Dodge Application Engineering
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Dodge® Mounted Hydrodynamic Bearings: Comparison of Babbitt and PTFE-Based Polymers

Abstract

Hydrodynamic bearings operate by generating a pressurized oil film that fully supports a rotating shaft. There is no shaft-to-bearing contact during normal operation, with minor wear occurring primarily at startup and shutdown when the oil film breaks down. Hydrodynamic bearings are generally used in applications where a primary concern is protecting the large and expensive shaft, so proper bearing material selection is critical. This document compares the properties of Babbitt/white metal and PTFE-based polymers as bearing materials in hydrodynamic bearing applications. Although research continues new materials, the industry has found that Babbitt is currently unsurpassed among materials available today for its ability to protect the shaft during hydrodynamic film breakdown or other lubrication regimes.

Introduction

Hydrodynamic bearings are a special type of fluid-lubricated plain bearings that operate by creating a fluid film that completely separates the shaft and bearing during normal operation. Fundamentally, there are only three parts to a hydrodynamic bearing: the rotating shaft, the bearing itself, and the fluid lubricant, usually oil. Hydrodynamic bearings are found in hundreds of different applications and are known for long life, high load carrying capacity, and excellent damping capabilities.

In ideal conditions, a hydrodynamic bearing could be made out of any material capable of withstanding the temperatures and pressures exerted by the system. During normal operation, the shaft and bearing are completely separated by an oil film. This means that theoretically, the shaft and bearing should never wear as long as the oil film is present. However, these bearings often operate in non-ideal conditions due to contamination, shaft misalignment, and rotor unbalance. In addition, these systems, which can be fans, motors, or other machines, are periodically stopped and restarted. Oil film thickness is a function of surface speed, so most bearing wear occurs during startup and shutdown. However, the oil film can break down and cause shaft wear for other reasons as well.

Large shafts and the downtime required to repair or replace them are very expensive, therefore bearings need to be able to operate in the presence of minor contamination and shaft misalignment without causing damage to the shaft. It is important to note that the shaft and rotor can be very heavy and have large rotating momentum, meaning that they can require a long period of time to come to a complete stop.

Fundamentals of Hydrodynamic Bearings

In order to select appropriate bearing materials, it is important to understand the fundamental operation of a hydrodynamic bearing. To allow room for the fluid film to develop, hydrodynamic bearings are designed so that there is radial clearance between the shaft and the bearing. Depending on the application, the amount of clearance can vary. When the shaft is not turning, it sits in the bearing and is separated by an extremely thin layer of oil. When the system starts, the lubricity of the oil molecules is the only lubrication between the shaft and bearing. This means that the asperities, the small "peaks and valleys" in the shaft and bearing surfaces, come into direct contact. This is known as "boundary lubrication," and is where friction is greatest as well as where the majority of the bearing and shaft wear occurs. As the shaft speed increases, oil is forced in between the two surfaces and a film develops that separates the two entirely. This is known as "full film lubrication" or "hydrodynamic lubrication." **Figure 1** shows (a) boundary lubrication, where the asperities come into contact and (b) hydrodynamic lubrication, where the two surfaces are fully separated by the oil film [1].

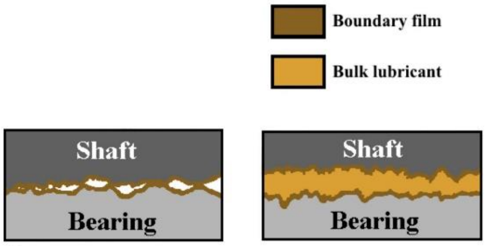

Figure 1. Boundary Lubrication (a) and Hydrodynamic Lubrication (b).

