Ann. Disaster Risk Sci. 2018, 1, 87-96

ENVIRONMENTAL POLLUTION CAUSED BY MECHANICAL SYSTEM FAILURE ON SHIPS

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Abstract

Ships and other types of vessels contain very large quantities of lubricants in their structural assemblies used for steering or motion. This lubricant serves to reduce friction between the parts and prevents their wear and tear. Due to increasingly demanding criteria related to environmental pollution, changes are implemented in design solutions regarding new lubrication methods which are less harmfull to the environment in case they come into contact with the environment. New design solutions apply new types of lubricants, which have different chemical structures, the tribological properties of interacting materials likewise change, so we need to use new construction materials that provide good machanical tribological properties for a structural system with regard to its motion and steering. New types of lubricants, as well as new construction materials, are quite underresearched. This complicates their use in realistic systems. The aim of this paper is to provide an overview of new solutions with regard to lubricants and construction materials, as well as estimating their adverse impact on the environment.

Keywords: environmental pollution, lubricants, new construction materials.

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1. INTRODUCTION AND AVAILABLE SOLUTIONS

Thanks to the development and improvement of the current technologies, in the application of new materials in the area of shipbuilding primarily due to ecological norms, MEPC 141(54) [1] there is a tendency to use composite materials. This paper places focus on monitoring of measures undertaken in shipbuilding regarding possible mechanical damages caused in mechanical systems on ships, and ecological impact of such mechanical damages on the environment, i.e. the sea.

The engineering challenges require consideration of various aspects of bearings, e.g. operating conditions, selection of shafts, slide bearings and design. Due to the substantially lower viscosity of water (0.66 cSt at 40^{o}C) in comparison to oil that can be found in slide bearings (32-68 cSt at 40^{o}C), the water-lubricated slide bearings operate at border/mixed regime over a relatively longer period of time [2]. Thus, the selection of materials and their tribological behaviour are very important for the proper design of bearings and extension of their lifecycle.

1.1. Environmental impact of leakage of lubricants

Using the available technologies, the leakage of lubricants into the sea and water can be eliminated. There are currently two types of conventional alternatives that can be found in use, and that are environmentally acceptable methods:

1) The maritime manufacturers have developed multi-disc seals that reduce the quantity of lubricant leakage into the environment, but shaft seals are still subject to damages, resulting in lubricant leakage into the environment, i.e. leakage of lubricants into the sea.
2) Bio-degradable lubricants are also available, but technically they belong to the group of mineral lubricants, and they leave visible traces on the surface of the sea.
3) Less conventional, but technically less deman-

ding design is the usage of polymer composite materials in case of slide bearings that use seawater from the environment as a lubrication agent. Seawater from the environment is pumped and used as lubricant, and after completed action it is returned into the environment, i.e. the sea. Seawater enters the front part of the stern, and it is pumped into the bearing assemblies such as the slide bearing of the propeller shaft. The quality of seawater that is supplied to the slide bearings is of critical importance, since it ensures exploitation value of slide bearing wear. The removing of foreign abrasive particles from the sea environment is done by specific devices that filter the foreign particles up to 80 microns. The use of such design solutions has several positive effects apart from ecology; there is no need to store the lubricants, to control the lubricant properties, and for the final treatment, that is, disposal of lubricants. The potential impact of environmental pollution equals zero, since the lubricant from the sea environment is used which is available in infinite abundance [3,4].

1.2. Method of lubricating slide bearings

Depending on the method of lubrication and design solutions, lubrication of mechanical systems in case of ships can be of open and closed circulation. The lubrication systems with a closed circulation use primarily grease as lubricant, e.g. slide bearing. Thus in open circulation slide bearings based on polymer composites are applied, using seawater as lubricant. In lubrication of slide bearings the main purpose is to reduce the friction, wear, and to reduce the heating of the slide bearing. This reduces the accompanying losses in the lubrication system that can be of great significance in the exploitation process; for instance, the decrease of the power loss, extension of the lifecycle of the bearing that is proportional to the bearing wear, and reduction of heating and thereby prevention of heating of the slide bearing [5]. These components are realised in a valid design, and with good lubrication, in which the surface of the sleeve and the bearing pads are separated by a thin layer of the lubricant in which there is liquid friction. In order to achieve liquid friction, it is necessary to ensure in the lubricant layer a pressure that allows balanced condition with the external load of the bearing. This is achieved by hydrostatic or hydrodynamic lubrication method [4,6].

