International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 15, Issue 1 [January 2026] PP: 109-118

The Influence of Material Composition on the Performance Characteristics of Journal Bearing in High-Speed Steam and Gas Turbine Engines

Nwakamma Ninduwezuor-Ehiobu
Entrust Solutions Group, Canada

Abstract
This literature review provides a focused analysis of journal bearing materials used in high-speed steam and gas turbines, which operate under intense mechanical stress, high thermal gradients, and challenging lubrication regimes. The review highlights how material composition directly influences key performance indicators such as load capacity, strength, thermal conductivity, and wear resistance.
Special attention is given to microstructural characteristics and alloying strategies that impact tribological behavior, fatigue life, and thermal deformation. Laboratory methods, including tribometers and pin-on-disk tests, are reviewed alongside industrial case studies and modeling tools like finite element analysis (FEA) and computational fluid dynamics (CFD), offering insight into real-world material behavior.
The study discusses trade-offs between performance, manufacturability, and cost, comparing traditional materials like babbitt and copper-lead alloys with advanced alternatives such as ceramic reinforced composites and functionally graded materials (FGMs). Innovations such as nanostructured coatings and AI-driven material design are noted for their potential to optimize reliability and reduce downtime.
Sustainability also emerges as a critical theme, with increased attention to lead free and recyclable materials and the application of life cycle assessment (LCA) in material selection. This review synthesizes current research to guide the development of efficient, durable, and environmentally responsible bearing systems for modern turbines.
Keywords: *"Journal bearings, steam turbines, gas turbines, tribology, material composition, high-speed rotation, thermal conductivity, fatigue resistance, wear behavior, composite materials, finite element analysis (FEA), lubrication, surface coatings, nanostructured materials, functionally graded materials (FGMs), sustainable materials, bearing life cycle, high-performance alloys".*

Date of Submission: 08-01-2026 Date of acceptance: 20-01-2026

I. Introduction

Journal bearings are fundamental to the operation of high-speed rotating machinery, particularly in steam and gas turbines. These bearings support rotating shafts by facilitating smooth motion under radial loads, utilizing a film of lubricant to reduce direct surface contact, friction, and wear (Mandal, Dey, & Pratihar, 2022; Kumar & Satapathy, 2023). In turbine systems, where operational environments are characterized by elevated temperatures and extreme rotational speeds, the reliability and performance of journal bearings are crucial to overall system stability and efficiency (Zaccardo & Buckner, 2021; Doshi et al., 2021).

Bearings in such applications are routinely exposed to dynamic mechanical stresses, high-frequency vibrations, and significant thermal gradients. These operating conditions demand materials with superior mechanical strength, thermal stability, and fatigue resistance. Even minor defects, such as increased surface roughness or thermal softening, can escalate rapidly and result in operational failures (Peng et al., 2022; Fahmi et al., 2022). Given that turbine shafts may rotate at speeds exceeding 3000rpm, the margin for bearing degradation is extremely narrow (Doll, 2022; Kirshenbaum et al., 2023).

The material composition of journal bearings significantly influences their ability to perform under such conditions. Ideal bearing materials must exhibit high load bearing capacity, excellent thermal conductivity, chemical inertness, and a low coefficient of friction. Moreover, they must retain these properties under cyclic loading and prolonged exposure to heat and vibration (Ouyang et al., 2022; Liu et al., 2022). Inadequate material performance can lead to wear, seizure, thermal cracking, or failure of the lubrication film. Surface fatigue, scuffing, and chemical incompatibilities with lubricants are frequent causes of bearing degradation (Hong et al., 2023; Zhang et al., 2023).

Advances in turbine design and performance targets have intensified the search for materials that can meet stringent operational requirements. While traditional materials such as Babbitt and copper-lead alloys remain in use, there is growing interest in reinforced aluminum alloys, polymer composites, and coatings engineered for specific tribological properties (Bianchini et al., 2022; Veers et al., 2023). Contemporary research focuses on aligning material microstructures and surface treatments with application-specific demands.

This study explores the relationship between material composition and journal bearing performance in high-speed turbine environments. By examining how variations in alloy constituents, microstructures, and surface modifications influence parameters like wear resistance, thermal stability, and lubrication compatibility, the research aims to identify materials best suited for extreme service conditions. The analysis incorporates both laboratory-based tribological testing and simulation data to establish a clear link between material properties and bearing reliability (Salwan et al., 2021; Zhai et al., 2021).

