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Journal Bearing Materials: Current Trends and Future Perspective

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***Abstract* — This research paper explores the current trends and potential future directions in the development and application of materials for journal bearings. Journal bearings are crucial components in various rotating machinery, influencing efficiency, reliability, and maintenance costs. The paper analyzes recent advancements in materials science, including the utilization of polymers, composites, ceramics, and surface coatings, emphasizing their performance, durability, and suitability for diverse operating conditions. Furthermore, it investigates emerging technologies such as nanomaterials and additive manufacturing, assessing their potential to revolutionize bearing materials. The study discusses challenges, such as balancing performance trade-offs and ensuring cost-effectiveness, while outlining future prospects for innovative materials and manufacturing techniques. The comprehensive analysis offered in this paper aims to provide insights into the evolving landscape of journal bearing materials, guiding researchers and industries toward enhanced performance and sustainability in machinery applications.**

Keywords— Journal Bearings, Bearing Materials, Friction, Wear-resistance, Nano-technology, Sustainability.

1. INTRODUCTION

The journal bearing, a vital machine element, provides support and radial positioning for a rotating shaft, significantly influencing system/mechanism operation. Optimal bearing performance directly impacts system success and efficiency, necessitating a meticulous selection of bearing materials to fulfill performance expectations. Despite rolling contact bearings offering reduced friction compared to sliding contact bearings, contributing significantly to various applications [1]. Widely utilized across industrial machinery, engines, automotive, hydraulic turbines, generators, and diverse machines in power, oil, gas, and petrochemical industries, journal bearings, alternatively known as plain, sleeve, or fluid film bearings, play a pivotal role. Material selection for these bearings is crucial to ensure optimal functionality. The primary objective of this paper is to examine the evolving research patterns concerning materials used in sliding contact bearings, spanning from Babbitt to metals, alloys, nonmetals, polymers, and composites. A comprehensive analysis of the tensile behavior, hardness, fatigue, and tribological properties of these diverse bearing materials is conducted, thoroughly discussed, and compared within the scope of this study.

Journal bearing materials must exhibit a blend of essential properties encompassing compatibility, conformability, embeddability, fatigue strength, resistance to cavitation erosion, and corrosion. However, no single material meets all these criteria entirely, necessitating a compromise and amalgamation of these attributes to ensure optimal performance within specific operational conditions. The occurrence of localized welds, resulting in scoring, seizure, or scuffing due to the interaction between the shafts and bearing material, must be prevented. This phenomenon, termed compatibility, necessitates the bearing material's ability to deform slightly under slight misalignments, ensuring reduced stress concentrations and the maintenance of oil film thickness, known as conformability [2]. Embeddability signifies the material's capability to embed hard particles on its surface, mitigating abrasive damage to both the shaft and the bearing. The material's resistance to scoring is reliant on these three factors, with compatibility being challenging to quantify, while conformability and embeddability inversely correlate with hardness [3].

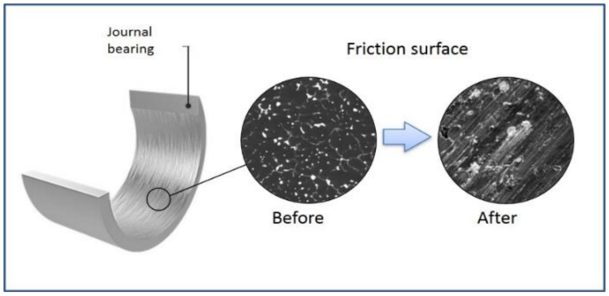

Figure 1. Journal bearing material behavior [12]

Apart from the aforementioned properties, bearing materials ideally possess specific mechanical traits, including compressive strength, fatigue strength, a low coefficient of friction (COF), minimal coefficient of thermal expansion, high thermal conductivity, favorable wettability, adequate hardness, elasticity, availability, and cost-effectiveness. Lubrication of journal bearing moving parts significantly influences wear and frictional behavior. Three primary lubrication methods exist: Full film or hydrodynamic, thin film or boundary lubrication, and extreme boundary lubrication. Hydrodynamic bearings maintain mating surfaces separated by a thick lubricant film, ensuring extended bearing life [4]. Boundary lubrication, with a thin film between surfaces, also contributes to prolonged bearing life. Journal bearing material behavior[12] conversely, extreme boundary lubrication involves high-load points where surfaces directly contact, resulting in wear and shorter bearing lifespans.

