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APPLICATION OF ACUSTIC EMISSION FOR DETECTION OF FATIGUE MICRODEMAGE IN MAIN AND CRANK BEARINGS FOR DIESEL ENGINES

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Abstract

The article presents reasons for applying the acoustic emission (AE) to detect fatigue microdamage in main bearings and crank bearings of marine main engines. Problem of determination of fatigue life for slide bearing bushes was characterized in general. There were demonstrated properties of the objects of research, which were bushings made of the MB58 alloy, as well as an overall description of the research. It was shown that the frequency bands of AE signals can indicate fatigue damage to the sliding layer of a bearing bush. The fatigue damage in the tested bushes was depicted in figures. General features of the AMSY-6 measuring system, used in the research, were also provided herein.

Keywords: *Frequency analysis, slide bearing, friction factor, bearing bush.*

1. Introduction

Tribological systems of diesel engines used for propulsion of sea-going ships (i.e. main engines), especially main bearings and crank bearings, have the greatest influence on safety of such ships and the marine environment [1, 2]. In the consequence of excessive wear of bearings, the only possible further proceeding is to apply a partial load on the internal combustion engines of this sort which results in producing a lower thrust. As a result, the ship is not able to achieve the speed which is required to perform a transport task in the given sea conditions. This is of particular importance in the case of deteriorating weather conditions. The consequence may be not only a failure to perform the transport task by the ship (significant delay in reaching the port), but also sinking of the ship in stormy conditions. This is due to the fact that production of less thrust by the ship's propeller causes not only lower speed of the ship, but also less force on the rudder when deflected. This force along with the propeller thrust ensure keeping the required directional stability of the ship, that is its maneuverability. Loss of the maneuverability results in loss of transverse stability of the ship [1, 2]. Excessive wear of bearings at high engine load is usually the cause of their seizure. Seizure of bearings always leads to stopping the main engine and thereby to a loss of the thrust. In such circumstances, nor maneuverability (directional stability) nor transverse stability can be secured to the ship. When in this situation the ship is performing a transport task during a storm, it may capsize causing a disaster [1, 2]. Even if the disaster does not happen, such failure as seizure of bearings causes vast operating costs. The costs are made up not only by refurbishment of the bearings, but mainly by consequences of not performing the transport task within the contracted time which results in contractual penalties to be imposed on the ship. That is why, diagnostics of main bearings and crank bearings of diesel engines is of significant meaning. It allows to prevent damage to the bearings during ship motion, particularly when any changes in their technical state can be monitored in early stages of their formation. Detection of the changes in the technical state of the bearings in the early stages of their formation is possible by applying the acoustic emission (AE) as a diagnostic signal. The applicability of AE to identify the technical state of this kind of bearings is signaled in publications [3, 4, 9, 10]. Usefulness of AE for predicting fatigue failure for such bearings is demonstrated in this paper. Such prediction is possible by identification of fatigue life for the bearing bushes, where the measure is the number of cycles of load changes leading to fatigue microdamage to the bushes.

2. Problem of determination of fatigue life for bearings

A reliable evaluation of fatigue life of sliding layers of bearings for diesel engines can be obtained only by performing field tests for the bearings. Unfortunately, this kind of tests are long and costly for obvious reasons, so in practice just laboratory tests, carried out in accordance with an approved testing program, are the source of information, despite it is only preliminary information, however also of practical utility for designers and manufacturers of the bearings [6, 9, 10, 11]. For this reason, such tests were performed in this research and included fatigue tests of critical elements of slide bearings, i.e. their bushes whose mostly sliding layers are exposed to damage in the case of significant changing loads [5, 6, 9].

The fatigue tests of the slide bearings were carried out in laboratory conditions, on a special test bench which allowed full control and repeatability of the tests. During the research, slide bearings were subject to such loads which are recorded in real operating conditions of marine internal combustion piston engines [6, 9, 10].

During the tests, whose the results are presented in this paper, the measurements of the parameters of the acoustic emission (AE), generated by fatigue microdamage in bearing bushings, were taken with the AMSY-6 equipment by Vallen Systeme GmbH, Icking (Germany) [9, 10]. The tests were performed on a laboratory bench of the SMOK bearing machine, designed to test fatigue life of slide bearings for internal combustion piston engines [9]. The machine's construction is protected by patent No. PL 137 523 [5, 6].

