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WORKING PERFORMANCES OF SELF-LUBRICATING SLIDING BEARINGS

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Abstract: Self-*lubricating* sliding bearings are widely used in numerous industrial applications, primarily regarding their specific lubrication mechanism. This lubrication mechanism is the main advantage compared with classical sliding bearings because their production is not complex and makes lower prices. According to the bearing material and type of exploitation, self-lubricating sliding bearings could operate with oil (grease) in their material structure or even without any amount of lubricant. This paper is dealing with the working performances of this kind of bearings, including their experimental investigation aimed to make a proper choice for a particular Engineering application and corresponding operating conditions.

Keywords: *self-lubricating bearings, working performances, experimental investigation*

1. INTRODUCTION

Most machine and equipment manufacturers are trying to reduce friction loss and make the simplest possible lubrication to settle production costs preserving most machine performances during their working life. According to significant investigations, more than 50% of bearing failures are lubrication related (Figure 1) which makes huge annual losses due to downtime and repairs to equipment damaged by poor lubrication [1].

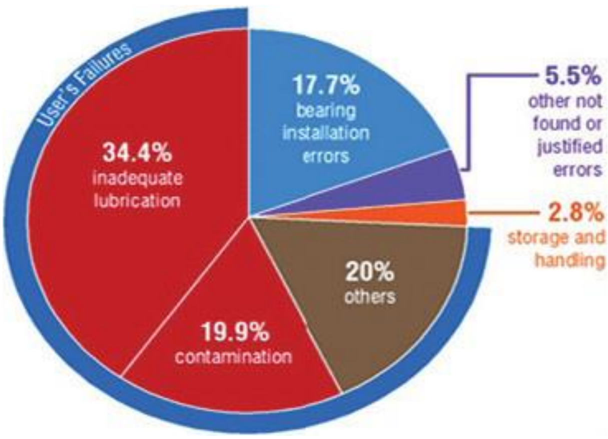

Fig.1.Bearing failures related to tribology performances

There are well-known groups of self-lubricating sliding bearings based on lubrication type, which determines their load capacity such as all other performances relevant for different applications:

- Sliding bearings that work without using any amount of oil or grease. These bearings are made of special plastics, graphite, or some ceramics materials.
- Sliding bearings contain a lubricant, either in special storage or in their material structure. The best known in this group are porous metal bearings made by the sintering process and they are the product of powder metallurgy [2].

2. BEARING PERFORMANCES

The mechanism of the self-lubrication in porous metal bearings improves the lubrication process better, but the coefficient of friction still takes values in a wide interval. That can be understood if we know that bearing life works in regimes from boundary to hydrodynamics lubrication. Lubrication quality and kind of regime are been defined due to all tribology parameters which have an impact on friction and wear process. Besides bearing temperature, quality, and quantity of oil supply, a significant impact has doubtless a coefficient of friction value under particular load capacity and sliding velocity. There are also several common applicated bearing materials, where most physical performances depending on the type of the production, such as bearing-shaft assembly performances, are very important for their use and exploitation in the life cycle.
Those important bearing performances for different most common in use self-lubricating bearing groups of materials were determined by experiments, where an overview from one of the significant manufacturers is presented in *Table 1* [3].

Table 1. Overview of common self-lubricating materials including their main physical performances with limits [3]

	Solid bronze	Sintered bronze	Wrapped bronze	PTFE composite	POM composite
Temperature range, °C	−40 .. +250	−10 .. +90	−40 .. +150	−200 .. +250	−40 .. +110
Friction coefficient, μ	0,08 .. 0,15	0,05 .. 0,10	0,08 .. 0,15	0,03 .. 0,25	0,02 .. 0,20
Permissible load, N/mm²					
– dynamic	25	10	40	80 (v ≤ 0,02)	120 (v ≤ 0,02)
– static	45	20	120	250	250
Permissible sliding velocity, m/s	0,5	0,25 .. 5	1,0	2,0 (p ≤ 1,0)	2,5 (p ≤ 1,0)
Shaft tolerance	e7 – e8	f7 – f8	e7 – f8	f7 – h8	h7 – h8
Housing tolerance	H7	H7	H7	H7	H7
Shaft roughness R_a, μm	0 .. 1,0	0,2 .. 0,8	0,4 .. 0,8	0 .. 0,4	0 .. 0,8
Shaft hardness, HB	165 – 400	200 – 300	150 – 400	300 – 600	150 – 600

