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MATERIALS SELECTION AND SOFTWARE APPLICATION AS DESIGN TOOLS FOR MARINE PROPULSION SHAFTING BEARINGS

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1. Introduction

Marine as well as machine building industry in general in friction units conventionally uses metallic antifriction materials or white metal (WM) bearing alloys, known commercially as babbitt alloys. ASTM Standard B 23-00 [2010] specification covers eight typical white metal bearing alloys, the tin-based alloys and lead-based alloys. Babbitts are among the most widely used materials for hydrodynamic lubricated bearings. Babbitts are either tin or lead-base alloys having excellent embeddability and conformability characteristics. They are unsurpassed in compatibility and thus prevent shaft scoring. Tin- and lead-base babbitts have relatively low load-carrying capacity. This capacity is increased by metallurgically bonding these alloys to stronger backing materials such as steel, cast iron, or bronze [Hamrock et al. 2004].

Copper-lead alloys, copper-nickel, bronzes and aluminium alloys are also used. Studies at sintered self-lubricating bronze bearings have shown that additional oil at bearing considerably decreased friction coefficient especially at high velocities and pressures. In addition, it has been seen that friction coefficient decreased more by additional additive as well effects of loads, spindle speed and oil types influence on friction coefficient [Ünlü and Atik 2007]. On the other hand, the Croatian Register of Shipping [2009] rules for classification of ships notified that cast copper alloys are recommended for applications such as shaft liners and bearing busches.

In recent years, an increasingly close attention has been given to industrial products environmental safety of the friction units of modern ships, hydraulic turbines, pumps, shipping locks, as well as oil-extracting and oil-processing equipment operating in water. For this reason oil lubrication of friction units is eliminated by using such natural lubricant as water or even without lubricants [Ginzburg *et al.* 2006], [Hamrock et al. 2004] and [Litwin 2010]. Some of these excellent water durability polymeric multiphase systems are based on thermoplastic, thermosetting, rubber and composites. Still their mechanical properties generally limit application to lightly loaded conditions and often to low speeds and conforming surfaces [Hamrock et al. 2004].

The Handbook of Plastics, Elastomers, and Composites [Harper 2002], [Bielinski et al. 2006] and [Ünlü et al. 2009] explain that polypropylene (PP), polyethylene (PE), polyoxymethylene (POM), polyamide (PA), polyimide (PI), polytetrafluoroethylene (PTFE), polyurethane (PU) and polyesters have thermoplastic matrices. Also other thermosetting materials like phenol-formaldehyde and epoxy resins, as well as composites with thermoplastic or thermosetting matrices reinforced with fillers such as carbon or glass fibre are used to fabricate journal bearings.

Glass fibers and carbon fibers which are short fiber reinforcements have been successfully used to improve the strength to high pressure and wear resistance. In addition glass fibers improve the load carrying capability and the thermal conductivity. This is a positive effect to lowering wear rate of pure polymer [Ginzburg et al. 2006], [Harper 2002].

Traditional and presently most common design of propeller shaft stern tube bearings is based on the application of white metal and the system of gravitational or forced lubrication of the bearings. A propeller shaft sealing system is designed to prevent the ingress of water into the stern tube where it could damage the bearings. The seal is also designed to prevent the leakage of stern tube oil into the sea or into the engine room bilge. These sealing systems are costly to maintain because they are normally designed to withstand extreme conditions such as axial and radial shaft displacement, ship vibrations and operating periods of up to five years. The simplest way completely to eliminate oil from the stern tube is to use seawater as the lubrication medium and proven polymer bearings in place of oil and white metal bearings. Use of seawater lubricated bearings eliminates the aft seal, as well as the storage, sampling and disposal of oil. An alternative arrangement involves polymer stern tube bearings offering significant advantages over the white metal ones. The advantages include a considerable reduction of the effective power loss resulting from heat generation in the bearings due to hydrodynamic friction of lubricants under identical operating conditions (bearing load and shaft speed), which results in fuel saving. Furthermore, polymer materials have good self-lubricating properties and lower friction coefficient than white metal; therefore they display improved performance in the area of mixed and dry fiction which occurs when starting and stopping the marine propulsion machinery. The application of seawater-lubricated polymer stern tube bearings eliminates the possibility of marine environment pollution which is not the case when using oil-lubricated white metal stern tube bearings. Also the use of polymer stern tube results in considerable financial saving during the ship's exploitation period.