The tests were planned in the way to obtain the minimum number of samples while maintaining the required reliability of the set quantitative ratings. The fatigue tests of the bearings were based on a staircase method involving a two-point strategy, which allows to determine a significant fragment of the characteristics $\sigma = f(p)$ at the reduced to minimum number of the fatigue tests (σ – hoop stress in the sliding layer of the bush, p – probability of microdamage in the sliding layer of the bush). The essence of this method is that the sets of the test results for the two fixed levels of load allow to evaluate the probability of bearing damage and, in consequence, to determine the characteristics $\sigma = f(p)$. Based on the research it can be stated that, after establishing two levels of the research performance, the number of 8 to 10 tests is sufficient to determine the empirical characteristics $\sigma = f(p)$ [9]. When conducting the fatigue life tests according to this method, an explicit statement of a fatigue damage may be issued only after examination of the bush, and this requires its dismantling during or after execution of the test.

In research of this sort, the applied measurement and control systems do not provide monitoring of the degradation process starting from the first microcracks in the sliding layer. In addition, disassembly and reassembly of the "bush-journal" tribological system change the alignment of the bearing components. These difficulties cause that the method of determining fatigue life of slide layers of the bearings can be interpreted differently, which makes the results provided by various research centers incomparable in terms of quantities. Moreover, diagnostic systems, currently applied for testing, that use vibro-acoustic sensors, record a damage being already significantly advanced, which also hampers rational operating actions to prevent the damage of the bearing bushes. Therefore, the performed research provides comparison of the recorded signals of acoustic emission (AE), which depend on the technical state of the sliding layer of the bearing bushes. The research also enabled to verify the possibility of efficient application of AE testing method for determining the moment of a coming signal informing on conversion of the fluid friction into the mixed friction in a slide bearing and initiation of microdamage process in the sliding layer of the bearing.

3. Object of research and overview of the tests

The tests were performed on the laboratory bench SMOK allowing application of loads that correspond to the model performances, including one-direction loads, which is important in the case of testing slide bearings for two-stroke engines. The dynamic loads are produced hydraulically. They are transmitted onto the tested bearing being installed in the head of the test bench [6, 9, 10].

During the research, the bearings were subjected to loads which were dynamic as for the value and reverse, in the wide frequency range. Gradients of the load reached up to 3 kN per 1^0 OWK (crank angle degree) and induced the nominal pressure on the surface of the sliding layer, exceeding 120 MPa. The frequency of load changes was adjusted for the range from 20 Hz to 73 Hz. The dynamic load of almost constant direction, which was put on the bearing bushes of alloy AlSn20CuMn1 (MB58), tested in the SMOK rig, is depicted in Fig. 1

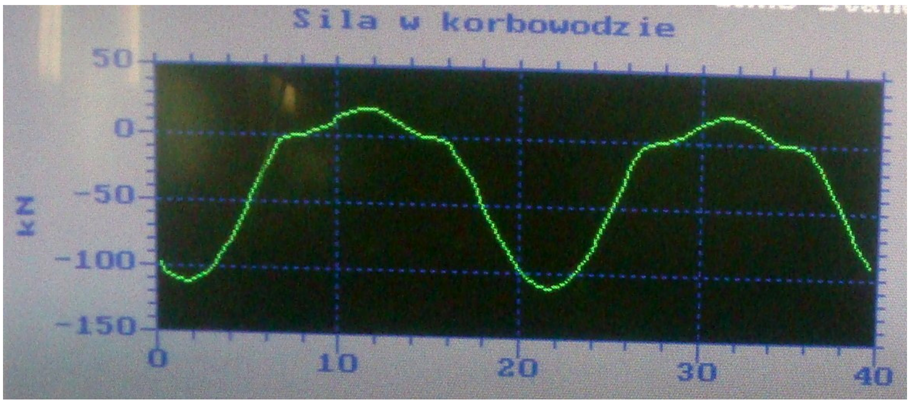


Fig. 1 Load during a test, applied to a bush made of MB58 alloy [9]

The research involved standard tests in which the maximum loads on the upper and lower shells (half-bushes) of the tested bearing bushes referred to the proportion of 3:1 [9]. The object of the research was a sliding bush made of alloy AlSn20CuMn1 (MB58) by Federal-Mogul Bimet in Gdansk-Oliwa. The selected MB58 alloy having the mesh structure is of relatively best sliding properties and relatively high fatigue resistance at the same time. The design parameters of this kind of bushes are presented in Table 1.

