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FATIGUE RESISTANCE INVESTIGATION OF THE SnCu6 OVERLAY IN PLAIN BEARINGS WORKING UNDER CONDITIONS OF ROTARY LOADING

BADANIA ODPORNOŚCI ZMĘCZENIOWEJ POWŁOKI ZE STOPU SnCu6 W ŁOŻYSKACH ŚLIZGOWYCH PODDANYCH WIRUJĄCEMU OBCIĄŻENIU

Key words:

fatigue strength, bearing alloys, plain journal bearings, experimental research

Słowa kluczowe:

wytrzymałość zmęczeniowa, stopy łożyskowe, łożyska ślizgowe poprzeczne, badania doświadczalne

Summary

Fatigue resistance of a three-layer slide bearing has been investigated on the MWO test stand in which rotary loading to the test bearing is gener-

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ated. The bearing material consisted of the bronze (CuPb22Sn3 + thin overlay of SnCu6 plated) sintered to the steel shell. Each of the tested bearing was subjected to the standard 20–hour test under conditions of full fluid lubrication. The methodology of the experiments, metallurgical test results and fractographic description of the lining crack–zone are presented. The values of the fatigue strength parameters were estimated as well.

INTRODUCTION

Among the most popular sliding material, used for dynamically loaded IC engine bearings, there are alloys known as leaded bronze, composed of cooper, lead, tin and small amount of the other chemical elements. The slide bearing surface layer made of that material is usually covered with very thin overlay of soft alloy for improving corrosion resistance and protection against seizure. The mechanical properties of the coating and the main alloy are quite different so the behavior of such a three-layer type bearing under working conditions with dynamical loading should be experimentally evaluated.

The object investigated in this work for fatigue resistance was a representative of such a three-layer type bearing with cooper-lead-tin (CuPb22Sn3) layer being sintered to the steel shell and finally galvanized very thin of tin-cooper (SnCu6) coating of the slide surface. Thickness of the coating was about 0,013 mm.

SUBJECT OF INVESTIGATION, TEST STAND AND THE TEST ARRANGEMENT

The shape of the standard half-bearing is presented in **Figure 1**. To adopt this bearing to test requirement the standard bearing is modified by under-cutting the slide bearing layer at both edges to make the working slide surface smaller. The thickness of the bearing shell is measured in three sections (A, B and C – **Fig. 1**). A preliminary selection is made observing the same circumferential outer length of both half-bearings as well as their spread R – measured before and after tests.

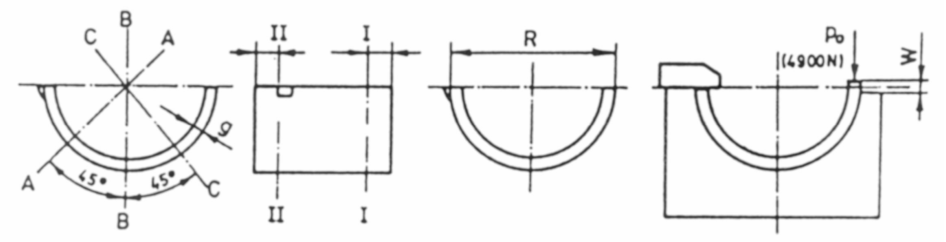

Fig. 1. Half-bearing standard measurement before and after testing on the MWO machine: g – bearing shell thickness, R – spread, w – overlap

Rys. 1. Standardowe pomiary półpanwi łożyskowej przed i po teście na stanowisku MWO: g – grubość półpanwi, R – rozpręż, w – przekrycie

Investigation of the fatigue strength of the bearing has been performed on the dynamic MWO machine with rotary loading [**L. 1**]. A scheme of the testing head unit of the machine is shown in **Figure 2**.

