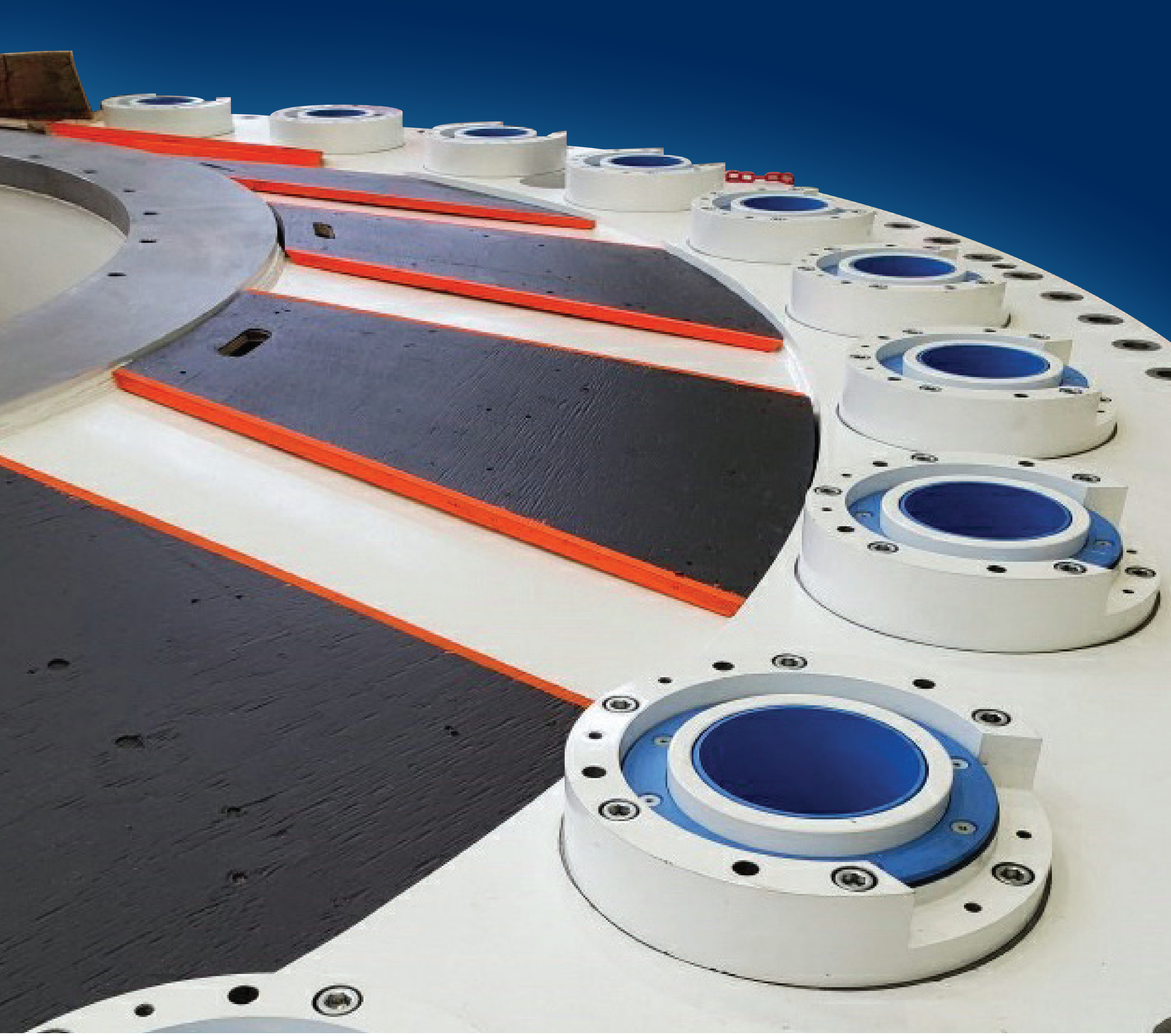

Summary of Technical Testing on Self-Lubricating Bearings Used in Hydro-Turbine Wicket Gate Applications

From Universities, Research Centres, and OEMs

A White Paper Published by Thordon Bearings Inc.

Tribology & Terminology

Tribology is the study of friction, wear, and lubrication that occurs when surfaces interact and move against each other. Understanding tribology helps engineers and designers to reduce resistance between moving components, improve the reliability and efficiency of mechanical equipment.

Some of the most important terminology in the field of tribology is presented, to aid the reader in understanding the information presented.

Tribology:

The study of friction, wear, and lubrication that occurs between interacting surfaces in relative motion.

Friction:

The resistance to motion between two surfaces in contact, resulting from the interactions between surface irregularities and adhesion forces.

Wear:

The progressive loss of material from a surface due to mechanical interactions with another surface, resulting in surface degradation and dimensional changes.

Lubrication:

The process of reducing friction and wear between surfaces in relative motion by introducing a lubricant, such as oil, grease, or a solid material.

Surface Roughness:

A measure of the texture or irregularities on a surface, which can affect friction, wear, and lubrication performance.

Asperities:

Microscopic surface irregularities or roughness features that contribute to friction and wear when surfaces come into contact.

Mixed Lubrication:

A lubrication regime where both hydrodynamic and boundary lubrication mechanisms are present, and the interacting surfaces experience partial contact with some asperities touching while other areas are separated by a lubricant film.

Boundary Lubrication:

A lubrication regime where the lubricant film is very thin, and asperities on the interacting surfaces come into direct contact, leading to higher friction and potential wear.

Hydrodynamic Lubrication:

A lubrication regime where a continuous fluid film completely separates the interacting surfaces, preventing direct contact and minimizing friction and wear.

Elasto-hydrodynamic Lubrication (EHL):

A lubrication regime where a thin film of lubricant separates surfaces under high pressure and the surfaces experience elastic deformation, leading to increased load-carrying capacity.

Transfer Film:

In tribology, a "transfer film" refers to a layer of material that has been transferred from one surface to another during sliding contact. Transfer films influence friction and wear behaviours and are particularly important in self-lubricating systems where they provide a protective layer, extending bearing life and improving performance.

Adhesion:

The attractive force between two surfaces in contact, which can contribute to friction and wear.

Abrasive Wear:

Material removal from a surface caused by the action of hard particles or a rough surface sliding against a softer material.

Understanding these key terms helps to provide the foundational knowledge necessary to study, analyze, and solve problems related to friction, wear, and lubrication. For further information, the Thordon Engineering Manual is an excellent resource, and available online.

A White Paper - Published by Thordon Bearings Inc.

July 2024

CONTENTS

1. Executive Summary

This document provides a comprehensive examination of self-lubricating bearing materials, with a particular focus on ThorPlas-Blue, a widely used polymer in hydro-turbine wicket gate bearing applications. The white paper addresses different aspects of self-lubricating bearings, including their historical development, testing methodologies, effects on friction and wear, and other pertinent factors.

The paper begins by tracing the historical progression of self-lubricating bearing materials, from their inception in the late 1960s to their current advanced forms. Key milestones, such as the early use of composites, advancements in hydropower applications, and ongoing developments driven by the demands of renewable energy and sustainability, are explored to provide context and insight into the growing significance of these materials in modern engineering.

The document then explores the various testing methods used to assess the performance of self-lubricating bearings, including Pin-on-Disk, Reciprocating Sliding, Endurance, and Creep Tests. This section highlights the complexity and critical nature of accurately evaluating these materials under diverse operational conditions.

Following this, an examination is conducted on the factors that affect the sliding friction coefficient of self-lubricated bearings. Variables such as bearing load, sliding speed, material temperature, travel distance, and counter-surface roughness are thoroughly scrutinized. This section challenges the conventional belief in the reliability of the friction coefficient, emphasizing its dynamic and context-dependent nature.

Insights into the wear patterns observed in self-lubricating bearings, influenced by factors like load, stroke length, and counter-surface roughness, are presented. The discussion underscores the adaptive nature of these materials over time, with initial wear-in phases leading to stable, long-term performance.

The document also covers specific bearing behaviors, such as creep and stick-slip phenomena, as well as the standard mechanical properties of ThorPlas-Blue. This section reinforces the material's versatility for various applications, based on its robust mechanical characteristics and resistance to common bearing-related issues.

For engineers and designers, a comprehensive review is provided of the mechanical and environmental factors that impact the performance of self-lubricated bearings. This section offers practical guidance for optimizing bearing selection and design in real-world scenarios.

Dedicated attention is given to ThorPlas-Blue, with an examination of its uniform composition, the effectiveness of self-lubricating additives, and its high mechanical strength. This detailed analysis clarifies why ThorPlas-Blue distinguishes itself, particularly in terms of its outstanding friction stability and resistance to wear.

The paper concludes with a succinct summary of key findings and identifies promising avenues for future research. This hints at the substantial potential for further advancements in the field of self-lubricating bearing materials.

In essence, this document emerges as an indispensable resource for professionals in tribology, mechanical engineering, and materials science. It offers a comprehensive and insightful understanding of self-lubricating bearings, from their historical origins to the exciting prospects for future innovation. Whether one seeks to deepen their knowledge or apply these materials innovatively, this document provides a valuable foundation.

Acronym	Researcher
IREQ	Institut de recherche en électricité du Québec, Canada
LTU	Luleå University of Technology, Sweden
PTL	PowerTech Labs, Canada
RDE	RD Énergie, Canada
TBI	Thordon Bearings Inc., Canada
USACE	U.S. Army Corps of Engineers, U.S.A.

2. Brief History of Self-Lubricating Bearing Materials

Self-lubricating bearings are a type of journal bearing that do not require any additional lubrication, such as oil or grease, to operate. Instead, they are made with materials that are inherently low-friction and self-lubricating to reduce friction and wear. The history of these materials can be traced back to the late 20th century. Their adoption in hydro-turbine applications has increased in recent years due to the growing emphasis on eliminating sources of oil and grease pollution, and the need for efficient and low-maintenance materials in mechanical systems.

Late 1960s — Early 1980s:

The first self-lubricated composite materials were developed and introduced to the market. These materials were designed to reduce friction, wear, and maintenance costs in various industrial applications. Thordon Bearings was a leader in this area, with the introduction of the Thordon XL elastomeric polymer alloy, introduced in 1967 for use in vertical pumps in a steel mill.

