Review of Journal Bearing Materials and Current Trends

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Abstract

In the past few years, the need for low-cost, high-performance materials is increasing. Design engineers and researchers are replacing the metals and alloys with advanced materials. Journal bearings are integral parts of machines, engines running to serve the purpose. They play a significant vital role in the performance, efficiency, minimizing the cost of operation, enhancing the durability and reliability of the system. Materials used for these moving elements have undergone tremendous change since the invention of Tin Babbitt. In this paper, a critical review of Journal bearing materials, right from the old-age Babbitt to advanced materials in use till date is presented. Metallurgical aspects and mechanical behavior of successful, widely used bearing materials along with their micro and nanocomposite alternatives are discussed. Tin Babbitt is an ideal material for journal bearing applications. So, it is taken as reference for comparing the quality of other bearing materials.

Keywords: Bearing Materials; Bearing Metal; Babbitt Metal; White Metal; Composite Bearings

1 Introduction

Journal Bearing is a machine element that supports, and radially position a rotating shaft. Bearing’s performance and efficiency affect the successful operation of the systems/mechanisms. So, bearing materials must be carefully chosen, to make these systems run successfully and meet the performance expectations. Rolling contact bearings offer lower friction than sliding contact bearings. However, use of sliding contact bearings is inevitable. They have their specific advantages (Pope 1997) and are high in use. Journal bearings are used in industrial machines, engines, and automobile industry, hydraulic turbines, electric generators, steam and gas turbines, compressors and other machines used in power, oil, gas, and petrochemical industries. Journal bearings are also called as plain bearings, sleeve bearings, and fluid film bearings. Selection of material for bearing

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applications depends on the type of bearing, type of lubrication and environmental conditions (Hamrock et al. 2004). This paper is aimed to review the research trends in sliding contact bearing materials starting with Babbitt, metals and alloys, nonmetals, polymers, and composites. Tensile behavior, hardness, fatigue and tribological properties of these bearing materials were discussed thoroughly and compared.

Journal bearing material should possess a combination of properties from compatibility, conformability, embeddability, fatigue strength, cavitation erosion resistance, and corrosion resistance. No single material satisfies all the requirements of a good bearing material. So, a compromise and mix of above properties is required for successful performance under a particular set of operating conditions (Sturk and Whitney 2013). Rubbing of the shaft and bearing material against each other should not produce localized welds, which leads to scoring or seizure or scuffing. This inherent tendency is called compatibility (Challen and Baranescu 1999). When there is a slight misalignment in the bearing assembly, the bearing material should undergo a small deformation to reduce stress concentrations and maintain oil film thickness. This ability is called conformability. Embeddability is the ability to embed hard particles in the surface of the bearing material and thus reduce any abrasive damage to both shaft and bearing. The ability of any bearing material to resist scoring depends on the above three factors. Compatibility is difficult to quantify, whereas conformability and embeddability vary inversely with hardness.

In addition to the above list of properties, there are some desirable mechanical properties of bearing materials; few are compressive strength, fatigue strength, low coefficient of friction (COF), low coefficient of thermal expansion, high thermal conductivity, good wettability, sufficient hardness, enough elasticity, its availability, and cost. Lubrication of moving parts in journal bearings plays a significant role in the wear and frictional behavior. There are three basic lubrication methods, Full film or hydrodynamic, thin film or boundary lubrication and extreme boundary lubrication. In hydrodynamic bearings, mating surfaces are separated by a thick film of lubricant. In the second method, mating surfaces are separated by a thin film of lubricant. These two methods give long bearing life (Pope 1997). In extreme boundary lubrication, surfaces come to get contact with each other at high load points, results in wear and shorter bearing life.

2 Development of Bearing Materials and Current Trends

Nowadays almost an infinite variety of materials are available often specialized for a particular application. In most cases, the selection is unique and manufacturer's assistance need to be taken (Pope 1997). Bearing materials can be metallic or non-metallic. Metallic bearings are made of white metal(tin and lead based), bronzes(copper based), aluminum based, porous metals, and coated metals (Harnoy 2002; Sturk and Whitney 2013). Non-metallic bearings are made of polymers, ceramics, and composites. Bearings can also be classified based on their geometry, half-round sleeves called as ‘bearings’ and full round sleeves are called as ‘bushes.’