Tab. 1. Basic design parameters of a sliding bush made of MB58 alloy [9]

L.p.	Design parameter	Parameter Value [mm]
1.	Outside diameter	56,6
2.	Wall thickness	1,3
3.	Lenght of the bush	$29{,}6_{-0{,}25}$
4.	Journal diameter	$52{,}7_{-0{,}02}$
5.	Thickness of the steel shell	1,3
6.	Diameter of the slot in the hull	$56{,}35^{+0.026}$

Fig. 2 shows surfaces of new half-bushes made of MB58 alloy.

Fig. 2. Surfaces of new half-bushes with sliding layers made of MB58 alloy before testing in the SMOK rig [9]

During the tests the recorded values included: loads (Fig. 1), temperature of the tested bearing and supporting bearings (Fig. 3), journal rotational speed, oil pressure, lubricating oil temperature and the ambient temperature.

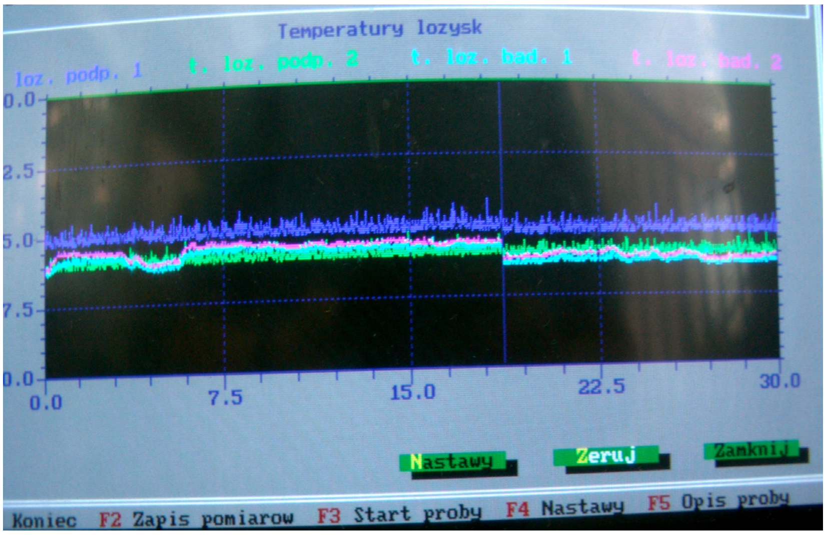


Fig. 3 Temperature spectra for the tested bearing and the supporting bearings [9]

The test was stopped when recording a significant increase in the amplitude-frequency values of AE signals. This situation is shown in Fig. 4.

