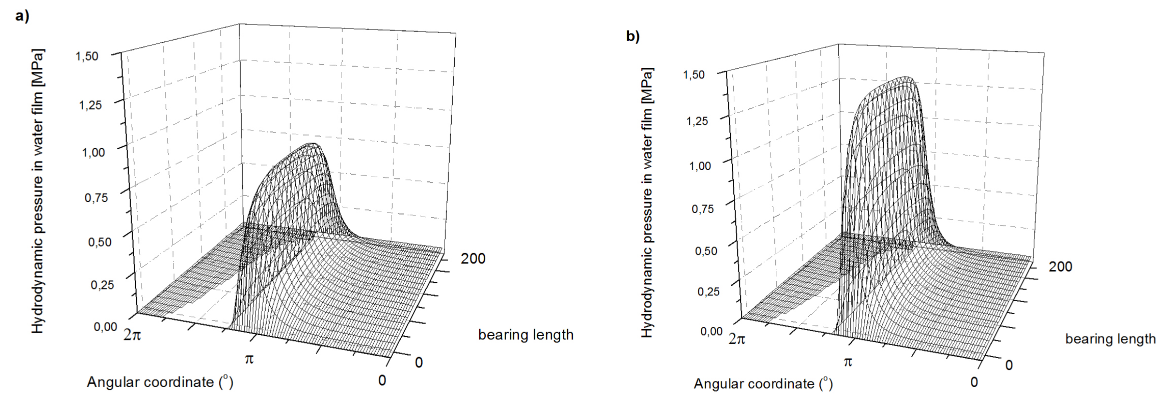


Fig. 1. Calculated pressure distribution in water lubricated bearing; a) flexible elastomer bush, b) composite material bush

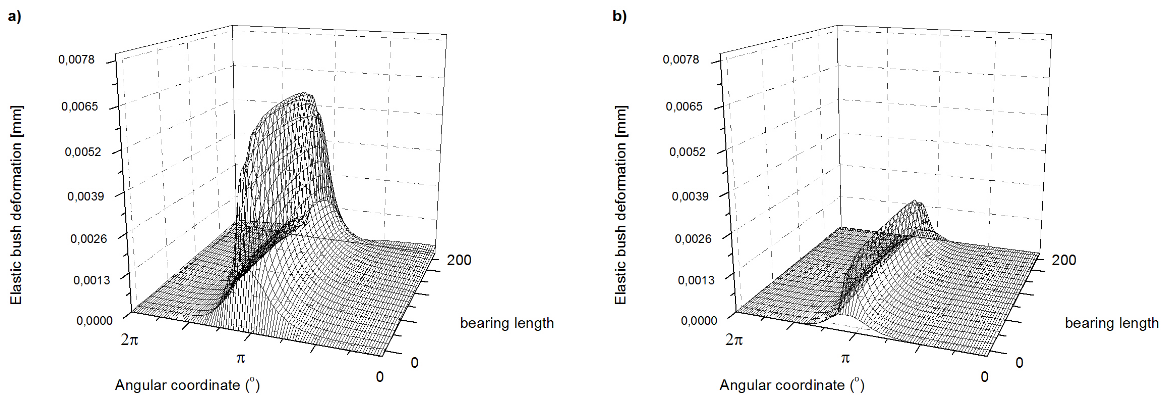


Fig. 2. Calculated deformation of water lubricated bearing bush under pressure; a) flexible elastomer bush, b) composite material bush

Another disadvantage of elastic bearings made from polymers is the fact, that due to their low heat conductivity value co-efficient, the extraction of heat generated in bearing interspace is much more difficult than it is in case of metal bearings. Therefore, a breakdown of lubricant circulation system, or prolonged work under conditions of mixed lubrication, usually results in bearing's failure and ensuing costly repair.

Greater load bearing capacity of stiff bearings in comparison to elastic ones, has inspired the authors to search for modern-day solutions in increased load bearings capacity found among ceramic bearings [16]. As part of the conducted research, own prototypes of ceramic tilting pad type bearings were prepared and numerous experimental tests were carried out, which confirmed much greater bearing capacity of ceramic bearings in comparison to classic polymer bush ones. Unfortunately, in addition to their benefits ceramic bearings also come with indisputable disadvantages, such as no possibility of handling large journal diameters and susceptibility to damage. Even small, local damage of their sliding surface results in complete elimination of proper water film formation possibility, as well as in destruction of the co-working sliding element, effectively eliminating the bearing from further use.

In this paper, the authors present an attempt at researching the possibility of more extensive use of other stiff bush bearings, represented by bronze bush bearings. The aim of the research was to investigate stiff metal bearings, as solutions offering theoretically greater load bearing capacity than comparable elastic bearings and capable of replacing typical polymer and rubber bearings in certain applications.

CHARACTERISTIC OF INVESTIGATED BEARINGS AND RESEARCH METHODOLOGY

Two different bronze bearings were selected for research purposes - a typical, centrifugally cast bronze bearing and a bearing made from sintered bronze. Despite both of them being made from bronze, the two bearings are characterized by differing tribological properties, and manufacturing technology.

Cast bronze bushes are substantially less expensive than bushes made from sinters, as the process of their production does not require high pressure and special moulds. Their additional advantage lies in the technology of centrifugal casting, which allows them to be manufactured for journals up to 2 meters in diameter. Most often cast bronze bearings are prepared from aluminum bronzes which have fairly good sliding properties and are sea water resistant. Unfortunately, the easier production process and the lower price are accompanied by inferior sliding material properties.

