Review Article

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A review: Enhancing tribological properties of journal bearings composite materials

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Abstract: Tribology is the science of studying friction, wear, and lubrication. Composite materials consist of two or more constituents (phases): the discontinuous phase represents the reinforcement and the continuous phase represents the matrix. Journal bearing is manufactured from various composite materials. This article reviews the literature on improving the tribological properties of journal bearings made of composite materials (polymer matrix composite materials and metal matrix composite materials) by dividing the previous studies into six primary sections depending on the kinds of composite materials. An efficient method was utilized to solve the problems of composite journal bearings in water lubrication such as wear resistance, reduced friction, and increased service life of journal bearings in various applications especially in ships. The impact of composite materials, which were added through thermoplastic such as polytetrafluoroethylene (PTFE), polyether-ether-ketone, POM, and PA_{66}, thermoset such as epoxy, polyester, and phenolic reinforced with fibers, and thermoplastic with thermoset (PTFE/epoxy composite) to reduce wear rate and coefficient of friction, and also the addition of nanomaterials to composite journal bearing to enhance the tribological properties in various applications were examined. The last section used metal matrix composite reinforced to other metal or alloy to give the attractive mechanical properties used to improve wear resistance and friction coefficient of journal bearing. The novelty of this article lies in the comprehensive analysis of various composite materials and their effect on the tribological properties of journal bearings, providing future insights into bearing design and optimization to improve performance.

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1 Introduction

The science and engineering of surfaces interacting in relative motion is known as tribology, and it encompasses the study and application of the concepts of friction, wear, and lubrication [1]. In its basic form, a journal bearing consists of a rotating shaft (referred to as the journal) secured within a stationary housing, with a thin film of oil positioned between them. Primarily, the function of such a bearing is to sustain a load exerted on a shaft, facilitating relative movement between different components of the machinery [2], as illustrated in Figure 1.

Journal bearings are manufactured from different composite materials. Composites have two or more phases, where the discontinuous phase represents the reinforcement, which is usually more solid and rigid than the second phase (matrix) representing the continuous phase. There are many types of reinforcement in composites, such as particles, fibers, and plates, which improve the overall tribological properties of the matrix.

Polymer matrix composites (PMCs) are a type of composites that have high strength and low cost and two types of polymer as a matrix (thermoplastics and thermosetting polymer) [3] as shown in Figure 2 [4]. Metal matrix composites (MMCs) are an important part of engineering materials that have increasingly replaced a number of traditional materials in the bearing, marine, and sports industries due to their lightweight and attractive mechanical properties [5]. In this type, non-metallic materials are incorporated into metal or alloy as reinforcement to obtain a new material with attractive engineering properties, such as enhanced tensile strength, ductility, and tribological behavior [5]. Also, can enhance the tribological properties by adding nanomaterials, because of their small size and high surface area, nanoparticles are considered the technology of the future for the twenty-first century. They also possess many

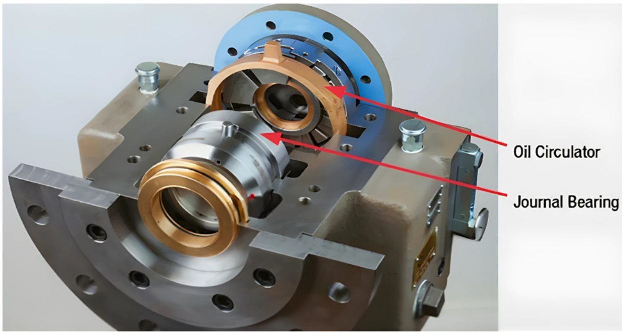

Figure 1: Combination of journal bearing [6].

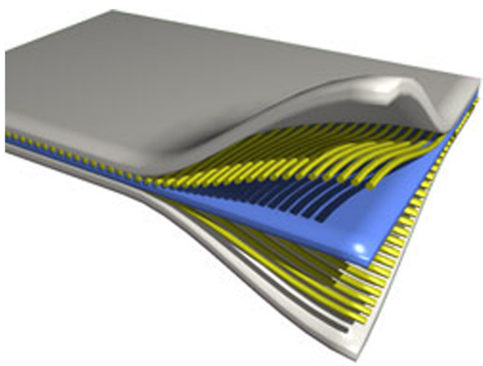

Figure 2: Combination of composite material [4].

other astonishing qualities. Nanoparticles are being employed more and more to solve engineering issues and enhance journal-bearing performance [7]. Using composite materials to improve the tribological qualities of journal bearings has been the subject of several recent investigations. For instance, a study conducted by Zhang *et al.* examined the application of carbon fiber (CF)-reinforced polymer composites in journal bearings and found that wear resistance had significantly improved [8]. An additional study by Bao *et al.* looked into adding graphene nanoparticles to composites made of epoxy, showing improved lubrication and decreased friction [9]. In their study, Shiv *et al.* investigated the impact of silicone-based nanofillers and hybrid nanofiller-reinforced polymer nanocomposites, leading to enhanced friction and wear resistance [10]. Furthermore, Chernets *et al.*'s study examined PA6 composites to improve the tribological properties as compared to metal polymers in dry friction bearings [11]. Finally, Pande *et al.*'s research examined the performance of journal bearings composed of silicon carbide and cadmium sulfide-reinforced aluminum (Al) alloy composites, and the results showed improved mechanical and wear properties [12]. These studies serve as comparisons to assess how well various composite materials enhance the tribological characteristics of journal bearings and highlight recent advancements in the field.

2 Tribological properties of journal bearing

Friction and wear in Figure 3 always occur in machine parts that work together. These negatively affect the efficiency of machines. Henceforth, it has become imperative to ascertain the frictional characteristics of machinery constituents. Materials employed in journal bearings possess various attributes, including diminished coefficient of friction (COF), elevated load-bearing capacity, and heightened thermal conductivity, compatibility, and robust resistance to abrasion. Such traits significantly impact the endurance and longevity of the bearing [13]. Numerous theories have been postulated to elucidate the occurrence of adhesion wear. Adhesive wear transpires when two surfaces undergo relative motion, wherein this movement proceeds unidirectionally or sequentially due to applied load and adhesion. This adhesion will be highly efficient and capable compared to a clean surface, and adhesion will occur between a number of these protrusions, which are larger in size and increase in area during movement [14]. The imperative property of journal bearings is wearing resistance, necessitating extensive research endeavors to enhance this attribute. Scholars have scrutinized material friction and wear characteristics extensively, recognizing their detrimental influence on the efficacy and durability of machine elements. Much of the scholarly discourse has focused on investigating these phenomena across varied environmental conditions. Consequently, there is significant interest in evaluating the impact of loads and velocities on material friction and wear behavior [15]. The lubrication (Figure 3) is the process or technique used to reduce or minimize the wear of one or both surfaces nearby, moving relative to each other by introducing a substance called lubricant between the surfaces to bear the load (pressure generated) and the opposing surfaces. When the surfaces of two objects touch and rub, friction and abrasion occur, so avoid abrasion on the surface and use lubricants generally. These layers of material separate surfaces and solid objects in contact and are very thin and often difficult to notice. In general, the thickness of this film ranges from 1 to 100 μm [16].