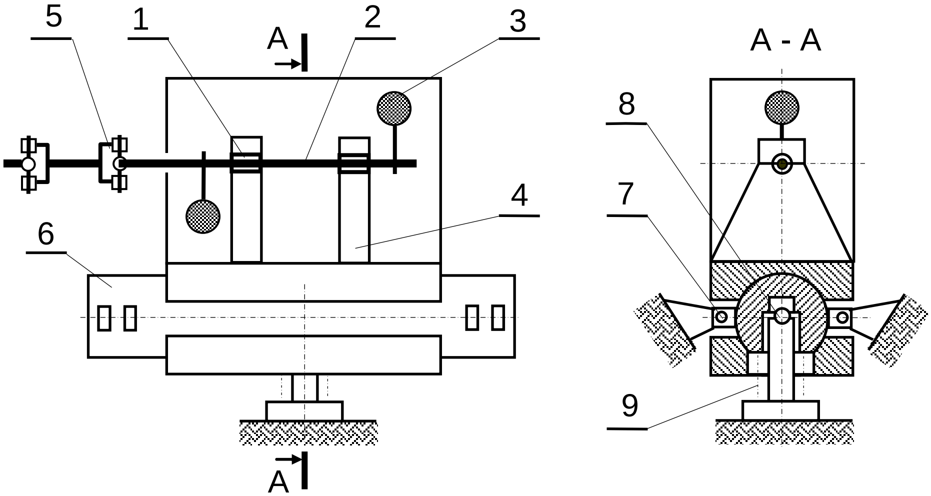

Fig. 2. Scheme of head unit of the MWO machine with rotating load vector: 1 – investigated bearing, 2 – shaft, 3 – unbalanced masses, 4 – bearing housing, 5 – Cardan universal joint, 6 – stabilising bar, 7 – flexible joint, 8 – ball joint

Rys. 2. Schemat głowicy badawczej maszyny MWO z wirującym obciążeniem: 1 – badane łożysko, 2 – wał, 3 – niewyważone masy, 4 – oprawa łożyska, 5 – sprzęgło Cardana, 6 – stabilizator, 7 – zawieszenie elastyczne, 8 – podparcie kulowe

Two model bearings 1 housed in the supports 4 are simultaneously investigated. Bearing loading is produced by rotation of a dynamically unbalanced shaft 2 with masses 3. Load can be controlled by proper selection of masses 3 and rotational speed of the shaft 2. Bearing housings are fixed to a stabilising bar 6 supported on ball joint 8 and four flexible joints 7. Bearings are fed with lubricating oil through the system of holes in the shaft.

Table 1. Geometry and hardness of the investigated bearings
Tabela 1. Parametry geometryczne i twardość badanych łożysk

Inner dia D of the full bearing [mm]	Effective bearing axial length L[mm]	Relative bearing clearance ΔR/R	Bearing shell thickness g[mm]	Bearing alloy layer thickness g_s [mm]	Bearing sliding layer roughness R_a [μm]	Bearing journal surface hardness [HRC]	Journal sliding surface roughness R_a [μm]
52,784– –52,796	14,2	0,0019–0,0021	1,820	0,240–0,312	0,20	60±2	0,16

Test parameters were as follows: rotational speed of the shaft n = 4000 rpm, fatigue test basis 3,6 × 10^6 loading cycles (test duration t = 20 hours), lubricant inlet pressure p_{ol} = 5 × 10^5 [N/m^2], lubricant: Selectol SAE 20W/30 mineral oil. During the test the following parameters were controlled and recorded: rotating loading force, the tested bearings temperature, the temperature and pressure of the lubricant at the inlet to the bearing and ambient temperature.

TEST RESULTS

Each of the 20-hour tests has been divided into two 10-hour sections. After completing the section the careful examination of the sliding surface has been performed in order to find out possible fatigue cracks. The slide layer has been recognized as destroyed by fatigue if a net of fatigue cracks is observed on the surface, even if there are no losses of bearing material. For the test result assessments the two-point strategy [**L. 2**] is adopted which is presented graphically in **Figure 3**.

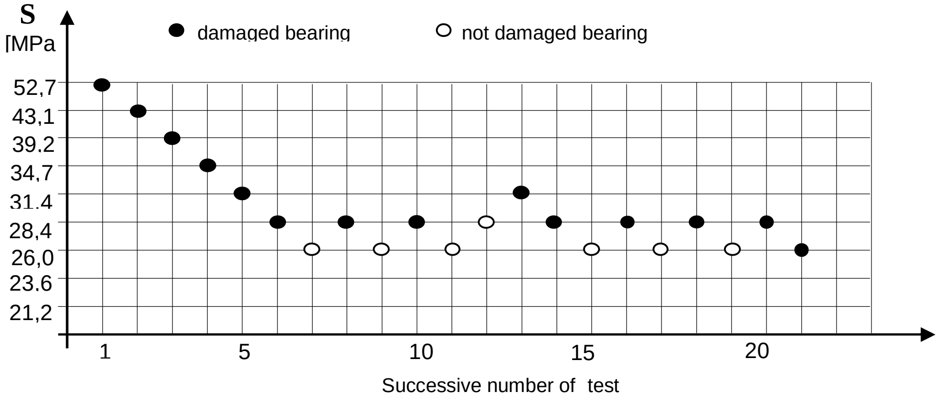

Fig. 3. Sequence of fatigue tests for SnCu6 material (L/D = 0.266, n = 4000 rpm, relative clearance ΔR/R = 0,0019, bearing temperature increase ΔT = 70°C)