The outcomes of this research have practical implications for turbine designers, plant operators, and materials engineers. By optimizing material selection for journal bearings, improvements can be made in turbine efficiency, maintenance intervals, and service life all of which are vital for cost-effective and sustainable energy production.

II. Methodology

This study employed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to systematically identify, screen, and evaluate literature related to the effects of material composition on journal bearing performance in high-speed steam and gas turbines. PRISMA's structured protocol ensures transparency, reproducibility, and a comprehensive evidence base.

A targeted search was conducted across major academic databases, including Scopus, Web of Science, ScienceDirect, and IEEE Xplore, using Boolean combinations of keywords such as *"journal bearing," "material composition," "steam turbine," "gas turbine," "thermal conductivity,"* and *"tribological performance."* Filters were applied to include only peer-reviewed articles, published between 2000 and 2024, and written in English.

Initial searches yielded 843 articles. After removing 193 duplicates, 650 records remained. Abstract and title screening excluded 486 irrelevant studies. From the remaining 164 full-text articles, 97 were removed due to insufficient focus on material-specific performance. A final set of 67 studies was retained for qualitative synthesis.

Inclusion criteria were defined as studies involving experimental, computational, or analytical evaluations of how material composition affects bearing metrics such as friction, wear, lubrication, thermal behavior, and load capacity. Excluded were reviews without primary data, non-English studies, conference abstracts, and those focused on bearing failures unrelated to materials.

Data from each study were extracted using a standardized template, capturing material type (e.g., babbitt, copper-lead, aluminum composites), operational conditions (e.g., speed, load, temperature), lubrication regimes, and performance outcomes. Where applicable, tribological tests (e.g., pin-on-disc), thermal analysis, and numerical simulations (e.g., finite element models) were noted.

To assess quality, a modified Cochrane Risk of Bias Tool was applied, evaluating aspects such as experimental repeatability, sample adequacy, control conditions, and material characterization methods. Most studies demonstrated moderate to low risk of bias, with a few lacking methodological clarities.

Overall, the findings showed that bearing material composition strongly influences durability and functional efficiency, especially in extreme operating environments. Materials like copper-lead alloys provided superior heat dissipation, while aluminum-based composites reinforced with silicon carbide or graphite fibers exhibited enhanced wear resistance. Surface treatments such as diamond-like carbon (DLC) and ceramic coatings further reduced friction, especially under variable or transient conditions.

The PRISMA-based approach enabled a robust synthesis of current trends, material performance trade-offs, and future directions in journal bearing design. This methodological rigor contributes significantly to the development of reliable, high-efficiency turbine systems.

2.1 Journal Bearing Fundamentals

Journal bearings operate on the principle of hydrodynamic lubrication, wherein a pressurized film of lubricant forms between the rotating shaft (journal) and the stationary bearing. This film eliminates direct surface contact, significantly minimizing friction and wear during high-speed operation (Liu et al., 2021; Bouyer et al., 2022). As the shaft spins, it entrains lubricant into a wedge-shaped clearance, generating pressure that supports the radial load and maintains shaft alignment.

This pressure distribution is governed by Reynolds' equation, which considers lubricant viscosity, shaft speed, geometry, and clearance. Efficient film formation depends on maintaining sufficient viscosity and speed; failure to do so may transition the system into boundary or mixed lubrication regimes, increasing the risk of contact and damage (Whalen, 2022).

The load-carrying capacity of a journal bearing is directly tied to the hydrodynamic pressure profile, influenced by bearing dimensions and material properties. Proper centering of the shaft within the bearing helps avoid instability phenomena like oil whirl and whip, particularly critical in turbine applications where high-speed rotation can amplify vibration (Medvedovski, 2023).

Key performance metrics include the coefficient of friction, which ideally ranges between 0.001 and 0.01 under full-film lubrication, promoting mechanical efficiency. However, disruptions in lubrication increase friction, heat, and wear. Load capacity, another crucial factor, must be sufficient to prevent film collapse and metal contact under dynamic loads (Ouyang et al., 2022).