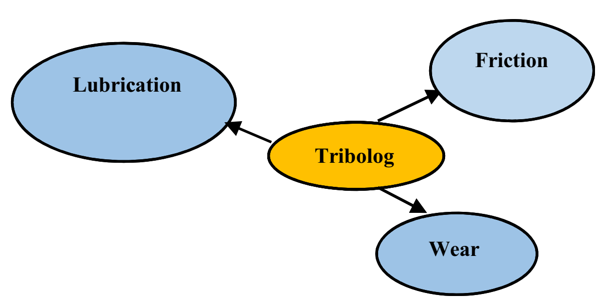

Figure 3: Tribological properties.

3 Tribological properties of composite materials

The four primary categories of tribomaterials, as depicted in Figure 4, encompass advanced materials like ceramic matrix composites, PMCs, carbon–carbon composites, and MMCs. Tribological materials exhibit distinctive characteristics encompassing wear, friction, lubrication, and mechanical properties, which are integrated into the design of materials intended for tribological purposes. The availability range of fiber reinforcements, fillers, and matrices and possessing technologies provide a comprehensive scope for customizing properties in composite materials as required for a particular application.

Materials composed of composites can be engineered to possess elevated tensile strength, modulus, and impact strength, thereby ensuring the preservation of structural integrity and offering enhanced wear resistance. In the case of antifriction materials employed in journal bearings, beyond considerations of structural robustness and dimensional stability, it is imperative for the material to exhibit a diminished COF and minimal wear [17].

4 Enhanced the tribological properties

Several researchers have enhanced the tribological properties using various composite materials and classified them according to Figure 5.

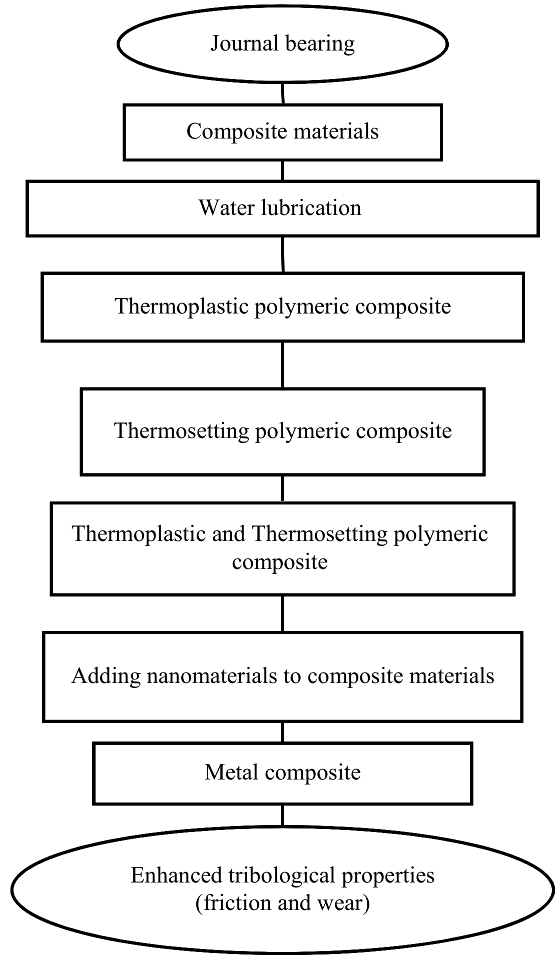

Figure 5: Methodology used to improve tribological properties in composite journal bearing.

4.1 Water-lubricated composite journal bearings

Several studies enhanced tribological properties in the water lubricant hydrodynamic journal bearing. Hirani and Verma [18] investigated the bearing wear problem in Indian Coast Guard Ships as shown in Figure 6. They analyzed the mixed lubrication of four journal bearings

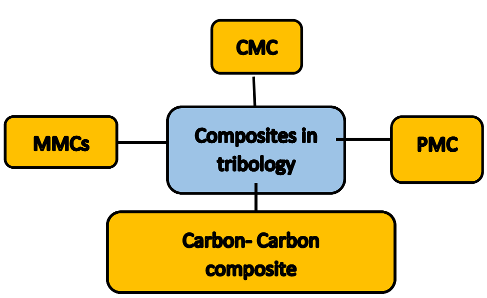

Figure 4: Types of composites.

Figure 6: Propeller shaft with bearings [18].

lubricated with seawater. Their results indicated that the dynamic viscosity increases with the increase in the rotational speed and particle size of seawater has no effect on the bearing wear. Also, all the four bearings have excessive and unplanned radial clearance which reduced their load capacity and results in rapid uneven wear. Solomonov [19] investigated the factors that improve the selection of water-lubricant bearing materials, model, and simulate the operating conditions of water-lubricated bearings. At the lowest sliding speed of 0.393 m/s, there was a notable increase in both the friction coefficient and specific wear rate, attributed to the boundary regime of lubrication and the adhesive abrasive wear characteristics of NF22 (Railko) material. Zhang *et al.* [20] outlined an effective approach for developing techniques and methodologies for a pin disc test rig, offering insights into determining the stiffness coefficients of hydrodynamic plain journal bearings lubricated with water. Furthermore, the diverse physical properties of water and oil across various bearing geometries and operational scenarios revealed a correlation between stiffness coefficient and load-carrying capacity. When the load was increased, a high stiffness coefficient in a small eccentricity ratio was obtained. Two materials, thermoset composite Nordon marine 605 and bronze material CuSn7Zn4Pb7-C, were used in water-lubricated composite journal bearing by Katana and Klarić [21]. The result showed that thermoset composite materials bearing lubricated sea water are much less harmful to the environment, but it is expensive and wear less than the bronze material as shown in Figures 7 and 8. The effect of surface texture on the tribological characteristics of water-lubricated rubber bearings in ships was investigated by Wang and Liu [22]. The tribological features of the flow field, such as pressure distribution within the water film, fluctuations in velocity, and the impact of water film thickness on the surface texture flow field, were examined by simulation studies. On the textured surface, the average velocity decreased, and water film pressure was the lowest. Wu *et al.* [23] studied the effect of three specimens of

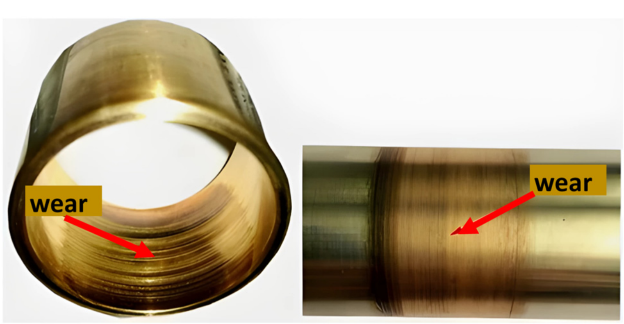

Figure 7: Bronze slide bearing and shaft wear [21].