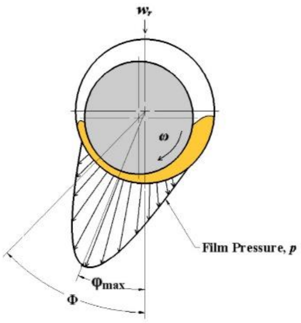

Figure 2. Pressure profile of a hydrodynamic bearing during normal operation

Figure 2 shows the pressure profile of a hydrodynamic bearing during normal operation. During hydrodynamic lubrication, the shaft does not sit completely in the direction of the load, denoted by w_r. Instead, the pressures generated by the fluid shear force create a converging oil wedge that causes the shaft to sit slightly to the side, as shown. For this reason, hydrodynamic bearings can be considered self-pressurized. The angle between the load direction and the minimum film thickness, denoted as Φ, is known as the "attitude angle." The fluid pressure is also not uniform. It is highest at the maximum pressure angle, denoted as ϕmax. Both the minimum film thickness and ϕmax can be calculated. As the bearing operates, even slight rotor unbalance causes the shaft to orbit, or "bounce" on the film, creating cyclical variation in film pressure.

Bearing Material Selection Criteria

In *Bearings and Lubrication: A Mechanical Designers' Workbook*, Shigley identifies the following 9 characteristics of bearing materials to determine suitability in hydrodynamic bearing applications [2].

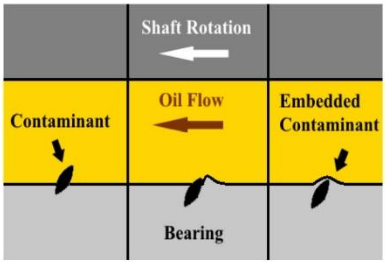

Figure 3. Bearing

Embeddability is the ability of the bearing material to embed small contaminants and prevent them from damaging the shaft. When contaminants come in contact with an embeddable bearing material, the fluid pressure forces them into the material, as shown in **Figure 3**. At the same time, the shear forces in the fluid cause the bearing material to "cold flow" and cover the contaminants. An embeddable material can embed a small number of contaminants without being compromised. This protects the shaft not only during normal operation, but also during boundary lubrication.

Figure 4. Edge Loading due to misalignment

Conformability is the ability of a material to "wear in" during the case of misalignment or manufacturing imperfections [2]. When there is misalignment between the shaft and bearing, there will be edge loading on the ends of the bearing, as shown in **Figure 4**. A conformable bearing will quickly wear at the edges, allowing the pressure to be distributed more evenly, whereas a non-conformable bearing will be more likely to fail and damage the shaft at these locations.

Coefficient of Thermal Expansion – Thermal expansion refers to the increase in size of a material in response to an increase in temperature. As the bearing temperature increases from the ambient temperature to the steady state operating temperature, the bearing should expand radially at a rate similar to the shaft to prevent excessive changes in clearance, which affects bearing performance and vibration. In hydrodynamic bearing applications, the shafts are usually made of a steel alloy and ground to their final dimensions. Therefore, the coefficient of thermal expansion for the bearing materials considered should be comparable to that of steel.

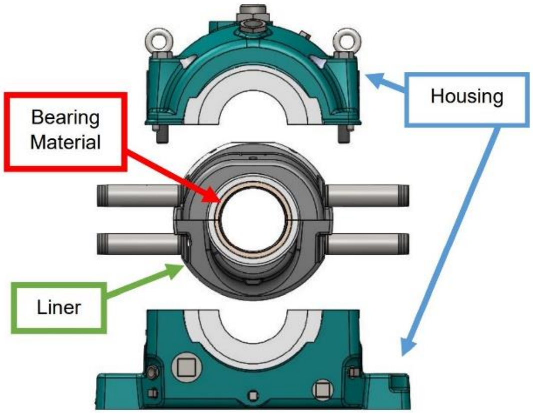

Figure 5. Mounted Hydrodynamic Bearing

Thermal Conductivity refers to a material's ability to transfer heat. The bearing material should dissipate heat generated by the fluid shearing and friction. A material with high thermal conductivity will allow heat to dissipate through the bearing material, whereas a material with low thermal conductivity will act as an insulator, allowing the heat to build up. This decreases the minimum film thickness and can cause the bearing to wear.