Constructions prepared from sintered bronzes represent another type of bronze bearings. Although their manufacture is more expensive than in the case of cast bearings, their structure allows for obtaining decisively better tribological properties. Sintered tin bronze containing solid grease usually in the form of graphite (6-12% by weight) or molybdenum disulfide (1-3% by weight) is the type most commonly used. Since the manufacturing process calls for pressing at high temperatures, sintered bronzes can be found most often in the form of semi-prefabricated sleeves of limited length, which have to be appropriately fitted in the bush using special glues or screws, and then undergo turning to obtain the exact, final internal diameter. Modern-day sintered materials are successfully used in water lubricated bearings of water turbine or water pump shafts.

Detailed data of the tested bearings is presented in Table 1. The first bearing was prepared from aluminum - iron - manganese bronze BA1032 (CuAl10Fe3Mn2), with the journal made of stainless steel X10CrNi18-8 (AISI 301) and another one of steel X30Cr13, the second bearing was prepared from sintered brass with graphite with a corresponding bush sleeve prepared from steel X30Cr13.

Working conditions during tests are presented in Table1 and Table 2 below.

Table 1. Data of bearings assigned for testing

<table>
<tr><th></th><th>Material of bush/ journal</th><th>Modulus of elasticity [MPa]</th><th>Journal diameter [mm]/Bush length [mm]/</th><th>Bearing slackness [mm]</th><th>Average bush roughness height</th><th>Average journal roughness height</th></tr>
<tr><td>1</td><td>CuAl10Fe3Mn2 / X10CrNi18-8 AND CuAl10Fe3Mn2 / X30Cr13</td><td></td><td rowspan="2">100/150</td><td></td><td>0.25 µm</td><td rowspan="2">0.32µm (grinded surface)</td></tr>
<tr><td>2</td><td>Sintered brass with graphite / X30Cr13</td><td>$1,1x10^5$</td><td>0,15</td><td>0.37 µm</td></tr>
</table>

Table 2. Experimental research conditions

Shaft diameter [mm]	Bearing length[mm]	Rotational speed of journal [rev/s]	Average pressure during tests [MPa]	Intensity of water flow through bearing
100	150	1, 2, 3, 5, 7, 9, 11	0.2, 0.4, 0.6	~6 litres/min

The research was conducted under conditions similar to those found in water turbine or stern tube bearings. In order to obtain maximum information about tribological properties of both bearings, a number of tests were planned for different loads and rotational speeds. Load was applied in static manner by a hanging weight. Three different load values were investigated, with average pressures of 0.2, 0.4 and 0.6 MPa. The rotational speed was modified within the range of 0 to 11 revolutions per second (rev/s). Measurements were carried out for the speeds of 1, 2, 3, 5, 7, 9 and 11 rev/s. It should be emphasized that in a horizontally operating propeller shaft, the bearing is forced to work under much more demanding conditions than in the case of vertical water turbine shaft. This stems from greater radial loads resulting from static and dynamic mass forces acting on the shaft - propeller assembly.

The test rig used in the research work had been described in earlier works [23,24]. The rig offers extensive research capabilities and allows for testing of bearings under conditions approximating those found in actual equipment. Measurement taken during the conducted tests included those of movement resistance, pressure in the lubrication film, temperature, flow intensity of cooling water, as well as shaft axis trajectory. The movement resistance measurements included also those of static friction coefficient. The temperature of water passing through the tested bearing was 15°C. The minimum flow intensity was 6 liters per minute which was sufficient to ensure proper cooling of the bearing.

All the bearing measurements were conducted after a 24 hour running-in period (low revolution range, mixed friction conditions).

The conducted cylindricity measurements of the prepared bronze bushes registered cylindricity flaw not greater than 0.015 mm which was considered satisfactory. It is important to emphasize that for polymer bush bearings it is usually hard to obtaining perfect cylindricity of internal bush. This stems from the difficulty of machining very elastic polymers and their deformation due to water swelling (soaking).

Test results of bearings prepared by casting technology – material CuAl10Fe3Mn2

Experimental research of bearing no. 1 working in combination with journal made of steel X10CrNi18-8 demonstrated that such an arrangement despite its excellent performance with lubrication provided by oil or grease is not fit for operation under water lubrication conditions. The experiment was terminated by seizure during the initial test trial phase, with the average pressure and revolution speed not exceeding 0.2 MPa and 5 rev/s respectively.

After an analysis, it was concluded that the seizure might have been caused by incorrect selection of the bush-journal combination. Following consultation with a company which had manufactured similar bearings for shipbuilding industry, a new shaft was prepared, this time with a hardened sleeve made from X30Cr13 steel (Table1). The effect of pairing the two materials was completely inadequate. As soon as the initial start-up, with only minimum loads at work, local abrasions appeared, as presented in Fig.4. The bush material was brought onto, spread over and pressed into the journal surface, in the form of characteristic circumferential irregularities.

In connection with the rapid seizing of the journal - bush sliding combination, it was decided that continuing to test the CuAl10Fe3Mn2 bush was pointless and that working with that material should be terminated.