In sea-going ships the use of polymer bearings that are lubricated by seawater, instead of the conventional white metal, lubricated by oil, would eliminate the need for oil in stern tube and also the possibility of pollution due to oil leakage. On the environmental aspect, undoubtedly the use of modern polymer bearings, in comparison to the usual white metal ones, eliminates the possibility of pollution.

Modelling of shafting parts, material properties and selection of materials are important tools to help designers, shipbuilders and other engineers understand the essential calculation concepts. To achieve that there are major design variables such as: bearing length and diameter, journal diameter, maximal clearance, polar angle (related to journal position within the bearing), lubrication medium and bearing temperature to be encountered.

To examine the practicability and the advantages of polymer propeller shaft bearings compared with conventional white metal bearing investigated on real ships, the present study uses characterizations methods for materials selection and a software application with two modules based upon data of stern tube bearing operating temperatures obtained from two types of ships (tanker and Ro-Ro passenger ship).

2. Materials and methods

2.1 Materials

Four different materials currently used for ship journal bearings were considered for the models calculation: One tin based alloy was used as comparative metallic material towards three different types of polymers.

Table 1 presents the materials elastic modulus and Poisson’s ratio obtained from literature [Hamrock et al. 2004], [Ginzburg et al. 2006], [Harper 2002].

2.2 Experimental

In order to select the materials for software application, it was necessary to know certain mechanical properties. Some of the materials where very well documented in literature, while others needed a reverse engineering approach. Therefore, a series of characterizations were done on two of bearings. To accomplish this goal infrared spectra of the materials were obtained with Perkin-Elmer 100 FT-IR spectrometer (wave-numbers 600–4000 cm^{-1}) at room temperature. Also, material morphology and particles were characterized using scanning electronic microscope with coupled energy dispersive X-ray spectrometer (SEM coupled EDS, JSM 6060 - HITACHI TM 3000).

Table 1. Mechanical properties of materials used in ships stern tube journal bearing design

White Metal Material	Young's modulus (MPa)	Poisson's ratio
Tin-based Babbitt – main alloy element Sb	52000	0.35
Polymeric Material		
Thermoplastic polyether polyurethane elastomer (polyether PU)	253	0.467
Carbon reinforced composite phenol-formaldehyde matrix (CRP-F)	15000	0.33
Polytetrafluoroethylene (PTFE) with 1% of fullerene black	500	0.46

2.3 Calculation parameters

For the actual power loss [kW] calculations a software composed of two modules *S11partialRJB* and *S11isoviscRJB* was developed. Computational model have been verified experimentally based upon data of stern tube bearing operating temperatures obtained from two tankers and a Ro-Ro passenger ship. Namely, chemical tanker of 46250 deadweight tonnage (DWT), product tanker of 52600 DWT and the Ro-Ro passenger ship of 496 gross tonnage (GT). Ships engines rotational speeds were within interval from 30 to 123 rpm with a step of 10 for tankers and from 100 to 608 rpm with a step of 100 for Ro-Ro.

For the white metal oil lubricated bearing a hydrodynamic lubrication model was used. The core of numerical calculation (finite difference methods for the numerical solution of Reynold's equation) was developed upon Matlab program *Partial* taken from [Stachowiak and Batchelor 2005], reworked into MS Excel/VBA. The polymeric water lubricated bearings, due to elastic deformation of the lubricated surfaces, need an elastohydrodynamic lubrication (EHL) program. *S11isoviscRJB* calculates polymer bearing elastic deflection based on [Hamrock et al. 2004] elastohydrodynamic lubrication analysis of isoviscous-elastic body lubrication regimes. Validation of these models is based upon actual the bearing temperatures for different driving regimes obtained from the real ships in service. Parameters of the two types of lubricants in ships' bearings are:

1. Oil density ρ = 910 kg/m^3, kinematic viscosity at 30°C, ν = 175 mm^2/s and specific heat capacity 1922 J/kgK.
2. Average seawater density ρ = 1025 kg/m^3 at average temperature of 15°C, considering trading area of the actual ships. At this condition the seawater as lubricant has a kinematic viscosity of 1.1843 mm^2/s and a dynamic viscosity of $1.21\cdot10^{-3}$ Pa·s.