The Sommerfeld number defines speed limits for journal bearings, integrating parameters like load, speed, and viscosity. Exceeding this limit without design compensation (e.g., enhanced cooling or material changes) risks film breakdown and bearing instability (Shen et al., 2023).

Wear resistance is essential, especially during transient operations or when contaminants are present. Factors such as material hardness, surface finish, and coating technology impact the wear rate. Furthermore, thermal conductivity of the bearing material affects heat dissipation; high-conductivity materials like copper-based alloys are preferred to prevent overheating and preserve lubricant properties (Yilmaz & Erdemir, 2021).

In summary, journal bearings in high-speed turbines depend on optimal lubrication dynamics, load capacity, thermal behavior, and material characteristics. A deep understanding of these interrelated parameters is critical for designing durable, efficient, and high-performance bearing systems.

2.2 Material Requirements in High-Speed Applications

Journal bearings in high-speed systems such as steam and gas turbines must endure extreme conditions including high rotational speeds, elevated temperatures, and fluctuating loads. To ensure operational reliability, the selection of bearing materials must prioritize mechanical strength, thermal stability, tribological performance, and chemical resistance (Zhai et al., 2021; Du et al., 2022).

Mechanically, materials must exhibit a balance of strength, hardness, ductility, and fatigue resistance. High tensile strength prevents permanent deformation under heavy dynamic loads, while appropriate hardness resists scoring and abrasive wear. Excessively hard materials, however, may become brittle. Ductility is essential to tolerate shaft misalignments and thermal expansion without cracking, while fatigue strength protects against failure from cyclic stresses typical of turbine environments (Wu et al., 2021; Mankhi et al., 2022).

Tribological performance is equally vital. Materials should offer low friction, high wear resistance, and lubricant compatibility. Low friction enhances energy efficiency and reduces internal heat, while wear resistance ensures long service life and stable shaft alignment. Materials such as diamond-like carbon (DLC) or ceramic coatings are increasingly used to improve surface durability in demanding applications.

Lubricant compatibility is crucial for maintaining stable hydrodynamic films. Incompatible materials may react chemically, degrading the lubricant and impairing bearing function. Alloys like babbitt provide additional benefits such as embeddability and conformability, helping accommodate contaminants without damaging the shaft (Ghasemi et al., 2021; Beeley & Smart, 2023).

Thermally, materials must resist oxidation, softening, and structural degradation at high temperatures. Resistance to thermal and chemical breakdown preserves bearing geometry and functionality during prolonged turbine operation. Oxidation-resistant alloys or protective coatings help reduce surface scaling and material loss in steam-rich or combustion environments.

High thermal conductivity is also critical, enabling rapid heat dissipation from the bearing interface to surrounding structures. Copper-based alloys are commonly used for this purpose but may require reinforcement due to their relative softness (Minneci et al., 2021; Basit et al., 2023).

Journal bearing materials for high-speed turbines must be optimized across multiple physical and chemical properties to ensure performance, durability, and reliability under extreme service conditions.

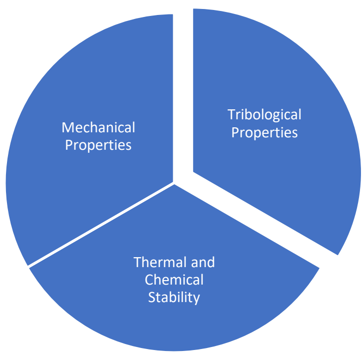

Figure 1: Material Requirements in High-Speed Applications

2.3 Common Journal Bearing Materials and Alloys

The performance of journal bearings in high-speed turbine systems depends significantly on the material's ability to withstand thermal, mechanical, and chemical stresses. Traditional metal alloys and newer composites have been optimized to improve attributes such as fatigue resistance, wear behavior, thermal conductivity, and conformability (Dong et al., 2021; Parveez et al., 2022).

Babbitt metals remain a widely used material, especially in legacy systems. Composed of tin or lead with additives like copper and antimony, tin-based Babbitts are favored for their corrosion resistance and fatigue strength, while lead-based variants offer cost advantages but lower performance. These materials provide excellent embeddability and lubricant compatibility, although their low load capacity and thermal conductivity limit use in modern high-load turbines. As such, Babbitt linings are often bonded to stronger steel or bronze backings to enhance structural integrity (Tawiah et al., 2023).