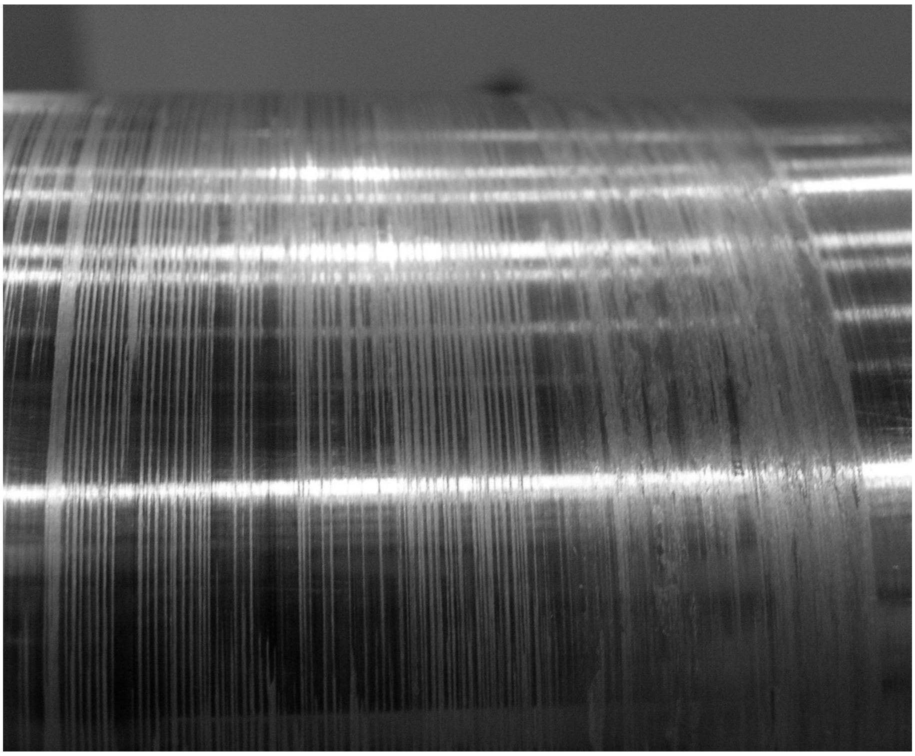


Fig. 3. Damaged shaft of stainless steel X10CrNi18-8, visible on its surface are the relocated wear products of bronze CuAl10Fe3Mn2 bush

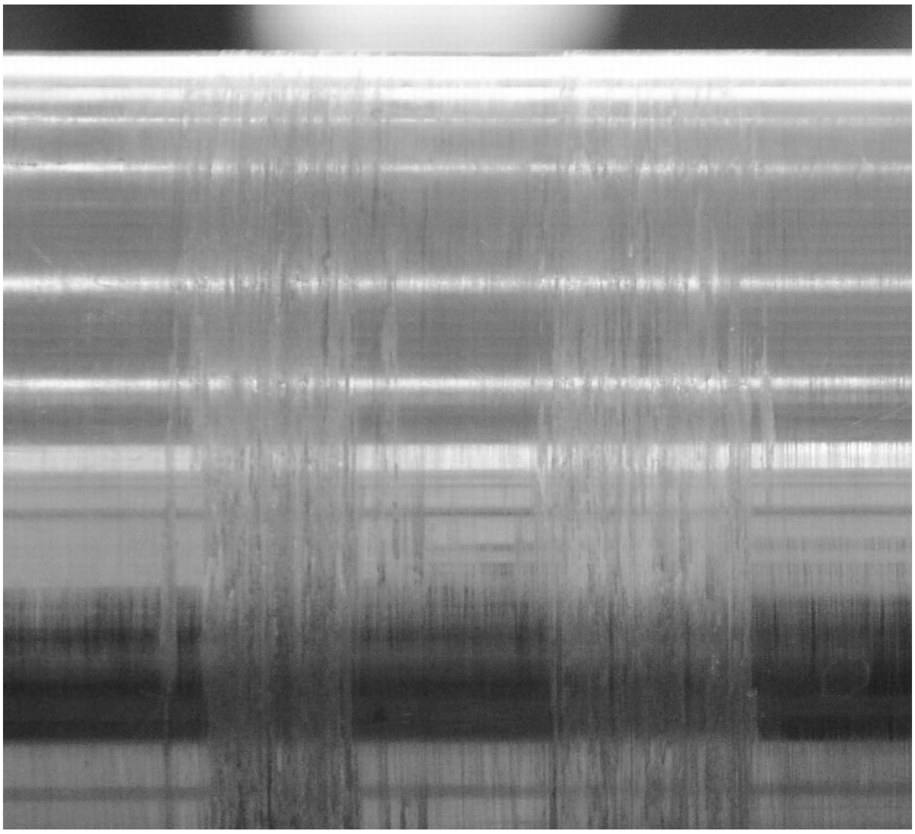


Fig. 4. Seized shaft of X30Cr13 stainless steel with visible, relocated wear products of CuAl10Fe3Mn2 bronze bush

Sintered brass bearing tests

Bearing no. 2 of sintered brass with graphite was tested during the second phase of the experiment. Due to the relatively high hardness of the used bronze (in comparison to the polymer), the bush of this type had to be matched with a journal of 35HRC minimum hardness. It is for this reason that a hardened stainless steel X30Cr13 (AISI 420) sleeve was placed on the steel X10CrNi18-8 shaft by a method of thermal compression. Following its placement, the sleeve underwent grinding and polishing which ensured obtaining perfect shape and diameter of the journal.

Start-up resistance in comparison to polymer bush bearing.