Rys. 3. Sekwencja testów zmęczeniowych dla materiału SnCu6 (L/D = 0,266, n = 4000 obr./min, luz względny ΔR/R = 0,0019, przyrost temperatury łożyska ΔT = 70°C)

Picture of the fatigue cracks on bearing surface after test is presented in **Fig. 4**.

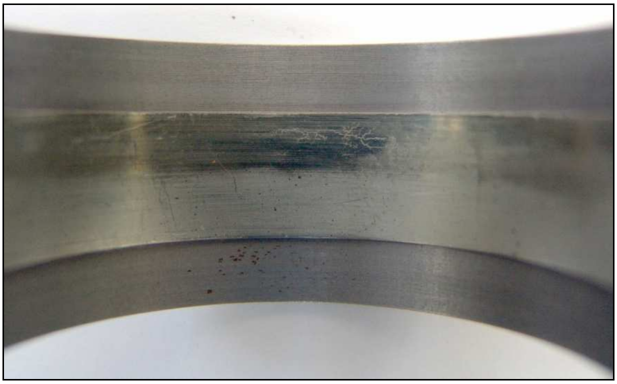

Fig. 4. Fatigue cracks of the SnCu6 surface layer after test on the MWO stand

Rys. 4. Pęknięcia zmęczeniowe zewnętrznej warstwy powłoki SnCu6 po teście na stanowisku MWO

The position of the cracked area is reflecting the stress distribution (being the result of bearing elastic housing design) in the bearing alloy. The cracks initiation can start at any time of fatigue process but it can be detected only after first or second test section (after 10 or 20 hours). It results in lower precision of the determination of the cracks initiation point on the bearing surface. The picture of the cracks net that is visible on the slide surface allows concluding that axial and circumferential normal alternating stresses are developing in the surface layer of the overlay (coating).

RESULTS OF PHYSICAL METALLURGY AND FRACTOGRAPHY INVESTIGATIONS

The chemical composition of the slide layers, the hardness measurement results of the particular regions of the slide surfaces as well as measured on the slide layer cross-section, together with scanning of that area, have been investigated. The slide layer chemical composition was examined with the use of energy dispersive X-ray apparatus ISIS 300, working with scanning electron microscope (Hitachi S-300N-JAPAN). The results of those measurements are shown in **Table 2**.

Table 2. Chemical element composition of the SnCu6 coating
Tabela 2. Skład chemiczny powłoki SnCu6

	N-K	O-K	Ca-K	Ni-K	Cu-K	Sn-L
pr3		4.87		1.13	6.10	87.90
pr4	0.00	3.53	0.91		6.38	89.18

It results from the table that the share of the elements other than Sn and Cu in the coating differs from attest specification delivered by the manufacturer (Bimet-Federal Mogul).

The thickness of bearing lining is equal to 0.388 mm, including the galvanized overlay. Hardness measurement was performed with the application of Vickers' method. Average value of bronze layer micro-hardness is equal 112 HV while micro-hardness of steel shell is about 180 HV.

Micro and macro observation of the slide surface was performed using Reichert type of metallographic microscope. The picture of slide surface cracks (after bearing test) in scanning microscope is visible in **Figure 5** in form of not oriented net. Because of small thickness of outer, galvanized soft layer the crack net development could be associated with local spalling.

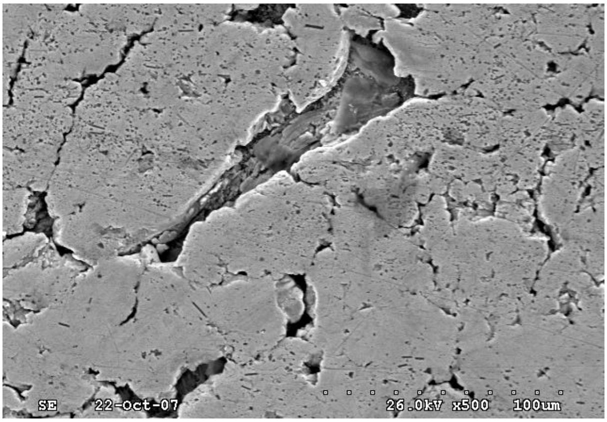

Fig. 5. Cracks on the SnCu6 slide surface – after testing on MWO stand (enlargement ×500)

Rys. 5. Pęknięcia na powierzchni ślizgowej SnCu6 po teście na stanowisku MWO (pow. ×500)

In **Figure 6** a transverse section of slide layer is shown. The region of cracks was limited only to the thin soft coating. In no case of damaged bearings cracks were passing through the main alloy (CuPb22Sn3) of the slide layer.