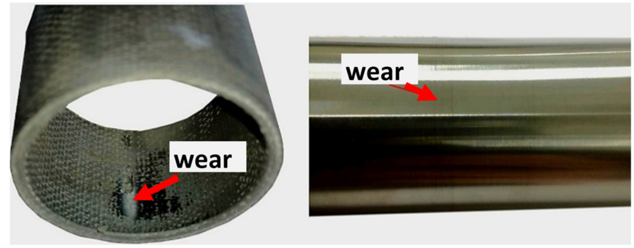

Figure 8: Composite slide bearing and shaft wear [21].

polymer materials water lubricant bearing (tenant, thordon SXL, and BTG rubber) as in Figure 9 on the tribological properties such as friction coefficient and wear rate. Rubber bearings exhibit greater suitability for operations at low speeds, attributed to their reduced friction and wear rates. Conversely, Gordon and tenant materials prove advantageous for heavy loads, given their lower friction and wear rates compared to rubber materials. Kim *et al.* [24] analyzed the effect of turbulence, elastic deformation, and the effect of inertia on the composite bearing in terms of load-carrying capacity and pressure field in a water lubricant journal bearing, and the analytical method was used to evaluate the elastic deformation by finite element (FE) analysis. According to the load-carrying capacity, the results showed that the turbulence increased about two times, and the laminar flow (elastic deformation) decreased the maximum pressure by 21%. Analysis was conducted by Georgios [25] on two sets of journal bearings, comprising one set of oil-lubricated bearings and another set of water-lubricated bearings, serving as the aft and fore bearings of the ship, respectively. The aim was to determine operational and tribological parameters during ship manufacturing. Through analysis, it is clear that the operation and performance of periodic bearing are significantly affected by the bushing liner design, especially in cases of high load bearing. The major findings of the study: this study includes several analyses of the tribological characteristics of composite journal bearings lubricated with water. Important discoveries include the rise in dynamic viscosity with rotational speed, the minimal impact of particle size on bearing wear, the relationship between load-carrying capacity and stiffness coefficient, and the advantages of thermoset composite materials over bronze in terms of wear resistance and environmental effects. Implication and justification of findings: These results have important ramifications for journal-bearing

Figure 9: Block specimen materials [23].

design and selection in maritime applications. There may be opportunities to optimize bearings for particular operating situations, as indicated by the increase in dynamic viscosity with rotational speed. The advantages of thermoset composite materials for the environment and wear resistance draw attention to the possibility of more long-lasting and sustainable bearing solutions. Advantages and disadvantages are as follows: this study's thorough examination of all the variables influencing the tribological characteristics of water-lubricated bearings is one of its advantages. The results' generalizability could be impacted by operational settings and possible material property variations, among other restrictions. To validate these findings in practical applications, more study is required.

4.2 Journal bearings of thermoplastic composite

Many researchers employed several thermoplastic materials to create the composite journal bearings depicted in Table 1 [26]. To obtain a good bearing material at light loads, graphite and polyimide (PI) fiber composites were studied to improve the journal bearing's friction coefficients. The results showed that these materials are promising candidates for low torque and sliding contact bearings at temperatures between 16 and 340°C (650°F). Jadhav *et al.* [27] studied the tribological behavior of composites journal bearing with polyether ether ketone (PEEK) as a base material and filler materials polytetrafluoroethylene (PTFE), molybdenum disulfide (MoS2), bronze. They investigated the wear rate of different materials and to suggested that the PEEK is the best material which minimizes the wear and gives the best values of parameters at which minimum wear occurs. Ku *et al.* [28] studied the behavior of tribological journal bearings.it is made from PTFE composites and Al alloys. The result was that Al alloy reduced friction coefficient of about 28% and works at max load 8000 N without adhesion as compared with PTFE was strong adhesion at load range 6,300–8,000 N. Three materials were analyzed by Schroeder *et al.* [29]: PEEK, PEEK filled with PTFE graphite (CF), and PEEK reinforced with CF. With an essentially nonexistent wear rate shown in the reciprocating sliding test, they found that adding PTFE and graphite to CF-reinforced PEEK significantly decreased the friction coefficient and improved resistance to scuffing and abrasion. Abdelbary *et al.* [30] examined how the loading mode affected the wear properties of polyamide (PA_{66}) compared to its steel counterpart in both dry and wet sliding conditions. While the polymer exhibited a marked increase in wear rates under constant load compared to steel, its wear rates were generally higher in wet sliding conditions compared to dry tests. Demirci and Düzcükoğlu [31] investigated the impact of PA_{66} + 18% PTFE (Polyamide66 + 18% polytetrafluoroethylene), PA_{66} (Polyamide66), and PA_{66} + 20% GFR + 25% PTFE (Polyamide66 + 20% glass fiber + 25% polytetrafluoroethylene), as well as bearing temperature and pressure, on the friction and wear of bearings. They demonstrated that contact temperatures, friction coefficients, and wear rate were influenced by the film composition, as well as increasing temperature and pressure, depending on the mechanical properties of GFR and PTFE. Notably, the PA_{66} journal bearing with 20% GFR + 25% PTFE exhibited the most favorable wear behavior. Singh *et al.* [32] conducted an investigation into the mechanical and tribological characteristics of composite materials comprising 20% short glass fiber reinforced with 80% POM and 20% PTFE blends. Their results showed that the POM/PTFE mix reinforced with 20% short glass fiber had a higher tensile strength than the pure polyblend. Golchin [33] explored the influence of Babbitt and PTFE on the friction and wear properties of journal bearings. Additionally, the study examined how utilizing PTFE-based materials in water-lubricated journal bearings led to a significant reduction in the friction coefficient compared to Babbitt. Ms Shingavi *et al.* [34] enhanced the wear rate of PTFE by adding filler materials (thermoplastic polymer) to PTFE and compared to un-filled PTFE and discussed the dominant interactive wear mechanism during sliding bearing and its composites. Deshmukh and Aher [35] studied the PEEK and PTFE composite to decrease the friction coefficient and wear rate in conventional bearings, and when increasing the applied load and sliding distance reduced the

Table 1: Thermoplastic materials

Literature	Thermoplastic materials					
	PI	PEEK	PTFE	PA_{66}	POM	ABS
[26]	√					
[27]		√	√			
[28]			√			
[29]		√	√			
[30]				√		
[31]			√	√		
[32]			√		√	
[33]			√			
[34]			√			
[35]		√	√			
[36]						√
[37]			√			
[38]			√			
[39]		√	√			
[40]		√				

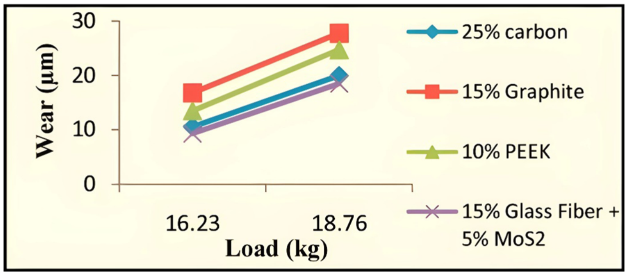

Figure 10: Impact of load on PTFE composite wear at dry conditions [37].