2.1 Metallic bearings

Metals with hardness less than 70 BHN can be used for bearing applications (Glaeser 1992). Aluminum, Copper, Gold, Silver, Indium, Iron, Tin and Lead can be used as bearing materials. Being
soft, these materials have to embed any debris, conform and provide bearing support for rotating the shaft. Tin and lead alloys developed for bearing applications are called Babbitt metals or bearing metals or white metals. These are invented by Issac Babbitt in 1839 (Hellemans and Bunch 1988, and are the most commonly used bearing materials. Use of lead-based bearing materials is decreased due to legislation, health, and environmental concerns. So, Tin based materials are replacing lead bearings in recent years (Potekhin et al., 2009). Tin Babbitt is an alloy of 4-8.5% copper and 5-8.5% antimony, tin(remaining) and lead, iron, arsenic, bismuth, zinc, aluminum, cadmium in very small proportions (ASTM 2014). Tin Babbitt possess excellent embeddability and conformability characteristics, shows a little tendency for adhesion, but their use is extremely limited by their low fatigue strength (Sturk and Whitney 2013). In general, a layer of white metal (≈ 0.4 mm) is cast as a bearing surface on steel, aluminum, bronze and cast iron sleeves (Harnoy 2002) to improve the fatigue strength.

![Fig.1. The microstructure of Tin Babbitt.](Image)

Babbitt alloys are usually produced by casting (Moazami Goudarzi et al. 2009). Babbitt possesses low recrystallization temperature, so they cannot be cold worked. As a result rate of solidification has an effect on microstructure and hardness. The microstructure of Tin Babbitt is shown in fig.1 (above). As seen, it is a multi-phase alloy (Sadykov et al. 2003 & Valeeva et al. 2014) consists of α-phase (solid solution of Sn, Cu, and Sb), β-phase (Sn-Sb compound), η-phase (Cu₂Sn₅ compound), ε-phase (Cu₃Sn compound), γ-phase (Cu₅₁Sn₈ compound) and Cu₂Sb phase.

Hard crystals of β-phase are dispersed in the soft matrix. They increase hardness but not enough to adversely affect frictional properties (Harnoy 2002). Sadykov et al. 2003 investigated the effect of Babbitt structure on its mechanical behavior and found that the size of β-phase has a strong influence on tensile behavior and hardness. Rapidly cooled Babbitt exhibits a fine Cu-Sn compound and has high fatigue strength than slowly cooled innings. Reduction in size (Sadykov et al. 2003) and dispersing (Moazami Goudarzi et al. 2009) these hard β phase particles is the most effective strengthening mechanism of Babbitt alloys it also improves its wear resistance (Valeeva et al. 2014).
2014). Table-1 shows the comparison of metallic materials for bearing applications. It clearly confirms that the white metal possesses most of the essential properties to be a good bearing material.

Moazami Goudarzi et al. 2009 studied the effect of solidification rate and heating on microstructure and hardness of tin based white metal. Their results have shown that rapid cooling inhibits the formation and growth of SbSn cuboids and increase hardness. For marine and sea water applications, 68.5%Sn-30%Zn-1.5%Cu alloy with high corrosion resistance to salt water and anodic to steel in sea water is used in stem tube propeller bearings (Glaeser 1992). White metal is considered as best bearing material, and other materials quality is determined by comparing with it (Harnoy 2002).

Table 1 Relative comparison of bearing materials (Sturk and Whitney 2013; Glaeser 1992; Harnoy 2002 and Hamrock et al. 2004)

<table>
<thead>
<tr>
<th>Property</th>
<th>Babbitt Metal</th>
<th>Al - based</th>
<th>Cu - based</th>
<th>Polymer based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatibility</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Conformability</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Embeddability</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Fatigue Strength</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Corrosion Resistance</td>
<td>Varies</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>Varies</td>
</tr>
<tr>
<td>Density</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

* All the numbers shown are arbitrary scale 1-High, 2-Moderate, 3-Low.