Fatigue damages of SnCu6 alloy at developed stage are mainly of structural nature. Development of arterial cracks was rarely observed. In this case the cracks were going also only through soft alloy and it usually happened at lower loadings. It could be explained as a process of initiating of the cracks development, before delaminating of the soft layer.

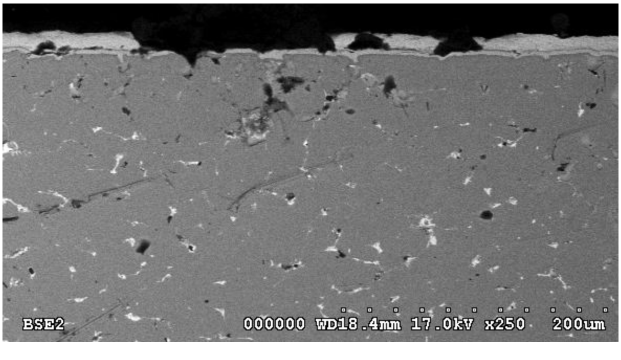

Fig. 6. Transverse section of the bearing slide layer – after test on the MWO stand (magnification 250×)

Rys. 6. Przekrój poprzeczny warstwy ślizgowej łożyska – po teście na stanowisku MWO (pow. 250×)

In **Figure 7** the other types of fatigue cracks are presented. They are developing in so called dam layer (or interlayer) Ni between soft and main alloys of the lining. They have structural form with spalling. It can be concluded that this interlayer could be the weak structural area of the investigated bearing.

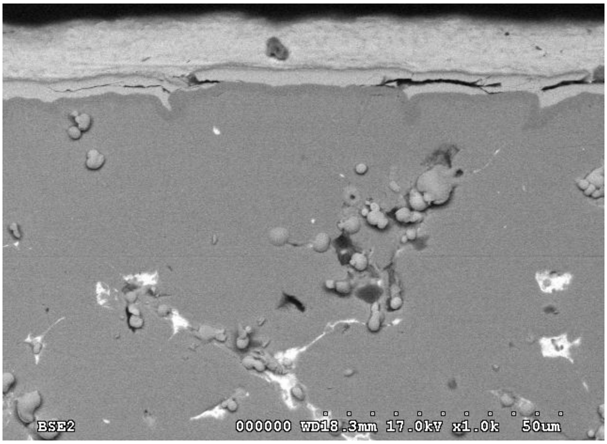

Fig. 7. Cracks in the dam layer (Ni) of the bearing lining after test on the MWO stand (enlarg. 1000×)

Rys.7. Pęknięcia w warstwie zaporowej (Ni) po teście na stanowisku MWO (pow.1000×)

STATISTICAL RESULT ASSESSMENT

As a statistical basis of standard test a number of 3.6×10^6 loading cycles was adopted. In the experiments a factor S_p is understood as a maximum value of the cyclic pressure $(p_{śr})_{max}$ on the bearing sliding surface under which P × 100% tested bearings are subject to the surface fatigue damage, after reaching the specified number of loading cycle. Probability level P, to determine S_p factor, is usually taken as 0.50. So the value of $S_{0,50}$ corresponds to the median of critical stress distribution for bearing that is subject to 3.6×10^6 loading cycles. Justification for adopting the median value as an estimate of bearing layer nominal fatigue critical stress is explained in literature [**L. 2**] in detail. $S_{0,50}$ factor value is empirically evaluated by the application of the two-point sequence method. Results of statistic parameters calculations on the basis of the fatigue test results presented graphically in **Figure 3** are shown in **Table 3**.