2.1. Coefficient of friction

Parameters determine the quality of friction in surface contact, define lubrication regime, and at the same time have an influence on the coefficient of friction value. Talking about the influence of constructive parameters on coefficient of friction value, many investigations showed that higher bearing wall thickness decreases the coefficient of friction. The same effect on friction has an increase in bearing length or clearance. The coefficient of friction value also depends on contact surface quality. Because of that great care used to be done in bearing calibration, selection, control, and fine shaft scraping.

Calculated values of Summerfield's number (S) and design variable (ψ) were calculated and placed as points in a diagram that separate areas of hydrodynamics and boundary lubrication [3]. One could observe that lubrication is at least very near hydrodynamic on higher sliding velocity values. On the other side, on lower velocities and higher loads we can talk about boundary lubrication (BL), where lubrication film thickness value is the lowest (Fig. 2).

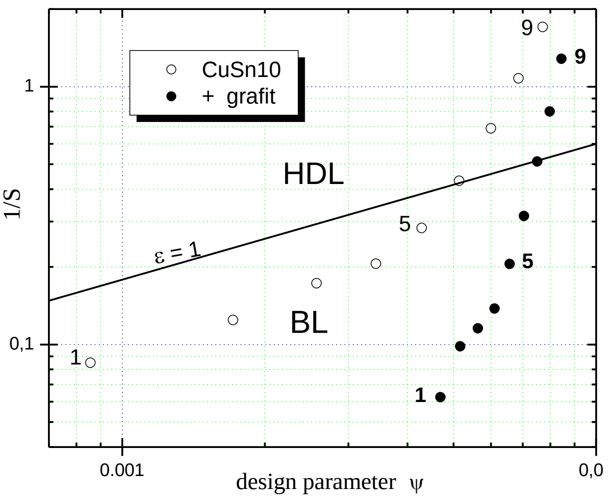

Fig.2. Lubrication regime line with working points

The coefficient of friction based on hydrodynamic lubrication theory in combination with values from already mentioned investigations and calculation of relative oil film thickness could indicate what kind of lubrication we could expect for corresponding working regimes. According to data in Fig.2, one could conclude that during the experimental investigations porous bearings of both materials were mostly working under a regime of boundary lubrication. Just for the highest values of sliding velocity (regimes 8 and 9), where the design parameter approaches higher values, we could talk about mixed lubrication, while under other regimes conditions were far from hydrodynamic lubrication.

2.2. Bearing temperature

By specific sort of bearing such as porous metal bearing, the temperature problem is very important and interesting to analyze with an aim to develop theoretical investigation in this field and so for exploitation of this sort of bearing. The working temperature of the bearing represents the temperature value that becomes constant after some time from start. Friction on the contact surface produces heat which is taken off only through the housing surface because there is a small amount of oil in porous bearing material. That's a reason for higher work temperature values for this sort of bearing in working life.

Working temperature is very important and it represents the temperature value that becomes constant after some time from start. The friction-produced heat is taken off only through the housing surface because there is a small amount of oil, at work temperature too, in a porous material. That is the reason for higher work temperature value for this sort of bearing in working life. The exploitation of this sort of bearing and many experiments show that working temperature becomes constant after a certain time from the start and its change in that time can be approximate with polynomial (1), which going to be explained and completed in a chapter of experimental investigations.

$$T(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3 + C_4 t^4 \qquad (1)$$

Also, complex phenomena of nonuniform temperature distribution on sliding bearing volume are very interesting to explore, by analyzing the mathematical model of porous metal bearing, starting from Reynolds differential equation (2) for temperature distribution of isotropic and homogeneous material in cylindrical coordinates:

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t}{\partial \theta^2} + \frac{\partial^2 t}{\partial z^2} = 0 \qquad (2)$$

On the inside surface of the bearing, we have boundary conditions of the second sort, while thermal flux produces heat in the shaft-bearing system. Boundary conditions of the third sort are on outside (noncylindrical) surfaces of the bearing, while we have an environmental temperature (T_0) and relation for heat exchange between the surface of bearing and outside air (3):

$$\dot{q}_A = \pm k\,[T_2 - T_0] \quad (3)$$

The Chapter on experimental investigations going to present also several results of temperature problem investigations on porous metal bearing samples, covering above mentioned theoretical basics.