The ability to start-up under acting load is a very important property of water lubricated sliding bearings. It is especially important in the case of marine propeller shafts, which put bearings under load regardless of whether the shaft is revolving or not. In sliding bearings, contrary to roller ones, there is often a problem with very high resistance during start-up under load (Fig. 5). This is caused by high, static coefficient of friction which occurs in the conditions of no hydrodynamic lubrication. In case of polymer bearings, this effect may be multiplied by stick-slip phenomena. Usually, after the shaft reaches even a low revolution speed (about a few rpm), there is a partial build-up of hydrodynamic pressure and the coefficient of friction rapidly drops. The collective graphs below (Fig.6) portray friction measurement results in the metal and polymer bearings, as a function of revolution speed and average loads.

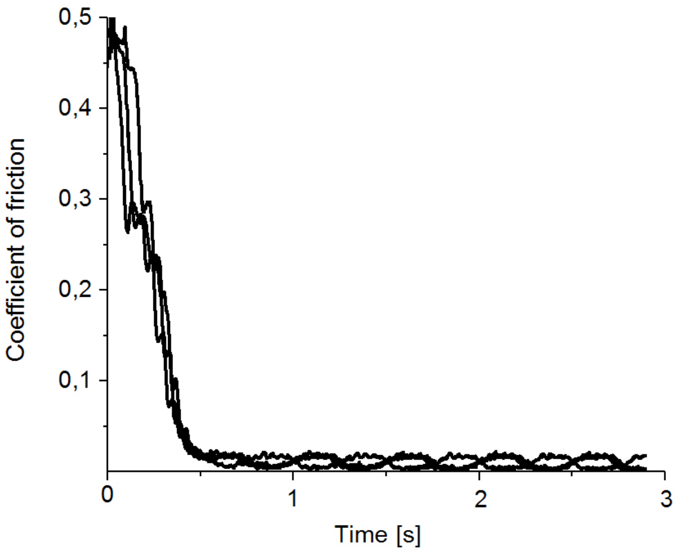


Fig. 5. Resistance measured during sintered bronze bearing start-up, three consecutive start-ups, loads 0.4 MPa

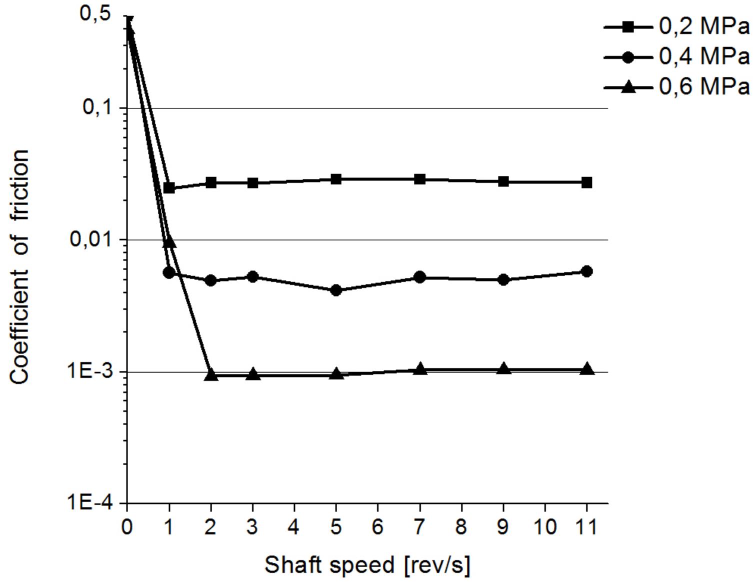


Fig. 6. Measured coefficient of friction for sintered bronze bearing with metal bush

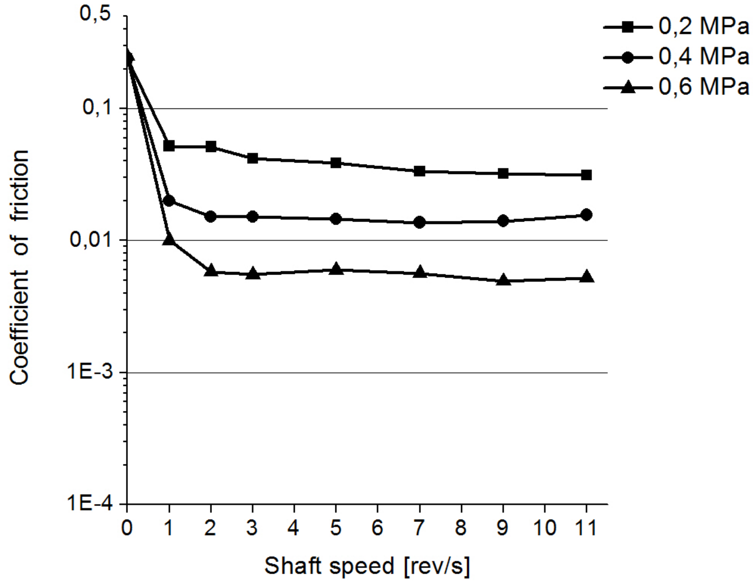


Fig. 7. Measured coefficient of friction for elastic, polymer bush bearing.