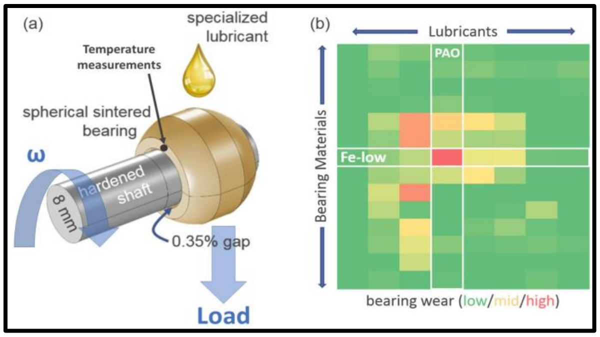

Figure 2. Journal bearing friction behavior [13]

2. BEARING MATERIALS: EVOLVING TRENDS

Presently, an extensive array of specialized materials tailored for specific applications is available, often requiring unique selection processes necessitating manufacturer guidance. Journal bearing friction behavior [13], bearing materials encompass both metallic and non-metallic types. Metallic bearings include white metal (tin and lead-based), copper-based bronzes, aluminum-based, porous metals, and coated metals. Non-metallic bearings consist of polymers, ceramics, and composites. Bearings are also categorized by their geometry, with half-round sleeves known as 'bearings' and full-round sleeves termed as 'bushes.'

2.1 Metallic bearing

Metals with a hardness below 70 BHN find application in bearing functions. Among these, Aluminum, Copper, Gold, Silver, Indium, Iron, Tin, and Lead serve as viable bearing materials. Due to their soft nature, these materials must embed debris, conform, and support shaft rotation. Specifically, tin and lead alloys, known as Babbitt metals or white metals, were developed for bearings. Although lead-based materials have seen reduced usage due to regulatory, health, and environmental concerns, tin-based materials have gradually replaced them in recent times [5]. Tin Babbitt, an alloy comprising copper, antimony, tin, and trace amounts of lead, iron, arsenic, bismuth, zinc, aluminum, and cadmium, demonstrates exceptional embeddability and conformability but has limited application due to its low fatigue strength. Generally, a layer of white metal (approximately 0.4 mm) is cast onto steel, aluminum, bronze, or cast iron sleeves to enhance fatigue strength.

Babbitt alloys are typically manufactured through casting methods. Due to its low recrystallization temperature, Babbitt materials cannot undergo cold working, causing the rate of solidification to influence both its microstructure and hardness. The micrograph displaying the microstructure of Tin Babbitt is depicted in Figure 1 (above). This multi-phase alloy consists of various phases, including the α-phase (a solid solution of Sn, Cu, and Sb), β-phase (Sn-Sb compound), η-phase ($Cu6Sn5$ compound), ε-phase ($Cu3Sn$ compound), γ-phase ($Cu31Sn8$ compound), and $Cu2Sb$ phase.

Hard crystals of the β-phase are dispersed within the soft matrix, enhancing hardness without significantly compromising frictional properties. They conducted research on the Babbitt structure and its mechanical behavior, determining that the size of the β-phase strongly influences tensile behavior and hardness. Rapidly cooled Babbitt exhibits a fine Cu-Sn compound and demonstrates higher fatigue strength compared to slowly cooled counterparts. The reduction in size and dispersion of these tough β-phase particles represent the most effective strengthening mechanism for Babbitt alloys, concurrently improving their wear resistance [6].

The impact of solidification rate and heating on the microstructure and hardness of tin-based white metal. Their findings indicated that rapid cooling hinders the formation and growth of SbSn cuboids, resulting in increased hardness. Specifically for marine and sea water applications, a 68.5% Sn - 30% Zn - 1.5% Cu alloy is utilized due to its high corrosion resistance in salt water and anodic properties in sea water, commonly employed in stern tube propeller bearings. White metal is acknowledged as the superior bearing material, often serving as the benchmark for evaluating the quality of other materials.