2.3. Bearing load capacity

Possible the most important performance of sliding bearing for selection crucial for their exploitation is bearing operating range, known as "*PV*-characteristics".
In the relevant literature, there are a few different methods to determine the limiting value of the *PV* range, but three of them are the most common (Fig 4).

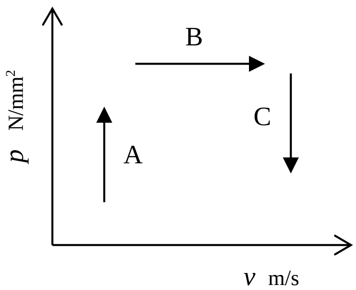

Fig.4. Methods for PV range determination

Method A means rising bearing load at the same velocity, B same load with rising speed, or method C, where the load is reducing on the same applied bearing operating speed.
This performance defines its bearing load capacity determined by experiments. It is a crucial parameter in the aim to make a proper choice of sliding bearing for the particular application. This characteristic shows operating ranges for sliding bearing, which means limits of bearing load *p* in correlation with operating sliding speed *v*.
Authors have numerous results of operating range achieved by own experimental investigations, where only some of them will be presented and explained under the experimental investigations chapter in this paper.
It is also possible to find a lot of data for operating range, those are results published in catalogs from bearing manufacturers as shown example in Fig. 5, for PTFE composite bearing material [4].

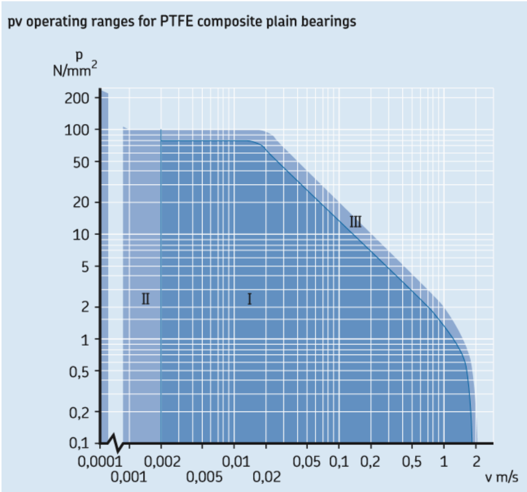

Fig.5. Bearing operating range for PTFE

3. EXPERIMENTAL INVESTIGATION

The expansion of technology, electronics, and home appliances has led to the mass use of sliding bearings primarily due to the positive properties related to shock absorption, overload, and less noise in operation. The experiments were performed to validate numerous theoretical research, test the properties of the bearing, and give guidelines to the exploitation and maintenance. Improvement of the properties of the tested sliding bearing is primarily dealing with their tribological characteristics. A complete performance overview could be obtained by combining experimental results with experiences from exploitation.

3.1. Test devices for experiments

Experimental investigations of sliding bearings used to be conducted into three different groups, up to the purpose:
- Experimental study of mechanical and tribological characteristics for just bearing materials;
- Investigation of oil or grease behavior for the bearing lubrication aimed to improve their operating;
- Experimental study of sliding bearing working performances.

The authors of this paper are presenting results, just a part of experimental investigations dealing with the study of above mentioned bearing working performances.
Depending on the methodology of the experiment, devices are used that observe direct contact between the surfaces of the shaft sleeve and the bearing, devices that simply simulate the operating conditions in which the bearing will work and can be tested in the working environment, ie directly on the machine where it is installed. The choice of testing device depends on the technical conditions and the possibility of using the obtained data. The basic idea is to measure the value of the coefficient of friction over the magnitude of the sliding friction moments on the contact surface of the shaft sleeves and the bearing. The radial load is entered via the loaders of various levers with a fixed-length ratio of 1:10. Applying such a loading system, only constant loads can be set, ie. testing is performed in static conditions during the exploitation (Fig. 6). This type of

load is most suitable for real working conditions, especially for self-lubricating sliding bearings.