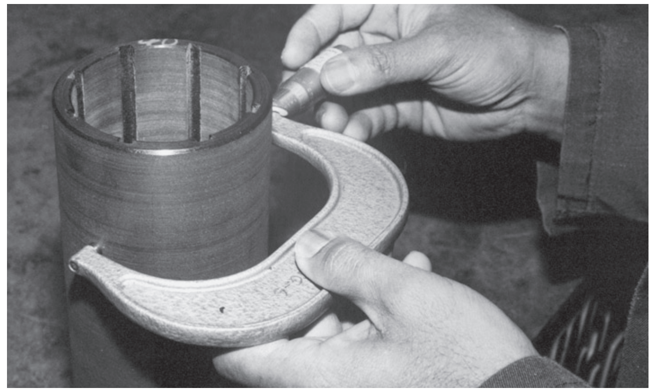

Image [1] – Thordon XL Elastomer Bearing

Mid -1980s — Late 1990s:

Researchers, suppliers, and maintenance engineers began exploring the potential of self-lubricated composites in hydro-turbine applications, focusing on improving the efficiency and longevity of components such as wicket gate bushings, shaft seals, and operating ring wear pads. Early adopters of these new materials experienced mixed results, with some installations exceeding expectations with exceptionally low wear rates, but also some field failures and challenges, mostly stemming from a lack of understanding of the unique material characteristics and differences in behaviour compared with the traditional greased bronze bushings. This sparked the development of the US Army Corps of Engineers (USACE) testing program for evaluating and characterizing self-lubricated bearings, specifically for hydro-turbines.

Early 2000s:

Self-lubricated composite materials continued to gain attention due to the potential to reduce maintenance costs, increase reliability, and improve the performance of hydropower plants. During this time, various research projects and pilot installations began to demonstrate the benefits of using these materials in hydro-turbine applications. Thordon launched another new polymer – ThorPlas-Blue, developed as superior option to the previous metal-backed options for high-load/low speed applications.

Image [2] – Thordon "ThorPlas-Blue" Thermoplastic Bearing

Mid-2000s — Early 2010s:

As the utilization of renewable energy sources increased, so did the interest in self-lubricated composite materials for hydro-turbine applications. Research and development efforts intensified, with a focus on optimizing material formulations, understanding wear mechanisms, and developing manufacturing techniques for cost-effective production. ThorPlas-Blue gained further popularity as the primary wicket gate bearing solution promoted by Thordon Bearings.

Early 2010s — 2020:

The use of self-lubricated composite materials in hydro-turbine applications became more widespread. Additionally, regulatory and environmental concerns related to the use of traditional grease lubricants in hydro-turbine systems further accelerated the adoption of self-lubricated composite materials. More hydro-turbine installations were gained with ThorPlas-Blue, field experience after 20 years of service showed excellent performance, and Thordon introduced another industry first – with a 15-year Bearing Wearlife Guarantee for Wicket Gate Bearings.

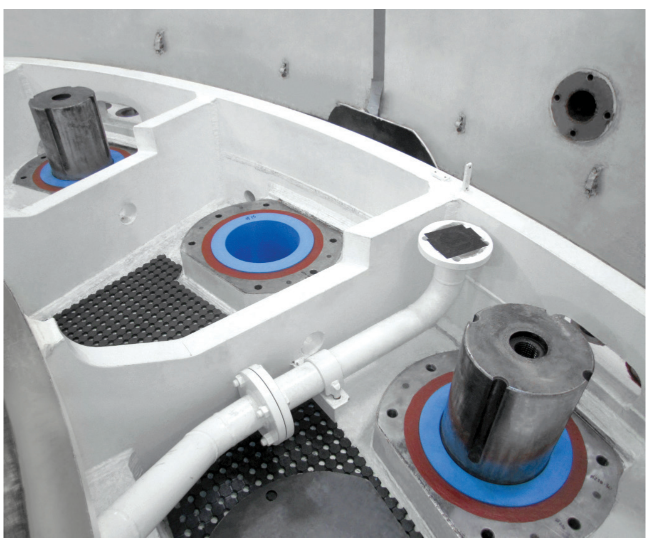

Image [3] – ThorPlas-Blue Wicket Gate Bearings for Hydro-turbines

2020 — Present:

The growing emphasis on renewable energy and environmental sustainability has led to even greater interest in self-lubricated composite materials. Changing usage of aging hydropower plant equipment (more frequent start/stops, more movement of wicket gates) is pushing materials beyond their original intended design operating conditions. Research continues to focus on optimizing material properties, refining manufacturing processes, and exploring new applications.

The development of self-lubricating bearing materials since the late 1960s represents significant advancement in industrial innovation, particularly in hydropower applications. Starting with Thordon's XL elastomeric polymer alloy and evolving through to high-performance thermoplastic material like ThorPlas-Blue, these composites have consistently aimed at enhancing performance, reliability, and environmental sustainability. This ongoing evolution sets the stage for the next critical aspect of self-lubricating bearing systems: understanding their testing methods and equipment, essential for evaluating the performance and reliability of these materials in various operational scenarios.

Bearing Materials Referred to in this Paper

Brand	**Manufacturer**
ThorPlas-Blue	Thordon Bearings Inc.
Orkot TXM®	Trelleborg Sealing Solutions
Devatex® 552	Federal-Mogul Deva GmbH
UHMWPE	Multiple manufacturers
HPSXL	Thordon Bearings Inc.
ThorPlas-White	Thordon Bearings Inc.

3. Understanding Testing Methods & Equipment

Standardized testing equipment in tribology is designed to simulate and measure the behavior of materials and lubricants under various conditions. These tests help researchers and engineers understand material behavior, design better products, and improve performance.

Testing equipment used in tribology includes:

Pin-on-Disk Test:

In this lab test method, a pin made from the self-lubricating bearing material is pressed against a rotating disk. The friction and wear characteristics are measured under various loads and speeds. This test method is commonly used to evaluate the friction and wear properties of self-lubricating materials.

Reciprocating Sliding Test:

This lab test method involves reciprocating a pin or a flat specimen made from the self-lubricating bearing material against a flat surface under a specified load and speed. The friction and wear characteristics of the pin or specimen are measured over a specified duration. The "Cameron Plint Style" test rig, and the "Universal Macro Tester (UMT)" shown here are both capable of performing this type of test.

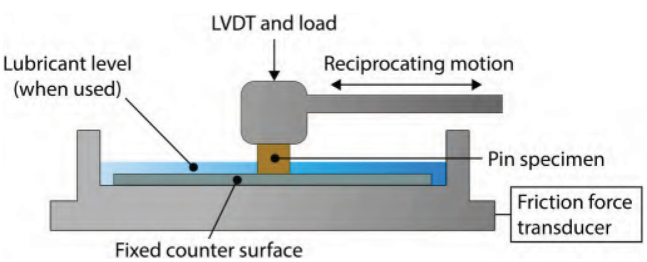

Image [4] – Reciprocating Sliding Test "Cameron Plint" Style

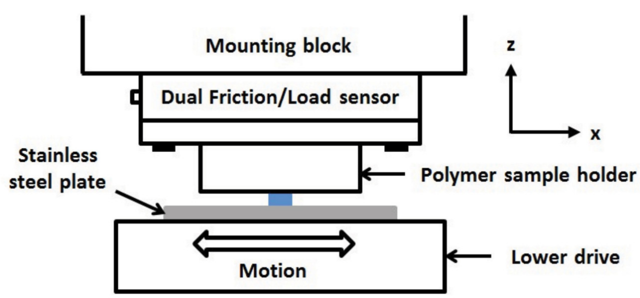

Image [5] – Reciprocating Sliding Test Universal Macro Tester

Endurance Test:

Endurance testing may be done in lab, or in the field, but usually involves testing of a bearing under a continuous load and oscillation or rotation over an extended period of time. The goal of the test is to evaluate the bearing's durability and lifespan under realistic operating conditions. Many different custom test rigs have been constructed for this purpose. One example is the large test rig built by PTL for testing bearing materials for the USACE, shown in the following sketch.

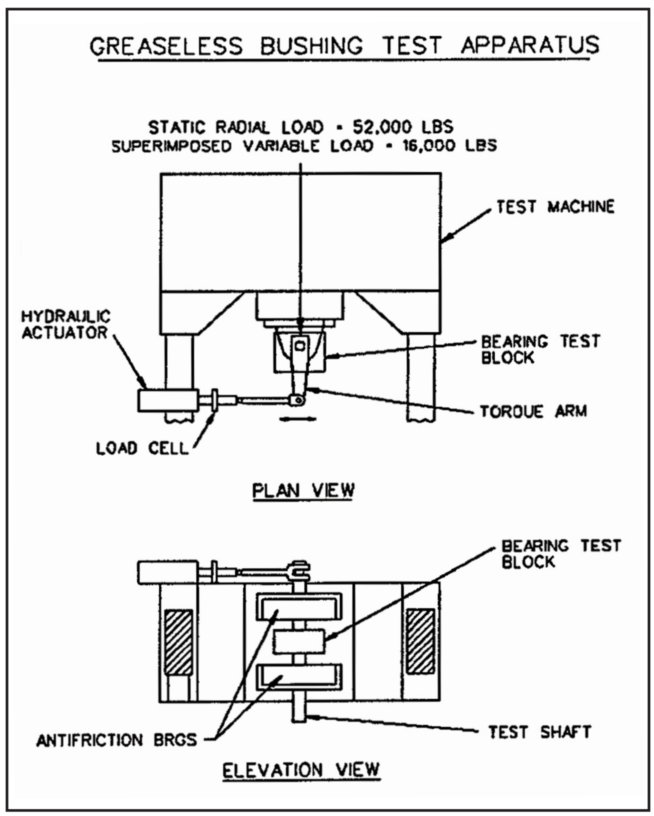

Image [6] – Custom Journal Bearing Test Rig, PTL and USCAE

Another example of a custom-built endurance testing machine is the test rig designed and built by IREQ and Tricomat to carry out bearing testing for Hydro-Québec, a large hydro utility in Canada.

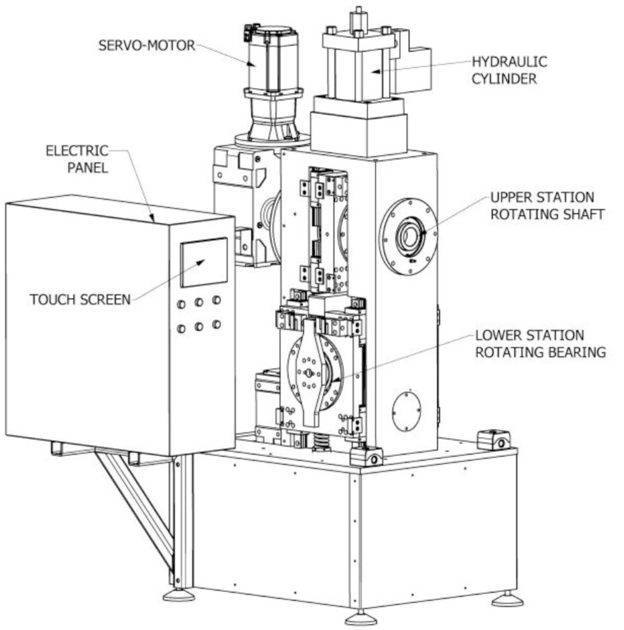

Image [7] – Custom Tribometer for Cylindrical Bearings, IREQ & Tricomat Inc.

Rotating Journal Bearing Test:

This test method involves testing a self-lubricating bearing in a rotating application, under specified loads and speeds. The bearing's temperature, vibration, and noise are measured, and the bearing is inspected for any signs of wear or damage. One example of the rig used for this type of testing can be found in the Journal Bearing Test Rig used by the tribology lab at LTU in Sweden.