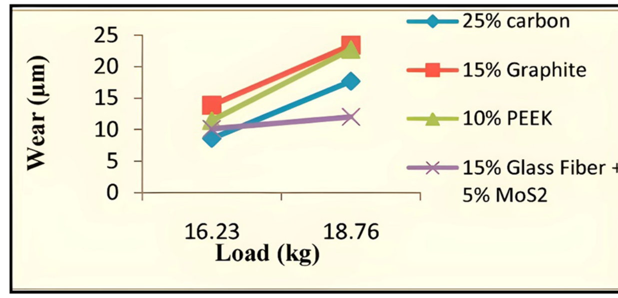

Figure 12: Impact of load on PTFE composite wear at wet conditions [37].

wear rate with PEEK and PTFE compound, the COF decreases when the trends in wear performance vary. The specific wear rate of PEEK and PTFE composite follows a continuous decrease in wear rate when choosing the compound. Shinde and Gajjal [36] investigated the composite materials for journal bearing applications without lubrication for a long operational lifetime. They experimentally utilized ABS on a dry journal bearing test rig and indicated that the ABS as composite materials is successful for unlubricated bearing applications. Desale and Pawar [37] investigated PTFE composites under an experimental method. The wear loss due to friction and wear increases with increased load, and the COF decreases with an increase in load due to the stability of transfer film under dry conditions (Figures 10 and 11), while in wet conditions, the wear loss increased with load due to the peeling off of transfer film and the friction coefficient decreased with increased load due to the presence of oil between sliding surfaces as shown in Figures 12 and 13.

In their study, Miler *et al.* [38] compared the efficiency of dry operation and solid lubricant (PTFE)-applied composite bearings under two load levels and various clearances. With an increase in clearance, the COF falls. The ideal condition for specimens that have been lubricated with PTFE is one in which the clearance size interval is filled with the locations with the lowest local coefficients of friction. The bearing bushes constructed of PEEK and 10% PTFE apiece, 30% glass fiber-reinforced PEEK, 30% CF-reinforced PEEK, and graphite and CF-modified PEEK were studied by Zhu *et al.* [39]. They were tested on a purpose-built articulated test platform and provided the best performance for the COF, wear loss, frictional energy, and temperature rise. Hintze *et al.* [40] researched the friction and wear characteristics of PEEK sliding on stainless steel. The materials are (PEEK) with 30% glass fibers. Adding fibers to PEEK increased the wear and strength but halved wear in the water-based lubricant composite journal bearing. The principal conclusions of the study are as follows: the tribological performance of journal bearings composed of different thermoplastic composites is the main topic of this investigation. Important discoveries include the superior wear resistance of PEEK composites with particular fillers, the lower friction coefficient of Al alloys compared to PTFE, the suitability of graphite and PI fiber composites for low-torque bearings at elevated temperatures, and the improved wear behavior of PA_{66} composites with particular formulations. The study also emphasizes how load and environmental factors affect these materials' wear and friction characteristics. Possible conclusion and explanation of findings are as follows: these results have important ramifications for journal-bearing design and selection in a variety of applications. It appears to optimize bearings for longevity and performance by considering the appropriateness of various thermoplastic composites for particular operating circumstances. Certain

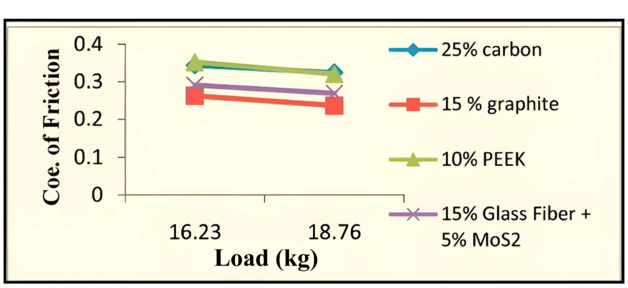

Figure 11: Impact of load on PTFE composite COF at dry conditions [37].

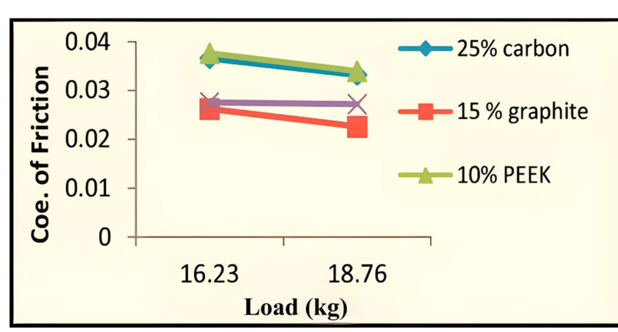

Figure 13: Impact of load on PTFE composite friction coefficients at wet conditions [37].

composites' advantages for the environment and wear resistance draw attention to the possibility of more long-lasting and sustainable bearing solutions. Limitations and strengths are as follows: this study's comprehensive examination of several thermoplastic composites and their tribological characteristics is one of its strong points. The results' application may be impacted by potential variations in material qualities and ambient factors, among other restrictions. To validate these results in practical settings and investigate the long-term performance of these materials under various operating circumstances, more investigation is required.