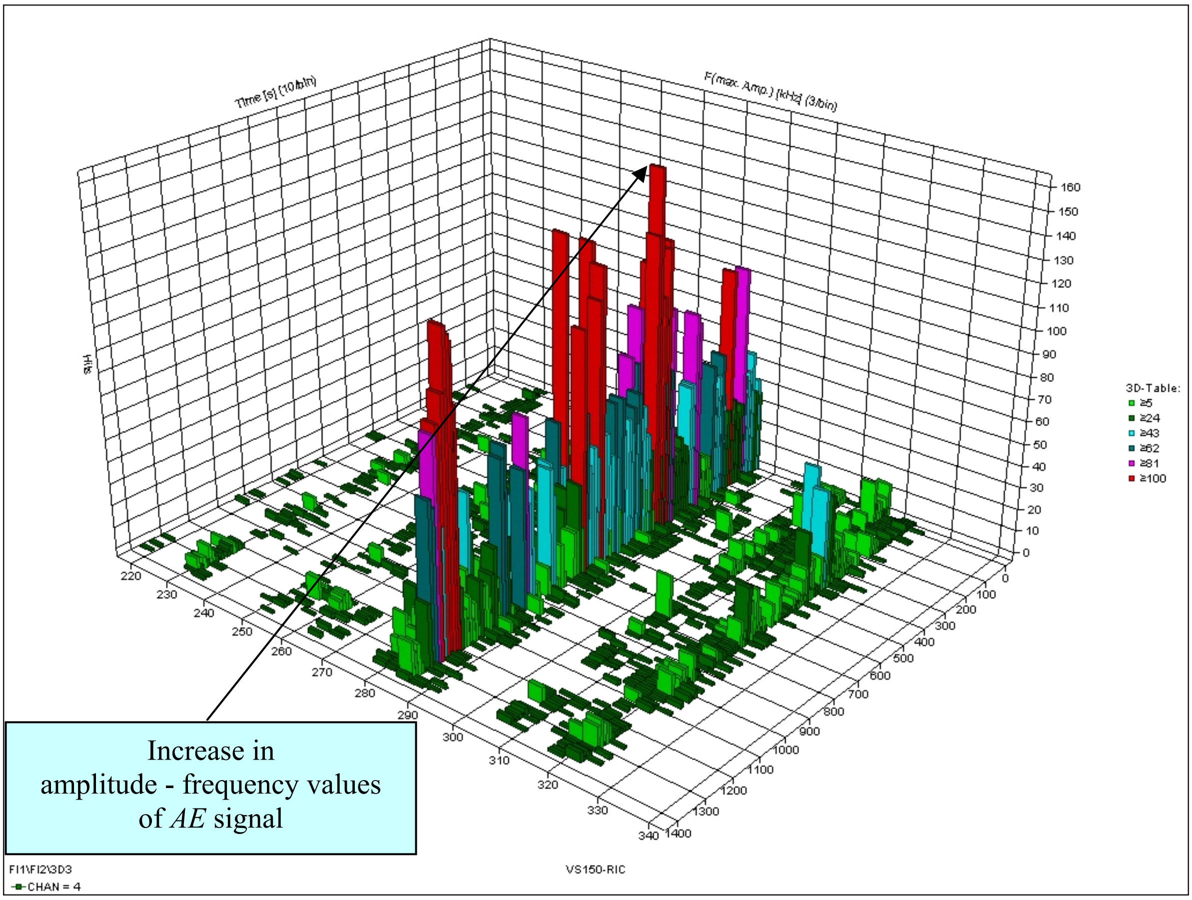


Fig. 4. Frequency bands of the signals recorded by the AMSY-6 equipment, indicating a fatigue damage in the sliding layer of the bearing bush [9]

After demounting the half-bushes (Fig. 2) there were observed radial scratches on their sliding surface and considerable abrasion on the edges of the bush (Fig. 5), which increased the frequency of the signals. However, no fatigue cracks were found on the sliding surface of the tested bush.

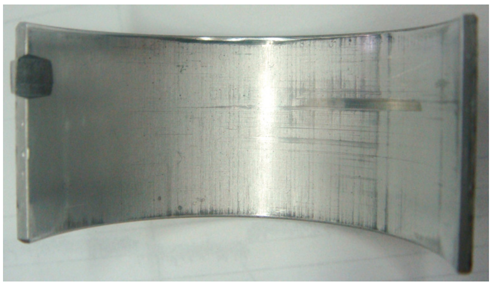


Fig. 5. Radial scratches on the surface of the MB58 bush and considerable abrasion on its edges [9]

The test was continued afterwards until recording another significant increase in the amplitude-frequency values of AE signals, and thereby the temperature of the bush to 121° C (Fig. 6). At this moment the bush was demounted again and its sliding layer was subject to examination.