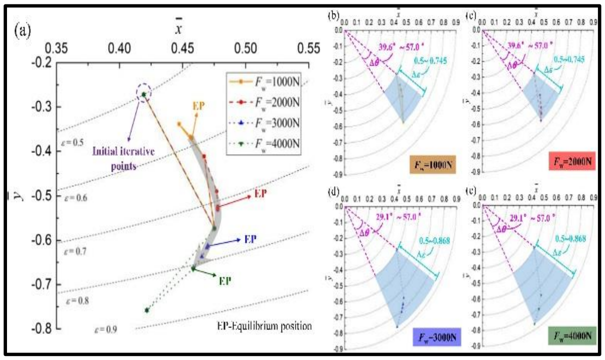

Figure 3. Journal bearing convergence behavior [14]

In addressing the fatigue limitations of Babbitt, researchers have devised copper-lead and lead-bronze alloys specifically tailored for bearing applications. Commonly, these alloys consist of Pb 22-26%, Sn 1-2%, and the remaining portion composed of Cu. The dissolution of Sn into Cu results in a bronze matrix with islands of Pb. Substantial efforts are ongoing to eliminate lead from journal bearings, with the ISO Cu-10%Pb-10%Sn alloy being prevalent in high-load applications due to its hardness and strength, widely utilized in automotive and aircraft industries. However, its compatibility and conformability remain inadequate [7].

Recent advancements in heavily loaded applications have seen the substitution of lead with nickel, albeit at the expense of sliding properties. This alloy, featuring higher strength and corrosion resistance compared to ISO Cu-10%Pb-10%Sn, incorporates 3% Bi to enhance sliding properties and is currently employed in numerous high-performance engines.

Leaded bronze alloys containing 3-4% tin are specifically utilized for heavily loaded bearings but exhibit limitations in sliding properties and lead phase corrosion. Journal bearing convergence behavior [14] typically used as substrates for coating soft bearing materials to adequately support the shaft, these alloys are applied in thin layers on metal backups. Known as 'bimetal' bearings, these layered bearings undergo periodic wear and replacement. If bimetals are further coated with an additional layer of soft material, they are referred to as 'trimetal' bearings.

Lead bronze alloys are prone to corrosion, while Tin Babbitt lacks fatigue strength. To address these shortcomings, Aluminum-Tin alloys were developed, with Al-6%Sn being the most prevalent. The addition of Cu and Ni enhances strength, resulting in better compatibility compared to bronze alloys. By adjusting its composition and structure through heat treatment, this alloy can operate effectively in high-temperature conditions. Another variant, the Al-40%Sn alloy, aimed to replace Babbitt, although it couldn't be cast similarly, leading to the adoption of thin shell bearings as a solution to retain fatigue strength where Babbitt falls short.

Two Al-Si alloys, Al-4%Si-1%Cd and Al-11%Si-1%Cu, were introduced for high-strength applications, matching Lead-bronze alloys in strength while offering superior corrosion resistance. The inclusion of Cd in the alloy enhances scuff resistance by providing a softer phase. These bearings feature microporous holes for impregnating oil or solid lubricant, suitable for applications requiring boundary lubrication to reduce maintenance costs.

Electro-deposition techniques apply thin overlays (about 10-30 μm) of Babbitt onto copper alloy substrates or bimetals. Although these thin layers are strengthened by the substrates' characteristics, their durability is lacking. Recent research has focused on enhancing the durability of these coatings. Presently, a thin layer (1-2 μm) of Tin or Lead serves as a corrosion-resistant coating, even though sputtering methods might compromise embeddability. However, sputtering forms a robust barrier that shields the lining from corrosion.

2.2 Non-metallic bearing

Non-metallic bearings are primarily suited for extremely light-duty applications, characterized by poor thermal conductivity and low intrinsic strength. Typically utilized with steel or injection-molded thermoplastic backups, these bearings serve in applications necessitating self-lubrication, high-temperature strength, and chemical resistance, such as in food handling equipment and space applications.

Materials like Teflon, nylon, phenolic, among others, form the basis of polymer bearings. These materials are more cost-effective compared to metal bearings and can incorporate solid lubricants during manufacturing to enhance their lubrication properties. Recent advancements in engineering polymers and a deeper understanding of their characteristics have substantially increased their usage in recent years. Additionally, the development of polymer-based composites has led to materials that amalgamate high wear resistance, low friction, and minimal wear rates.