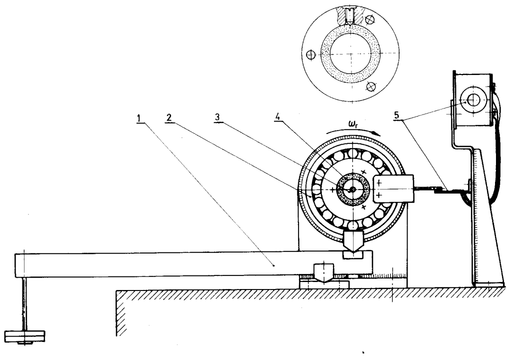

Fig.6. Application load system for sliding bearing

This testing machine is located in Laboratory for Machine elements at Department for Machine Design, belongs to Mechanical Engineering Faculty at the University of Belgrade, and is permanently in use for teaching and research purpose. The machine is powered by an electric motor of P = 1.1kW with a maximum speed of n=2770min^{-1}. Desired rotation speed for bearing can be changed continuously via the AEG frequency regulator, which allows variation of sliding speeds, depending on a different kind of research but also for more precise setting and control of the set speed during the experiments.
Test rig for this investigation used for testing sliding self-lubricating bearings USL 5-30 (*Fig.7.*) was developed in cooperation with Sinter doo company from Užice in mid-Serbia.

Fig.7. Test rig USL 5-30 in laboratory

Using this test rig system for experiments it is possible to apply a portable NI DAQ system [5]. The main reason for DAQ applying in this measurement is the need to continue following two channels for friction torque by DNS and bearing temperature simultaneously. Even not necessary to have a high sample rate for this kind of experiment, the advantages of getting results and its disposal for further analyses are evident (*Fig. 8*).

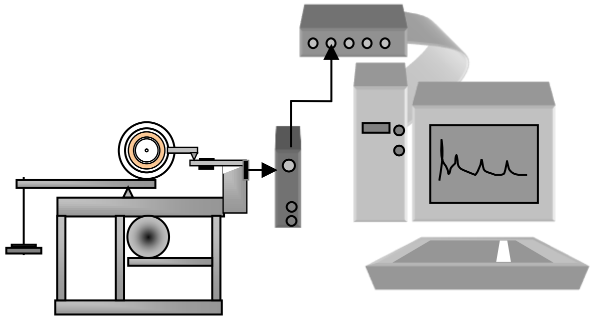

Fig.8. DAQ system for experimental investigations

3.2. Bearing samples

Here are presented just a part of experimental investigations attended to study sliding bearing working performances [6]. Samples for testing, made in sintered Bronze have dimensions Φ20/Φ30×20mm, as a common dimension for some household and agriculture machines purposes. (Fig. 9.).

Fig.9. Samples of porous metal bearing made in Bronze

The bearing manufacturer was the same as for the testing machine Sinter doo company, porous metal bearing samples made in sintered bronze (CuSn10). Before testing realization, complete physical and metallographic analysis and sample selection have been conducted. Obtained physical characteristics for this porous metal-bearing material are shown in *Table 2.*

Table 2. Physical characteristics of bearing samples

Material	unit	CuSn10
density	g/cm^3	6,4.......6,5
open porosity	%	22,45.......23,17
radial fracture force	F	3500.......3600
hardness	HB	33,26.......36,24

All selected and measured bearings are controlled and mounted, where shaft/bearing mounting clearance takes value (18...21)µm. During the introduction phase of every experimental investigation, samples were worked out for a couple of hours, just to be prepared aim to simulate real exploitation conditions. Experiments are been conducted under the common external environmental conditions in the Laboratory, which means a temperature of about 20±3^{0}C and the air humidity range (40…70)%.

3.3. Selected results of experiments

The dependence of temperature upon a time has been followed on the working regime with parameters: the radial load of F = 170 N and rotation speed of n = 4780 rpm (for boundary value of *PV* characteristics) [6]. Temperature values were measured every 2,5 minutes from the start until these parameters become constant and the result of this measurement is shown in *Fig. 10*.