Additionally, based upon the results of the shafting alignment calculation (i.e. calculation the elastic line of shafting), the tanker for oil products bearing was under a constant load of 250 kN. The chemical tanker bearing was under a constant load of 222 kN and catamaran bearing under constant load of 3.6 kN with an arc bearing angle of 360°.

3. Results and discussion

Figure 1 presents FT-IR spectra of the tested polymeric materials compared with the equipment database. Figure 1a is the A tested material and Figure 1b is the B tested material.

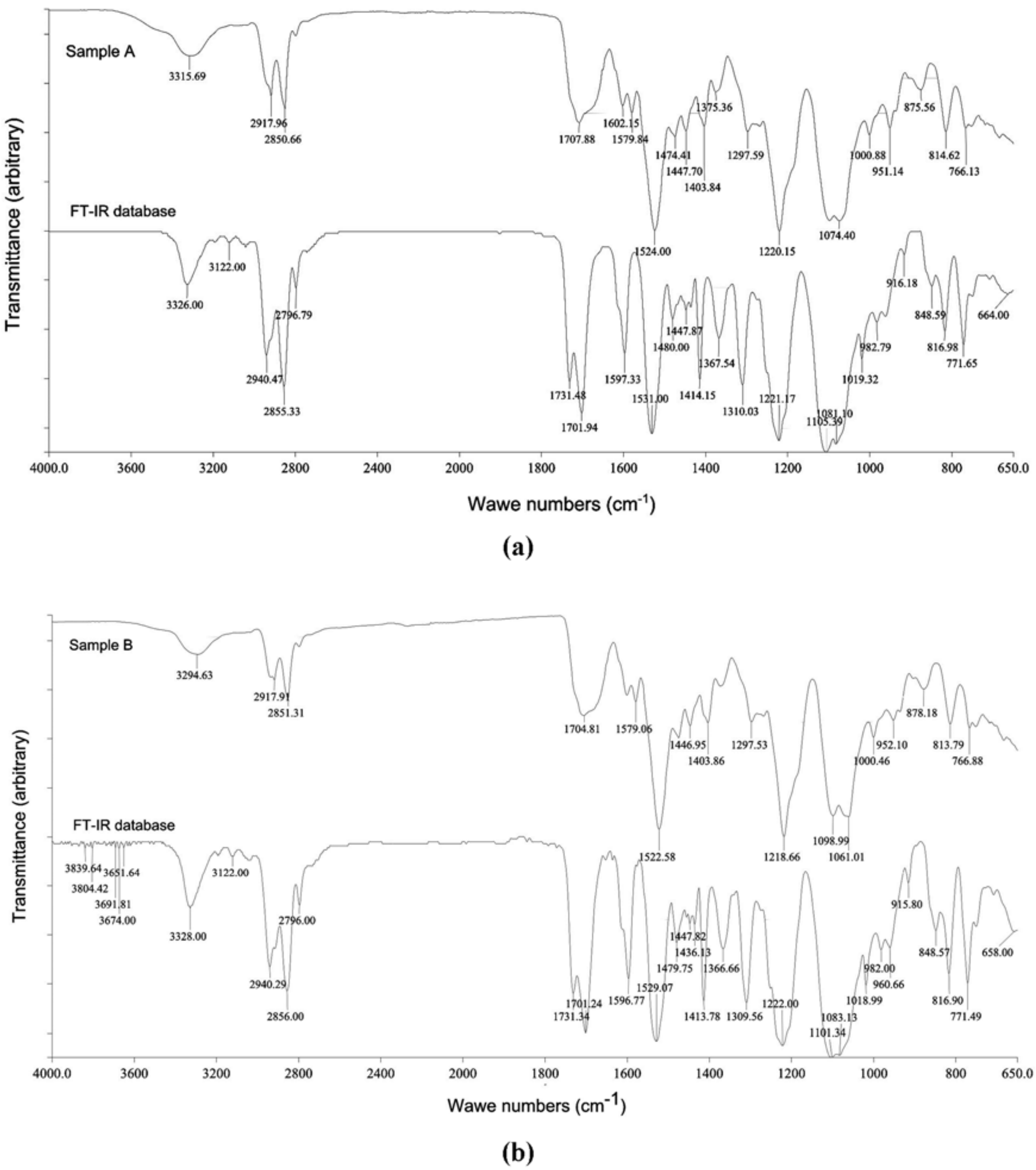