Polymers possess notable thermal conductivity and offer adaptability, allowing the blending of solid lubricants, mixing various polymers in the melt phase, layering, interweaving, or impregnating into porous materials to precisely suit diverse applications. In comparison to metals, polymers exhibit lower rigidity, thus providing conformability, excellent vibration absorption, high embeddability, superior corrosion resistance, and a low wear rate. However, they demonstrate a significantly higher coefficient of thermal expansion—approximately 5-10 times greater than metals—and possess low melting points that confine their utility to light load applications. Their adherence to materials such as aluminum further restricts their usage based on shaft material compatibility [8].

Polyamideimide coatings, derived from polymers, are extensively employed on aluminum-based linings, incorporating graphite or MoS2 as solid lubricants. These coatings serve as alternatives to electro-deposited and sputtered layers, albeit exhibiting poor heat conduction. Consequently, these coatings transfer less heat from the bearing in comparison to metal coatings, thus limiting their application scope.

At elevated temperatures, the materials discussed above experience diminished strength and hardness. Consequently, ceramic bearings have been developed to endure such extreme conditions. These ceramics boast chemical inertness, lightweight properties, exceptional hardness, self-sufficiency in lubrication, and the ability to retain these attributes even under very high temperatures. However, ceramics tend to be brittle, lack wear resistance, and are relatively expensive to manufacture. Silicon nitride ceramics, produced through the hot isostatic pressing sintering process, have already found applications in critical scenarios.

Attempts to use engineered ceramics in piston and sleeve bearings aimed at enhancing efficiency were unsuccessful due to their requirement for lubrication. As liquid lubricants suitable for use with ceramics are not available, trials were conducted using solid lubricants such as zirconia, SiC, SiN, and Al2O3 as bearing materials. Notably, ceramics prove highly suitable for artificial hip and knee joints owing to their extremely low wear rate [9].

Composite bearings have existed since the advent of composite materials. Metal/polymer matrix composites are well-suited as bearing materials. Typically, the matrix is reinforced with solid lubricants like carbon graphite and molybdenum disulfide to enhance lubrication properties. The wear performance of these materials depends on the type and volume fraction of the reinforcement. Fiber-reinforced plastics blended with solid lubricants improve bearing strength and wear resistance. A diverse range of composites utilizing carbon, E-glass, stainless steel fibers for epoxy resin, polyester resin, and PTFE as matrix materials were manufactured and tested.

3. BEARING MATERIALS: MECHANICAL BEHAVIOR

The mechanical properties of metals and alloys hinge on alloying elements, impurity percentage, microstructure, and processing techniques. The similarity in the α-phase of Tin Babbitt across various alloy states, emphasizing the significant impact of β-phase size on tensile behavior. The η-phase, with a small volume fraction, showed a limited effect on mechanical properties. By controlling solidification rates during casting, the authors achieved distinct β-phase grain sizes ranging from 250 to 50μm. In their findings, for cast specimens, strain rate did not notably influence elongation. However, a decrease in grain size from 250 to 50μm correlated with enhanced ductility, flow stress, yield strength, ultimate tensile strength, and elongation ranging from 5% to 12%.

A comprehensive universal experimental assessment of friction and wear is lacking. Various experiments aimed at evaluating tribological behavior are conducted under specific conditions or addressing partial tribological tasks. It is essential to interpret tribological results within the appropriate context, considering the material as part of a broader tribological system. Materials can exhibit diverse behaviors under varying friction or wear conditions [10].

The 'Tribotestor M’06' experimental setup is to discern parameters and characteristics of journal bearings. It is recommended prioritizing rotational frequency over circumferential speed and conducted tests on sintered bronze under dry test conditions. Their observations showed an increase in the frictional factor from 0.07 to 0.08 as the rotational frequency escalated from 500 to 4000 rpm.

The tribological behavior of brass, WM-2, and WM-5 under heavy industrial service conditions with oil lubrication. They conducted tests using the equipment HFN type 5 journal bearing test equipment, studying wear and friction characteristics concerning sliding distance, sliding speed, bearing load, and material hardness. Their findings revealed that brass outperformed WM-2 and WM-5 due to its hardness, exhibiting lower wear compared to the other two tin alloys.