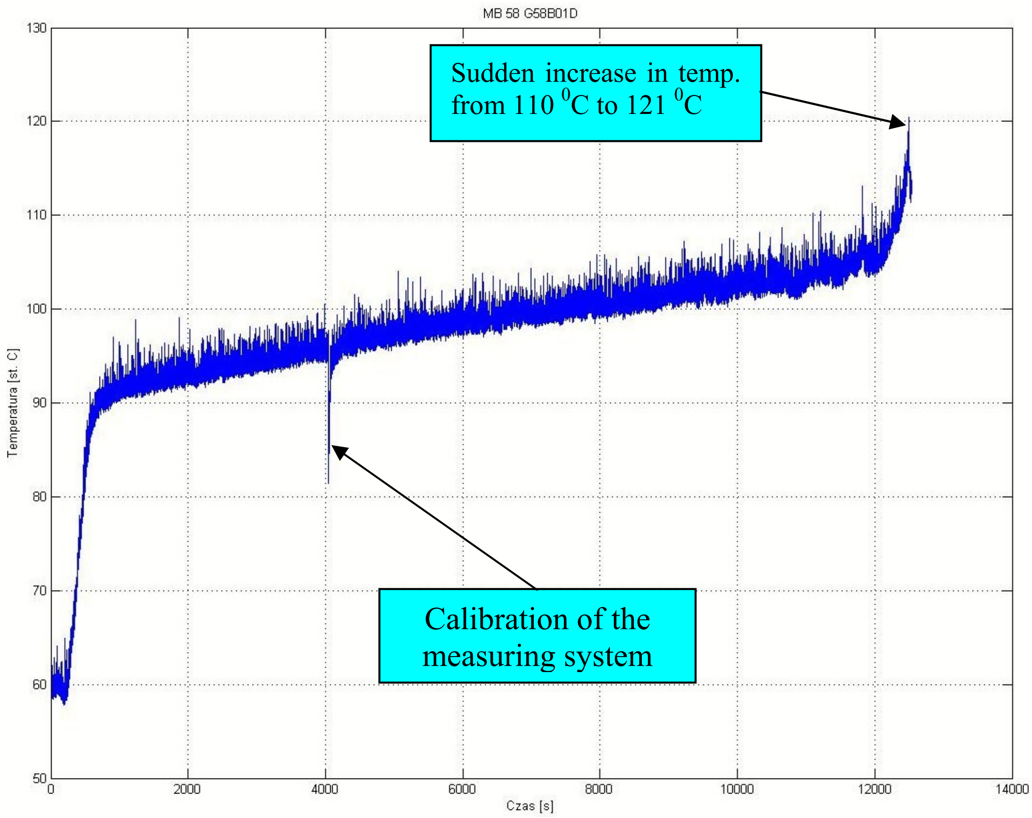


Fig. 6. Temperature of the bush of MB58 alloy during testing, at the pressure of 71 MPa [9]

The existence of a standard net of fatigue cracks was recorded on the tested bush of MB58 alloy, as shown in Fig. 7a and b, and Fig. 8.

a) b)

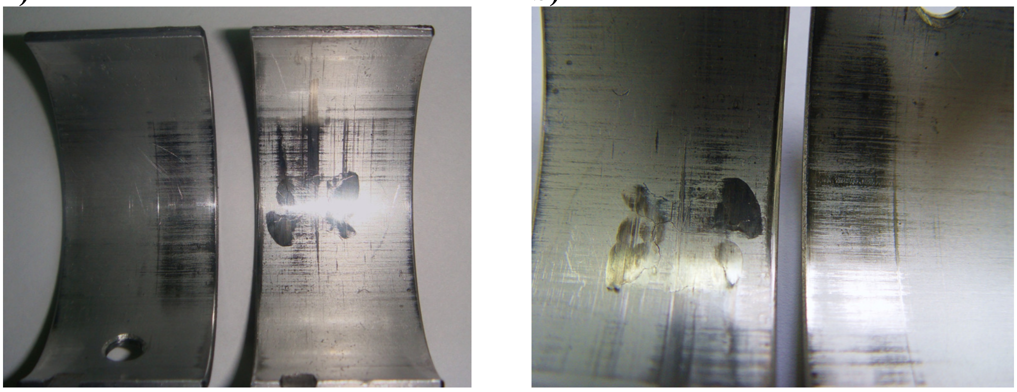
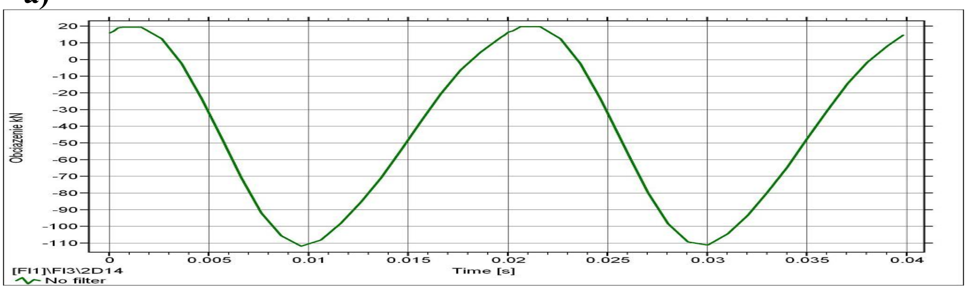