To overcome the fatigue limitation of the Babbitt, researchers have developed copper-lead and lead-bronze alloys for bearing applications (Challen and Baranescu 1999). Pb 22-26%, Sn 1-2%, and remaining Cu are the most commonly used alloy compositions. Sn completely dissolves in Cu and forms bronze matrix with Pb islands. Significant efforts are underway to eliminate lead in journal bearings (Sturk and Whitney 2013). ISO Cu-10%Pb-10%Sn is most common alloy used for high loads; it is hard and strong. These are widely used in automotive and aircraft industries (Harnoy 2002). Its compatibility and conformability are poor. In the past decade, most of the developments have been happening in the area of high loaded applications. Lead is also replaced with nickel at the expense of sliding properties. However, this alloy features higher strength and corrosion resistance compared to ISO Cu-10%Pb-10%Sn. 3% Bi is added to improve the sliding properties. This alloy is in use currently in many high-performance engines.

Leaded bronze alloys with tin 3-4% are used exclusively for heavily loaded bearings. Its limitations are, lacking adequate sliding properties and corrosion of lead phase. Usually, these are used as substrates for coating soft bearing material thus properly support the shaft; these are used in the form of thin layers on the metal backups as shown in fig.2 (below). These layered bearings wear out periodically and are replaced with new ones. These are called ‘bimetal’ bearings. If bimetals are coated with another layer of soft material, then they are called as ‘trimetal’ bearings.
Lead bronze alloys are susceptible to corrosion. Tin Babbitt lacks fatigue strength. Aluminum-Tin alloys were developed to overcome these two problems (Challen and Baranescu 1999). Al-6%Sn is most common alloy in this category. Cu and Ni are added to increase strength. Compatibility is better than bronze alloys. Its composition and structure can be altered by heat treatment to operate in high-temperature conditions. Al-40%Sn alloy was developed as a replacement for Babbitt, but it cannot be cast like Babbitt. So, thin shell bearings were adopted to overcome it. This alternative retains its fatigue strength where Babbitt fails to work.

Two Al-Si alloys were developed to meet the high strength applications. One is Al-4%Si-1%Cd and other with Al-11%Si-1%Cu. Both are equally strong as Lead-bronze alloys. However, they find advantage when it comes to corrosion resistance. Cd in the alloy offers soft phase to improve scuff resistance. These bearings contain microporous holes for impregnating oil of solid lubricant and distributing on bearing surface (Harnoy 2002). These are used in applications in which boundary lubrication is adequate and to reduce maintenance cost.

Thin overlays of Babbitt about 10-30 µm are coated on copper alloy made substrates or bimetals by using the electro-deposition technique. Then these thin layers are strengthened by substrates characteristics. The durability of coatings by electro-deposition is poor (Sturk and Whitney 2013). So, much of research last few years is aimed to increase the durability of these coatings. Now a day a thin layer (1-2 µm) of Tin or Lead is used as corrosion resistant coating. Sputtering can be used to overcome this limitation but loses embeddability. It forms a strong barrier, which protects the lining from corrosion.

2.2 Non-Metallic Bearings

Non-metallic bearings are suitable for extremely light duty applications (Sturk and Whitney 2013). They have poor thermal conductivity, low intrinsic strength. These are mainly used with steel backups or injection molded thermoplastic backups. These are used in applications where self-lubrication, high-temperature strength, and chemical resistances are required to maintain (Harnoy 2002). Ex: food handling equipment, space applications.

Teflon, nylon, phenolic, etc. are used in the manufacture of polymer bearings. These are less in cost compared to metal bearings. Solid lubricants can be blended in their manufacture to improve their lubrication properties. Recent advances in manufacturing engineering polymers and understanding their properties has increased their use in the recent past (Harnoy 2002). Polymer based composites were developed which combine high wear resistance, low friction and wear rates and
good thermal conductivity. There is flexibility, like blending solid lubricants, mixing various polymers in the melt phase, can be combined in layers, interwoven, impregnate into porous materials, to exactly suit the application. When compared to metals, Polymers are less rigid. So, they have conformability, good vibration absorption, good embeddability, high corrosion resistance, low wear rate. However, they have a high coefficient of thermal expansion about 5-10 times more than metals, have low melting points that limit their use to light load applications. They adhere to materials like aluminum, so their use is also limited by shaft material. Polyamideimide (polymer based) coatings are widely used on aluminum-based linings with the addition of graphite or MoS₂ as solid lubricants. These coatings are alternatives to the above electro-deposited and sputtered layers. These coatings poorly conduct heat. So, heat transfer from the bearing is less compared to metal coatings that limit the use of these bearings.