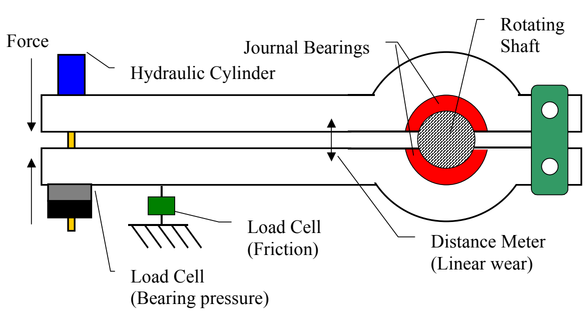

Image [8] – Custom Journal Bearing Test Rig - LTU

Creep Test:

Creep testing involves holding a continuous compressive load on the bearing material for an extended duration and monitoring compression over time – without rotation or sliding motion. There are many standard and custom setups, but two examples are shown below.

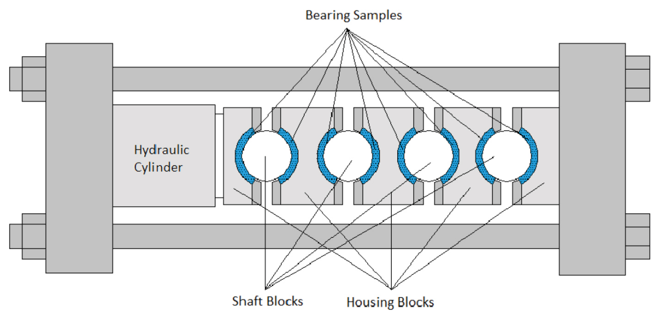

Image [9] – Creep Testing Configuration – PTL

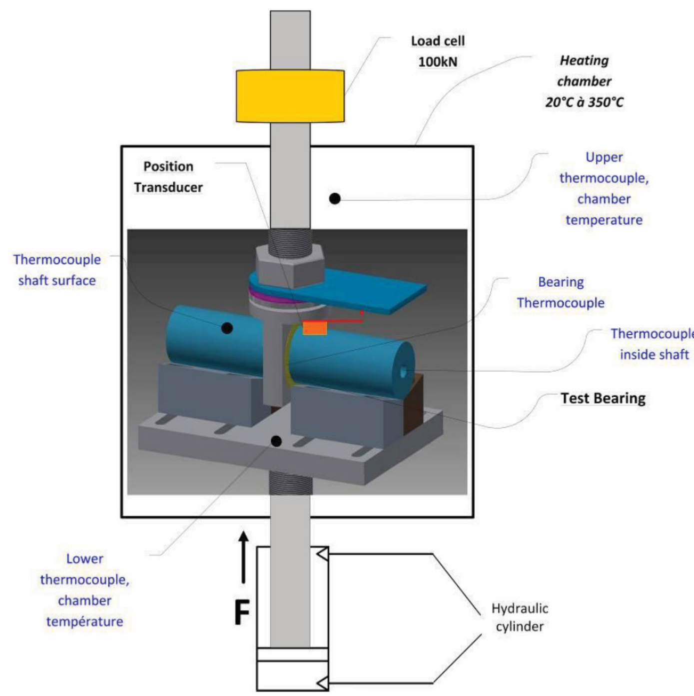

Image [10] – Test Setup for Accelerated Creep Test, IREQ

Stick-Slip Test:

This is a custom test set up to evaluate sliding friction and replicate stick-slip behaviour commonly found in sliding wear pad applications. A weight is applied to the test sample while it is pulled along a linear counter surface. Although the construction of the example in Image 11 is quite rudimentary, it provides a quick and effective means of evaluating this specific parameter in a manner that closely matches the real-life application in a sliding gate mechanism.

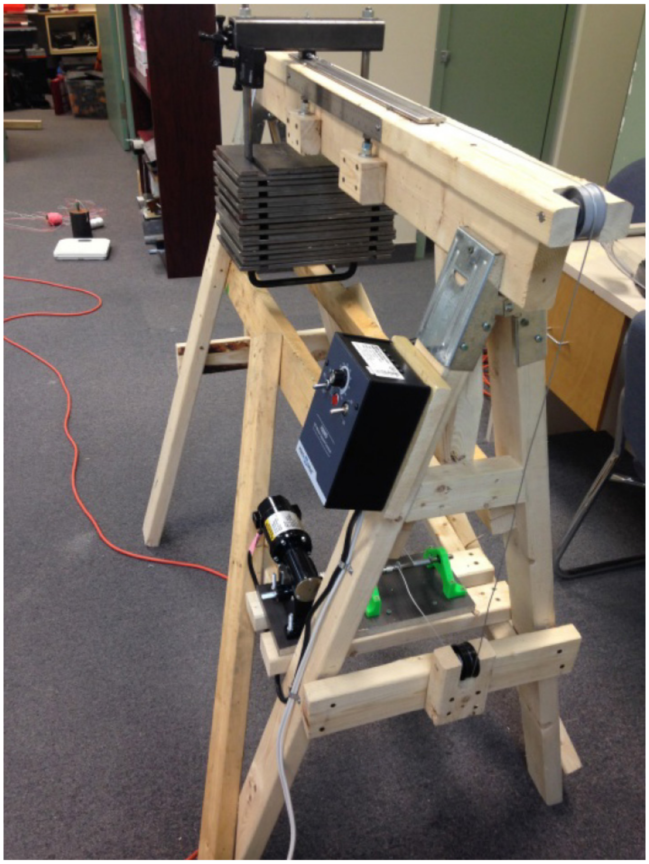

Image [11] – Custom Test Bench for Stick-Slip Testing, RDE

To effectively evaluate self-lubricating bearing materials, it is crucial to use a combination of test methods. This approach not only assesses the material's performance but also identifies potential areas for enhancement. Selecting an appropriate standardized test requires a thorough consideration of the material's intended application, operating conditions, and performance goals. Each test method comes with its own set of strengths and weaknesses. Therefore, choosing the most suitable method hinges on aligning it as closely as possible with the specific needs of the application.

The diverse testing methods used in tribology play a vital role in advancing our comprehension of self-lubricating materials. The following sections will shift the focus to a more detailed analysis of key tribological aspects of the materials that have been tested, with a specific focus on the performance of ThorPlas-Blue.

4. Influences to the Sliding Friction Coefficient

a) Bearing Loading	**c) Material Temperature**	**e) Counter-surface Roughness**
b) Sliding Speed	**d) Travel Distance (behaviour over time)**	

The friction coefficient of self-lubricated bearing materials is a critical parameter that has a significant influence on their performance, suitability for the application, and service life. The friction coefficient describes the ratio of the frictional force to the normal load between the bearing and the mating counter-surface. Contrary to common belief, the coefficient of friction for a specific material is never a single point value – it is influenced by many factors, including loading, time, sliding speed, and counter-surface roughness. While it is not practical to mention every factor, it is possible to demonstrate the influence of some of them, based on the extensive research done with materials commonly found in hydro-turbine applications.

a) Influence of Bearing Loading (TBI03, LTU06)

The influence of loading on the friction coefficient in self-lubricated bearings is significant. Testing done by LTU with ThorPlas-Blue material subjected to a low-speed oscillating load test shows a clear decrease in friction coefficient as loading (bearing pressure) is slowly increased in small increments until reaching 90 MPa. In this case the friction during the test started at ~0.06, reached maximum ~0.08 after about 20-hour test time and finally decreased towards just above 0.05 at the end of the test.

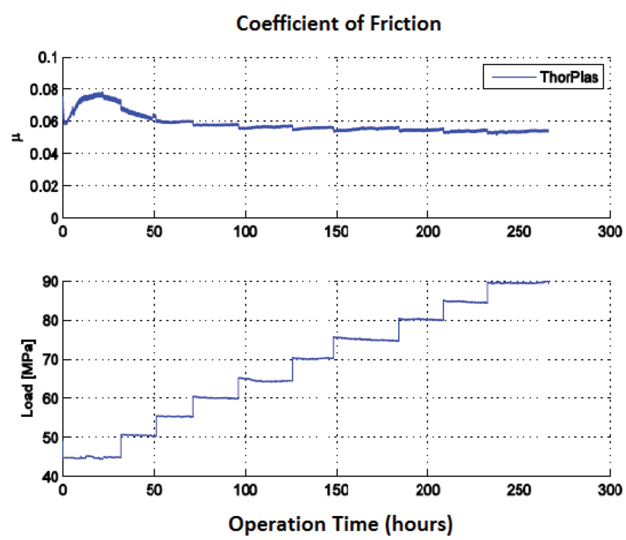

Figure [1] – ThorPlas-Blue Journal Bearing Test, with Increasing Load

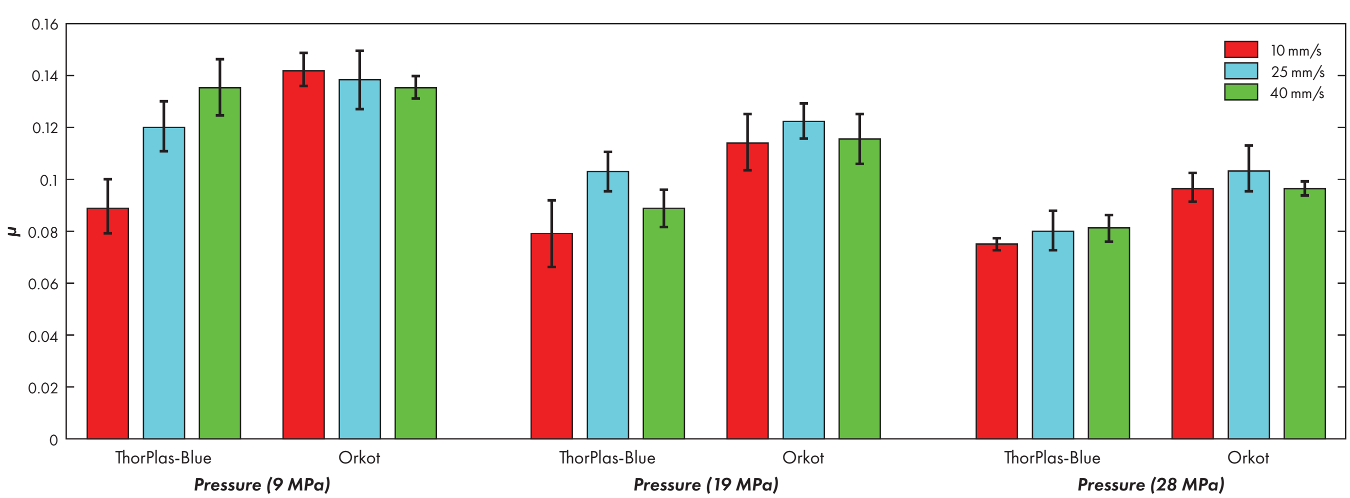

Figure [2&3] – Average Friction with Varying Sliding Speeds and Loads

In the subsequent analysis of the material samples tested, it was concluded that the reason for the decreasing friction with increasing load is likely the "squeezing" of solid lubricant particles out of the structure of the bearing material, resulting in added solid lubricant in the sliding interface. As load increases, more of the solid lubricant particles are squeezed out, thus decreasing sliding friction.