The impact of varying antimony amounts (ranging from 5 to 23 wt.%) on the sliding wear resistance of different white metals under lubricated conditions. It was noted that antimony concentrations between 5-20 wt.% did not significantly affect wear resistance, but concentrations beyond 20 wt.% led to a substantial increase in wear rate. Researchers have explored multiple methods to develop bearings with superior wear properties compared to cast Babbitt.

In a separate study, examined 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. Their findings correlated scratch hardness with the coefficient of friction (COF), revealing higher COF at increased normal loads and scratch velocities for both materials.

The liquid forging is to produce a Babbitt layer, achieving a homogeneous structure with 40-50 μm crystals, cubic β-phase, and disintegrated needles of the γ-phase, resulting in a low wear rate over the entire sliding distance.

A test was done fabricating bearings through casting and thermal spraying, finding that thermally sprayed Babbitt exhibited superior performance and tribological behavior even after 7000 hours of service. The thermal spraying method displayed higher bonding strength, eliminated hot spots, and reduced porosity compared to the melting process.

In the realm of composites, aluminum-based Particulate Metal Matrix Composites (MMCs) are notably preferred for tribological applications due to their exceptional wear resistance and high specific strength. Researchers have extensively explored aluminum MMCs featuring various reinforcements, commonly employing ceramic particles like Al2O3, SiC, TiC, and graphite.

Test investigated the dry sliding behavior of A356/ SiC, A356/SiC + Graphite, A6061/Al2O3, noting that ceramic particles helped minimize scoring. A356/SiC+Graphite exhibited superior resistance to severe wear compared to the other two types.

The impact 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 most significant influence on wear rate, followed by temperature and sliding velocity.

The tribological behavior of graphite-reinforced zinc-aluminum composites (ZA-27) in lubricated semi-dry and dry conditions, observing that composite bearings exhibited lower friction compared to un-reinforced ZA-27 in all three conditions. The un-reinforced ZA-27 showed seizing at much lower loads and experienced a higher coefficient of friction compared to composites under semi-dry and dry tests.

The composite coatings containing Al-12Si reinforced with TiB2, prepared by laser cladding, and evaluated their performance against AISI440C tool steel in dry conditions. They observed the formation of a substantial amount of oxides from both interacting bodies due to oxidation at high flash temperatures generated during sliding. This process led to debris formation, which acted as a protective layer, minimizing further wear on the composite coating.

Metal Matrix Nano Composites (MMNCs) have been crafted utilizing matrix materials such as Al, Mg, Cu, and assorted metals and alloys. Reinforcements including ceramic compounds like SiC, Al2O3, and Carbon nanotubes (CNT) have been widely incorporated. The reinforced 2024Al with multi-walled carbon nanotubes (MWCNTs) and explored the damping behavior across various frequencies and temperatures. The study noted a substantial frequency-dependent effect on the nano-composite's damping capacity, particularly above 230°C, showcasing enhanced damping even at 400°C.

In another study, it was produced Cu-Al2O3 nano-composites via mechano-chemical techniques, demonstrating improved properties concerning density, micro hardness, and abrasive wear resistance. The authors observed an escalation in abrasive wear resistance corresponding to the increase in volume percentage of Al2O3 nanoparticles, while wear resistance decreased with an increase in hardness.

4. LONG-TERM SUSTAINABILITY

Journal bearings are essential components used in various machinery, including engines, turbines, and industrial equipment, to support rotating shafts while minimizing friction. Choosing sustainable materials for journal bearings is crucial to reduce environmental impact and enhance long-term viability.

Traditionally, journal bearings have been crafted from materials like bronze, brass, and babbitt (a tin-based alloy). However, these materials often require mining and extraction processes, which can be energyintensive and environmentally damaging. Moreover, their production involves finite resources and can create hazardous waste.

In recent years, advancements in material science have led to the development of sustainable alternatives for journal bearings, promoting eco-friendly and efficient solutions:

Polymer Composites: Materials like polytetrafluoroethylene (PTFE), also known as Teflon, combined with other reinforcing agents, offer excellent lubrication properties and durability. These composites reduce friction, thus minimizing wear and extending the lifespan of bearings. They are also lighter, corrosion-resistant, and require less energy for production compared to traditional metals.