The recorded coefficient of friction values demonstrate that a metal bush bearing has a higher static friction coefficient, amounting to approximately 0.5. Under the same conditions, the coefficient of friction in the compared polymer bearing was approximately 0.25. This means that the metal bush bearing requires at least twice as much starting torque as the polymer bush one. One can also see that in the metal bearing the drop in movement resistance is faster, since after reaching the revolution speed of 0.5 rev/s the coefficient of friction decreases by a factor of five to the value of approximately 0.1. This is undoubtedly connected with more rapid forming of hydrodynamic lubrication film in a stiff bearing than in an elastic (polymer) one. In addition, it should be noted that a metal bush bearing operating under static load conditions also has lower resistance to motion (regardless of load values), which might indicate local presence of mixed lubrication in proximity to the edge of the polymer bearing.

Testing hydrodynamic pressure distribution

Presented below are selected experimental test results of hydrodynamic pressure distribution in a metal (stiff) bearing and comparable elastic polymer one (Fig. 8 ÷ 10). When analyzing the obtained results one can notice significant influence of bush stiffness on the pressure distribution shape. The metal bearing has significantly higher maximum pressure value, which changes as a function of average loads and speeds.

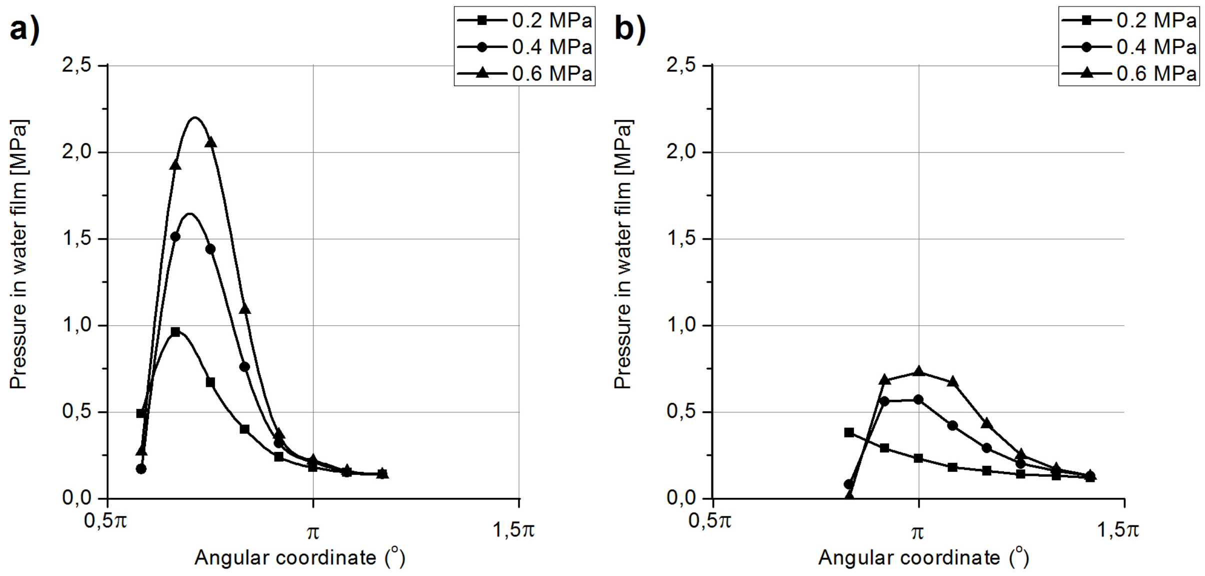


Fig. 8. Measured pressure distribution in water film of the lower bush half, speed 3 rev/s ; a) metal bush bearing, b) polymer bush bearing

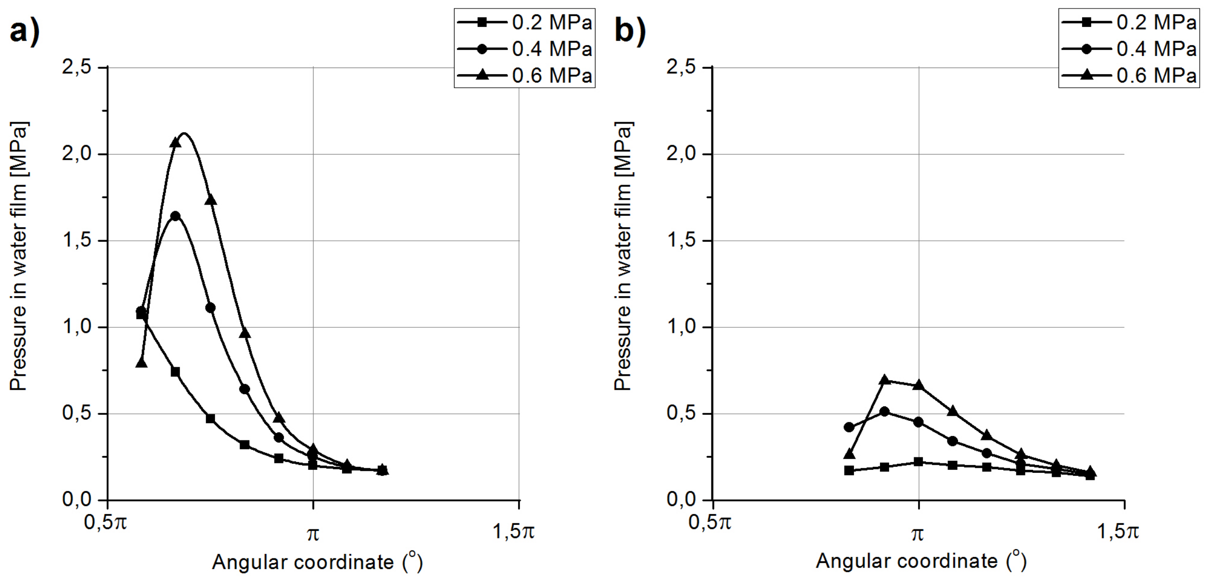


Fig. 9. Measured pressure distribution in water film of the lower bush half, speeds 7 rev/s; a) metal bush bearing, b) polymer bush bearing