Further research done at LTU using a pin on disc tribometer included two different materials (ThorPlas-Blue & Orkot TXM®) evaluated under varying loads and speeds. It can be clearly seen that for both materials the measured friction coefficient is generally decreasing with increasing bearing pressure. The range of friction coefficients observed across the various speed and load ranges tested can vary as much as ~50%, highlighting the need to understand the load and speed conditions when undertaking bearing design and material selection for a specific application.

b) Influence of Sliding Speed (LTU06)

The same test data from LTU noted in the previous section highlights that sliding speed is also an important factor influencing friction coefficients. From the two samples tested, friction is seen to vary more with changing sliding speed in the ThorPlas-Blue thermoplastic than the Orkot® thermoset laminate, but in all cases, it is clear that there is some influence of sliding speed on the measured friction.

From the LTU research paper, it is suggested that the sliding friction generates heat at asperities in the bearing material and counter-surface, increasing temperature at the interface. The higher the sliding speed, the higher the resulting temperature, and as the local material temperature reaches the softening point of the polymer, the accompanying increase in adhesive wear can lead to higher coefficient of friction values. The increase in material temperature may also change the mechanical characteristics of the bearing material. This explains some of the differences in behaviour between ThorPlas-Blue and Orkot TXM®, as they are fundamentally different types of materials (thermoplastic vs. thermoset laminate) and therefore are not affected equally by increasing local material temperature.

c) Influence of Material Operating Temperature (IREQ01)

Temperature changes in the bearing material may be caused by localized heating from high loads or high sliding speeds as noted in the previous section, but also because of ambient conditions. For example – outdoor applications in northern climates can regularly experience temperatures ranging from -30°C up to +35°C between winter and summer seasons. This is important in bearing design, as the mechanical properties of many self-lubricated bearing materials will change with large changes in temperature.

While there is no specific research within the scope of this paper to evaluate friction of ThorPlas-Blue at varying temperatures, the importance of considering temperature and the effect on mechanical properties is highlighted in a paper authored by IREQ. More discussion regarding the influence of temperature on the creep-behaviour will follow in subsequent sections.

d) Friction Coefficient Behaviour Over Time/ Travel Distance (VAT01, LTU01, TBI02)

The friction coefficient in self-lubricated bearings can also change over time due to various factors such as wear, temperature, and chemical degradation. Most importantly, as the bearing material wears, its surface topography changes and solid lubricant particles are released to the interface, which can affect the friction coefficient. Many tests have been done evaluating the friction and wear characteristics of material over a relatively long test duration, some considering sliding distance and others using test hours – but the main conclusion is that friction is not always stable through the life of the bearing.

Testing done by PTL on an oscillating journal bearing test rig shows a very stable friction over 120 hours of testing of the ThorPlas-Blue thermoplastic material.

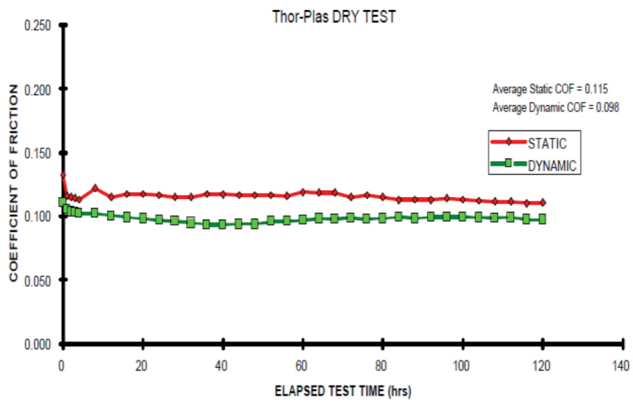

Figure [4] – Friction vs. Time (hours) for ThorPlas-Blue, Long Duration Journal Bearing Test

Testing done by LTU for Vattenfall in Sweden on a journal bearing test rig shows a similar stable friction coefficient for the ThorPlas-Blue.

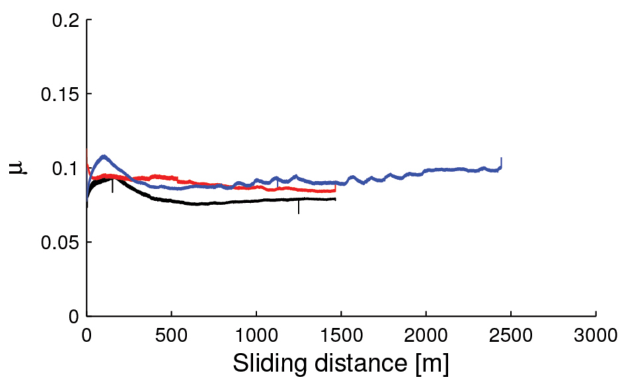

Figure [5] – Friction vs. Sliding Distance (m) for ThorPlas-Blue, Long Duration Journal Bearing Test

In the same test, this can be directly contrasted with the friction data from DevaTex® material (thermoset laminate), which is showing substantially more variation over the full test duration.

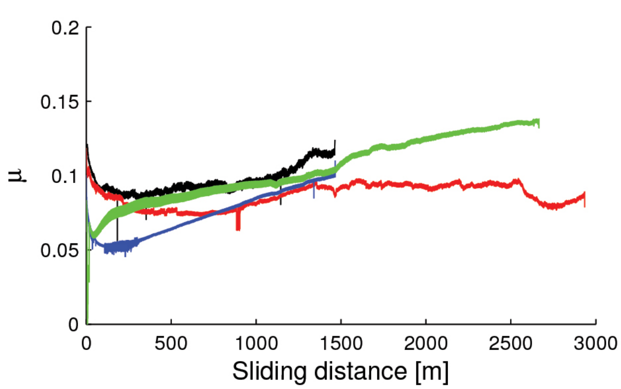

Figure [6] – Friction vs. Sliding Distance (m) for DevaTex®, Long Duration Journal Bearing Test

In another lab-scale test done with a pin on disc tribometer, this same stability of friction for the ThorPlas-Blue thermoplastic material is demonstrated. With the thermoset laminate material, the variation in friction coefficient over the full test duration is more significant.

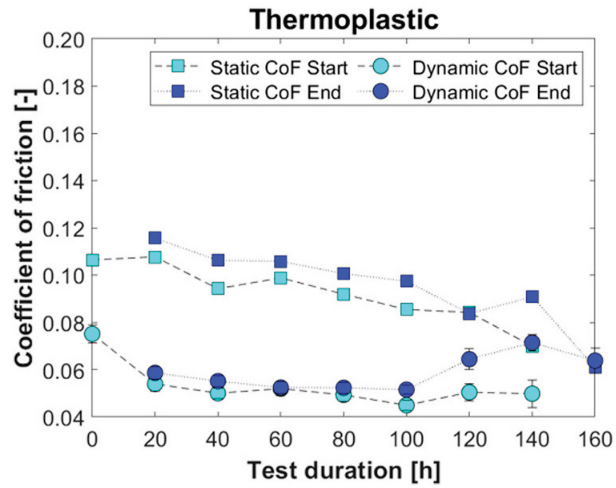

Figure [7] – Static and Dynamic Friction vs. Time (hours), (Results for ThorPlas-Blue)

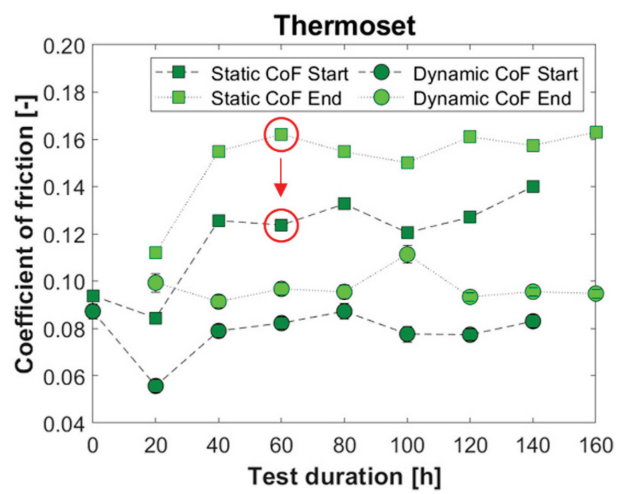

Figure [8] – Static and Dynamic Friction vs. Time (hours), (Results for Orkot®)

Another interesting observation is the varying of the instantaneous coefficient of friction during a single half cycle of oscillation recorded during this testing. Data from the LTU testing shows this clearly, highlighting the difference between static friction vs. dynamic, and even slight changes in dynamic friction through the cycle length.

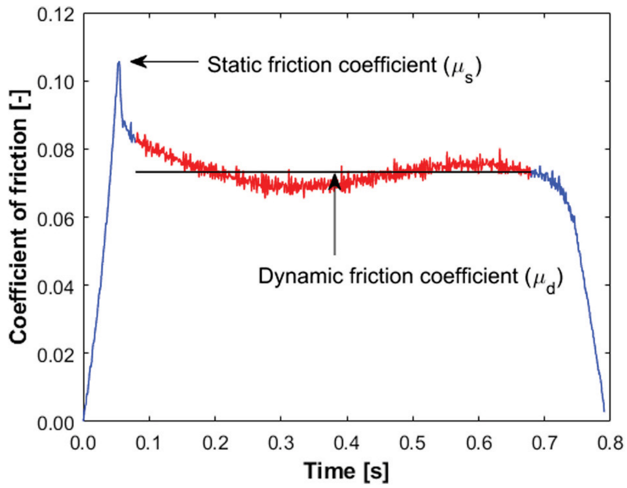

Figure [9] – LTU Instantaneous Friction Coefficient During Half Cycle

e) Influence of Counter-surface Roughness (TBI01, LTU13)

The roughness of the counter-surface (usually machined stainless steel) that is paired with the bearing material can also affect the measured friction coefficient. As the counter-surface roughness increases, the friction coefficient generally increases due to an increase in the real contact area at the sliding interface. However, if the counter-surface is too rough, it can cause excessive wear on the bearing, reducing its service life.

During lab testing using a pin on flat tribometer, LTU evaluated ThorPlas-Blue, DevaTex 552®, and Orkot TXM® against stainless steel counter-surfaces with varying surface finishes as shown in Figure 10.