4.3 Journal bearings of thermoset composite

Table 2 illustrates how some researchers have enhanced tribological qualities with thermosetting materials. To address the issues of white metal bushing journal bearing seizing and thermal residual stress with interference construction of polymeric journal bearing, Kim and Park [41] developed a hybrid composite journal bearing reinforced with CF and phenolic. Examination of the wear and friction characteristics of asbestos fiber-reinforced phenolic composites *versus* CF-reinforced phenolic composites revealed superior properties in the former, despite the CF-reinforced phenolic exhibiting approximately 60% of the dry friction coefficient observed in asbestos fiber-reinforced phenolic. Kim *et al.* [42] proposed a solution to the residual thermal stress and white metal liner journal bearing seizing associated with the interference installation of phenolic asbestos journal bearings. Using an intuitive design approach, they developed a hybrid composite journal bearing made of phenolic-reinforced CF. Comparative analysis showed improved wear properties in CF-reinforced phenolic composites and asbestos fiber-reinforced phenolic composites compared to asbestos phenolic composites. He *et al.* [43] studied the polyester fibers with different orientations reinforcing ultrahigh molecular weight polyethylene to prepare a composite with a multi-layer direction subjected to the bearing. The result showed that the random addition of fibers can reduce the friction coefficient by about 60% due to the increase of polyester in the composite. Yu and Kim [44] utilized asbestos-phenolic materials for the composite bearings. Finite element method was used to examine the failure of a sizable aramid/glass phenolic composite bearing intended for maritime use. Because the glass-phenolic composite has a greater hardness than the aramid-phenolic composite, the hardness of the bearing rises as the volumetric content of the aramid-phenolic composite decreases. Additionally, since it is more compatible and has a lower COF than glass-phenolic composite, the thin aramid-phenolic composite may be employed as a liner material. Babu *et al.* [45] manufactured and tested the biaxial glass fiber Al_2O_3/SiC epoxy journal bearing under different conditions against the gun metal bearing. The results of the complete analysis showed that the bearing made of composite has a good performance compared with the gunmetal, and the COF was very low. To address the metallic journal bearing seizure issue *via* the use of the FE approach in an oil-cut situation, Choe *et al.* [46] created composite journal bearings using phenol/CF and epoxy/CF composites. The FE research results show that the journal bearing made of carbon/epoxy composite has a friction coefficient of 0.35 (Figure 14). Table 3 lists the maximum and average friction coefficients for each material. The carbon/phenol composite had an average friction coefficient of 11.5% lower than the carbon/epoxy composite and a maximum friction coefficient of 22.4%.

Bhatia *et al.* [47] reviewed the properties of boron carbide (B4C) reinforced epoxy composite. The result of

Table 2: Thermosetting materials

Literature	Thermosetting materials		
	Phenolic	Polyester	Epoxy
[41]	√		
[42]	√		√
[43]		√	
[44]	√		√
[45]			√
[46]	√		√
[47]			√
[48]			√
[49]			√

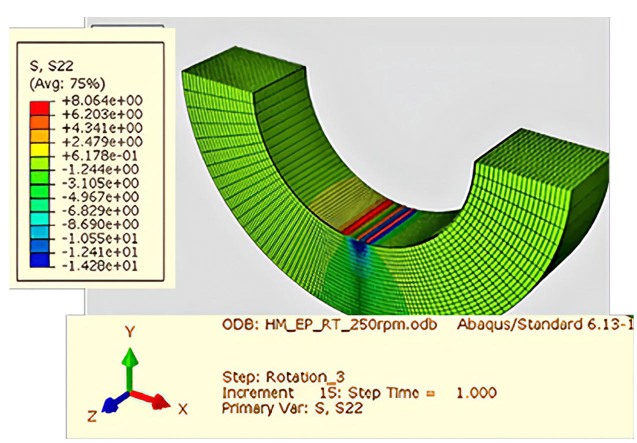

Figure 14: FE analysis results of the carbon/epoxy composite journal bearing [46].

Table 3: COF of composite material [46]

Friction coefficients of the composite materials			
		Carbon/ phenol	**Carbon/ epoxy**
Friction coefficients	Maximum	0.20	0.26
	Average	0.15	0.17

this study improved tensile strength due to enhancing the bonding between the reinforcement and the matrix and lower than the neat epoxy. Muhammad [48] investigated the application of glass fiber-reinforced material (30–45% by volume) and a liquid thermosetting resin onto a male or female mold simultaneously using hand layup. Through this process, composite materials were effectively enhanced in hardness, stiffness, stability, and density. This improvement was achieved through a straightforward layup method employing fiber cloth, paper card, and epoxy. The tribological performance of composite materials made of epoxy resin was investigated by Cao and Luo [49]. By adding fillers to the epoxy resin, they improved the mechanical characteristics of the composites and attempted to increase the composites' load-bearing capacity during friction. The addition of filler alters the wear process of materials and enhances the mechanical characteristics of epoxy resin composites. The principal conclusions of the study are as follows: this investigation focuses on journal bearings composed of different thermoset composites and their tribological performance. The creation of a hybrid composite journal bearing reinforced with both CF and phenolic to address issues with thermal residual stress and white metal bushing journal bearing seizing, the superior properties of asbestos fiber-reinforced phenolic composites despite the lower dry friction coefficient of CF-reinforced phenolic composites, and the decrease in friction coefficient and improvement in wear properties attained by utilizing various thermoset composite materials and reinforcements are some of the key findings. Implication and justification of findings are as follows: These results have important ramifications for journal-bearing design and selection in a range of applications. It is possible to customize bearings for particular operating circumstances to enhance performance and decrease wear, according to the development of hybrid composite bearings and the optimization of fiber orientation and reinforcement materials. The advantages of some composites for the environment and wear resistance draw attention to the possibility of more long-lasting and sustainable bearing solutions. Limitations and strengths are as follows: This study's comprehensive examination of different thermoset composites and their tribological characteristics is one of its strong points. The results' application may be impacted by potential variations in material qualities and ambient factors, among other restrictions. To validate these results in practical settings and investigate the long-term performance of these materials under various operating circumstances, more investigation is required.

4.4 Adding nanomaterials

Table 4 illustrates how the researchers added many nanomaterial types to enhance the tribological capabilities. Pansare *et al.* [50] looked at a wide variety of composite materials. The results obtained in a roller journal bearing indicated that 15% glass fiber + 5% MoS_2-filled PTFE had the highest wear resistance, followed by 35% carbon, pure PTFE, 40% bronze, and 25% carbon. Baskar *et al.* [51] observed the wear and friction performance for the

Table 4: Addition of many types of nanomaterials

Literature	**Nanomaterials**								
	MoS_2	**TiO_2**	**WS_2 + CuO**	**CNT**	**NG**	**GNS**	**C70**	**AL_2O_3**	**GNO**
[50]	√								
[51]		√	√						
[52]		√							
[53]				√					
[54]	√	√			√				
[55]						√			
[56]				√			√		
[9]									√
[57]								√	
[58]		√							

journal-bearing materials tested with TiO_2, WS_2, and CuO nano additives dispersed in the CMRO chemically modified rapeseed oil causing the lowest COF and wear rate.

Jadhav *et al.* [52] studied PEEK and filler materials like PTFE, bronze, and the conventionally used brass by adding the MoS_2 nanoparticles, modifying the tribological properties of composite journal bearing as compared with unfilled (PEEK) nanoparticles in connecting rod of an internal combustion engine. Chauhan *et al.* [53] investigated the impact of nanoparticle inclusion in water. Their findings revealed that incorporating nanoparticles led to heightened load-carrying capacity. Additionally, the bearings demonstrated elevated damping characteristics, while stiffness coefficients suggested enhanced shaft stability across varying speeds.