Fig. 7. Image of a net of cracks on the surface of the sliding surface of the MB58 bush after the fatigue tests finished: a) general view, b) zoom out of the damage [9]

Fig. 8. Net of cracks on the sliding surface of the MB58 bush (zoom out of the part of the sliding surface shown in Fig. 7b) [9]

Comparison of the curves, averaged and real, of the load cycles for the tested bearing is shown in Fig. 9.

a)



b)

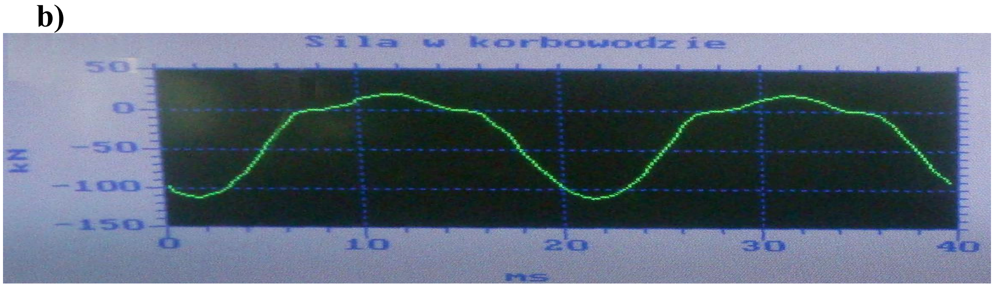


Fig. 9. Run of load on the slide bearing and the tested MB58 bushes:
a) averaged curve recorded by the AMSY-6 equipment, b) real curve resulting from the operation of the SMOK rig [9]

Fig. 9a demonstrates a curve of averaged load for a slide bearing, in a longer period of sampling and updating of its changes by the AE testing system. On the other hand, the curve shown in Fig. 9b shows the real load on the bearing, resulting from the operation of the SMOK rig.

The macroscopic view of the fatigue damage in the surface of the MB58 bush is provided in Fig. 10 and Fig. 11.

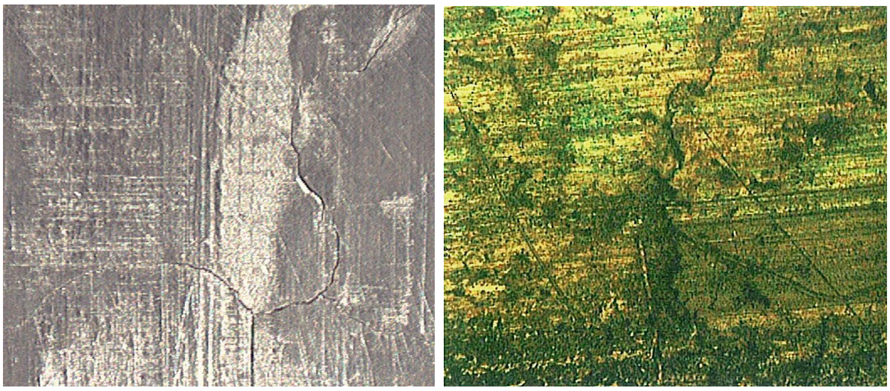


Fig. 10. The image of fatigue damage in the surface of the MB58 bush tested in the SMOK rig (zoom out of the part of Fig. 8) [9]

A more precise view of damage in the surface of the bush was obtained due to scanning images (Fig. 11). Fatigue cracks are concentrated mainly in the middle of the bush, which results from the proper design of the flexible housing of the tested bearing. Arrangement of the damaged areas towards the circumference corresponds exactly to the areas of the maximum cyclic pressures in the oil film and the maximum circumferential pressure gradient (the angles ψ ranging from 275^0 to 290^0). Arrangement of the cracks on the surface of the bush is indicative of variable normal stresses, circumferential and axial, in the sliding layer.