Copper-lead alloys offer higher strength and superior thermal conductivity, making them suitable for high-load, high-speed turbines. Typically composed of 20–25% lead within a copper matrix, these alloys combine the mechanical benefits of copper with the friction-reducing properties of lead. However, their susceptibility to corrosion and environmental restrictions on lead use require overlays of softer metals or design refinements (Abdal et al., 2023).

Aluminum-based alloys are valued for their lightweight nature, fatigue resistance, and corrosion tolerance. Common alloying elements include tin, silicon, and copper. Although they offer good wear resistance and are more cost-effective, their lower embeddability compared to Babbitt can pose reliability challenges during contamination or shaft misalignments. Al-SiC composites and surface treatments like micro-texturing are increasingly applied to address these limitations (Dharnidharka et al., 2021; Song et al., 2023).

Polymer-based bearings, such as PTFE and PEEK composites, are gaining attention for specialized applications like aerospace or cryogenics. These materials offer low friction, high chemical resistance, and in some cases, self-lubricating properties. Their low density and damping capacity help reduce noise and vibration. However, limited thermal conductivity and load capacity restrict their use in core turbine components.

To enhance material performance, surface coatings and textures are applied. Diamond-like carbon (DLC) and titanium nitride (TiN) coatings reduce friction and improve wear resistance, especially during lubrication failures. DLC is known for its chemical inertness and performance in dry conditions, while TiN offers high hardness and thermal stability (Beake, 2021; Wang et al., 2021). These coatings are typically applied using PVD or CVD techniques.

Surface micro-texturing, such as dimples or grooves, is another strategy that enhances lubricant retention, promoting better hydrodynamic film formation and reducing start-up wear.

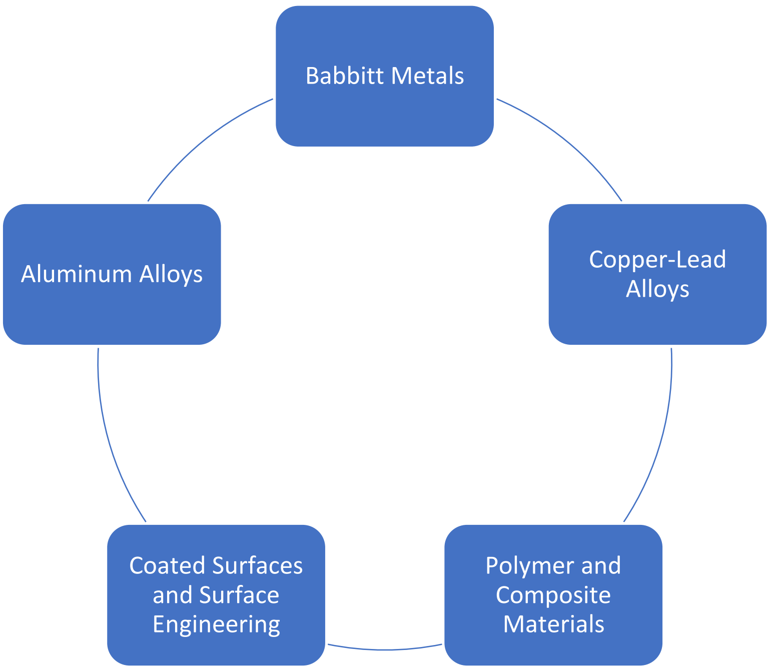

Figure 2: Common Journal Bearing Materials and Alloys

2.4 Influence of Material Composition on Performance

The composition of journal bearing materials directly governs their performance in high-speed turbine environments, impacting load capacity, thermal conductivity, tribological behavior, fatigue, and creep resistance

(Mills et al., 2021; Fu et al., 2022). These characteristics are interrelated and influenced by both the constituent elements and their microstructural arrangement (see Figure 3).

Load-carrying capacity depends on elastic modulus and yield strength. Materials with higher stiffness such as copper alloys or ceramic-reinforced aluminum composites maintain lubricant film stability under pressure. Alloying elements like nickel or antimony increase yield strength without sacrificing ductility, helping prevent plastic deformation in stress-prone areas and enhancing structural integrity during dynamic loading.