Venkatesan *et al.* [59] studied the addition of carbon nanotube (CNT) to hybrid polymer composites. The result shows improve in the strength of about 5%, wear properties were found by experimental method investigating the wear properties in the CNT content. Figures 15 and 16 show the wear increased with time while the COF increased according to the load applied. There is a variation after reaching a certain height.

Umesh *et al.* [54] explored the influence of nanographene on the dry sliding wear characteristics of PTFE and MoS_2-filled PA_{66}/PA6 blend composites. The introduction of TiO_2 and nanographene notably bolstered the wear resistance of nanocomposites owing to the collaborative effects of PTFE, MoS_2, and nanographene. Li *et al.* [55] investigated the impact of graphene sheets (GNs) and perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA) addition on the tribological and mechanical properties of a PI matrix. Their study revealed that the incorporation of GNs–PTCDA substantially enhanced both the tribological and mechanical attributes of the PI matrix. Notably, GNs–PTCDA imparted the filled PI composites with the lowest friction coefficient and wear rate. For applications where reducing the dry friction was the goal, Upadhyay and Kumar [55] conducted a thorough analysis of the chemical, physical, thermal, and tribological behaviors of infused epoxy substrates made by infusing Fullerene C70 and multiwalled CNTs in weight concentrations 1, 3, and 5 wt%. Bao *et al.* [9] studied adding graphene oxide with polyether amine to the epoxy resin. A friction coefficient decreased by 54%, and the wear rate dropped by 94% compared with pure resin in 0.2 wt% polyether amine-functionalized graphene oxide/epoxy composite materials represented the best tribological performance. Nabhan *et al.* [57] used Al_2O_3 as nanoparticles in HDPE reinforcement. The results of HDPE nanocomposites have improved friction and abrasion resistance properties of the HDPE compared with the pure HDPE for application in journal bearing. Reddy *et al.* [58] studied the performance of short journal bearing with and without adding nanoparticles in the base lubricant and proved that the static characteristics in terms of load capacity and friction improved with adding TiO_2 as compared with unfilled nanoparticle journal bearing. The principal conclusions of the study are as follows: the addition of different nanomaterials to journal bearings is the means of improving their tribological capabilities. Important discoveries include the increase in wear resistance when glass fiber and MoS_2 are added to PTFE, the decrease in wear rate and COF when TiO_2, WS_2, and CuO nanoadditives are used in lubricants, and the improvement of load-carrying capacity and damping properties when nanoparticles are included in bearings. The study also emphasizes how adding graphene sheets and perylene derivatives to PI matrices significantly improves their mechanical and tribological capabilities. Findings' significance and justification: These results have important ramifications for the advancement of high-performance journal bearings. The longevity and effectiveness of bearings in a variety of applications depend on factors including higher wear resistance, less friction, and increased load-carrying capacity, all of which can be achieved by adding nanomaterials. The study also implies that desired tribological qualities can be achieved by customizing the

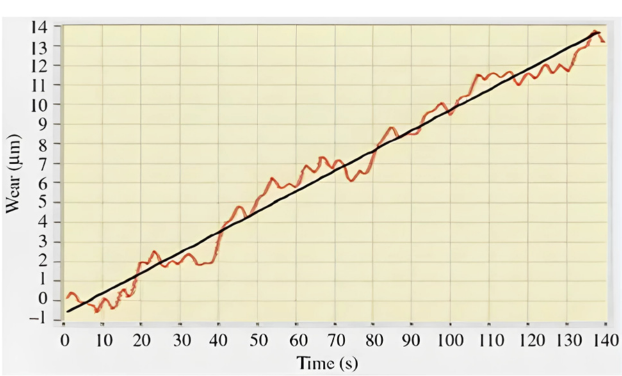

Figure 15: Wear test on the pin-on-disc machine [59].

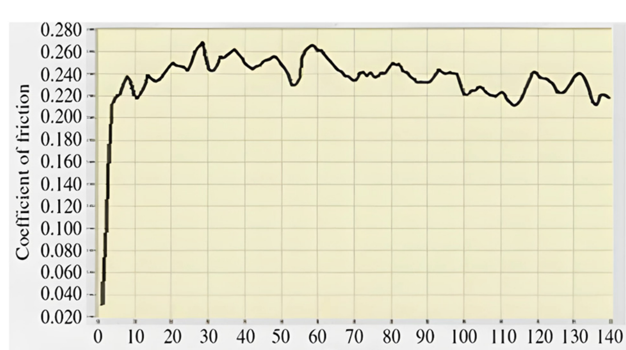

Figure 16: Wear test on the pin-on-disc machine for COF [59].

concentrations and choice of suitable nanomaterials. Limitations and strengths are as follows: One of the study's strengths is how thoroughly it examined how different nanomaterials affected the tribological characteristics of journal bearings. The reproducibility of the results could be impacted by potential heterogeneity in the dispersion and distribution of nanomaterials inside the composites, which is one of the constraints. To improve the production methods and assess the long-term performance of these nanocomposite bearings in various operating environments, more study is required.

4.5 Journal bearings of thermoplastic and thermoset composite

As indicated in Figure 17, the team of researchers used thermoplastic and thermosetting materials to improve the journal bearing's tribological properties. Better tribological qualities in cylindrical journal bearings consist of aramid fiber-reinforced epoxy and PTFE lubricating liners. As a result, the friction characteristics of PTFE materials have a low friction coefficient of about 0.06–0.17 at 69 MPa unit load and a decrease of about 0.1 at 276 MPa unit load [60,61]. According to the steady state of sliding, the tribological properties of PTFE-filled SiO_2 epoxy composites were studied under load 60 N and 140 MPa pressure. As a result, the friction coefficient COF and wear rate decreased in a dry sliding journal bearing. COF is around 0.095, and the wear rate is 8.4×10^{-7} mm^3/Nm at 12% PTFE. Zahabi *et al.* [62] used a hybrid (PTFE)/glass fiber in epoxy resin as a hierarchical braided structure. The composites were prepared through the transfer molding process. The results showed that the self-lubrication and a lower COF obtained of about 0.112, 0.105, and 0.096 in the load of 20, 30, and 40 N respectively, which proved that the PTFE glass/epoxy compound is a feasible alternative in wet bearing parts. Key findings of the current study: The current study focuses on using a combination of thermoplastic and thermosetting materials to improve the tribological capabilities of journal bearings. Important discoveries include the enhancement of tribological characteristics through the application of PTFE lubricating liners and epoxy reinforced with aramid fiber; the decrease in wear rate and COF in SiO_2 epoxy composites filled with PTFE; and the viability of employing a hybrid (PTFE/glass fiber) in epoxy resin as a hierarchical braided structure for wet bearing components. The findings' significance and justification are as follows: These results have important ramifications for the advancement of high-performance journal bearings. The longevity and effectiveness of bearings in a variety of applications depend on greater wear resistance, less friction, and increased load-carrying capacity, all of which can be achieved by combining the usage of thermoplastic and thermosetting materials. The study also implies that the necessary tribological qualities can be adjusted by carefully choosing the right material combinations and configurations. Limitations and strengths are as follows: This study's comprehensive examination of the impact of mixed thermoplastic and thermosetting materials on journal-bearing tribological characteristics is one of its strongest points. The potential complexity of producing and processing these composite materials is one of the restrictions, though, and it could have an impact on how repeatable the outcomes are. To optimize the fabrication processes and assess the long-term performance of these composite bearings under various operating situations, more research is required.