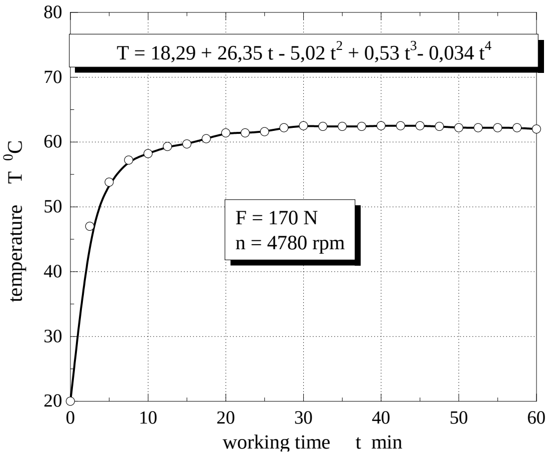

Fig.10. Bearing temperature due to working time

The temperature distribution on bearing volume has been done on working regime determinate with radial load *F* = 550 N and rotation speed of *n* = 1350 rpm. In eight different points outside around the bearing are measured temperature values, analogously tester (Fig.11).

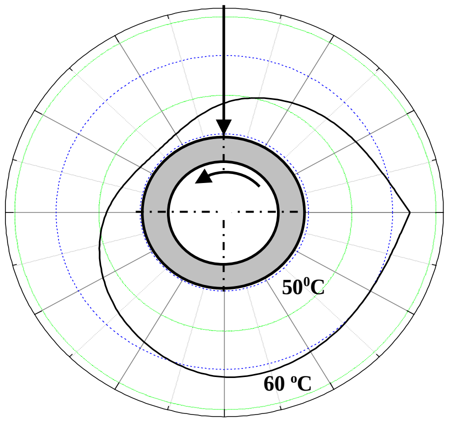

Fig.11. Temperature distribution on bearing volume

Investigation results, made on different operating conditions show that the maximum measured value of operating temperature was T = (76...84)°C. The coefficient of friction values, measured at start of operating, were μ_O = (0,135...0,180), and the values of stationary friction coefficient were μ = (0,029...0,060).

The experimental investigation aimed to determine the bearing PV operating range for selected material and sample dimensions is conducted using method A (shown in *Fig.4*). Results of those experiments could be presented in form of *Table 3*. where limiting values of load and sliding speed are grouped in five working regimes.

Table 3. Results of pv - range determination

regime no.	*v*, m/s	W, N	*p*, N/mm²	*pv*, W/mm²
1	1,25	1400	3,5	4,375
2	2,0	900	2,25	4,50
3	3,0	500	1,25	3,75
4	4,0	300	0,75	3,0
5	5,0	210	0,525	2,625

Based on those results it is possible to present a diagram of the limiting PV operating range for this kind of bearing and explained material, with five selected working regimes represented with points in the PV diagram shown in *Fig. 12*.

Observing all presented experimental results, those mostly were focused on porous metal bearings, where the lubricant is in material volume. But current trends in new ecological and low energy efficiency bearings lead us to think in direction of using new trends in polymer-based or different composite materials for particular bearing applications. Current and future studies of those bearing materials are conducted aimed to compare them with porous metal bearings and find possible advantages in the particular industry use. Regarding their advantages, plastic bearings are a good solution for many applications in machinery that require a clean and oil-free operation, corrosion resistance, high damping characteristics for vibrations, ability to reliably work under static or dynamic loads in dry conditions [8].