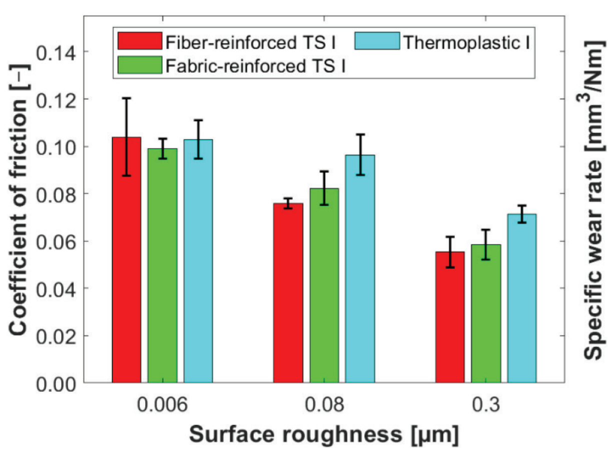

Figure [10] – Avg. Friction with Varying Surface Roughness

While this testing shows that extremely smooth counter-surfaces can increase friction coefficients, an extremely rough surface is also not desirable as it can increase the wear rate of the bearing material.

Additional testing was completed by RDE as part of an evaluation of sliding friction and wear behaviour of various bearing/counter-surface pairs. This test compared friction coefficients of ThorPlas-Blue against two different stainless steel counter-surfaces: rough (raw), and smooth (polished).

Sliding Friction on **Polished Steel Surface**		Stainless steel 304L, Polished		
		μ static	μ dynamic	
			1.5 mm/s	3 mm/s
Orkot TXMM	400 PSI	0.13	0.14–0.14	0.16–0.16
	200 PSI	0.10	0.12–0.12	0.13–0.14
UHMWPE	400 PSI	0.09	0.08–0.08	0.09–0.10
	200 PSI	0.07	0.08–0.08	0.08–0.10
ThorPlas-Blue	400 PSI	0.09	0.10–0.11	0.09–0.12
	200 PSI	0.10	0.11–0.11	0.09–0.12

Figure [11] – Sliding Friction on Polished Steel Surface

Sliding Friction on **Raw Steel Surface**		Stainless steel 304L, Polished		
		μ static	μ dynamic	
			1.5 mm/s	3 mm/s
ThorPlas-Blue	400 PSI	0.17	0.12–0.13	0.12–0.14
	200 PSI	0.15	0.11–0.13	0.12–0.13

Figure [12] – Sliding Friction on Raw Steel Surface

This testing did not include surface finish measurement data, but it is useful to emphasize that an entirely raw steel mating surface will likely increase in friction and some level of machining or polishing is desirable. Most manufacturers will specify an optimal surface roughness for their materials, so they should be consulted for each application.

5. Influences to the Material Wear Rates

a) Bearing Loading	**c) Stroke Length** (distance between reversals)
b) Sliding Speed	**d) Travel Distance (behaviour over time)**

Self-lubricated bearings are designed to operate without external lubrication and rely on dispersed solid lubricant particles to reduce friction and wear. The wear rate of self-lubricated bearing materials is an important factor that affects their performance and durability, but is influenced by loading, sliding speed, stroke length, and total sliding distance.

a) Influence of Loading (TBI03, TBI02, LTU06)

The loading (bearing pressure) of a self-lubricated bearing material affects its wear rate, as higher loads can cause more significant wear due to increased frictional forces. As the load increases, the contact pressure between the bearing material and the counter surface also increases, leading to increased friction and higher wear rates. Thus, it is essential to select a self-lubricated bearing material that can withstand the required load and provide the necessary load-bearing capacity without excessive wear.

The best evidence of this influence of loading comes from testing that was done by LTU in 2009 on the Journal Bearing Test Rig. This test was done at multiple load steps increasing gradually from 45 MPa up to 90 MPa, over a duration of 250 hours.

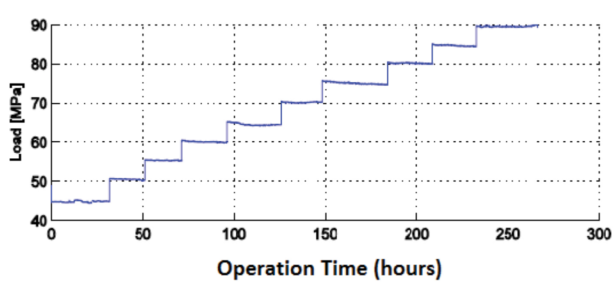

Figure [13] – LTU Load Steps Used for Increasing Load Wear Test

When the wear data is isolated for each step, it becomes clear that while bearing pressure remains below 50 MPa, there is very little wear, but as pressure is increased the slope in the wear rate curves become much more apparent.

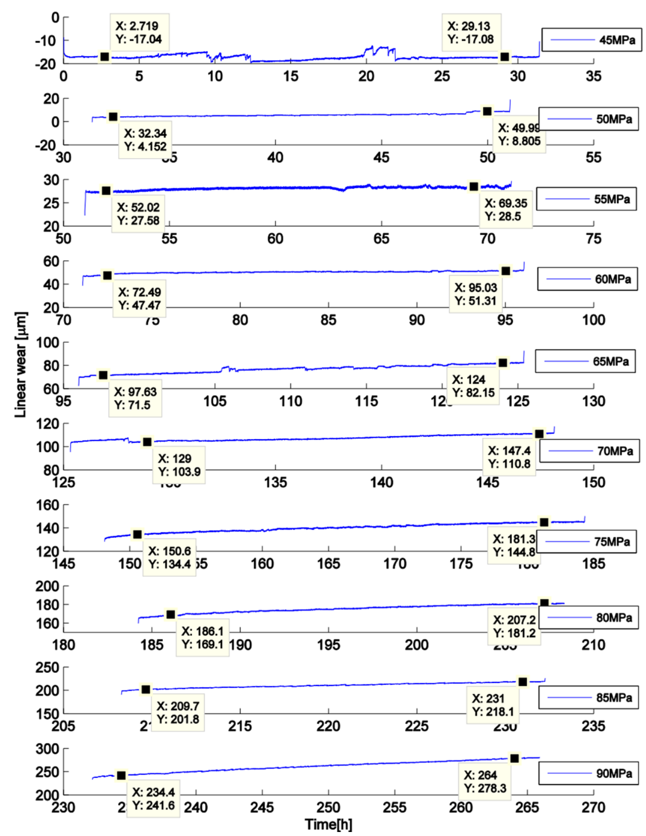

Figure [14] – Linear Wear vs. Time (hours) for Increasing Load Test (ThorPlas-Blue Results)

Thordon Bearings has quantified this change in wear rates with increasing loads, summarizing wear factors that could be used when designing ThorPlas bearings.

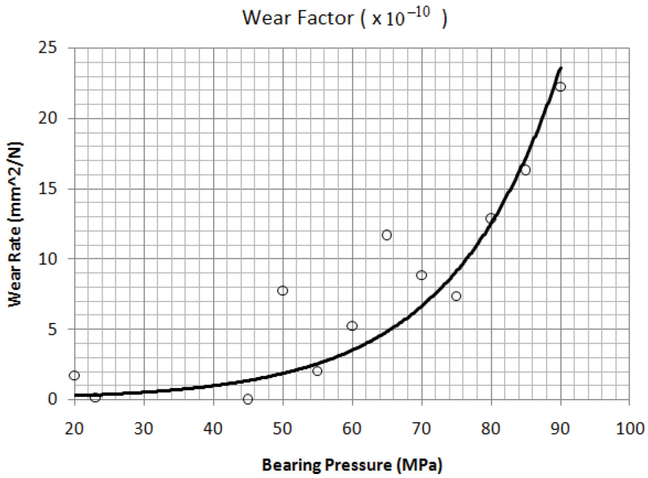

Figure [15] – Wear Rate Factor, with Increasing Bearing Pressure for ThorPlas-Blue

With help of this test data, design engineers can estimate the potential wear by knowing bearing pressure and traveling distance.

Additional testing done by LTU researchers in 2017 evaluated specific wear rates at three different bearing pressures, and three different sliding speeds. The ThorPlas-Blue wear rate at higher sliding speeds decreases almost in half between 9 and 19 MPa, while there is no significant wear rate change as load is increasing from 19 to 28 MPa. The specific wear rate coefficient at the lower sliding speed (10 mm/s) is stable over all pressures tested.

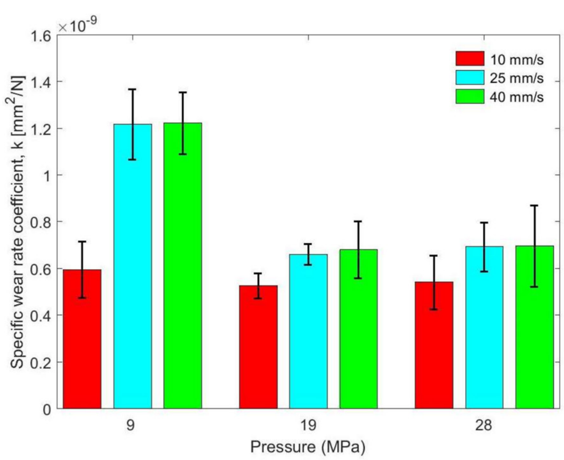

Figure [16] – LTU Specific Wear Rates with Varying Loads and Speeds (ThorPlas-Blue Results)

Detailed microscopic surface analysis of the test samples reveals that even though more polymer material is transferred to the counter surface and distributed more uniformly at low pressures, the transferred layers formed at the higher pressure contain higher amounts of the solid lubricant elements contained within the ThorPlas-Blue material. This suggests that at higher pressures, more solid lubricant is squeezed from the bulk of polymer and deposited on the counter surface and contributing to lower wear rates.

b) Behavior over Time / Travel Distance (VAT01, LTU01, TBI02)

The wear rate of self-lubricated bearing materials can also vary over time. Time alone does not cause wear, so wear rates are more often evaluated as a function of travel distance. At the beginning of service life, the material may exhibit higher wear rates due to surface roughness and a lack of wear-in. As the material continues to operate, the contact surfaces will undergo wear-in and become smoother as bearing material is transferred to the sliding interface, reducing the wear rate. However, as the material continues to wear, the wear rate may increase again due to changes in surface properties and increased roughness.

Test data from long-term testing performed at LTU shows consistent wear behaviour with small variations between tests and a very low wear rate over the full 2,500 m sliding distance test duration at a 20 MPa bearing pressure. The slight "negative wear" trend observed at the beginning of the test can be partly attributed to material transfer, but can also be influenced by initial run-in and shaft heating.

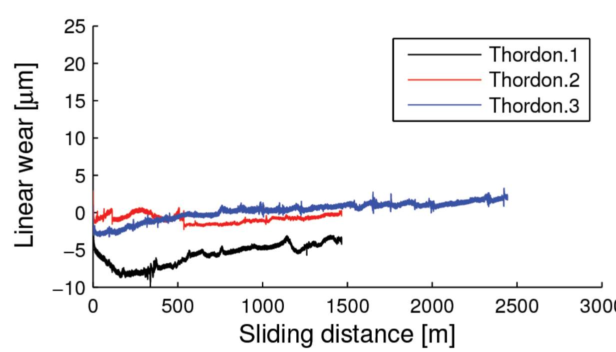

Figure [17] – Wear vs. Sliding Distance on Journal Bearing Test Rig (ThorPlas-Blue Results)

Testing done by PTL showed a similar, almost flat, wear curve for ThorPlas-Blue at a bearing pressure of 23 MPa. There was very little change in measured wear over the duration of the 120 hours of testing (approximately 6,400 m travel distance).