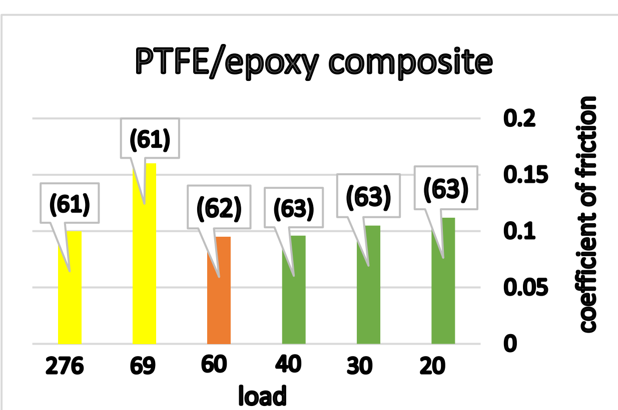

Figure 17: Combined thermoplastic and thermosetting materials for three researchers.

4.6 MMC journal bearings

As seen in Table 5a–c, numerous researchers have employed various materials to enhance the tribological qualities in journal bearings. The dry sliding wear behavior of heat-treated and cast zinc-aluminum (ZA-27) alloy supplemented with silicon carbide and graphite particles was investigated by Kiran *et al.* [63]. It was discovered that the wear volume loss increased with an increased load and sliding speed but the wear resistance improved with an increase in the aging time of SiC and Gr. Unlu and Atic [64] made composite bearing from composite structure by reinforcing casting technique 3% (Al_2O_3 and SiC) and (3% Al_2O_3 + 3% SiC) into pure AI. Their approach provided the best tribological characteristic in the bearing compared to the pure AI. Goel *et al.* [65] compared the tribological properties between the phosphorous bronze and new bronze material (Al–Ni–Cu) journal bearing. The result that phosphorous bronze helped in reducing the wear and friction whereas (Al–Ni–Cu) was prevented the wear and friction in fully lubricated because absorbed oxygen by forming a protective layer [66]. Eight Al alloys that ranged in tin content from 5.4 to 11% and were alloyed with lead, copper, silicon, zinc, magnesium, and titanium were examined for their characteristics. It was demonstrated that tribological behavior and mechanical qualities do not necessarily correlate. It has been established that consuming more than 6% of tin is excessive. The alloy's setting load rises as the magnesium content does. There is less order of magnesium and tin in the secondary structures of alloys with greater wear rates. Babu *et al.* [67] talked about successful tin babbits because the mechanical characteristics and metallurgical features made them popular bearing materials and can enhance the tribological properties by reinforcing Al or lead bronze and suitable for medium to high speed. Also studied, ceramic is suitable for high-temperature bearings and can be used in place of polymer bearings when lubrication cannot be provided. Gao *et al.* [68] presented an experimental method of the tribological behavior of tin-bronze-based composite coating on the bushing of plant journals in an aerospace application and used a triballoy alloy T-401 as reinforcement to the tin bronze. The results indicated that T401/tin bronze has superior tribological properties with lower wear rate and friction coefficient compared to leaded tin bronze. This is because that Tin-401 reduced the plastic deformation of surface under wear and frictional heat. Thus, reducing the probability of surface mating. Gangatharan *et al.* [69] compared the tribological characteristics of four different materials for plain bearings used in centrifugal pumps: Al 2024 alloy, red brass (UNS C23000), Al 2024 reinforced with graphite (4 wt%), and Al 2024 reinforced with hexagonal boron nitride (4 wt%). The results showed that the COF of the composites was lower than that of pure Al alloy and red brass. Also, the wear rate of pure Al and red brass alloy will be greater than that of composite materials. Sharma *et al.* [70], studied the enhancement the tribological characteristics of journal-bearing materials and the stir-casting method by producing copper–aluminum (Cu–Al), copper–phosphorous (Cu–P), aluminum–fly ash (Al–F), and copper–lead (Cu–Pb) composites. They showed that the lowest COF in (Al–F) and the average friction coefficient is 32% as compared to (Cu–Pb). Also, (Cu–P) has lower friction coefficient (about; 0.029) as compared to (Cu–Pb) is (about; 0.037). The wear resistance in (Cu–P) is 36% higher as compared to (Cu–Pb) as shown in Figures 18 and 19.

The NU308-bearing rings were investigated by Liu *et al.* [71] after undergoing strengthened grinding treatment (SGT) at room temperature. They examined the samples ability to resist wear and friction after performing the SGT is greater and better wear resistance. Also, the SGT has improved the reliability of the NU308 bearing rings. Susilowati *et al.* [72] found how the weight percentage of graphite affected the Cu, Sn, Zn, and Gr composite's mechanical characteristics. The hardness, density, and

Table 5: Metal materials

Literature	(a) Metal materials								
	Zinc	Al	Cu	Lead	SiC	Ni	Mg	Si	Ti
[63]	√	√							
[64]		√			√				
[65]		√	√			√			
[66]	√		√	√			√	√	√

Literature	(b) Metal materials				
	Tin babbit	Tin bronze	T401	Al2024	Red brass
[67]	√				
[68]		√	√		
[69]				√	√

Literatures	(c) Metal materials								
	Nu 308	Cu	Zn	Sn	Gr	Cu–Al	Cu–P	Al–f	Cu–Pb
[70]						√	√	√	√
[71]	√								
[72]		√	√	√	√				

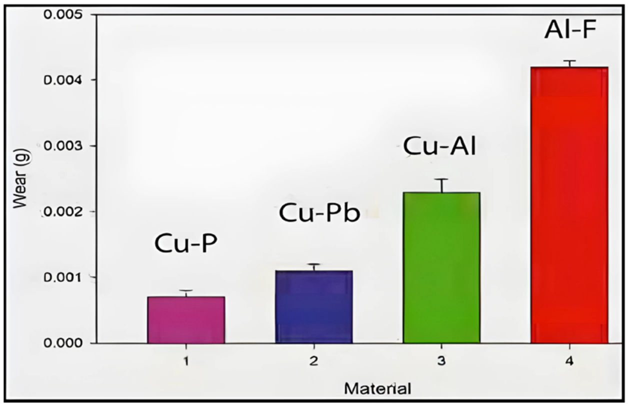

Figure 18: Variation wear of material after testing [70].