1.3. Water-lubricated bearings

As a lubricant, water is environmentally acceptable, non-toxic, easily available and it has a higher specific thermal capacity in relation to typical lubricants that are used with slide bearings, which affects better cooling of the system. However, the main drawback of using water as lubricant is its very low viscosity. In spite of low water viscosity, water-lubricated systems can be found in the parts of the system, e.g. machines that are used in mining and textile industry, rolling mills, water pumps, etc. The second usual application of water-lubricated slide bearings is found in shipbuilding, and the installation method and the operating principle can be seen in Figure 1.

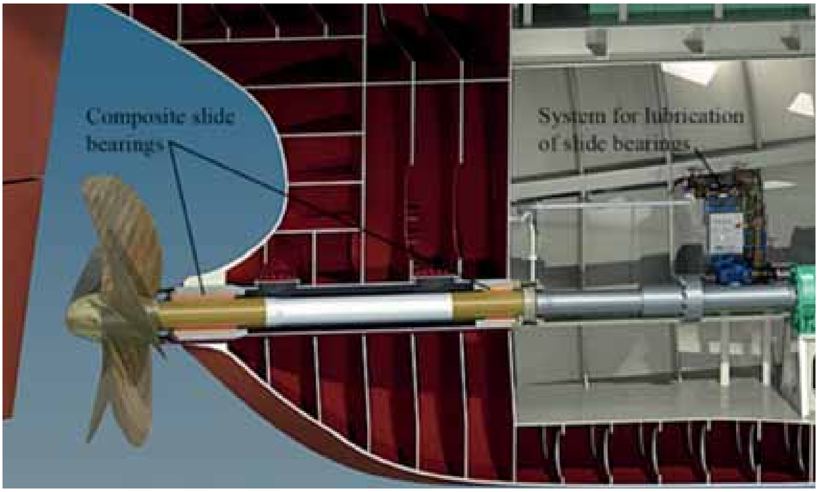

Figure 1. System for lubrication and slide bearings.

Rubber bearings have gradually become the usual application in pumps, sea-going and many ships of commercial purposes as early as the beginnings of 1940s. The need for better materials, for the implementation in water-lubricated slide bearings was realised in 1942 when a part of US ships experienced great damages in the bearing assemblies in the combat on the Mediterranean. The damage of bearings and shafts can be caused by high-frequency of turning action from rotating shafts. The slide bearings with parts of natural rubber were soon replaced by acrylonitrile-butadiene rubber (NBR), synthetic elastomer that does not show the hysterized softening of materials. The slide bearings with acrylonitrile-butadiene rubber (NBR), that can be seen in Figure 2 have some drawbacks, and these are high friction and wear factors that are the main drawbacks of slide bearings with such design solution [4].

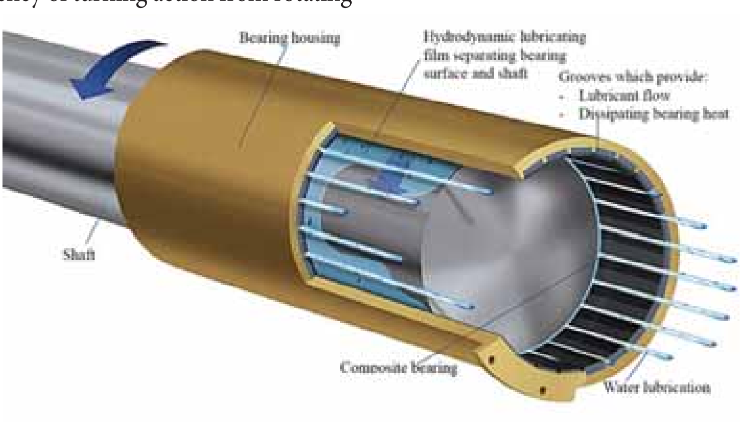

Figure 2. The system for slide bearing lubrication.