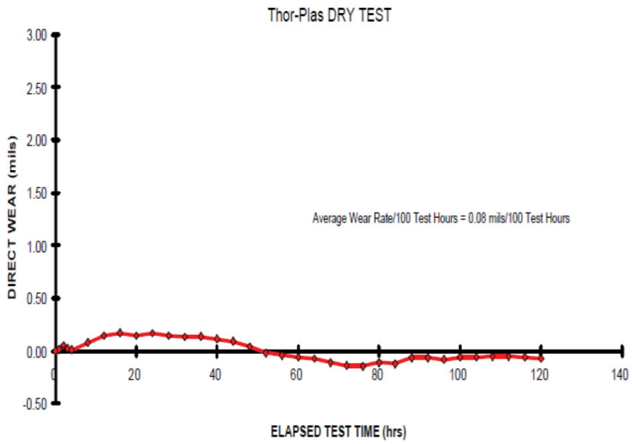

Figure [18] – Wear vs. Test Duration, on Journal Bearing Test Rig (ThorPlas-Blue Results)

Additional testing done by LTU in 2020 using a pin-on-disc test rig presents specific wear rates at varying points during a test duration of 160 hours (3,600 m travel distance) at a bearing pressure of 26 MPa.

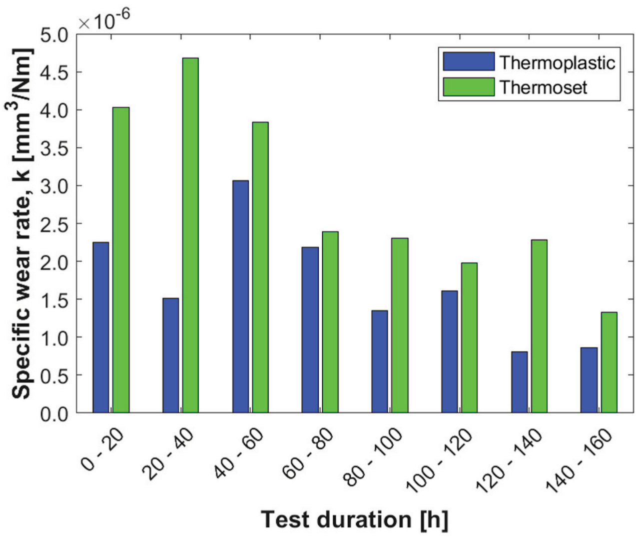

Figure [19] – LTU Specific Wear Rates Throughout Test Duration

The specific wear rates during the first 20 hours are around 3 times higher than during the last 20 hours of operation (140−160 hours) and appear to stabilize towards the end of the testing. The higher initial wear rate is due to the running-in wear, like trends observed in other testing.

It is also clear that different materials will exhibit different wear rate performance when evaluated over a long duration, with significantly higher wear rates observed in the thermoset laminate material vs. the ThorPlas-Blue thermoplastic.

c) Influence of Stroke Length (LTU12)

The influence of stroke length is another interesting factor to consider when studying the wear behaviour of ThorPlas-Blue bearings in oscillating motion applications. The length of travel between direction reversals can have a significant impact on the material wear rates.

Testing done by LTU in 2021 evaluated this behaviour using a pin-on-plate setup, a test pressure of 40 MPa, and 3 different stroke lengths varying from 4.5 mm up to 22.5 mm, over a test duration of ~150 hours (4392 m travel distance).

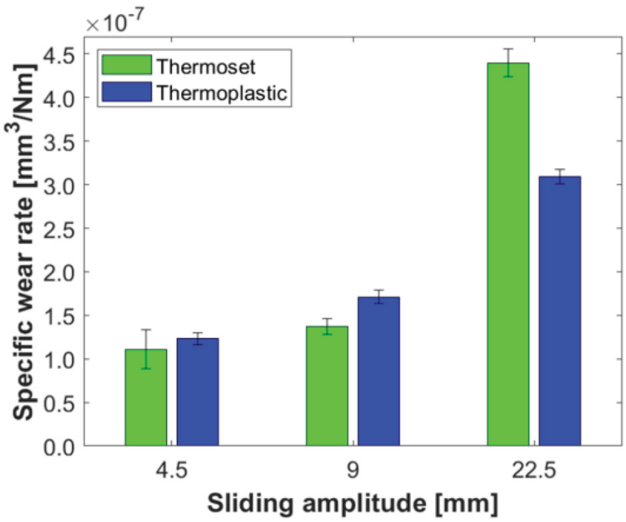

Figure [20] – LTU Specific Wear Rates With Varying Stroke Length

The increasing wear rate with increasing stroke length is attributed to a higher contribution from abrasive wear at longer stroke lengths. The lowest wear rates are obtained at the shortest stroke length, mainly owing to more retention of wear debris and hence increased formation of transfer layers of self-lubricating material. This was confirmed through detailed microscopic investigation into the wear tracks and surface characteristics of the tested samples. Surface analysis reveals higher abrasive wear of the stainless-steel counter surface at the longest stroke length due to lower wear particle entrapment.

d) Influence of Counter Surface Roughness (LTU13, TBI01)

The roughness of the counter-surface can also affect the wear rate of self-lubricated bearing materials. Rough surfaces can cause increased wear due to increased frictional forces and contact pressures. In contrast, smoother counter surfaces can reduce wear by decreasing friction and contact pressures. Therefore, it is important to select a self-lubricated bearing material that is compatible with the counter-surface roughness and can provide optimal wear resistance and lubrication.

Research done at LTU evaluated the friction and wear performance of ThorPlas-Blue with varying roughness profiles on the stainless steel countersurface. Testing was done on a flat-on-flat test configuration, at a test pressure of 28 MPa, over a 20 hour (461 m sliding distance) test duration.

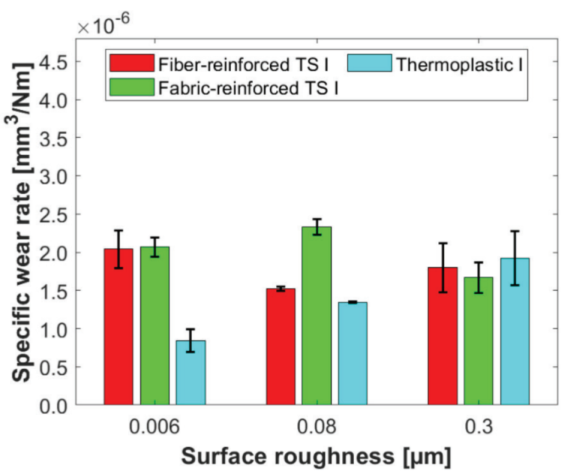

Figure [21] – LTU Specific Wear Rates With Varying Counter Surface Roughness

Results from this LTU study show that overly smooth surfaces result in higher friction and wear of the counter surface, while rougher surfaces have a negative effect on the wear. The dominant wear mechanism of the bearing materials changes from delamination wear to abrasive wear between the lowest and the intermediate roughness for steel surfaces with the parallel lay. It can be concluded that counter-surface topography has a significant influence on the tribological behaviour of these bearing materials and that the effect differs between the self-lubricating polymer composites.

This LTU testing indicated that it is possible to reduce the specific wear rates significantly, by optimizing the counter surface topography of the surfaces. In this testing, the ThorPlas-Blue showed lower wear rates with low surface roughness (Sa = 0.3 µm), while the reinforced thermosets showed lower wear rates at the intermediate roughness (Sa = 0.7 µm).

6. Other Parameters of Interest

a) Creep Behaviour	**c) Standard Mechanical Properties**
b) Stick-Slip Characteristics	

Creep and stick-slip are two common phenomena that can occur in self-lubricated bearing materials. Both phenomena can have significant effects on the performance and lifespan of bearings, and it is important for engineers and designers to understand them to optimize bearing design and operation.

a) Creep Behaviour of ThorPlas-Blue (TB102, IREQ01)

Creep is a deformation phenomenon that occurs in materials under stress over time. In the context of self-lubricated bearings, creep can occur in the bearing material due to the load placed on it and can cause the material to gradually deform over time. This deformation can result in changes to the dimensions of the bearing, as well as changes to its mechanical properties, such as elastic modulus and yield strength.

Evaluation of the creep resistance has been completed by Powertech Labs as reported in a summary paper from Thordon Bearings, as well as IREQ for Hydro-Québec.

PTL performed a test by directly loading eight bearing halves in tandem. A hydraulic cylinder was used to apply a compressive load to the blocks. The total deformation of eight samples was monitored, and the bearing pressure was controlled constantly at 55 MPa. The test lasted 360 days (1 year).

It is reported that the amount of creep for each bearing half was 0.073 mils (0.00184 mm). The wall thickness of each sample was 9.53 mm. From this test, it concludes that at the given level of bearing pressure, the creep of ThorPlas-Blue was almost negligible and therefore, for most engineering applications within the 45 MPa bearing pressure design limit used for ThorPlas-Blue, creep is not a concern.

Evaluation of the creep resistance of cylindrical bearings was also carried out by IREQ, with the intention to evaluate the effectiveness of accelerating creep-testing by increasing the test temperature. This testing was completed at a bearing pressure of 50 MPa, with temperature slowly increased in 5°C increments, from 25°C up to 70°C. Deformation was measured at each step. Five different bearing materials were evaluated as shown in Figure 23.