Compressive Strength – The material should not deform excessively under the loads caused by the shaft and fluid film pressure. Hydrodynamic bearing characteristics are in part determined by the radial clearance, and excessive deformation can affect bearing performance. Usually, very high strength materials do not have the embeddability and conformability characteristics that are required in hydrodynamic bearings. The balance is often achieved by backing a thin layer of the bearing material with a liner made from a much stronger material supporting the bearing surface, such as cast iron or steel, as shown in **Figure 5**.

Fatigue Strength – The material should not fail due to cyclical loading. In large bearings, fatigue is not limited to startup and shutdown. It may also result from the orbiting, or "bouncing" of the shaft during normal operation due to rotor unbalance.

Wear Rate – The bearing material should not wear excessively, especially during boundary lubrication. However, it should be softer than the shaft material. As with compressive strength, a bearing material with too much wear resistance may not be ideal. In the event of a lubrication failure or excessive vibration, the bearing should protect the shaft from damage.

Compatibility – Material compatibility refers to the resistance of a bearing and shaft combination to seizure, scoring, or galling due to the formation of micro-welds during boundary lubrication. In the case of steel shafts, the only bearing materials that would pose a compatibility risk are ferrous metals.

Corrosion Resistance – There are some applications where the oil can be exposed to contaminants that can corrode the bearing material, affecting its embeddability, conformability, and wear rate. Heavily contamination can affect the performance of a lubricant and should be avoided, regardless of the bearing material. However, a suitable hydrodynamic bearing material should have at least a mild level of corrosion resistance.

Babbit/White Metal Bearings

Babbitt, also known as white metal, refers to a group of tin- or lead-based alloys first invented by Sir Isaac Babbitt in 1839. Babbitt alloys have been the standard hydrodynamic bearing material for over 100 years due to their ability to successfully meet the above characteristics for proper bearing material selection.

On most hydrodynamic bearings, the Babbitt is directly cast in a thin layer onto bearing liners made of cast iron, steel, bronze, or other hard metal, creating a metallic bond. Although the Babbitt has lower compressive strength than cast iron or steel, the liner material provides sufficient structural support. Babbitt also has high thermal conductivity, allowing it to quickly transfer heat from the bearing surface to the liner. The coefficient of thermal expansion for Babbitt alloys is very similar to that of carbon steel, ensuring that the clearance between the shaft and bearing remains consistent in hot and cold conditions. Babbitt alloys are soft, providing very high levels of embeddability and conformability. On the bearing shown in **Figure 6**, the shaft was ground inconsistently, resulting in chatters on the shaft. Because of its high level of conformability, the bearing “wore in” at the high spots on the shaft, distributing the shaft load and preventing the shaft from wearing. In the event of a loss of lubrication, Babbitt bearings will soften due to increased temperature and “wipe”, temporarily attaching to the shaft and protecting it from damage while the machine comes to a stop.

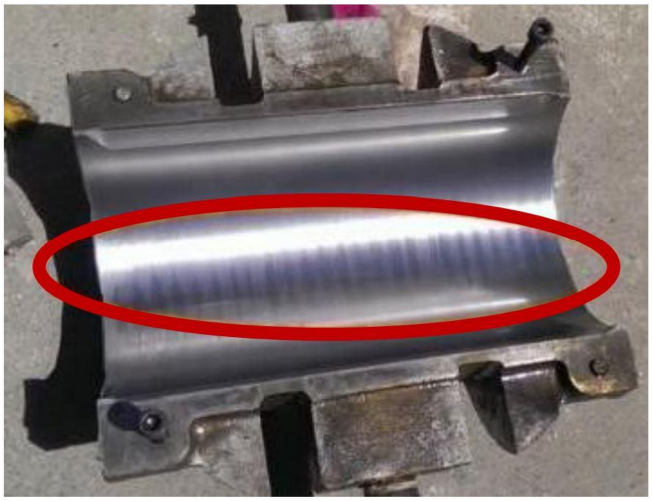

Figure 6. Babbitt-lined bearing conformed to imperfections on the shaft.