The currently available materials for implementation in water-lubricated slide bearings include complex polymers, and these are: UHMWPE (Ultra-high-molecular-weight polyethylene), PEEK (Polyether ether ketone), PTFE (Polytetrafluoroethylene) and polymer and thermoset composites with commercial designations such as: Thordon SXL [7], ORKOT [8], NORDEN [9].

1.4. Material selection

The improvement of polymer materials has led to such polymer composites that in some applications achieve far better mechanical properties in relation to metals (Babbit metal, bronze). In this way the polymer composites have classified themselves among very valuable engineering materials as well as bearing materials [6].

In every selection of the proper material for the slide bearings, the first consideration is to ensure that the heat developed by friction is gradually absorbed and uniformly transferred to the surrounding part of the assembly or the heat is conducted by means of a lubricant. There must be a balance in the system in which the temperature boundary / balance is reached, which is below the temperature boundary / balance of the state of material. In the reverse case, there will be a change in the material properties, and it may lead to damage of the material and final breakdown. Another requirement for material selection is the type of the surrounding that may act on the slide bearing, for example a very abrasive or clean environment, as well as the final purpose of the selected material [3].

1.5. Sliding properties

When speaking of sliding properties of the materials one refers to the behaviour in case of friction, i.e. factor of friction, wear of material, and heating of the material. Friction and wear in polymer materials depend on: quality of surface treatment, type and quality of lubrication, intensity of surface pressure, sliding speed, temperature of the engaging surfaces, properties of materials that are in contact, percentage of humidity, and others [10].

Tests carried out in assemblies that use polymer composites, e.g. slide bearings of ship propellers in dry friction have shown that the resulting friction and wear coefficients are such that in certain load conditions they can operate also without lubrication, until the nearest dock [11].

1.6. Polymer composites

For the materials from the group of thermoplastics it is typical that during heating they become softer. Here the final temperature of heating needs to be kept below the critical value so as to avoid its thermal degradation. They harden again by cooling creating thus amorphous or crystalline structure, depending on the type, retaining at the same time the properties they had before heating [4]. Composite materials with polymer matrix are obtained by joining two or several materials of dissimilar properties with the goal of obtaining improved material properties, e.g. Polytetrafluoroethylene (PTFE) composite which is widely used due to its good properties, e.g. wear resistance, low friction coefficient, chemical resistance, etc. In the area of shipbuilding one finds an increasing number of polymer composites, with the application primarily in slide bearings that use seawater as lubricant [6].

1.7. Thermoset composites

Various types of polyester matrix with the same reinforcement agent can show different properties. For the properties of composites not only the type of reinforcement agent is important, but also its direction and distribution in the matrix. When heated, thermosets create irreversible chemical connections among polymer chains that are mutually strongly networked [12]. Upon reheating, they do not change their state, but remain solid until being completely degraded under the action of high temperature. This indicates also a major problem in their application, they cannot be recycled by softening the matrix, but only mechanically milled to yield tiny granules that contain both fibres and matrix. This indicates an issue towards the ecological environment, such as the sea. Thermoset composites are used in slide bearings, that can be lubricated by grease or seawater [4,12].

Possible damages that can occur in slide bearings are: abrasive wear, adhesive wear, bearing damage caused by overheating and corrosive and mechanical damaging of the sleeve that can damage the slide bearing [13].

2. DISCUSSION ABOUT ASSESSMENT OF CRITICAL OPERATING LIFECYCLE OF COMPOSITE BEARING MATERIAL IN RELATION TO BRONZE-BASED BEARING MATERIAL

The review of literature [14] has shown a very frequent phenomenon that the lubrication system of the slide bearing does not function properly and the reduced quantities of lubricant result in scuffing of the slide bearing.