At very high temperatures, all the above discussed materials fail due to drop in their strength and hardness. Ceramic bearings are developed for serving in such applications. These are chemically inert, light in weight, very hard, needless lubrication, and retain most of these properties at very high temperatures. They are brittle, not wear resistant and expensive to manufacture. Ceramics like Silicon nitride manufactured by the hot isostatically pressed sintering process are already applied in critical applications (Harnoy 2002).

Engineered Ceramics were tried to use as bearings in piston and sleeves aiming improved efficiency. These attempts were not successful because they need lubrication. Liquid lubricant to serve in conjunction with ceramics is not available, so attempts were made with solid lubricants. Zirconia, SiC, SiN, Al₂O₃ was used as bearing materials (Skinner 1999 and Shi et al. 2003). Ceramics are the most suitable materials for artificial hip and knee joints due to their very low wear rate (Bal et al. 2007 and Skinner 1999)

Composite bearings are in existence right from the evolution of composite materials. Metal/polymer matrix composites are suitable for using as bearing materials (Lancaster 1979). In general matrix is reinforced with solid lubricants like carbon graphite (Sharma et al. 1998) and molybdenum disulfide, to improve the lubrication properties. Wear performance of material depends on the type of the reinforcement and its volume fraction (Giltrow et al. 1971). Fiber reinforced plastics with solid lubricants blended to improve bearing strength and wear resistance (Harnoy 2002). A variety of composites with carbon, E-glass, stainless steel as fiber reinforcement for epoxy resin, polyester resin, and PTFE as matrix materials were fabricated and tested (Tsukizoe and Ohmae 1983).

3 Mechanical Behavior of Bearing Materials

Mechanical properties of metals and alloys depend on their alloying elements, % of impurities present, microstructure, and their processing technique. According to the study of Sadykov et al. 2003, α-phase in Tin Babbitt looks similar in different states of the alloy, tensile behavior strongly depends on the β-phase size. η-phase volume fraction is small, so, it got less effect on mechanical properties. Authors achieved different grain sizes of β-phase, 250 - 50µm by controlling the rate of solidification in casting. For cast specimens, there was no noticeable dependence of elongation on strain rate. As the grain size decreased from 250-50µm, they observed an increase in ductility, flow stress, yield strength, ultimate tensile strength, and 5-12% elongation. Elongation of rolled Babbitt
has 26% more elongation and 50-60% decrease in flow stress compared to cast Babbitt. Rolled Babbitt yields 20-30% more elongation as strain rate varied from $10^{-2}$ to $10^{-4}$. Normally, cracks were initiated at the boundary of α and β phases.

Eshaghi et al. 2011 investigated the effect of T6 heat treatment on wear behavior of hypo eutectic Al-Si Alloys with iron contents of 0.15, 0.7, and 1.2 wt% in a dry condition at various loads. They observed 0.7% wt. Iron is showing high wear resistance. T6 heat treated iron exhibited high wear resistance that is attributed to the decrease in length and volume fraction of hard and brittle β-Al5FeSi iron-rich intermetallic.

There is no universal experimental examination of the friction or the wear (Kadnář et al. 2011). There are varieties of experiments to determine the tribological behavior, aimed to examine material under specific conditions (G. W. Stachowiak and Batchelor 2005, G. Stachowiak and Batchelor 2004, Mang and Dresel 2007 and Bayer 1995) or partial tribological task. Tribological results need to be interpreted in right context. i.e., not just as a bearing material, but the material has to be viewed as part of the tribological system. Materials can behave differently, in different conditions of friction or wear. Kadnář et al. 2011 fabricated experimental setup, ‘Tribotestor M’06’ which is aimed to determine the parameters and features of the journal bearing. They recommended preferring rotational frequency over circumferential speed, conducted tests on sintered bronze in dry test conditions. They observed an increase in frictional factor from 0.07 to 0.08, as rotational frequency increased from 500 to 4000 rpm. Feyzullahoğlu et al. 2008 investigated the tribological behavior of brass, WM-2 and WM-5 in heavy industrial service conditions under oil lubricated conditions. Tests were conducted on Tecquipment HFN type 5 journal bearing test equipment. Wear and friction characteristics studied with respect to sliding distance, sliding speed and bearing load and hardness of the material. It was observed that brass performance is better that WM-2 and WM-5 due to its hardness. Wear in brass is less that other two tin alloys.