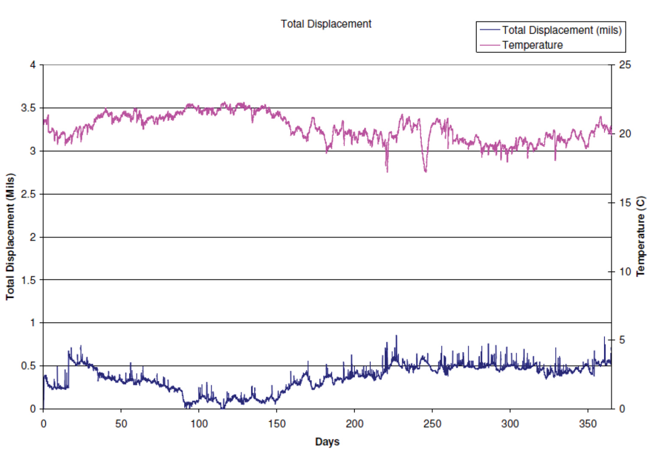

Figure [22] – Displacement vs. Time During Long Term Creep Test

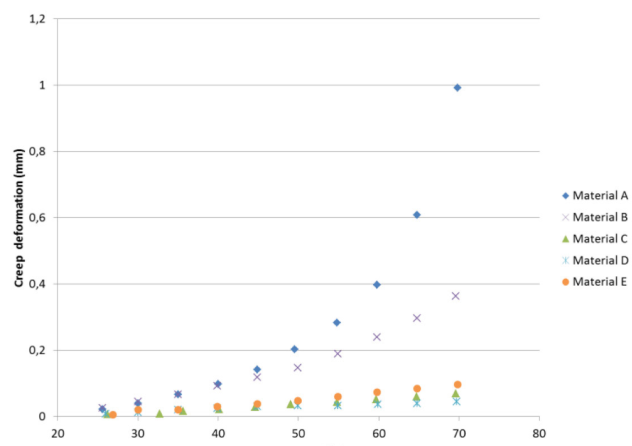

Figure [23] – IREQ Deformation vs. Temperature During Accelerated Creep Test (Material C = ThorPlas-Blue)

One of the conclusions from this report is that at high loads, creep resistance can be a significant parameter in deciding which material should be used. ThorPlas-Blue (Material C) did not deform significantly, even at 70°C for six hours. Extrapolation of deformation overtime at a specific load and a given temperature can be estimated for longer time period (weeks, months or even years). Using this approach, ThorPlas-Blue (Material C) is expected to remain stable for longer periods, decades at room temperature.

b) Stick-Slip Behaviour of ThorPlas-Blue (TBI01)

Stick-slip is a behaviour that may be observed with any self-lubricated bearings, and is related to the friction between the bearing material and the surface it is in contact with. Stick-slip occurs when the bearing moves intermittently rather than smoothly, due to the difference between the static friction coefficient that is resisting motion when stationary (the "Stick" phase), and the dynamic friction coefficient between surfaces once sliding begins (the "Slip" phase). If the bearing material has a large difference between static and dynamic friction coefficients, this stick-slip can be quite severe, resulting in vibration, noise, and increased wear on the bearing material.

ThorPlas-Blue has excellent resistance to stick-slip, due to the small difference between the static and dynamic friction coefficients. Very little testing has been done specifically on stick-slip behaviour of self-lubricated bearing materials, but one report completed by RD Energie reports on the stick-slip behaviour of various sliding bearing/face pairs typically found in wear pad applications. This was a qualitative test designed to compare between various test conditions and materials, so results are presented in a simple table showing severity of stick-slip observed in each test run, ranging from "no stick-slip" up to "constant and intense stick-slip".

ThorPlas-Blue demonstrated excellent behaviour in all cases with virtually no stick-slip observed, except in the case of low pressure & low speed, where some intermittent stick-slip was noted when running against an unpolished surface.

		304L SS, Raw		304L SS, Polished		UHMWPE	
		1.5 mm/s	3 mm/s	1.5 mm/s	3 mm/s	1.5 mm/s	3 mm/s
Orkot TXMM	400 PSI	#7	#8	#9	#10	#11	#12
	200 PSI	#1	#2	#3	#4	#5	#6
UHMWPE	400 PSI	#13	#14	#15	#16	#17	#18
	200 PSI	#19	#20	#21	#22	#23	#24
Thordon HPSXL	400 PSI	#25	#26	#27	#28	#29	#30
	200 PSI	#31	#32	#33	#34	#35	#36
ThorPlas-White	400 PSI	#37	#38	#39	#40	#41	#42
	200 PSI	#43	#44	#45	#46	#47	#48
ThorPlas-Blue	400 PSI	#49	#50	#51	#52	#53	#54
	200 PSI	#55	#56	#57	#58	#59	#60

Without Stick-Slip | Internittent Stick-Slip | Constant Stick-Slip | Constant & Intense Stick-Slip

Figure [24] – TBI "Stick-Slip" Behaviour of Various Material Pairs

c) Standard Mechanical Properties of ThorPlas-Blue

Most materials will report standardized mechanical properties according to ASTM or ISO test methods. For ThorPlas-Blue, this information can be found in Appendix III.

7. Other Macro Conditions to be Considered

Self-lubricated bearings are widely used in various applications due to their ability to operate without the need for additional lubrication. However, the performance of self-lubricated bearings can be affected by a range of macro conditions, including mechanical and environmental factors. Most often these are the parameters that application engineers are considering when making decisions regarding the suitability of a particular material. The detailed research presented in the preceding pages helps to support and inform these decisions.

Mechanical Factors

Edge Loading & Misalignment:

Edge loading occurs when the bearing is subjected to a misaligned load, causing the load to be distributed unevenly across the bearing's surface. When the bearing is not properly aligned with the shaft, it can cause uneven load distribution and increased friction, leading to premature wear and failure.

Impact & Vibration:

High impact loads can cause deformation or fracture of the bearing material, resulting in decreased load carrying capacity and increased friction. Vibrations can cause the bearing to experience high levels of stress, leading to reduced performance and potential failure.

Overloading:

Applying too much load to the bearing can cause deformation or fracture of the bearing material, resulting in decreased load carrying capacity and increased friction.

Overheating (exceeding PV limits):

Overheating of the bearing material is most often caused by a combination of pressure (P) and velocity (V) that is exceeding the capability of the material and causing softening of the material. This "PV" factor is commonly used as a design guideline for application design of sliding bushings and wear components.

Environmental Factors

Temperature:

Extreme high temperatures or extreme low temperatures affect bearing performance since they can alter the mechanical characteristics of the material.

Wet or Dry Conditions:

Wet conditions are generally not problematic for self-lubricated bearings but can reduce the effectiveness of the transfer film of solid lubricant, while dry conditions can result in higher heat at the bearing interface.

Corrosive Environments:

Corrosive environments can cause chemical reactions with the bearing material, resulting in surface damage and wear.

Dust and Debris:

Excessive dust and debris in the operating environment can cause abrasion and wear on the bearing surfaces, reducing performance and lifespan.

Practical Design Considerations

To maximize the performance and lifespan of self-lubricated bearings, it is important to consider these macro conditions and select a bearing material that can withstand the specific operating environment and load requirements. Additionally, regular maintenance and inspection can help to detect and address any issues before they become more severe.

8. Explanation of ThorPlas-Blue Performance (LTU06)

Although the exact material composition of ThorPlas-Blue is proprietary, the extensive research and testing does identify a few of the reasons why the material performs well in the testing and in-service in the field.

Homogeneous Material

As part of the research done by LTU, a study of the structure of ThorPlas-Blue material was carried out using a 3D X-ray microscope, and some of the images highlights the homogeneous nature of the ThorPlas-Blue material.

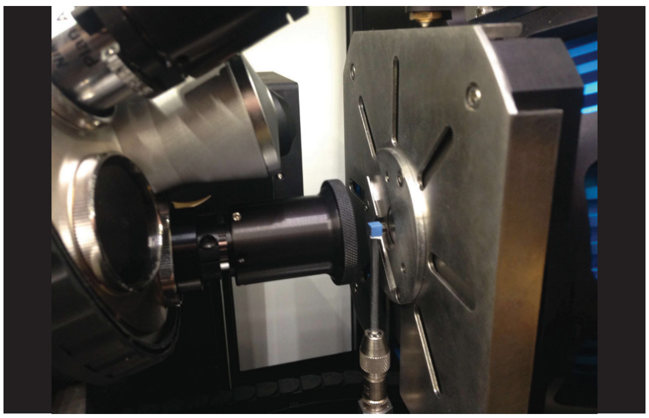

Image [12] – Experimental Setup for 3D X-ray Scanning

In the 3D scan of the ThorPlas-Blue material shown below, the grey colour (phase I) is the base polymer, the black (phase II) are small pores in the material, and the green (phase III) represents the solid lubricant particles.

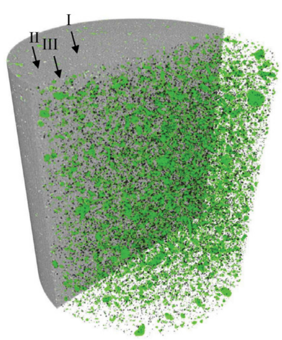

Image [13] – 3D X-ray Scan of ThorPlas-Blue Sample

The uniform distribution of these solid lubricant particles throughout the material helps to explain the stable friction and low wear rates of ThorPlas-Blue observed in testing and real-world applications.

Effectiveness of Self-lubricating Additives

In some self-lubricated bearing materials, solid lubricants such as graphite, and Molybdenum disulfide (MoS_2) are added to reduce the coefficient of friction and wear during sliding between the polymer composite and a counter surface by formation of protective and lubricating transfer layers. The exact lubricants and quantity used will vary by manufacturer and may not be disclosed. These solid-lubricant materials typically do not have the mechanical strength and stiffness required to support significant bearing loads, so they are combined with the base polymer composite materials.

High Mechanical Strength

Testing of ThorPlas-Blue at extreme bearing loads demonstrates the ability of the material to support high bearing loads in low-speed motion due to the high strength of the base polymer material. The mechanical properties of ThorPlas-Blue show a substantially higher compressive yield strength than many other common engineering plastics.

The performance of ThorPlas-Blue, as evidenced by the extensive research, can be attributed to its unique material composition. The homogeneous distribution of solid lubricant particles within the base polymer, evident in 3D X-ray microscope imagery, contributes significantly to its stable friction and low wear rates. This characteristic, combined with the effectiveness of self-lubricating additives, enhances the material's ability to reduce friction and wear under sliding conditions. Moreover, the high mechanical strength of ThorPlas-Blue, demonstrated through testing under extreme bearing loads, underscores its exceptional strength compared to other engineering plastics.

9. Conclusions, and Future Research Work

It is clear from the extensive testing and research that there is strong interest in gaining a greater understanding of the behaviour and performance of self-lubricated bearing materials. The testing and analysis provided the opportunity to complete a comprehensive review of the many factors influencing the sliding friction coefficient, material wear rates, and other key parameters in self-lubricated bearing materials, with a particular focus on the ThorPlas-Blue thermoplastic performance. Some of the most important conclusions can be summarized here.

Influences to the Sliding Friction Coefficient

This white paper identified several key factors that significantly influence the coefficient of friction: bearing loading, sliding speed, material temperature, travel distance, and counter-surface roughness. Contrary to the traditional view of a fixed friction coefficient, it was discovered that this coefficient could vary by up to 50% under different load and speed conditions. This underlines the importance of considering these variables in bearing design and material selection, due to their substantial impact on bearing performance.

A comparative analysis revealed that materials showed sensitivity to sliding speed changes, with variations in friction coefficient, confirming the importance of understanding sliding speed when determining the frictional behavior of bearing materials.

While the study did not focus specifically on ThorPlas-Blue's temperature-related frictional response, it highlighted temperature's significant influence on mechanical properties. An important observation was the variability of friction over the lifespan of a bearing, which contradicts the assumption of consistent friction levels and points to the dynamic nature of friction in bearing materials.

Further testing indicated potential fluctuations in the instantaneous coefficient of friction within a single oscillation cycle, emphasizing the differences between static and dynamic friction. This finding illustrates the complexity of frictional behavior, stressing the necessity of accounting for these dynamic changes in practical applications and analyses.

Influences to the Material Wear Rates

Bearing loads have a direct relationship with wear; higher loads lead to increased wear due to amplified frictional forces. ThorPlas-Blue, when under higher pressures, effectively transfers solid lubricants to the counter surface, suggesting the potential for lower wear rates in these conditions.