yield strength values exhibited an upward trend with graphite weight percentages of 0.5 and 1.0; however, the wear rate and porosity values declined when the weight percentage reached 1.5 or 2.0. Conversely, there was an increase in the wear rate and porosity. Hence, at a graphite weight percentage of 1.0, the Cu–Sn–Zn/Gr alloy demonstrated hardness, wear rate, density, porosity, and compressive strength values of 55 BHN, 1.88 × 106 mm^3/mm, 6.67 g/cm^3, 23.3%, and 538 MPa, respectively. The primary conclusions of this study are that different metal matrix composites can be used to improve the tribological characteristics of journal bearings. Important discoveries include the enhancement of wear resistance in zinc–aluminum alloy by adding graphite and silicon carbide particles; the superior tribological properties of composite bearings reinforced with Al_2O_3 and SiC; and the decrease in wear and friction in phosphorous bronze and (Al–Ni–Cu) journal bearings. The effect of graphite weight percentage on the mechanical and tribological characteristics of Cu–Sn–Zn–Gr composites is also highlighted in the study. The findings' significance and justification are as

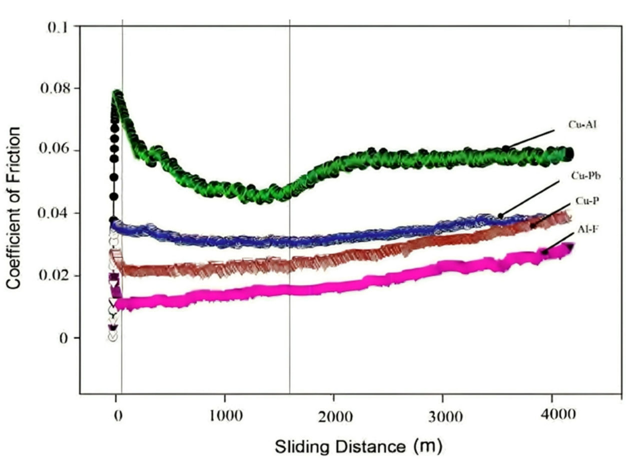

Figure 19: Variation of COF [70].

follows: These results have important ramifications for the advancement of high-performance journal bearings. The longevity and effectiveness of bearings in a variety of applications depend on greater wear resistance, less friction, and increased load-carrying capacity, all of which can be achieved through the use of metal matrix composites. The study also implies that the desired tribological properties can be adjusted through the right metal matrix composite selection and processing methods. Limitations and strengths are as follows: This study's comprehensive examination of how different metal matrix composites affect journal-bearing tribological characteristics is one of its strongest points. The reproducibility of the results could be impacted by potential variability in the composites' properties brought about by various processing methods, which is one of the constraints. To optimize the fabrication processes and assess the metal matrix composite bearings' long-term performance under various operating circumstances, more study is required.

5 Conclusion

This review article reviews the most important literature related to the topic of improving the tribological properties of journal bearing manufactured from composite materials. The composite materials presented by researchers in the field varied, as most of them resorted to use thermoplastic composite materials, others used thermoset composite materials, and some used nanomaterials, while a very limited number of researchers enhanced the tribological properties by using thermoplastic and thermoset composite materials, and finally, a number of previous researchers have used metal composite materials to enhanced tribological properties. Among the most important conclusions reached after this extensive and in-depth research are the following:

1. Most researchers focused on the use of journal bearings made of different composite materials such as thordon SXL, rubber, and thermoset composite Nordon 605 operating with water lubrication in various applications, especially in ships. It is found that the appropriate composite material was used to reduce the friction and wear at light loads is rubber. For high loads, thordon and nordon composites are most suitable materials although they are expensive.
2. A large amount of research has provided an improvement in the tribological properties of journal bearings by using composite materials with a thermoplastic matrix such as PTFE, PEEK, PA_{66}, and others. It was found that PTFE is the most widely used material in reducing

friction and wear and improving lubrication in mechanical parts, especially journal bearings due to its non-reactive nature, and also has great sliding ability, meaning a low COF.
3. Epoxy, polyester, and phenolic are the most important thermosetting composite materials that contributed to improving the tribological properties of journal bearings, previous researchers used types of fibers, especially CFs to reinforce these materials and improve wear and friction. It was found that carbon phenol reduced the maximum and average COF by 11.5 and 22.4%, respectively, when compared with carbon epoxy [41], while very few literature used polyester to improve the properties, due to its unpleasant and pungent odor that is harmful to human health, in addition to its low hardness when compared to epoxy and phenolic.
4. One of the most important materials that has recently appeared and has enhanced tribological properties due to its unique mechanical properties is known as nanomaterials. A large number of previous researchers have used different types of nanomaterials that have had a major role in reducing wear and improving the COF in journal bearings in various applications. The most important of these types are CNTs because they possess a unique combination of strength, hardness, and light weight compared to similar nanomaterials. As a result, when added to composite polymer materials, it improves wear resistance to 5%, and the COF increases with the applied load and then varies after reaching a certain height.
5. Very few previous researchers have used composite materials (thermoplastic with thermoset) to improve the tribological properties of journal bearings, and the reason is that they are very expensive. The most important composite material used by previous researchers was PTFE/epoxy composite to reduce the COF and improve it relative to the applied load.
6. MMC materials are an important category of engineering materials that have increasingly replaced traditional materials. Therefore, most previous researchers turned to using them to improve the tribological properties of journal bearings due to their attractive properties after combining and strengthening them with metal materials or alloys. The best result achieved by the researcher was when using it. Metallic composite materials such as Cu–P, Cu–Pb, Cu–Al, and Al–F have reduced wear resistance by 36% at Cu–P and the lowest COF at Al–F by 32%. Limitations and future research are as follows: Although this study yielded thorough insights, it is not without limitations. Specifically, the properties of composite materials can vary widely, and different processing methods may have different effects on the same data. Subsequent investigations ought to concentrate on refining the processes of manufacture, investigating novel combinations of composite materials, and assessing the materials' long-term efficacy in diverse operational scenarios. Contribution to knowledge is as follows: By offering a thorough summary of the developments made in enhancing the tribological characteristics of journal bearings using composite materials, this review article makes a valuable contribution to the field. It draws attention to the possibilities of various composite categories and suggests future lines of inquiry for this area of study.

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Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted article. The other datasets are available on reasonable request from the corresponding author with the attached information.

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