Ishihara et al. 2010 studied the effect of amount of antimony varying from 5 to 23 wt.% on sliding wear resistance of different white metals under lubricated condition. They observed that 5-20 wt.% of antimony was not affecting the wear resistance. However, beyond 20 wt.% wear rate is increasing strongly. Investigators come up with various methods for producing bearings with better wear properties than cast Babbitt. Bora et al. 2010 studied the tribological behavior of tin based bearings WM5 (60.3Sn-2.6Cu-20.2Sb-16.6Pb) and WM2 (89.2Sn-3Cu-7.2Sb-0.4Pb) using scratch and Martens hardness techniques. Results were correlated in terms of scratch hardness and COF. They observed that the both materials give higher COF at higher normal loads and scratch velocities.

Valeeeva et al. 2014 produced Babbitt layer by liquid forging, with the homogeneous structure of 40-50 μm crystals and cubic β-phase and disintegrated needles of the γ-phase and achieved low wear rate over the entire distance of sliding. Azizpour 2011 fabricated bearings by casting and thermal spraying and observed that thermal spraying Babbitt has better performance and tribological behavior even after 7000 hours of service. The bonding strength of thermal sprayed Babbitt is higher than melting process and eliminated hot spots, and lowered percentage of porosity.
The hardness of metal bearings depends on the chemical composition and phases in the alloy. The hardness of white metal alloy (Challen and Baranescu 1999) is 27-29 HV, for Aluminum alloys is 23 – 62 HV. These include Al-Sn, Al-Sn-Cu, Al-Sn-Cu-Ni alloy systems. For Bronzes, it varies from 46 – 140 HV, consisting of Cu-Pb, Cu-Pb-Sn alloys. The increase in hardness increases the strength at the cost of other essential bearing material properties.

Fatigue occurs due to cyclic nature of the loads applied on bearings (Challen and Baranescu 1999). Fatigue strength of Tin Babbitt is about 50 MPa, Aluminum alloys are about 120 MPa, Copper alloys range from 130 – 170 MPa. Recommended fatigue limit for bearing materials for low and medium speed engines are 12-14 MPa for Tin Babbitt, 20-35 MPa for Aluminum and 38 MPa for Copper based bearings. As the temperature of bearing increases from 20 to 160 °C, the fatigue strength of tin Babbitt decreases to half (Pratt 1973).

Fatigue strength of coated metals depends on two factors; one strength of overlay and thickness of the coating (Sturk and Whitney 2013). As shown in fig.3, if thickness decreases coatings fatigue strength increases. If this thickness is less than optimum value of 0.010 – 0.020 mm then the layer is susceptible to wear out. At the beginning of the 20th century, bearings were thick (>5 mm). However, engines and machines have become small with an increase in power and strong. This has led the change in thickness of bearings and now 50-120 µm serving the heavy duty applications (Harnoy 2002). 800 µm is common thickness for automotive applications.

**Fig. 3.** Effect of lining thickness on fatigue strength Harnoy 2002, Glaeser 1992.

B. S. Ünlü 2011 and B. Ünlü 2009 conducted experiments on white metal (SnPbCuSb), pure Sn, pure Pb, pure Cu bearings against SAE 1050 steel shaft to determine tribological and mechanical properties. Tests were conducted on the radial journal bearing test rig and observed high COF and bearing temperature in pure Cu bearings. Wear resistance increased by 4-5 times, adhesive wear tracks decreased due to alloying. Wu et al. 2011 studied wear and frictional properties of Lead Babbitt under sea water lubrication. It was observed that the COF decreased with increase in sliding speed and increase in load to 30N and stayed steady at high loads. Wear rate slightly
increased with load and decreased with sliding speed. Formation of new phase namely lead carbonate was observed and attributing to the low COF and wear.