Figure 1. FT-IR spectra of (a) bearing A compared with the equipment database, (b) bearing B compared with the equipment database

Results comparing the FI-IR spectra for both samples have indicated that both of the analysed bearings are polyether based thermoplastic polyurethane.

Figure 2 shows the morphology of the polymeric material and particles using scanning electron microscopy (SEM). To identify the particles chemical composition a number of Energy Dispersive Spectrometry (EDS) analysis were performed. The particles marked with squares 1, 2 and 3 are samples of this test.

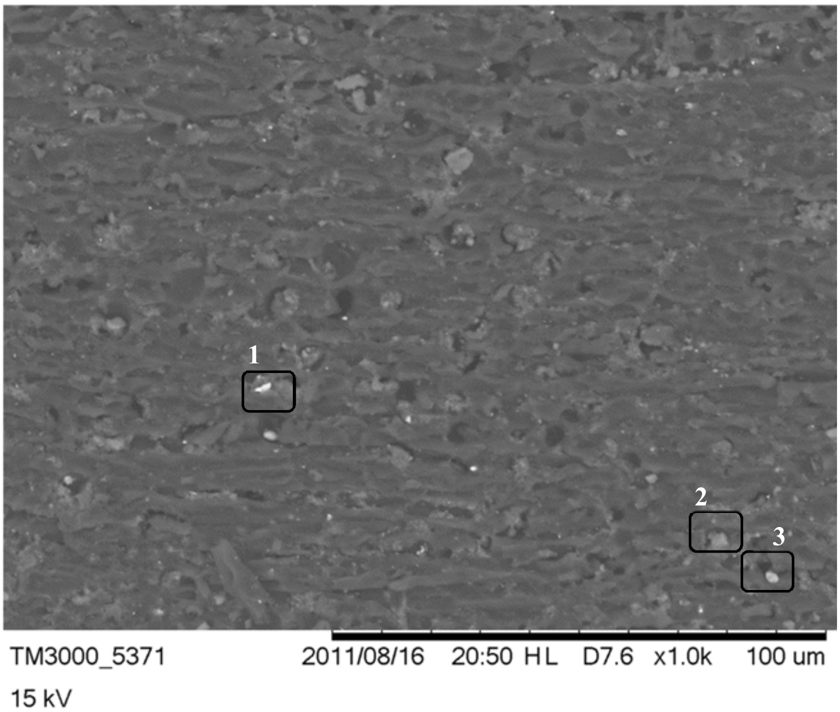
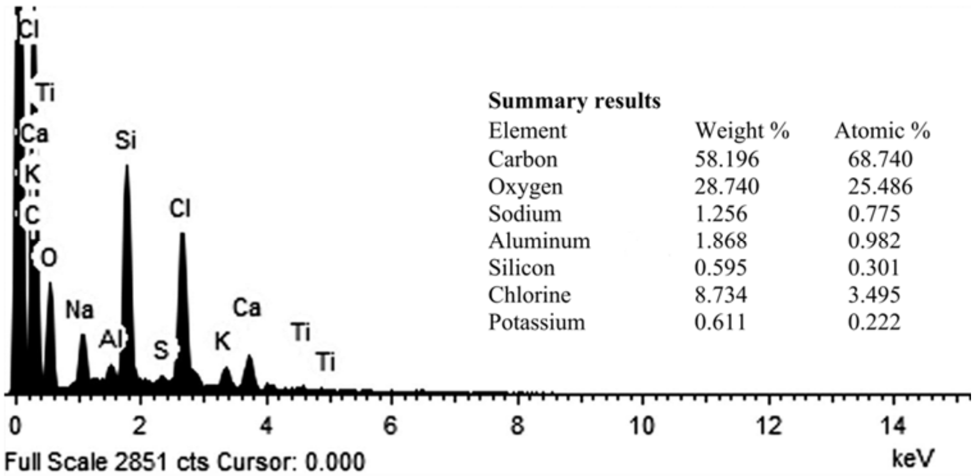