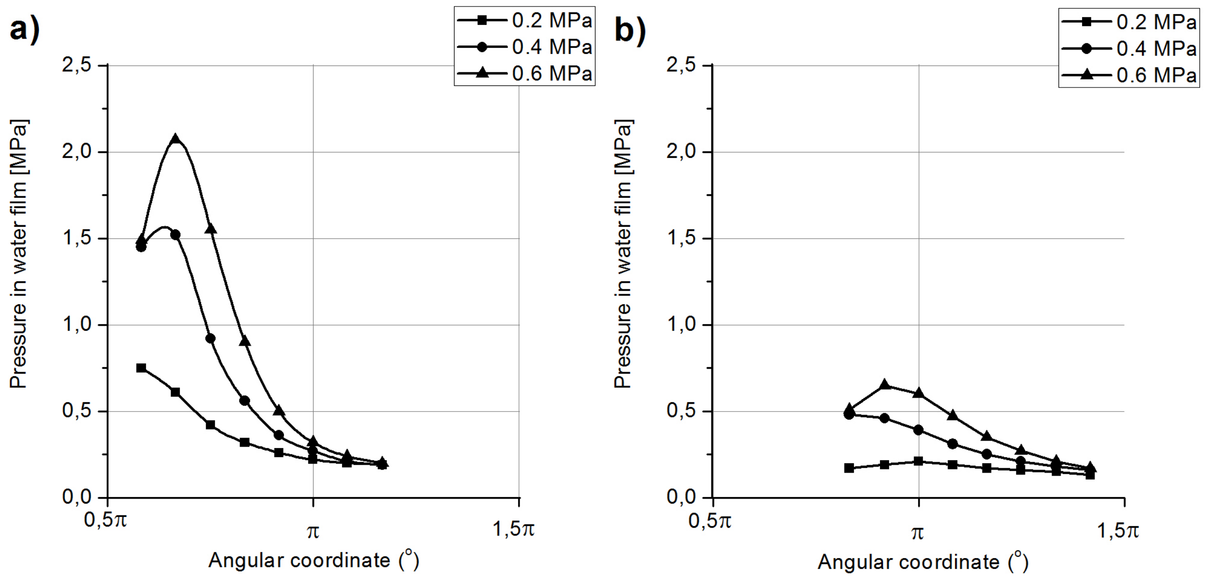


Fig. 10. . Measured pressure distribution in water film of the lower bush half, speeds 11 rev/s; a) metal bush bearing, b) polymer bush bearing

Bush inspection following tests

After completing the tests, a detailed inspection of bushes' sliding surfaces was conducted to assess the degree of wear. Photograph of the CuAl10Fe3Mn2 bush no.1 is presented in Fig.11. On the sliding surface of the bush, three clearly visible seizure areas were identified. The first of them was located near the bush centre, the other two closer to the edge. The wear marks were of intensive character and eliminated the bearing from further use.

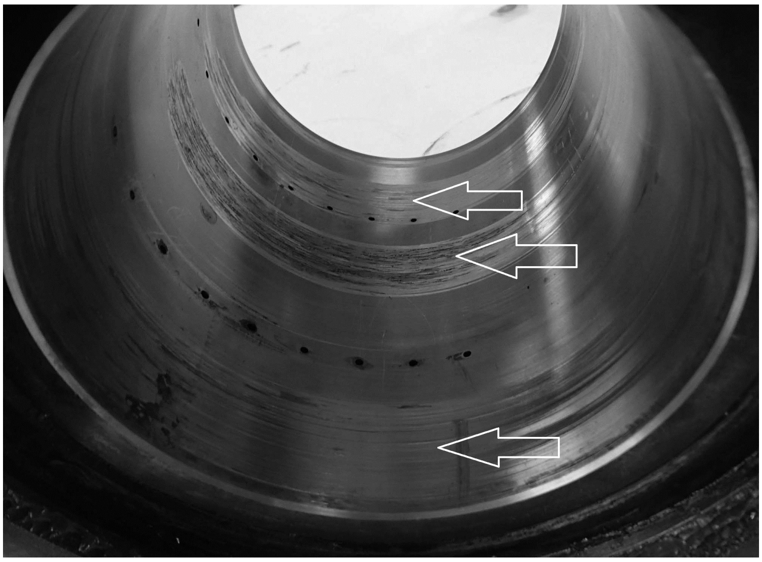


Fig. 11. Bush of bearing no.1 cast from bronze CuAl10Fe3Mn2 after tests. Arrows mark three clearly visible areas of sliding surface seizure