Ceramics: Ceramic materials such as silicon nitride and zirconia are gaining traction due to their exceptional hardness, wear resistance, and high-temperature tolerance. They offer improved performance and longevity compared to traditional metals while reducing the need for frequent replacements.

Biodegradable Materials: Some researchers are exploring biodegradable polymers derived from renewable resources like plant-based materials or recycled plastics. These materials aim to reduce the environmental impact by decomposing naturally at the end of their lifespan, minimizing waste generation.

Self-Lubricating Materials: Advancements in material engineering have led to the creation of self-lubricating materials like graphene or carbon nanotubes, which can significantly reduce the need for external lubrication, further enhancing sustainability by reducing maintenance requirements and energy consumption.

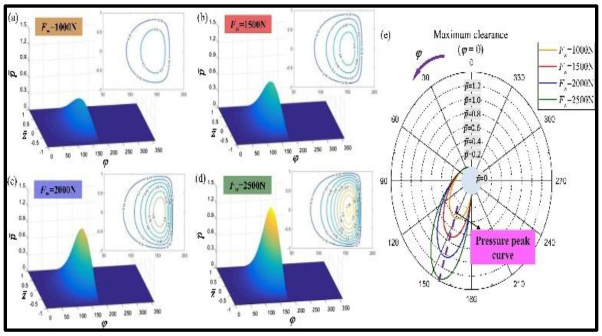

Figure 4. Pressure distribution, contour and peak curve for bearing [14]

The sustainability of these materials in journal bearings lies in their life cycle analysis. It involves evaluating environmental impacts throughout the material's entire life, from extraction to disposal. Factors considered include raw material extraction, manufacturing processes, usage, maintenance, and end-of-life disposal or recycling.

Several criteria determine the sustainability of these materials:

Resource Efficiency: Sustainable materials should utilize renewable resources or recycled content to reduce reliance on virgin resources and minimize environmental impact.

Energy Consumption: Materials requiring less energy for production and exhibiting lower frictional losses during operation contribute to overall sustainability.

Longevity and Maintenance: Materials with extended lifespans, reduced wear rates, and lower maintenance requirements offer enhanced sustainability by reducing replacements and associated resource consumption.

End-of-Life Considerations: Biodegradable or recyclable materials contribute positively to sustainability by minimizing waste generation and promoting circularity.

In conclusion, Pressure distribution, contour and peak curve for bearing [14] the transition towards sustainable materials for journal bearings represents a significant stride in reducing the environmental footprint of machinery. Continued research and development in this field are crucial for advancing materials that offer improved performance, durability, and reduced environmental impact throughout their life cycle. By prioritizing sustainable materials in journal bearings, industries can contribute to a more eco-friendly and resource-efficient future.

5. FUTURE PROSPECTIVE

The future prospects of journal bearing materials are promising, marked by ongoing research, technological advancements, and a growing emphasis on sustainability and performance. Several key directions indicate the evolution and potential of these materials:

Advanced Composite Materials: The future of journal bearing materials lies in the development of advanced composite materials that combine various elements like polymers, ceramics, and nanoparticles. These composites offer superior strength, reduced friction, and enhanced wear resistance compared to conventional materials. Researchers are exploring innovative combinations to create materials that exhibit optimal properties for specific applications, such as high-temperature environments or extreme load conditions.

Nanotechnology Integration: Nanotechnology presents immense potential in enhancing the properties of journal bearing materials. Nanostructured materials, such as carbon nanotubes, graphene, and nano-composites, offer remarkable strength, durability, and self-lubricating capabilities. Integrating nanotechnology into bearing materials can significantly reduce friction, improve load-bearing capacity, and increase efficiency while maintaining longevity.

Smart and Self-Monitoring Materials: The future envisions the integration of sensors and smart technologies within bearing materials. These materials will possess self-monitoring capabilities, allowing real-time assessment of conditions like temperature, pressure, and wear. By providing predictive maintenance insights, these smart materials can prevent failures, optimize performance, and prolong bearing life, leading to increased reliability and reduced downtime.