In order to determine the loading limit of the slide bearing made of thermoset composite in case when the bearing is left without lubrication, a device for testing slide bearings has been designed.

The device for testing slide bearings without lubricant supply consists of a housing into which the composite slide bearing, the subject of our testing, has been pressed in, a thermometer that measures the temperature of the sleeve and housing thermometers and measuring doses used to measure the friction factor [15]. The parts of the testing device for slide bearings can be seen in Figure 3.

Prior to and after measuring on the testing device, the mass of the sample, surface roughness and diameter have been measured, while the diameter and surface roughness were measured on the sleeve. By the difference of the mass of the test bearing the wear rate described by Equation (1) can be determined.

$$k = \frac{W_m}{\rho \cdot F_N \cdot s} \quad (1)$$

During the trial, the temperature of the housing and the sleeve as well as the factor of friction were measured. Using the difference of the sleeve temperature and factor of friction the power loss described by Equation (2) can be determined.

$$P_R = \mu \cdot F_N \cdot v \quad (2)$$

The surface pressure on the surface of the slide bearing due to the action of load on the sleeve can be described by Equation (3).

$$p_{vs,\max} = \frac{16}{3\pi} \cdot \frac{F_N}{d \cdot B} \quad (3)$$

The factor of friction obtained on the test instrument has been described by Equation (4), whereas Figure 3 shows the parts of the test instrument which affect the measuring of the factor of friction. It should be noted that normal force FN is equal to the weight loading factor Fg.

$$\mu = \frac{F_{T2} \cdot L}{r} \cdot \frac{1}{F_N} \quad (4)$$

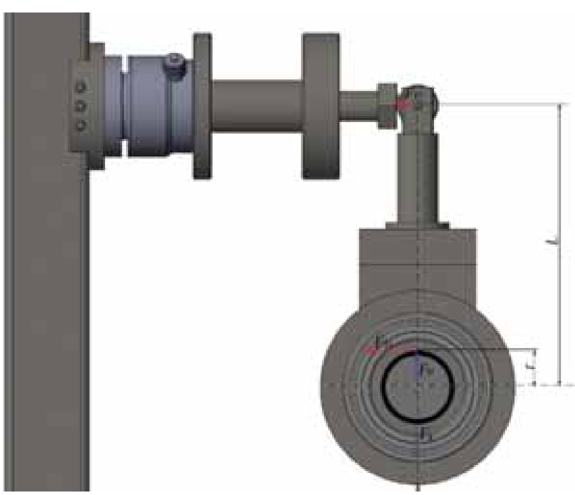

Figure 3. Scheme of the action of forces in determining the factor of friction.

During the performance of the test the data were collected by means of the measuring amplifier type Spider 8 manufactured by Hottinger Baldwin Messtechnik GmbH (HBM) [16] and software package Catman [17].

During measuring by means of Catman software package the recording frequency was 60 Hz which means that in two hours of measuring, the time necessary for testing, there are about 430,000 data.

Such a big amount of data is very difficult to process within a certain standard software package such as e.g. Office Excel (Microsoft) so we used the software package NI DIAdem (National Instruments) [18] developed for the analysis of large amounts of data.

Two materials were selected for the test, one of them thermoset composite of type Norden Marine 605 [19] used to produce slide bearings in shipbuilding, and the other bronze of type CuSn-7Zn4Pb7-C [20] which is also used for this application visible in Figure 4 and Figure 5.

The target of the trial is to test the properties of the material in operation without lubricant supply in the period of 120 minutes, with constant measuring of the factors of friction, and temperatures of housing and sleeve in order to determine the working lifecycle of the bearing in case of lubricant supply failure.

The dimension of the samples of test slide bearing is defined as the internal diameter x external diameter x bearing length (34.3x39x27 mm), of surface roughness Ra 2.40-3.50 µm.