Thermal conductivity, crucial for dissipating heat from the bearing interface, is also composition sensitive. While pure copper offers excellent conductivity, it lacks sufficient strength. Therefore, copper-tin or copper-chromium alloys offer a balance between heat transfer and mechanical performance (Adeniyi & Ighalo, 2021). Metal matrix composites reinforced with SiC or AlN particles further improve heat dissipation and maintain thermal stability (Sharma et al., 2021).

Tribological properties including friction and wear are influenced by grain structure, phase distribution, and the presence of solid lubricants. Babbitt alloys, with their soft matrix and embedded hard particles, allow conformability and low friction under boundary lubrication. In contrast, aluminum composites with uniform ceramic dispersion offer higher wear resistance. Additives like graphite or MoS_2 lower friction, while surface coatings such as DLC or nitrides further enhance durability, though they must be chemically compatible with the base material (Zeng & Ning, 2021; Kolawole et al., 2023).

Fatigue resistance is vital under cyclic stresses. Alloys like Cu-Sn or Ni-based materials, strengthened with Ti or V, exhibit improved crack resistance and fatigue life due to refined grain structures. Similarly, creep resistance—the ability to resist time-dependent deformation—depends on alloying with elements like W, Mo, or Co, which stabilize grain boundaries and reduce dislocation motion under thermal stress (Grilli et al., 2021; Ou et al., 2023).

Material composition and microstructural engineering are critical to improving journal bearing performance. Through alloying, reinforcement, and surface modification, materials can be optimized to handle the high speeds, temperatures, and loads characteristic of turbine operations.

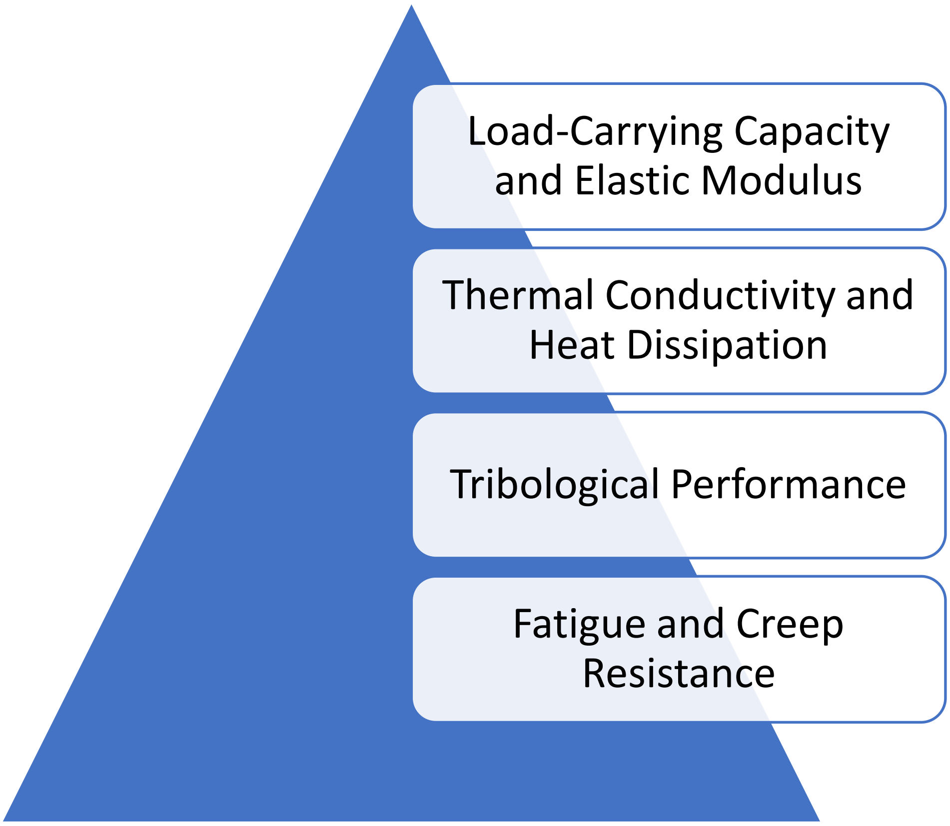

Figure 3: Influence of Material Composition on Performance

2.5 Case Studies and Experimental Findings

Understanding journal bearing performance in high-speed turbine environments requires a synergy of laboratory tests, field case studies, and computational simulations (Ghorbani et al., 2021; Yang et al., 2022). Each method offers unique insights into how materials respond to thermal, mechanical, and lubrication stresses under real-world conditions.