Figure 2. SEM micrograph of thermoplastic polyether polyurethane elastomer. White and light gray particles result from additives

Figure 3 presents the EDS qualitative spectrum and quantitative results from particle 3 shown in Figure 2.



Summary results

Element	Weight %	Atomic %
Carbon	58.196	68.740
Oxygen	28.740	25.486
Sodium	1.256	0.775
Aluminum	1.868	0.982
Silicon	0.595	0.301
Chlorine	8.734	3.495
Potassium	0.611	0.222

Figure 3. EDS results for particle 3 show in Figure 2

EDS chemical composition results for plastic matrix presented basically C, O and Cl. Namely having 74.991 wt % C, 21.179 wt % O and 3.636 wt % Cl. Notice that the main elements present in additive particle of Figure 3 are C, O, Na, Cl and Ca with traces of Ti. Traces of iron, cobalt and tungsten were also present in two EDS spectrum.

The material characterization of the unknown polymer was essential due to its elastohydrodynamic lubrication behavior and surface elastic deformation. Therefore the polymer mechanical properties, i.e. elastic modulus and Poison's ratio, were important to proper inform the software application.

Figure 4, Figure 5 and Figure 6 show the comparison of power losses in the aft stern tube bearing in case of Babbitt and polymer applications as bearing material for chemical tanker, product tanker and Ro-Ro ship respectively.

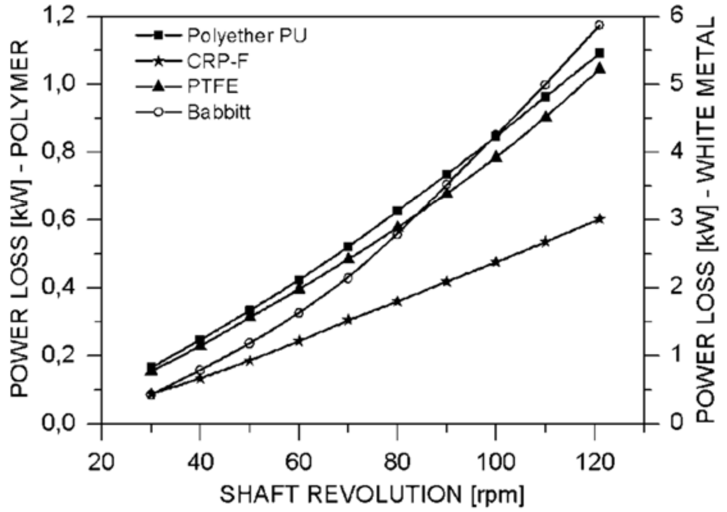
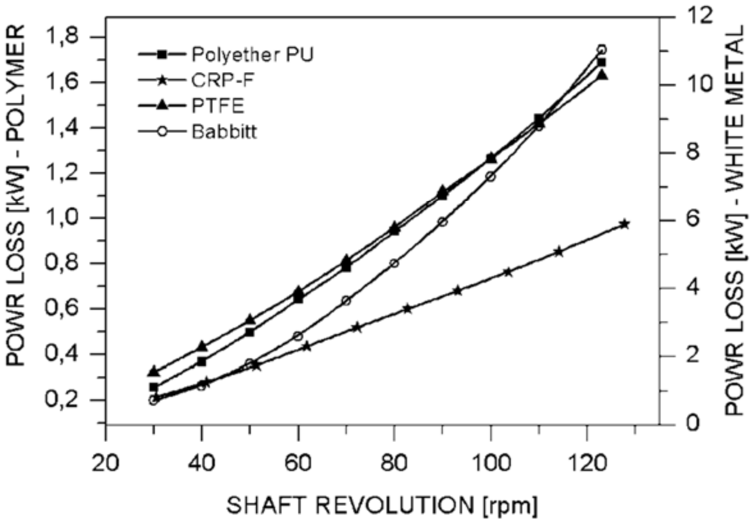