In Composites, Al based Particulate Metal Matrix Composites (MMCs) are more suitable for tribological applications due to their superior wear resistance and high specific strength. Several researchers have investigated Al MMCs with a variety of reinforcements. Ceramic particles like Al₂O₃, SiC, TiC, and graphite are very commonly used reinforcements for Al MMCs. Wilson and Alpas 1996 investigated the dry sliding behavior of A356/SiC, A356/SiC+Grahlte, A6061/Al₂O₃, and observed that ceramic particles were minimizing scoring. A356/SiC+Grahlte exhibited better resistance to severe wear compared to other two types. Radhika et al. 2014, studied the influence of applied load, sliding velocity and temperatures on the wear rate of AlSi10Mg alloy reinforced with graphite and Al₂O₃ using Taguchi’s L9 orthogonal array. They found that load had the highest contribution to wear rate followed by temperature and sliding velocity. Sharma et al. 1998, investigated the tribological behavior of graphite reinforced zinc-aluminum composites (ZA-27) in lubricated semi-dry and dry conditions. They observed that composite bearings were able to run at lower friction than un-reinforced ZA-27, under all three conditions. The un-reinforced ZA-27 seized at much lower loads experienced high coefficient of friction compared to composites under semi-dry and dry tests.

Anandkumar et al. 2011, investigated composite coatings containing Al-12Si reinforced with TiB₂ prepared by laser cladding, and studied these coatings against AISI440C tool steel in dry conditions. They observed a large proportion of oxides of elements of both bodies in the interaction. It was due to oxidation of materials at high flash temperatures generated during sliding, followed by cracking and formation of debris, which protects the composite coating from further wear.

Metal Matrix Nano Composites (MMNCs) were also fabricated with Al, Mg, Cu, and other metals and alloys as matrix materials. Ceramic compounds like SiC, Al₂O₃, and Carbon nanotubes (CNT) were widely used as reinforcements (Casati & Vedani, 2014). Deng et al., 2007 reinforced 2024Al with multi-walled carbon nanotubes (MWCNTs) and studied their damping behavior under various frequencies and temperatures. Authors observed a significant effect of frequency on the damping capacity of nanocomposite above 230°C and improvement in damping capacity even at temperature 400°C. Shehata et al., 2009 produced Cu-Al₂O₃ nanocomposites by mechanochemical methods and evidenced the improvement in properties in terms of density, microhardness, and abrasive wear resistance. Authors observed an increase in abrasive wear resistance with increase in Vol. % of Al₂O₃ nanoparticles and decreased with increase in hardness.

4 Conclusions

Bearing material selection is a significant step in the design of the equipment. It affects the overall efficiency of the equipment. Designers need to choose appropriate materials for their bearing requirement. Varieties of bearing materials are available. Babbitt is the first choice of engineers since it is an ideal one where fatigue strength is not a concern. They are suitable for supporting low speed, steady shafts with small loads. Even though, many new bearing materials have come up in recent past; research is still going on 'Babbitt' material to understand its tribological behavior in various operating conditions and to improve its fatigue strength.
Aluminum based, copper based bearing materials exhibit good fatigue strength compared to Babbitt but lacks other essential properties. These properties can be enhanced by overlaying Babbitt on aluminum or lead bronze backup sleeves. These are suitable for supporting moderate to higher speeds with medium to high loads. These can perform well at high temperatures.

Ceramics, because of their superior properties they are suitable for bearings running at very high temperature. Where lubrication cannot be provided, many metal bearings were replaced with polymer bearings. These are suitable for low to the high load supporting applications. Both and micro and nanocomposites can be made to suit exactly the requirement. So, a numerous number of composites are available and under development. These composites can be operated with minimum or without lubrication. Present research in polymer-based composite bearings is aimed to develop materials that offer high wear resistance and low COF, alternatives for heavy metal bearings, perform better in minimal or without lubrication.

References