The sleeve was made of stainless steel type AISI 316, external diameter 34.05 +/- 0.005 mm and surface roughness 1.40-1.50 µm.

Figure 4. Composite slide bearing and shaft wear

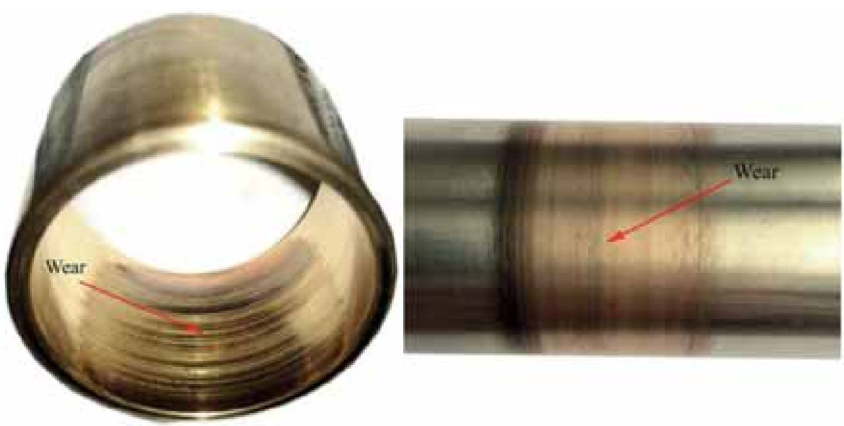

Figure 5. Bronze slide bearing and shaft wear

The force at which the samples were loaded during the trial was F1=115 N, which was taken on the basis of previous studies of materials of similar mechanical and tribological properties, with peripheral speed of a sleeve which amounted to v=0.53 m/s [14,11].

The measuring equipment used during the trial is presented in Table 1.

Table 1. Measuring equipment used in the trial.

Measured value	Measuring system	Collection of signals	
		Using machine management systems	Using external measuring computer
Friction force, F_{T2} [N]	Measuring dose *HBM TYP U3*	ü	
Rotation speed [min-1]	EMCO Maximat Standard 65- 1550 min-1		ü
Temperature of the slide bearing housing [˚C]	Thermometer TC *LTD International,* Type K, Class 1	ü	

3. TRIAL RESULTS

The test was planned so that for every test group at load of F1=115 N and peripheral speed of the sleeve of v=0.53 m/s three different samples of two different materials were tested, these being thermoset composite and bronze. The statistical data processing was done with the software package NI DIAdem and the results were obtained regarding the mean temperature of sleeve, housing and mean value of friction [21]. It needs to be noted that in the test with bronze bearing material the maximum time during which the bearing could operate without lubrication was 30 minutes after which the scuffing occurred. In order to suppress the scuffing process grease type Kluber Oil UH1 was added [22].

The changes that occurred on the test samples such as the change of mass, surface roughness and internal diameter can be seen in Table 3 For these measurements various measuring instruments were necessary and they are presented in Table 2.

The measuring equipment used during the trial is presented in Table 2.

Table 2. Measuring equipment used prior to and after the trial

Measured value	Measuring system
Internal diameter of slide bearing [mm]	*Mahr,* D 189
Surface roughness Ra [µm]	*Mitutoyo,* SURFTEST SJ210
Sample mass m [g]	*Kern & Sohn GmbH,* PRJ 1200-3N
External diameter of the slide bearing [mm]	*Mitutoyo,* type 293

Table 3. Change of mass, surface roughness and internal diameter after testing

Type of test bearing material	Mass prior to testing	Mass after testing [g]	Mass difference W_m [g]	Surface roughness Ra prior to testing [µm]	Surface roughness Ra after testing [µm]	Internal diameter of the sample prior to testing,	Internal diameter of sample after testing, [mm]
Thermoset composite Norden Marine 605	9,528	9,524	0.004	2.60	1.60	34,246	34,255
Bronze type CuSn7Zn4Pb7-C	64,139	63,464	0.675	0.62	3.82	34,240	34,392

After data processing in the software package NI DIAdem in Table 4 the amounts of mean temperature of sleeve and housing of the slide bearing and the mean friction factor can be seen. Also, the measurement results are presented in diagrams that are shown in Figures 6 and 7.