Laboratory testing, particularly using pin-on-disk and tribometer setups, plays a foundational role in characterizing wear behavior, friction, and thermal resilience. In pin-on-disk tests, a journal material sample is loaded against a rotating disk, simulating shaft contact under various lubrication and temperature conditions. Results consistently show that tin-based Babbitt alloys, while conformable, experience higher wear at elevated temperatures compared to aluminum or copper-lead alloys.

Tribometers allow more complex motion and lubricant analysis, assessing how well a material supports film formation and resistance to breakdown. Materials enhanced with DLC coatings or ceramic reinforcements generally exhibit lower friction and better wear resistance under simulated turbine conditions (Winnicki, 2021; Liu et al., 2023).

Industrial case studies validate lab findings. For instance, replacing lead-based Babbitts with aluminum-tin alloys in a 25 MW gas turbine extended bearing life by 30%, thanks to improved thermal conductivity and fatigue strength. In a 500 MW steam turbine, switching to polymer-metal composite bearings resulted in better damping and fewer failures during start-up and shutdown events. DLC-coated bearings in aerospace turbines have demonstrated exceptional resistance to oil starvation and thermal gradients, particularly in high-altitude, variable-load environments (Fragiacomo et al., 2023; Shezan et al., 2023).

Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) complement experimental work by modeling stress, temperature, and lubricant behavior. FEA has been used to compare deformation zones in copper-lead vs. aluminum bearings, while also showing how TiN coatings reduce stress concentrations and heat buildup. CFD models simulate lubrication film dynamics, capturing pressure distribution and film thickness under adverse conditions like misalignment or transient loads.

Together, these methods form a comprehensive toolkit for predicting, validating, and improving journal bearing design and material selection in demanding turbine systems (Hess & Shang, 2022; Shutin et al., 2023).

2.6 Challenges and Considerations

Journal bearings in high-speed turbines must withstand extreme thermal, mechanical, and chemical stresses, making material selection a multifaceted engineering challenge (Brun et al., 2021; Chen et al., 2021). Engineers must balance performance, cost, machinability, and lubricant compatibility—each with its own trade-offs.

High-performance materials like MMCs, ceramic coatings, and advanced alloys offer excellent wear resistance and thermal stability, but their cost and processing complexity can limit practical use. For instance, while Al–SiC composites provide a strong strength-to-weight ratio and high thermal conductivity, they are more difficult to machine than Babbitt or copper-lead alloys, increasing manufacturing costs (Jiang et al., 2021).

Babbitt metals remain attractive for their low cost, ease of casting, and good embeddability, but are limited in high-speed, high-temperature operations due to their low melting points and strength. Similarly, copper-based alloys offer excellent thermal conductivity but may need reinforcement or coatings to handle mechanical wear.

Machinability is another critical factor. Materials requiring special tooling or finishing extend production time and may complicate repair processes. This is a key consideration for large-scale turbine installations or when in-situ repairability is essential.

Equally important is the interaction between bearing materials and lubricants. Incompatible combinations can lead to additive degradation, surface fouling, or reduced film stability. For example, some copper alloys catalyze additive breakdown, increasing the risk of wear or corrosion. Similarly, surface-active elements in Babbitt may interfere with film formation under high loads or temperatures (Jiang et al., 2021).

Tribochemical reactions over time can alter surface topography and frictional behavior, negatively impacting lubrication regimes. Selecting materials with chemically stable surfaces and known lubricant compatibility is therefore essential for reliability and efficiency (Tang et al., 2023).

Practical repairability and surface renewal are also key considerations. Ceramic coatings may crack or delaminate under cyclic loading, complicating maintenance, while Babbitt linings are easier to re-cast or re-bond, making them suitable for systems requiring routine servicing (Han et al., 2023).