Material wear rates evolve over time. Initially, higher wear rates due to surface roughness decrease as materials wear in. However, wear rates may increase again over longer periods due to changes in surface properties.

Comparatively, the homogeneous ThorPlas-Blue thermoplastic, demonstrates significantly lower wear rates than Orkot®, a thermoset laminate, particularly over extended durations. This comparison highlights the differences in durability and longevity between these material types.

Stroke length also plays a crucial role in wear rates. Longer stroke lengths lead to increased wear, primarily due to more abrasive wear. In contrast, shorter strokes promote the formation of protective transfer layers, reducing wear rates. This finding emphasizes the influence of stroke length on the wear characteristics of materials.

Other Parameters of Interest

ThorPlas-Blue demonstrated exceptional creep behavior, showing negligible creep at pressures up to 45 MPa, which underscores its reliability for long-term applications. In addition to this, the material's resistance to stick-slip was particularly noteworthy, proving especially effective at lower pressures and speeds.

ThorPlas-Blue is also distinguished by its superior mechanical properties, notably its high compressive yield strength. This characteristic is a key contributor to the material's stable friction performance and its low wear rates.

The homogeneous nature and uniform distribution of solid lubricant particles throughout the ThorPlas-Blue thermoplastic are key factors in its stable friction behavior and low wear rates. Its mechanical properties surpass those of many common engineering plastics, contributing to its effectiveness in bearing applications.

What's Next? Possible Future Research?

This study has shed light on the multifaceted nature of self-lubricated bearing materials, particularly ThorPlas-Blue, revealing significant insights into their behavior under various conditions. However, this exploration has only scratched the surface, unveiling numerous avenues for future research that promise to further our understanding and application of these materials.

Key areas of interest for future work may include a detailed examination of ThorPlas-Blue's temperature-dependent frictional response, an in-depth analysis of its long-term wear characteristics, and a more nuanced understanding of the interplay between static and dynamic friction. Additionally, the influence of stroke length on wear rates and the material's creep behavior under diverse conditions present intriguing topics for further study.

A comparative analysis with a broader range of self-lubricated materials could provide valuable context, while investigating the material's stick-slip behavior at various speeds and pressures could refine its practical applications.

Finally, application-specific studies could further demonstrate the material's performance in real-world scenarios, tailored to specific industry needs.

The path ahead is ripe with potential, inviting deeper study into the complexities of self-lubricated bearing materials, with the promise of groundbreaking advancements and innovative applications on the horizon.

ThorPlas-Blue Research Around the World

There have been numerous studies and tests conducted on self-lubricating bearing materials to evaluate their performance and effectiveness in various applications. The papers summarized here are not an exhaustive list, but the common theme between them is that they all incorporate some testing of the ThorPlas-Blue self-lubricating bearing material. A summary of the research papers and testing can be found in the appendices.

As evidenced by the amount of published research, there is a lot of interest in understanding and characterizing these self-lubricated bearing materials, with many differing objectives and goals depending on the organization carrying out the testing.

Manufacturers of self-lubricating bearing materials often conduct their own tests to evaluate the performance of their products. These tests typically include endurance testing, load testing, and environmental testing to ensure that the bearings meet specific performance criteria, as well as evaluating performance against competitors.

Technical universities carry out research that is usually driven by a sponsoring organization, but with the goal of advancing knowledge and understanding of material behaviour and identifying future research opportunities.

The Research & Development departments of large government organizations like IREQ (Hydro-Québec) and USACE are interested to improve reliability of their equipment and support their operations staff in choosing optimal materials for each application.

Key Themes of Research & Testing

The key themes that emerge from the body of testing and research on self-lubricating bearings can be broadly grouped together and are summarized here.

Reducing Friction and Wear:

Self-lubricating bearings have been shown to reduce friction and wear compared to traditional lubricated bearings. This is due to the low-friction properties of the self-lubricating materials used in these bearings.

Extending Lifespan:

Self-lubricating bearings can have a longer lifespan than traditional lubricated bearings. This is because the self-lubricating materials used in these bearings are designed to withstand harsh environments and can continue to provide lubrication over an extended period.

Reducing Maintenance:

Self-lubricating bearings require less maintenance than traditional lubricated bearings. They do not require regular lubrication or other forms of maintenance, which can reduce maintenance costs and downtime.

Understanding Application-Specific Performance:

The performance of self-lubricating bearings can vary depending on the application. The selection of the appropriate self-lubricating material is critical to ensuring optimal performance for the specific application.

Summary of Testing & Parameters

The parameters that are most important for a testing program for self-lubricating bearings will depend on the specific application and the desired performance characteristics. However, the following parameters are generally considered to be among the most important for testing of self-lubricating bearings.

Friction Coefficients and Wear Rates:

Friction and wear are important parameters to measure when testing self-lubricating bearings, as they can affect the bearing's performance and durability. Test methods such as pin-on-disk, reciprocating sliding, and rotating tests can be used to measure friction and wear.

Load Capacity:

The load capacity of a bearing is the maximum load that it can support without failure. This is an important parameter to consider when testing self-lubricating bearings, as it can affect the bearing's durability and lifespan.

Temperature and Environmental Performance:

Self-lubricating bearings may be used in high-temperature or harsh environmental conditions, so it is important to test their performance under these conditions.

Durability and Lifespan:

Endurance testing, fatigue testing, and accelerated aging tests can be used to evaluate the bearing's durability and lifespan.

Application-Specific Performance:

The performance of self-lubricating bearings can vary depending on the application. Therefore, it is important to consider the specific application when designing a testing program and to evaluate the bearing's performance under conditions that are representative of the application.

APPENDIX I – REFERENCES

Title	Date	Author
Greaseless Bushings for Hydropower Applications	1999	US Army Corps of Engineers (USACE)
Advanced Materials Selection Guide for Lock, Dam, and Hydroelectric Plant Components	2002	USACE
Greaseless Bushings for Hydropower – Pros & Cons	2003	USACE
Wear measurements of self-lubricating bearing materials in small oscillatory movement	2006	R.Gawarkiewicz Gdansk Technical University (GDU)
Journal bearing test with Thordon Thorplas using increasing load	2009	Lulea Technical University (LTU)
Friction and Wear Characteristics of ThorPlas Bearings and Their Application in Hydro Turbines	2011	G. Ren Thordon Bearings (TBI)
Challenging Edge Loading – A Case Study for Homogeneous Polymer Bearings Operating in Wicket Gates	2011	G. Ren Thordon Bearings (TBI)
Performance and surface characteristics of slow oscillating journal bearing types subjected to various motion patterns.	2013	J. Ukonsaari (LTU)
STICK SLIP EVALUATION - Self-lubricated Bearing Material Assessment and Friction Evaluation	2015	RD Energie
Friction and Wear of Self-Lubricating Materials for Hydropower Applications with Different Lubricating Conditions	2017	K. Berglund (LTU)
Material Characterization and Influence of Sliding Speed and Pressure on Friction and Wear Behavior of Self-Lubricating Bearing Materials for Hydropower Applications	2018	M. Rodiouchkina (LTU)
Mechanical properties of polymeric self-lubricated bearings: Creeping contribution to "apparent" wear measurements	2019	L'Institut de Recherche d'Hydro-Québec (IREQ)
Tribological characterisation of polymer composites for hydropower bearings: Experimentally developed versus commercial materials	2021	J. Somberg (LTU)
Tribological behaviour and transfer layer development of self-lubricating polymer composite bearing materials under long duration dry sliding against stainless steel	2021	M. Rodiouchkina (LTU)
Effect of stroke length on friction and wear of self-lubricating polymer composites sliding against stainless steel at high contact pressures	2022	M. Rodiouchkina (LTU)
Tribology of self-lubricating polymer composites for hydropower applications	2022	M. Rodiouchkina (LTU)
Influence of Counter Surface Roughness and Lay on the Tribological Behavior of Self-Lubricating Bearing Materials in Dry Sliding Conditions at High Contact Pressures	2022	M. Rodiouchkina (LTU)

APPENDIX II – SUMMARY OF TESTING & PARAMETERS

Type of Test	Test Rig	Test Method	Test Lab	Main Parameters
Rotating 125 mm dia. shaft, constant load + oscillating load	Custom	Custom	Powertech	Friction & Wear, application specific, comparative test of materials
Rotating 40 mm dia. shaft, constant and increasing load	Custom	Custom	LTU	Friction & Wear, application specific, evaluation of material capability
Linear Pin on Plate		Custom	LTU	Friction & Wear, analysis of transfer film development
Linear Pin on Plate		Custom	LTU	Friction & Wear, comparative test of various materials
Static Creep Test		Custom	Powertech	
Static Creep Test	Custom Tribometer	Custom	IREQ	
Stick Slip	Bench test	Custom	RD Energie	
Flat on Flat	Cameron Plint Tribometer			
Flat on Flat	CETR UMT-2 Tribometer			

APPENDIX III – LIST OF IMAGES & FIGURES

THORPLAS TYPICAL PHYSICAL PROPERTIES

Property		Unit of Measure	Value
Specific Gravity		–	1.40
Hardness (ASTM D2240)		Shore-D	83
Ultimate Tensile Strength (ASTM D638)		MPa (psi)	66 (9,600)
Elongation at Break		%	~10
Tensile Modulus of Elasticity (ASTM D638)		MPa (psi)	2,930 (425,000)
Compressive Strength (ASTM D695)		MPa (psi)	>400 (58,000)
Compressive Stress at Yield (2% offset) (ASTM D695)		MPa (psi)	91 (13,200)
Compressive Young's Modulus of Elasticity (ASTM D695)		MPa (psi)	3,280 (476,000)
Notched Impact Resistance (ASTM D256)		J/m (ft.lb/in.)	40 (0.75)
Coefficient of Friction			
Dry (ASTM D3702) 0.27MPa or 40psi		–	0.15-0.30
Dry (>200 bar or >3,000psi)		–	~0.1
Wet (>200 bar or >3,000psi)		–	0.10-0.17
Abrasive Wear (Rotary Drum Dry Abrasion) (ASTM D5963)		mm^3 ($in.^3$)	~200 (0.012)
Thermal Conductivity		W/m-k (Btu/hr-ft.F)	~0.25 (~0.14)
Coefficient of Thermal Expansion (ASTM D696 modified)		cm/cm/°C (-20°C to 100°C)	$4.6x10^{-5}$ ($2.6x10^{-5}$)
		(in/in/°F) (-4°F to 212°F)	
Absorption % in Water (22°C) (ASTM D570)	24-hours	Vol %	< 0.05
	Long-term	Vol %	< 0.15
Melting Temperature		°C (°F)	> 250 (> 480)
Operating Temperatures – Min. /Max.	Dry	°C (°F)	-50/110 (-58/230)
	Wet	°C (°F)	-10/80 (14/176)

Note: Properties are typical values, unless otherwise noted, and may be altered to some extent by processing conditions.

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