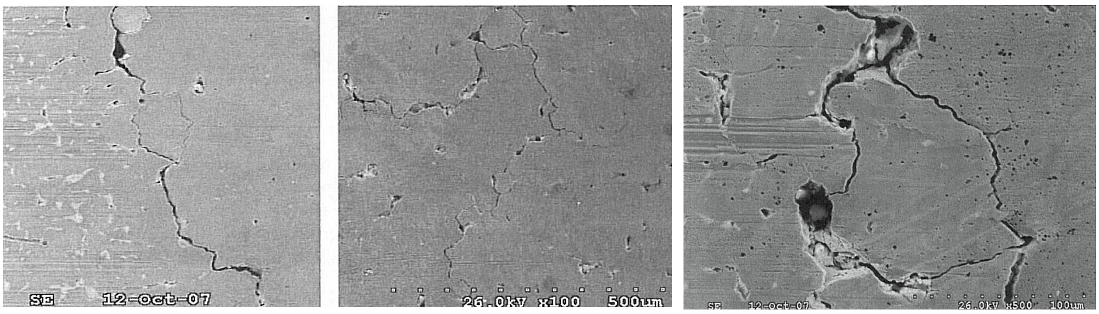


Fig. 11. Scanning images of fatigue cracks in the sliding surface of the MB58 bush (zoom out of the part of Fig. 8) [9]

Testing of the bearing and bushes type MB 58 was carried out at the rotational speed of 3000 rpm, the load of 20-111 kN and the pressure of 71 MPa.

The tests on the SMOK bench were performed until the time of occurring clear fatigue damage in the surface layers of the bearing bushes (Fig. 7). The acoustic emission (AE) was recorded continuously. This enabled recording of AE signals coming from the bearing working with the tested bushes, when they were in a good technical condition and then, when some fatigue damage developed inside of them. The collected measurement data was then subjected to further analysis, parametric and frequency, in order to select the signals characterizing the so-called emergency states for the bushes type MB58 of the tested bearing.

Load on the bearing bushes was controlled during the research by a computer using feedback, which enabled to obtain results of high repeatability. The computer control system was monitoring changes in the parameters such as: the transverse force on the tested bearing, the rotational speed of the journal, the temperature of the bush, the temperature of the lubricating oil and the limit value of signals in the security systems, and allowed to correlate the acoustic emission (*AE*) parameters with the aforesaid parameters. Measurement of the *AE* parameters was possible due to detection of low-energy elastic waves propagating in the tested bush. Furthermore, application of the vector inverter made that the rotational speed was invulnerable to changes in the friction torque. During the research, equal momentary values of journal rotational speed and load were maintained.

4. Overall description of amsy-6 measuring system

The tests of the sliding layer of the MB58 bush, by using the method of acoustic emission (*AE*), were performed with the AMSY-6 measuring system by Vallen Systeme GmbH, fitted with the software: Visual AE™; Visual TR™; Visual Class™, and 12 measurement channels, and a set of sensors: VS30-V; VS150-RIC; VS75-V. Table 2 presents characteristics of the AE sensors. Pentium laptop PC featured with 32 - bit Windows software was used to record the measured AE signals and to define the position coordinates. A number of low-, mid- and high-pass filters were applied in order to filter out the interference following from the work (operation) of the electric engine, hydraulic pump, lubricating oil pump, pre-expansion valve, and other impacts induced inside the laboratory as a result of external noise. The employed appliance consisted of: the calibrator type ACAL3 for check-out of the AMSY-6 system, preamplifiers type AEP4H-ISB, preamplifiers type AEP4 fitted with BNC ends at the input and output.

In addition, the AE sensors were mounted on waveguides in order to eliminate the impact of the temperature and to filer the high-energy low-frequency signals. In parallel with recording the AE parameters there were also recorded the temperatures of the supporting bearings and the tested bearing as well as the loads on the tested bearing for later correlation of the values [9].

Tab. 2. Characteristics of AE sensors [9]

Sensor Type	Frequency Range [kHz]	Housing Type	Temperat. Range [^{0}C]	Capacity [pF]	Connector Type	Comment: Amplifier Resonance
VS30-V	23 - 80	V	-5 ÷+85	140	Microdot	Flat response
VS150-RIC	100 - 450	R	-40 ÷ +85	-	BNC	Preamplif. 34 dB
VS75-V	30 - 120	V	-5 ÷ +85	140	Microdot	Resonance at 75 Hz

The interferences were filtered out by narrowband filters. There were filtrated interferences produced by working machines like: the electric engine, hydraulic pump, lubricating oil pump and other devices, e.g. pre-expansion valves, and - other disturbances existing inside the lab and resulting from the external noise.