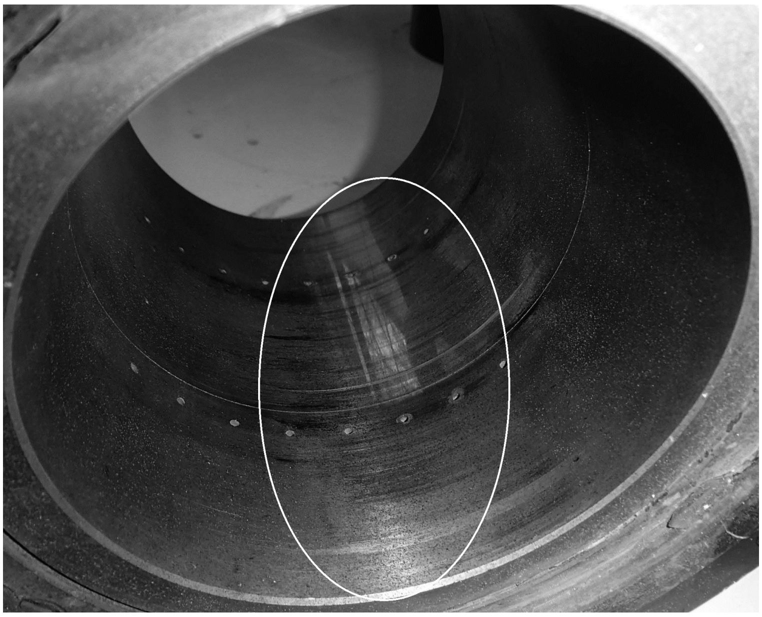
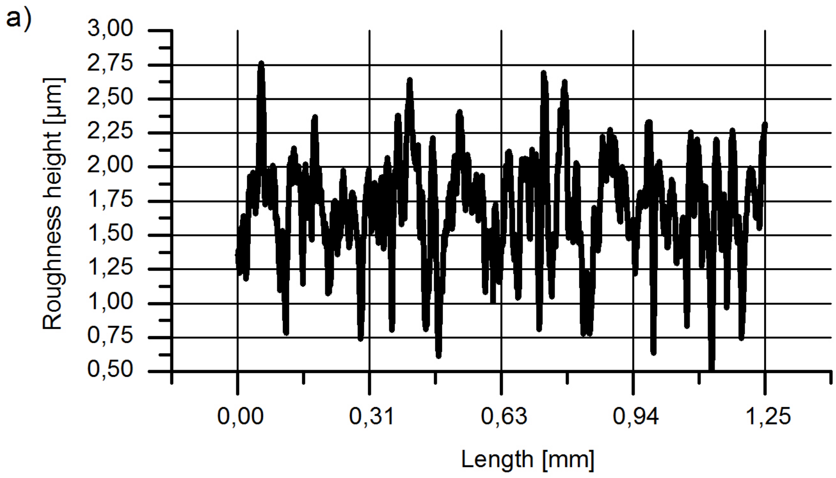


Fig. 12. Bush of bearing no. 2 made from sintered bronze. White line indicates the area of visible smooth, mirror luster of sliding surface where contact between journal and bush took place. The surface is perfectly smooth, with no scratches or chippings

The sintered bronze bush of bearing no. 2 had a completely different appearance. The sliding surface showed no signs of visible wear. In the area of bush-journal contact there formed a very smooth, mirror luster confirming the ability of the sliding material to undergo running-in under water lubrication conditions.

Following macroscopic examination, graphs of sliding surface roughness were prepared (see below). Fig. 13 portrays surface roughness profiles of the cast bronze and the sintered bronze bearings, conducted along bearing axis prior to their testing. In case of the cast bronze bearing, the average surface roughness was 0.35μm Ra, while for the sintered bronze one it amounted to 3.27 μm Ra. Presented in the graphs is typical roughness character after machining, however it should be noted that the sintered bearing bush has significantly higher surface roughness resulting from the porous structure of bronze filled with soft graphite.

Illustrated in Fig.14 are graphs of surface roughness after testing. In case of the cast bronze bearing, one can notice a significant increase in surface roughness, as well as appearance of cavities and chippings from the abraded material (indicated by arrow). The maximum roughness height increased to approximately 20 μm and the depth of scratches reached in excess of 20 μm. The sintered bronze bearing surface roughness graph has completely different character. There is a clearly visible smoothing of the sliding surface (indicated by arrow). After running-in of the sliding surface, there appeared only a small number of narrow scratches up to 2 μm in depth - the roughness remnants of the machining process. The average surface roughness amounted to 0.25 Ra, while the local surface roughness in the area between the scratches did not exceed 0.01 Ra.



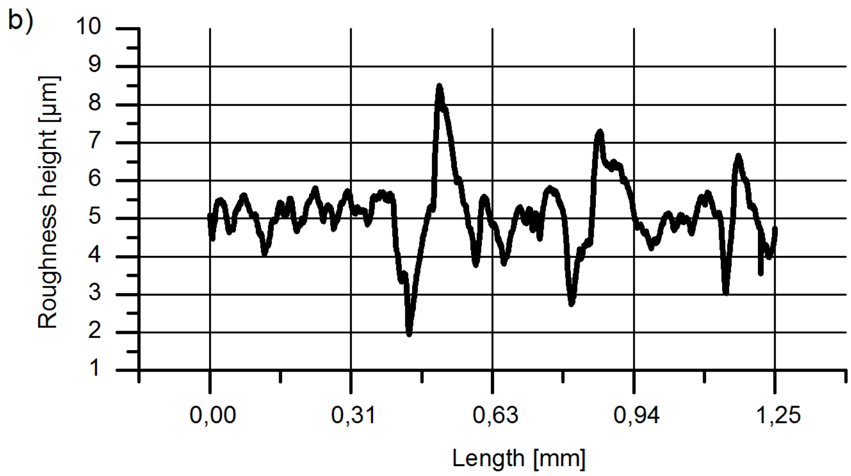


Fig. 13. Sliding surface roughness of bronze bearing bushes before tests a) cast bronze bearing, b) sintered bronze with graphite bearing. Visible typical machining marks. In case of bearing b) visible higher surface roughness