Table 4. Temperature of sleeve, housing, and mean friction factor

Type of test bearing material	Mean sleeve temperature [˚C]	Mean housing temperature [˚C]	Mean friction factor [-]	Error in measuring the mean friction factor [-]
Thermoset composite Norden Marine 605	45,895	35,521	0.2377	0.000005
Bronze type CuSn7Zn4Pb7-C	50,623	44,423	0.3625	0.000076

In order to determine the specific wear rate k the composite density needs to be known, and it amounts to 1,300 kg/m^3 and the density of bronze which amounts to 8,650 kg/m^3 and the travelled path of the sleeve along the slide bearing which amounts to 3,850 m. The surface pressure between the slide bearing and the sleeve is 0.21 MPa. The specific wear rate as well as the power loss as result of sliding of the sleeve along the slide bearing can be seen in Table 5.

Table 5. Specific wear rate and power loss

Type of test bearing material	Specific wear rate k, equation (1) [mm^3/Nm]	Power loss Pr, equation (2) [W]
Thermoset composite Norden Marine 605	1.36 x 10^{-15}	14,489
Bronze type CuSn7Zn4Pb7-C	2.43 x 10^{-13}	22,094

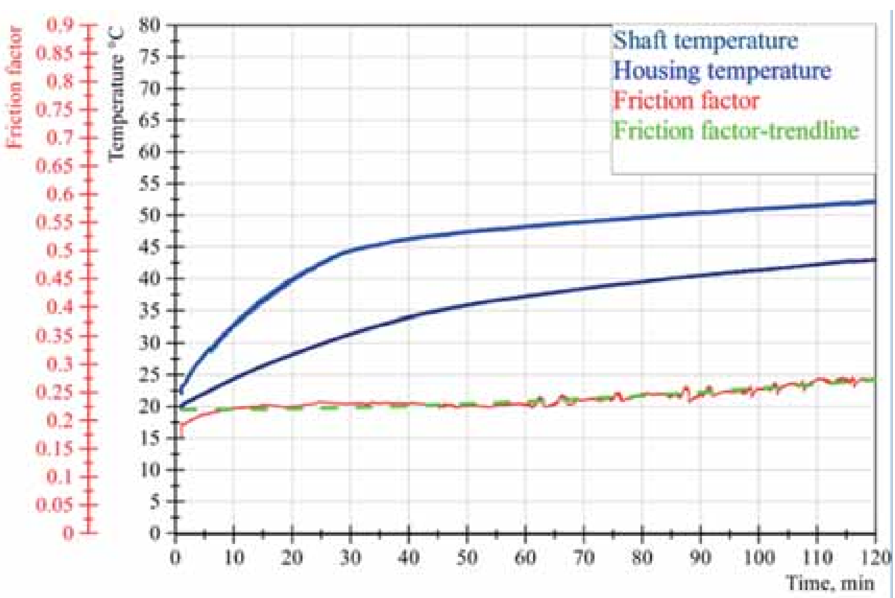

Figure 6. Results of testing composite bearing material

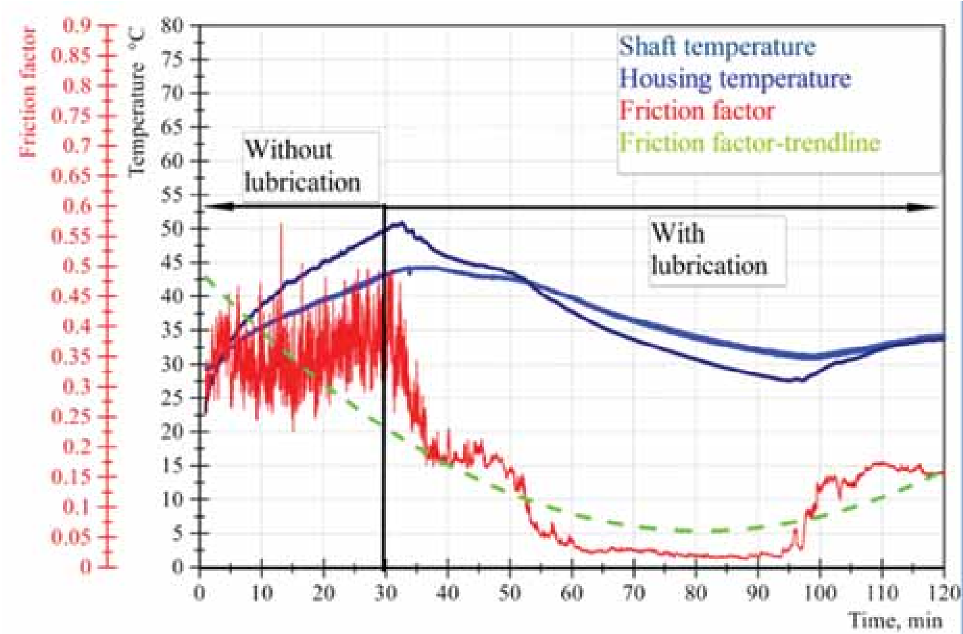

Figure 7. Result of testing bronze bearing material

4. CONCLUSION

As can be seen in Table 5, the specific wear rate as well as the power loss are significantly lower in case of composite bearing material in relation to bronze which speaks in favour of the reliability of the material in conditions without lubrication.

Thermoset composite materials lubricated by low-viscosity lubricants such as brine (seawater) are negligibly harmful for the environment in which they exist and that can be defined as their area of operation.

Figure 7 shows that bronze as the bearing material can operate for a very short period without lubrication (ca. 30 min.) which results in bearing scuffing. In order to avoid the process of scuffing in the phase when it was noted that the temperature rises very fast and results in strong vibrations of the test instrument and in order to continue the measuring, the lubricant of type Kluber Oil UH1 [22] was added, not harmful for the environment, but the drawback of such lubricants is their high price which limits their application [23].