Surface treatment methods like laser cladding, electroplating, or diamond burnishing must align with the base material's metallurgy to ensure durable bonding. Materials that support cost-effective refurbishment without degrading performance are preferred in systems where downtime carries high financial risk (Xu et al., 2022; Geng et al., 2023).

2.7 Future Trends and Innovations

As turbine systems evolve toward higher efficiency, reliability, and sustainability, journal bearing materials are undergoing significant innovation. Emerging trends focus on nanostructured and functionally graded materials (FGMs), AI-driven material design, and eco-friendly alternatives (Binali et al., 2022; Veers et al., 2023).

Nanostructured materials, with grain sizes below 100 nm, exhibit enhanced hardness, thermal stability, and wear resistance, making them ideal for high-speed bearing applications. Their fine microstructures reduce surface degradation, extend service life, and improve performance under thermal cycling and dynamic loads.

Functionally graded materials optimize performance by gradually varying composition across the bearing's cross-section. For example, a ceramic-reinforced surface provides wear resistance, while a ductile core improves thermal conductivity and mechanical resilience. FGMs mitigate thermal cracking and delamination, making them well-suited for the demanding thermal gradients in turbines.

The integration of artificial intelligence (AI) and machine learning is transforming journal bearing development. AI algorithms trained on materials datasets can predict optimal compositions and surface treatments based on desired outcomes like low friction or high fatigue resistance (Rossopoulos & Papadopoulos, 2022). These tools reduce reliance on extensive trial-and-error testing and support real-time design optimization and health monitoring.

For instance, AI-driven models can recommend alloy modifications tailored to specific lubrication regimes or predict degradation trends from sensor data, allowing predictive maintenance and failure prevention. This digital-materials fusion accelerates innovation and enhances system reliability.

Environmental sustainability is another driving force in material innovation. As regulations phase out lead-based Babbitt alloys due to toxicity, attention is shifting to lead-free and biodegradable alternatives such as aluminum-tin alloys and natural fiber-reinforced composites (Zhang et al., 2021; Afroz et al., 2023).

Recyclability is becoming a key selection criterion. Aluminum-based materials, with mature recovery systems and low environmental impact, align well with circular economy goals. Life-cycle assessment (LCA) tools now guide decisions by evaluating environmental impact from production to disposal (Thien et al., 2022).

The future of journal bearings lies in multifunctional materials, data-driven design, and environmentally responsible engineering, aligning with the broader goals of efficiency, longevity, and sustainability.

III. Conclusion

The performance of journal bearings in high-speed steam and gas turbines is fundamentally linked to the selection and engineering of suitable materials. Operating under elevated temperatures, high rotational speeds, and cyclic mechanical loads, these bearings demand materials that balance mechanical strength, thermal conductivity, wear resistance, and chemical stability. Through a comprehensive review of traditional and advanced materials including babbitt alloys, copper-lead systems, aluminum composites, and polymer-based solutions this study highlights the critical role of material composition and microstructure in determining tribological behavior, fatigue life, and thermal performance.

Laboratory-based tribological testing, industrial case studies, and computational simulations collectively offer valuable insights into material performance under operational stresses. Techniques such as pin-on-disk testing and tribometer analysis provide quantitative assessments of wear and friction, while field evidence supports the application of advanced materials like DLC-coated bearings in reducing failure rates. Simulation tools like FEA and CFD further aid in visualizing stress distribution, lubrication film behavior, and thermal response, allowing engineers to optimize bearing design without costly prototyping.

Material-lubricant compatibility, manufacturability, and repairability emerge as essential considerations, especially in high-cost, high-risk turbine applications. The use of coatings, functionally graded structures, and composite reinforcements enables materials to meet complex service demands, though trade-offs in cost and processing must be evaluated.

Looking ahead, advancements in nanostructured materials, functionally graded composites, and AI-driven material discovery are poised to reshape the future of journal bearing design. Simultaneously, sustainability concerns are driving the development of lead-free and recyclable materials, supported by life-cycle assessment tools that evaluate environmental impacts across the product lifespan.

In conclusion, achieving high-performance journal bearings in turbine systems requires an integrated approach that combines materials science, tribology, digital modeling, and sustainability principles. Ongoing innovation in these areas will be key to improving turbine efficiency, reliability, and environmental compliance in next-generation energy systems.

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