Table 3. Assessment of the statistic parameters for the SnCu6 coating fatigue strength

Tabela 3. Oszacowanie parametrów statystycznych wytrzymałości zmęczeniowej powłoki SnCu6

Slide material	Statistic parameter estimation	
SnCu6	$S_{0,50}$ [MPa]	**27.16**
	s(S) [MPa}	1.082
	s($S_{0,50}$) [MPa}	0.442
	95%-confidence interval for $S_{0,50}$ – lower limit – upper limit	 26.28 28.04
	95%-confidence interval for S – lower limit – upper limit	 25.04 29.28
	Total number of tests	21
	Corrected $S_{0,50}$ [MPa] value	**35.86**

Assembly clearance as well as the change in temperature of the tested object (ΔT = 90°C above the assembly temperature) were taken into account for introducing the $S_{0,50}$ factor correction [**L. 3**]. Corrected $S_{0,50}$ factor can be treated as quantitative estimator for slide bearing layer fatigue resistance providing that the test results are subject to the normal distribution and the width of the confidence interval is the same as the one experimentally evaluated.

BOUNDARY STRESS CALCULATIONS

The boundary stresses have been calculated for the loading conditions described by the corrected $S_{0,50}$ value. A calculation procedure based on the computer programme ANSYS has been applied. The calculation results are presented in **Table 4**.

The calculated value of critical circumferential stress amplitude has appeared to be higher than absolute value of (compressive) mean stress. Thus the stress cycle is characterized by stress ratio $R = \sigma_{min}/\sigma_{max} = -1.77$ which means that the circumferential stresses, that rotate together with oil pressure on surface of bearing tested in the MWO machine, change from compression to tension. The radial stresses (practically equal to the local oil film pressure) are characterized by stress ratio $R = \sigma_{min}/\sigma_{max} = -\infty$.

Table 4. Boundary stress amplitude value that is corresponding to the $S_{0,50}$ factor
Tabela 4. Graniczna amplituda naprężeń obwodowych odpowiadająca wskaźnikowi $S_{0,50}$

Boundary circumferential stress amplitude		Boundary normal stress amplitude that are reduced according to the Huber method	
Stress ratio R = $\sigma_{min}/\sigma_{max}$= –1.77		Stress ratio R = 0	
Amplitude stress [MPa]	Mean stress [MPa]	Amplitude stress [MPa]	Mean stress [MPa]
33.1	–9.2	41.4	41.4

CONCLUSIONS

For the loading pattern that is characteristic for the test devices such as the MWO machine the mechanism of cracks generation, because of the alternating normal stresses in the damage area, could be explained as follows:

- Soft bearing material as the SnCu6 alloy is much more sensitive to the tensile loading than to the compressive one, especially in the area that is weaken by empty spaces. That might be the reason for cracks generation. Additionally in the case of the thin-wall bearing shell, assembled in the elastic housing, the circumferentially and axially oriented cracks can appear owing to elastic deflection of the support. It has been observed for bearing loading applied in the MWO tester.
- Mainly structural cracks can be noticed when analyzing the metallographic description. It is related to the porosity of the SnCu6 alloy structure. This is different from other much stronger structure as, for example, the aluminum alloy where arterial type of cracks was dominant [**L. 3**].
- The fatigue damage is manifested by appearance of the dense small cracks and voids of pitting nature. The slide surface is a place of cracks nucleation. But when in slide layer there are bigger soft material concentrations or voids it is also possible to observe generation of cracks in any place of the bulk thickness [**L. 4**]. During consequent development of the process the micro-cracks are spreading out and going to the next defected parts of the alloys. These cracks can reach the inter-boundary of the damaged layer (**Fig. 7**). The continuous surface of separation is then developed which leads to delaminating the overlay. The micro-cracks space net that is typical for this kind of damage is not precisely oriented but rather random. The

eventually oriented fracture is due to the not uniform structure of the alloy.

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Streszczenie

Odporność trójwarstwowego łożyska ślizgowego na zmęczenie badano na stanowisku MWO, w którym generowane jest wirujące obciążenie badanego obiektu. Materiał łożyskowy składał się z brązu CuPb22Sn3 pokrytego cienką powłoką ze stopu SnCu6. Brąz spiekany był na stalowej łusce. Każde z badanych łożysk poddane było standardowemu 20-godzinnemu testowi w warunkach pełnego smarowania hydrodynamicznego. Przedstawiono metodykę badań doświadczalnych, wyniki badań metaloznawczych i analizę fraktograficzną uszkodzonych obszarów warstwy powierzchniowej łożyska. Oszacowano wartości parametrów charakteryzujących wytrzymałość zmęczeniową obiektu badań.