Thermoset slide bearings could operate without problems throughout the trial so that it can be concluded that in case of the lubrication system failure there would be no major damages of the system slide bearing / sleeve which is of very high significance for the ecological system of a ship in which the slide bearing of this type has been installed as well as for the reliability of the mechanical system in which the composite bearing materials are used [23,24].

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ZAGAĐENJE OKOLIŠA PROUZROČENO GREŠKOM U MEHANIČKIM SUSTAVIMA BRODOVA

Sažetak

Brodovi i ostale vrste plovila u svojim konstrukcijskim sklopovima koji služe za njihovo upravljanje ili pokretanje sadrže vrlo velike količine maziva koje služi za smanjivanje faktora trenja između djelova te smanjenje trošenja. Zbog sve zahtjevnijih kriterija vezano za zagađenje okoliša, dolazi do promjene konstrukcijskih rješenja u pogledu primjene novih metoda podmazivanja koja su manje štetna za okoliš ukoliko dođe do njihovog kontakta s okolišem. Nova konstrukcijska rješenja primjenjuju nove vrste maziva koja su manje štetna za okoliš. Zbog drukčijih svojstava novih maziva koja posjeduju drukčiju kemijsku strukturu mijenjaju se tribološka svojstva materijala koji se naalaze u međusobnom dodiru, stoga moramo koristiti nove konstrukcijske materijale koji daju dobra mehaničko tribološka svojstva nekog konstrukcijskog sustava vezano za pokretanje i upravljanje. Nove vrste maziva kao i novi konstrukcijski materijali vrlo slabo su istraženi što otežava njihovu primjenu u realnim sustavima. Cilj ovog rada je dati pregled novih rješenja u pogledu maziva i konstrukcijskih materijala te procijeniti njihov negativan utjecaj na okoliš.

Ključne riječi: zagađenje okoliša, maziva, novi konstrukcijski materijali.