The software of **AMSY-6** measuring system allowed: measurement of the basic descriptors of AE, signal analysis by using Fast Fourier Transformation and mathematical statistics, calculation of the coordinates of the signal source (localization) and automatic classification of the signals. This system recorded, processed and transformed pulses into data, localized the signal source, calculated mathematical statistics and presented all the results in graphs and numbers in real time. Parametric channels enabled to record the environmental conditions, external load and the EA parameters like: the recording time, the signal energy, the signal amplitude, the number of exceedances of the threshold level, the rise time, *RMS* – energy derivative, the position in the frequency domain, the distribution of peaks of the amplitude, the frequency spectrum obtained through Fourier transformation, displacement in the dominant frequency over time.

Basing on the files with the AE measurements there was built a classifier enabling identification of AE signals being produced by fatigue damage in the bush surface. The fatigue damage mapped into the spectrum of AE recorded during work of the tested bearing bushes on the SMOK bench, was identified by using the classifier based on the results of measurements [9].

A characteristic development of surface cracks and chipping was noticed on the surface of the sliding layer of the bush of MB58 alloy. Furthermore, occurrence of surface cracks was observed in the grain boundaries [9].

From the test results we can conclude that dynamic load does not lead to a sudden catastrophic fatigue damage of the bushes in slide bearings. Fatigue damage develops slowly, and its extent can be evaluated on the basis of parametric (amplitude-frequency) analysis of the recorded AE signals [9].

For example, an initiation moment of fatigue crack in the sliding layer of the bush was recorded after exceeding 1 236 990 cycles within 8 hours and 19 min (Fig. 5). Development of cracks to the state shown in Fig. 7, proceeded after consecutive 200 990 cycles generated within following 1 hour and 8 minutes.

The results show that the recorded acoustic emission signals are indicative of correlation between a change in the state and the occurrence of damage in the sliding layer of the bearing bush.

The obtained results provide a ground for conclusion that it is possible to select acoustic parameters enabling early detection of fatigue damage in the sliding layer of the bearing.

It can be considered that application of the contemporary methods and measuring systems adopted to analyze the acoustic emission AE [5, 7] for testing the slide bearings, provides opportunity to identify precisely the initiation moment of a fatigue crack. As a result, it is possible to determine the lifespan of the sliding bearing bush, where the measure is a destructive number of cycles for the set mechanical and thermal loads leading to fatigue damage to the bush. This means that the results of the research can be applicable for building classifiers [8], useful for diagnostic tests conducted to identify the technical state of the bushes of slide bearings for marine diesel engines in real operating conditions.

5. Remarks and conclusions

The aim of the research was to demonstrate the ability to identify technical conditions of sliding bearings for diesel engines by using acoustic emission (AE) as a diagnostic signal, enabling detection of occurrence of fatigue cracks. This was achieved as a result of measuring values of the parameters of acoustic emission AE being produced by fatigue damage in the bush (made of MB58 alloy) during testing them in the SMOK rig.

On the base of the conducted tests and the analysis of the recorded acoustic emission signals, it was found that there were frequency bands of AE signals that corresponded to damage in the material of the bearing bushes.

The results provide a foundation to conclude that in the case of taking a higher number of measurements and verification of the obtained results (examination of bearing bushes after dismantling) it is possible to select the AE parameters which enable detection of microdamage in the sliding layer of the bearing in the early stage of its development.

The fatigue properties of the bearing materials were not presented in the form of Wöhler diagram, which presents functional dependence of destructive dynamic load σ from the fatigue life N of the bush, as the object of the research (σ – hoop stress in the sliding layer of the bush, N – number of cycles at which the first fatigue symptoms occur in the sliding surface of the bush). The stochastic nature of the fatigue tests causes that for clear description of the fatigue resistance of the tested bearing bushes, it is necessary to implement a third variable - the probability p of occurrence of the surface fatigue crack at a certain combination of σ and N values. The field of σ-N-p is a geometric illustration of the function combining the fatigue load, lifespan and probability of surface crack occurrence in the sliding layer of the bearing of defined properties as for construction, material and geometry.

Experimental determination of a complete field of σ-N-p is generally unworkable, because it would require examination of a very large number of bearing bushes, which due to financial and time-consuming aspects results in fundamental limitation of the range of fatigue research. For these reasons, the research was planned in the way to execute a minimum number of tests, however sufficient to maintain the demanded reliability of the determined quantitative rates.

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