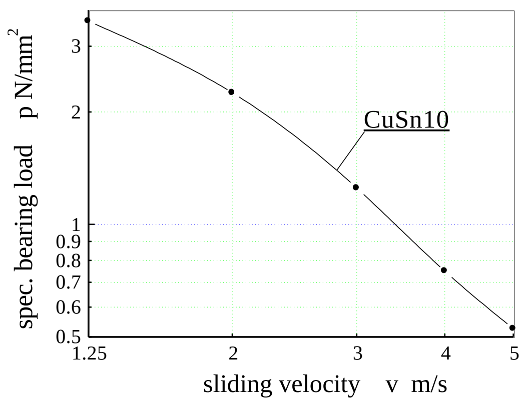

Fig.12. PV operating range due to regime points

Sliding bearings made of composite materials with polymer matrix, which are also subject to our research last years, belong to the group of self-lubricating bearings operating without oil or grease. There is a filler added to the base material whose purpose is to reduce the coefficient of friction of the base material and therefore to eliminate the need for additional lubrication. PTFE-based composite bearing, with the cross-section shown in *Fig 13*. are dry bearings designed to operate without lubricant and it is particularly suitable for high loads and medium speed applications. Its operating temperature is up to 250 °C and the best using sliding velocity is up to 2 m/s. Some typical applications of these bearings are in the automotive industry, materials handling equipment, home appliances, consumer goods, textile machinery, etc. On another side, in the same group is the POM composite sliding bearing, specially designed to operate with boundary lubrication. This kind of bearing requires only a trace of lubricant to operate satisfactorily for long periods, so they are considered pre-lubricated bearings. The sliding surface has a highly effective grease retention system with lubrication pockets, which serve as "lubricant reservoirs". This POM Composite consists of three bonded layers: a copper-plated steel backing strip and a sintered porous tin bronze matrix covered with acetyl (POM), *Fig 13*.

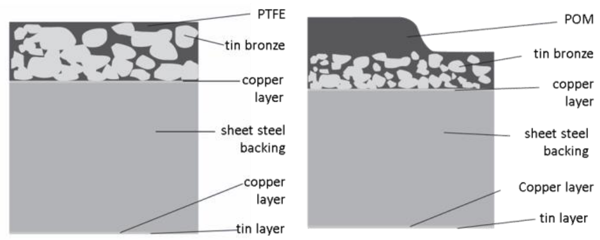

Fig.13. Cross-section of PTFE and POM composites

Several investigations conducted last year were subjected to composite bearing research, using the same equipment for experimental investigations, in Laboratory for Machine Design at Mechanical Engineering Faculty, University of Belgrade. Experiments with this group of bearings aim to get more results that are going to help designers easier to select the exact self-lubricating bearing which fits the best for a particular industrial application [9].

Dimensions of examined composite bearing samples are selected due to a possibility of comparison with properties of porous metal bearings and taking into account constructive performances of the own test rig used for experiments. Examined selected samples for testing have dimensions of ∅20 / ∅23 × 20mm, as a common size for some of their typical applications. In combination with shafts made of steel 16MnCr5 (Hardness: 60 HRC), loose fit in the shaft-bearing interface was defined by ∅20 H7/f7, where an operating clearance in testing belongs to the range 20-62 µm. Similar trends in results of operating performance investigations with this kind of bearings give us practical guidelines, that could be very useful in comparison with other bearings, which is partly mentioned in the conclusion chapter.

4. CONCLUSION

Investigations presented in this paper show that the temperature of porous metal bearing becomes constant after (30...50) minutes from the working start and its dependence on time can be the best polynomial approximate (*Fig.10*). The results presented in this paper also show that temperature distribution around porous metal bearing (*Fig.11*), made by experiments This distribution is very similar to the pressure distribution given by hydrodynamic lubrication theory. That means that maximum temperature values are in the area near load and rotating direction and for a minimum situation is the opposite. Comparing those experimental results with the numerical solution of bearing temperature distribution are in progress and going to be published soon in papers and Conferences. Friction coefficient measured at start of testing were μ_O=(0,135...0,180), but the values of stationary friction coefficient have significant lower values μ = (0,029...0,060).

Similar trends and results are observed in experiments with composite bearings, where both temperature and coefficient of friction values of tested bearing become constant till 1 hour of operating, and their dependence from time could be polynomial approximate.

Presented results overview with bearing study represent an introduction in further researches of plastic bearings subjected to make simpler machine maintenance and better energy efficiency. Great expansion and clearly explained advantages of polymer and composite bearings application in several branches of industry, encourage us not only in the investigation of new materials but also for new qualitative bearing behavior analysis in dry, maintenance-free conditions under different lubricants during exploitation life.

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