Figure 4. Comparison of chemical tanker power loss of stern tube Babbitt bearing vs various polymer bearings at propeller shaft revolution from 30 to 123 rpm



(b)

Figure 5. Comparison of product tanker power loss of stern tube Babbitt bearing vs various polymer bearings at propeller shaft revolution from 30 to 123 rpm

As shown in Figure 4 and 5 the tankers power loss due to friction of the polymeric bearings is approximately 6.5 (polyether PU) to 12.5 times (CRP-F) smaller than the power loss in the bearing of the white metal at a maximal speed of the propeller shaft of 123 rpm.

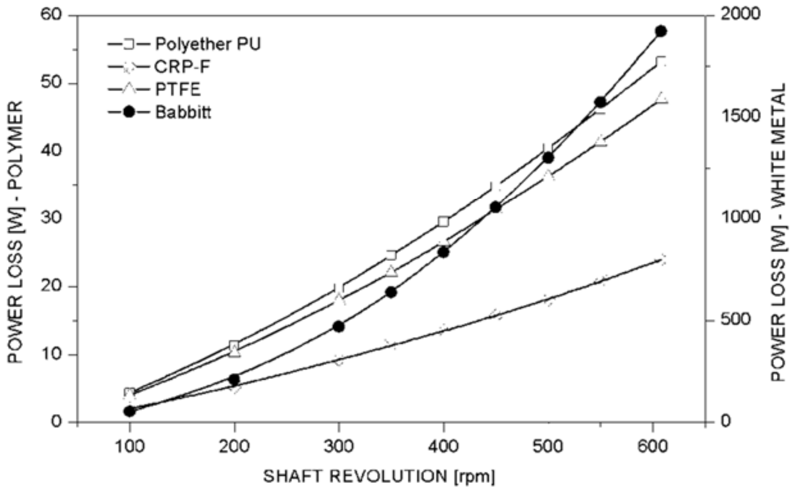


Figure 6. Comparison of Ro-Ro passenger ship power loss of stern tube Babbitt bearing versus various polymer bearings at propeller shaft revolution from 100 to 608 rpm

As presented in Figure 6 the Ro-Ro passenger ship power loss due to friction in the polyether PU bearing is about 36 times less and carbon reinforced composite with phenol-formaldehyde matrix is nearly 84 times less than the power loss in the bearing of the white metal at a maximum speed of the propeller shaft of 608 rpm.

4. Conclusions

The analysis focuses on the value of effective power loss in marine stern tube bearings due to viscous friction in the lubricant film comparing white metal bearings with polymer ones. Therefore reduction of the system power loss is achieved using lubricant with low viscosity such as seawater in case of polymer bearing.

Comparing the power loss of the stern tube polymeric materials and the white metal and taking into consideration the chemical and the product tankers as well the Ro-Ro ship, it is possible to verify that the actual power loss is, at least 6.5 times less for tankers and 36 times less for Ro-Ro ship. This considerable difference in power loss is due to high nominal shaft rpm using stern tube polymer bearings.

Among polymeric bearing materials, it was observed that the carbon reinforced composite with phenol-formaldehyde matrix works more efficiently than the others calculated polymer applications.

Implementation of these models and a materials selection approach can lead even to a solid basis to propose a different design approach to ship designers: polymer bearings instead of white metal bearings. There may be some drawbacks to this solution, such as a need for careful machining of shafts and the bearings, necessity of proper preparation (e.g. filtration) of sea-water, etc. that have not been considered within the scope of this paper. Anyhow, the use of polymer stern tube bearings shows the possibility of significant savings in fuel and oil consumption and also contributes the environment ship requirements and related energy efficiency design index.

Proposal for future research in the application of polymeric materials for stern tube bearings is focused on issues of propulsion shafting alignment and wear of polymer stern tube bearings.

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