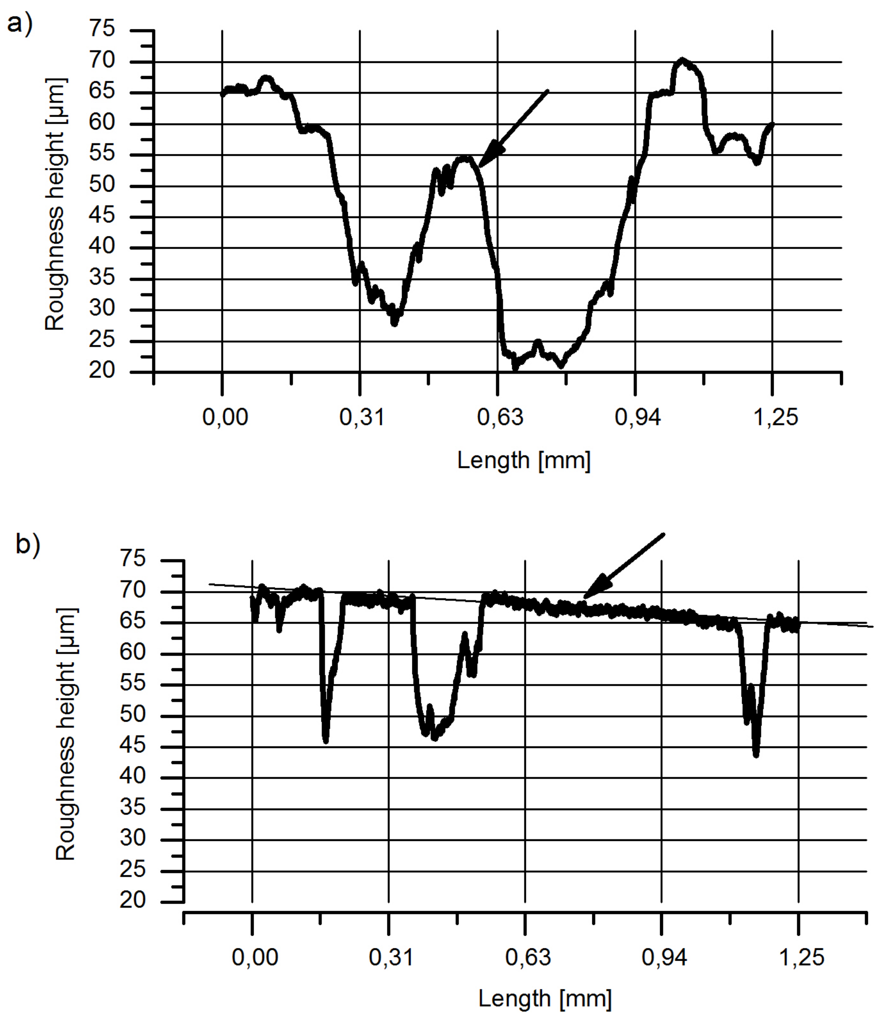


Fig. 14. Sliding surface roughness of bronze bearing bushes after tests a) Cast bronze bearing, b) sintered bronze with graphite bearing. Description in text

DISCUSSION AND CONCLUSIONS

The conducted tests demonstrated that cast bronze CuAl10Fe3Mn2 is not suitable for water lubricated horizontal shaft journal bearings regardless of the used journal material (X10CrNi18-8 or X30Cr13). Such a sliding combination has a tendency for seizing and is not capable of running-in under water lubrication conditions.

Bronze bearings have greater starting torque than polymer bearings and this fact needs to be taken into account in shafting design. The coefficient of friction for a polymer bearing recorded during start-up was approximately 0.25 and for a sintered bronze bearing about 0.5.

The conducted measurements of pressure distribution confirmed evident influence of bush elasticity on distribution of hydrodynamic pressure. In a polymer bearing maximum pressure reaches lower values than in a stiff bearing but it takes place over a somewhat larger angle of contact.

In comparison to a polymer bearing, a bronze bearing experiences lower movement resistance during operation, as its stiff bush allows for occurrence of complete fluid friction. In comparison, a polymer bearing experiences mixed friction which increases resistance levels.

Sintered bronze bearings require use of a fully hardened journal surface, which without a doubt complicates the process of shaft manufacture and increases its cost.

Sintered bronze bearings are in comparison to polymer ones, considerably easier for undergoing machining of the internal opening, however at larger diameters they require special technology for preparing the sliding surface which consists of multiple connected rings.

Sintered bronze bearing are characterized by excellent running-in ability under water lubrication conditions. Their surface roughness decreases and the sliding surface becomes smooth and mirrored. In the investigated case, the average roughness changed from the initial Ra 0.37 to Ra 0.25

Based on the conducted research, it can be concluded that bronze bearings may constitute an interesting alternative to polymer and rubber bearings. Although they require hardened journal surface, they nevertheless offer a greater load bearing capacity, durability and lower movement resistance levels. These bearings are particularly attractive for use with journals of relatively small diameters working under heavy loads. The authors are currently preparing tests for these types of bearings operating under dirty water lubrication conditions.

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