A disadvantage of Babbitt as a bearing material is the cost associated with manufacturing the bearings. Babbitt is a relatively inexpensive material, but the process of casting it onto the liner can be labor intensive. Babbitt also has a relatively low upper temperature limit, at least when compared to other materials. Although its melting point is over 500°F, its temperature limit for normal operation is less than 250°F. However, the properties of most industrial lubricants available limit the normal operating temperature to around 200°F.

PTFE-Based Bearings

In recent years there has been increased interest in the use of polymers as an alternative to metallic materials in hydrodynamic bearings. There are hundreds of different polymers that are used in bearing applications including variations of nylon, polyoxymethylene (POM, also known as "acetal"), polyether ether ketone (PEEK), and polytetrafluoroethylene (PTFE). Each of these materials are suitable for a wide variety of applications and have varying degrees of load carrying capacity, surface speed capacity, resistance to harsh chemicals, acceptable temperature ranges, and compatible materials. In large bearings, PTFE and PTFE-based polymers appear to have the best combination of traits for applications as hydrodynamic bearings and are popular in thrust bearing applications.

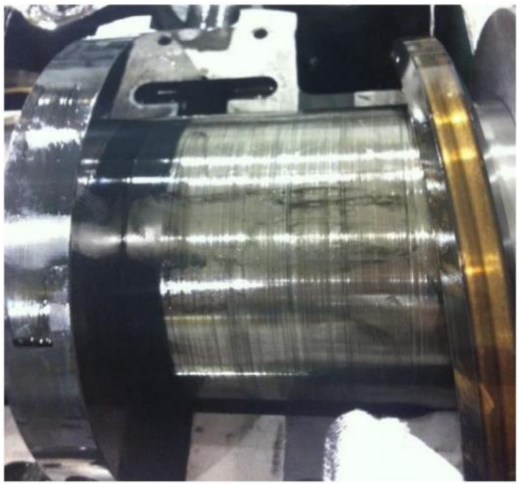

Figure 7. Scored shaft and discolored oil after test of PTFE-based bearing.

The most desirable property of PTFE in hydrodynamic bearing applications is that it has a very high maximum operating temperature. Many PTFE-based polymers are advertised as being able to withstand temperatures in excess of 400°F, although very few oils available today can operate in this condition. It is also important to note that operating at temperatures above 200°F presents a safety hazard. PTFE also has a very low coefficient of friction when paired with steel, reducing the startup torque required [3]. However, once hydrodynamic lubrication is reached the coefficient of friction is of minimal importance because there is no shaft-to-bearing contact. Another benefit of PTFE in hydrodynamic bearings is that the manufacturing cost is significantly lower than Babbitt. Instead of requiring casting at high temperatures, PTFE can be bonded directly to the liner. Several PTFE-based polymers are also advertised as having high embeddability, although available technical literature on the subject is limited.

Drawbacks to PTFE-based materials include their thermal conductivity and coefficient of thermal expansion. PTFE has low thermal conductivity, causing it to act as an insulator and preventing heat from flowing from the bearing surface into the liner. Even though the PTFE has a high maximum operating temperature, a relatively minor increase in oil temperature will reduce the oil viscosity and film thickness and a major increase can drastically reduce bearing life. If the layer of PTFE is thick enough, the high coefficient of thermal expansion can cause the clearance between the shaft and bearing to change excessively, which can affect bearing performance and can even cause rapid failure.

Recently, a PTFE-based polymer was tested in a hydrodynamic bearing application. The shaft was ground and the test was conducted in a controlled environment with an oil circulation system. The bearing was subjected to a constant load with minimal misalignment.