Bio-inspired Materials: Drawing inspiration from natural structures and mechanisms found in living organisms, bio-inspired materials offer innovative solutions for journal bearings. Mimicking the design principles of biological structures such as bones or shells can lead to materials with exceptional strength, resilience, and self-healing properties, contributing to longer-lasting and more robust bearings.

Focus on Sustainability: Sustainability remains a driving force in material development. Future materials for journal bearings will prioritize eco-friendly compositions, utilizing renewable resources, recycled materials, or bio-based alternatives. Manufacturers are increasingly considering life cycle assessments to ensure minimal environmental impact throughout the material's entire lifespan, from production to disposal or recycling.

Additive Manufacturing (3D Printing): Additive manufacturing techniques, like 3D printing, offer the potential for customized and complex bearing designs. This method allows for intricate geometries, optimizing load distribution and performance. Additionally, 3D printing reduces material waste and energy consumption compared to traditional manufacturing processes, contributing to sustainability.

Data-Driven Material Design: Time dependent behavior curve for bearing [15] with advancements in computational modeling and data analytics, the future of journal bearing materials involves data-driven material design. Machine learning algorithms and simulations aid in predicting material behavior, optimizing formulations, and accelerating the discovery of novel materials with tailored properties, leading to faster innovation cycles.

In summary, the future of journal bearing materials is characterized by a convergence of advanced technologies, sustainability-driven approaches, and a quest for superior performance. Continued research and collaboration across disciplines will pave the way for materials that offer enhanced durability, reduced friction, improved efficiency, and minimal environmental impact, contributing to the evolution of more resilient and sustainable machinery across industries.

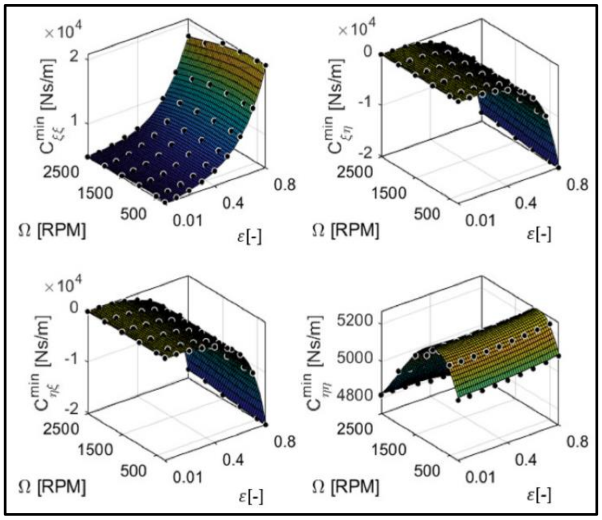

Figure 5. Time dependent behavior curve for bearing [15]

6. CONCLUSION

Selecting the appropriate bearing material stands as a pivotal phase in equipment design, exerting a profound impact on overall operational efficiency. Designers must judiciously opt for materials that align with the specific bearing requisites. An array of bearing materials is available, with Babbitt being the preferred choice among engineers, particularly in scenarios where fatigue strength is not a primary concern. Babbitt materials excel in supporting low-speed, steady shafts under light loads. Despite the emergence of numerous new bearing materials, ongoing research persists on 'Babbitt' to comprehensively understand its tribological behavior across diverse operating conditions and enhance its fatigue strength. Aluminum-based and copper-based bearing materials showcase superior fatigue strength when compared to Babbitt. However, they fall short in other crucial properties. To bolster these deficiencies, overlaying Babbitt on aluminum or lead bronze backup sleeves is a viable solution. These composite materials prove suitable for supporting moderate to higher speeds with medium to high loads, demonstrating commendable performance even under elevated temperatures.

Due to their exceptional properties, ceramics are well-suited for bearings operating at extremely high temperatures. In scenarios where lubrication is unfeasible, polymer bearings have replaced many metal bearings. These polymer bearings are suitable for applications ranging from low to high load support. Both micro and nano-composites can be precisely tailored to meet specific requirements, resulting in a wide array of available composites currently in use or under development. These composites are capable of functioning with minimal or no lubrication. Ongoing research in polymer-based composite bearings aims to create materials that offer heightened wear resistance and low coefficients of friction (COF), serving as alternatives to heavy metal bearings while excelling in lubrication-free or minimal lubrication environments.

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