Initially, the material seemed very promising. However, after approximately 1,000 hours the bearing material failed and severely scored the shaft, as shown in **Figure 7**. The oil was also very discolored, leaving black residue on the thrust collar and oil rings. The surface finish of the polymer, which was very smooth at installation, was found to be very rough on both liner halves, as shown in **Figure 8**. It appears that the PTFE-based polymer did not properly embed the contaminants, which caused accelerated wear of the material and damage to the shaft.

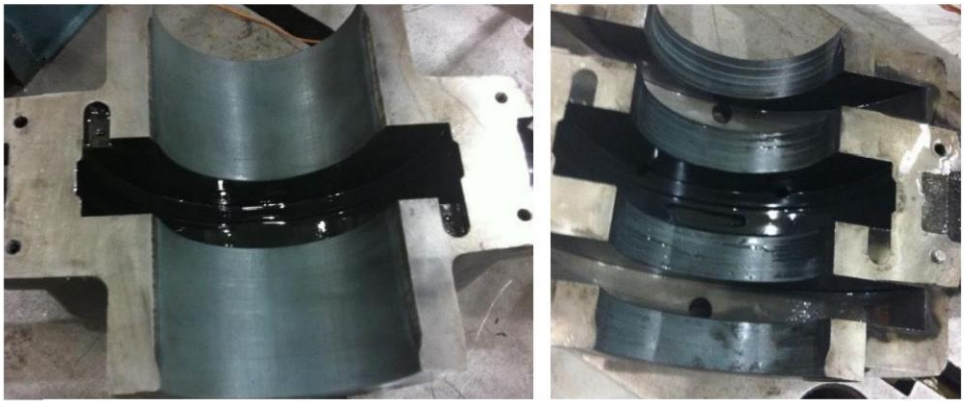

Figure 8. PTFE-based lower half (left) and upper half (fight) after

approximately 1000 hours of testing

Conclusion

Based on decades of industry experience and the data available, Babbitt is the most suitable bearing material for hydrodynamic bearings at this time. Its level of embeddability and conformability are not matched by any material that the industry has encountered. Testing of PTFE-based polymers will continue, but existing test data raises serious concerns regarding their suitability as hydrodynamic bearing materials. A detailed comparison of Babbitt and PTFE is shown in Table 1.

Characteristic	Babbitt	PTFE
Embeddability	Very High	Low
Conformability	Very High	Low
Coefficient of Thermal Expansion	Similar to steel	Significantly higher than steel
Thermal Conductivity	High	Very Low
Compressive Strength	Moderate	Low
Fatigue Strength	Moderate	Low [5]
Wear Rate	High	Moderate
Compatibility (with steel)	Very High	Very High

Unlike the test environment, many bearing applications experience much higher degrees of rotor unbalance, cyclical loads, and misalignment, and some do not have oil filtration systems and are in dirty environments that experience much higher levels of contamination. Repairing or replacing a shaft, and the downtime required to do so will always be more expensive than replacing a bearing. Industry has found that the additional cost of manufacturing Babbitt bearings is worth the expense because of its shaft-saving benefits and proven history of success in industrial applications.

References

[1] Hamrock, B., Schmid, S., and Jacobson, B., 2004, Fundamentals of Fluid Film Lubrication. McGraw-Hill, New York, NY.

[2] Shigley, J. and Mischke, C., 1990, Bearings and Lubrication: A Mechanical Designers' Workbook. McGraw-Hill, New York, NY.

[3] Golchin, A. 2015. "Polymeric Materials for Bearing Applications: Tribological Studies in Lubricated Conditions." Ph.D. thesis, Lulea University of Technology.

[4] MatWeb, LLC, 2017, from http://www.matweb.com

[5] Budinski, K. and Budinski, M., 2009, Engineering Materials, Properties and Selection, 9th Edition. Pearson.