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# Mechanical and Tribological properties of the Lead-Free Composite-A review

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## ABSTRACT

In recent years, there has been a growing demand for materials that are both eco-friendly and cost-effective while maintaining high performance levels. Design engineers and researchers are increasingly turning to advanced materials as substitutes for traditional metals and alloys. Journal bearings, integral components of machinery and engines, play a crucial role in their operation, significantly impacting efficiency, operational costs, system longevity, and reliability. The pursuit of eco-friendly and high-performance materials has spurred notable progress in tribological research, particularly concerning journal bearings. This study offers a comprehensive examination of lead-free composite materials for journal bearings, delving into various types such as polymers, ceramics, and metallic alloys. It meticulously evaluates their mechanical and tribological properties, as well as their microstructural characteristics. The insights gleaned from this review are invaluable for engineers and researchers seeking to enhance the design and performance of journal bearings while aligning with environmental regulations and sustainability objectives.

**Keywords:** Eco-Friendly, Lead-Free Composite, Journal Bearings, Mechanical Properties, Tribological Properties.

## 1. Introduction

Environmental issues related to hazardous materials' usage have become one of the most significant considerations when choosing materials for various applications. These problems primarily arise in bearing applications because of the presence of Lead. Lead has widely acknowledge as an essential element in bearing alloys utilized in conventional Internal Combustion Engines (ICE) and turbochargers due to its outstanding dry lubrication characteristics and anti-friction properties [1], [2]. However, a shift towards alternatives both friendly and environmentally was necessitated by the lead's detrimental effects on both human and environment health. A lot of study done recently to identify substitutes for these materials in industrial uses. Among these uses, journal bearings have attracted the attention of researchers looking for lead-free alternatives because they are essential parts of many machines and automobile systems. [3], [4]. Advanced nanocomposites and state-of-the-art manufacturing techniques like additive manufacturing are explored , showing promising results in enhancing the efficiency and sustainability of lead-free composite journal bearings. [5], [6], [7]. This pursuit is particularly crucial in industrial applications where journal bearings are fundamental components, ensuring the smooth operation of rotating machinery. [8], [9], [10] The adoption of lead-free composites in journal bearings represents a reduction in the use of harmful substances, contributing significantly to environmental sustainability [11]. By eliminating lead, these composites decrease the risk of soil and water contamination, mitigating the potential harm to ecosystems and human health [12], [13]. The development of advanced composite materials incorporating nanotechnology has led to significant improvements in tensile strength and wear resistance [14]. This enhanced mechanical resilience translates to a longer bearing lifespan, reduced maintenance costs, and enhanced overall system efficiency, making lead-free composite journal bearings a preferred choice in various industries. This review aims to comprehensively explore the behaviour of lead-free composites, which provides a holistic understanding of their mechanical, tribological, and microstructural properties applicable to journal bearings.

### 1.1 Factors to be Considered in Selecting Journal Bearing Materials

A journal bearing is a component that positions and supports a rotating shaft radially. Journal bearings are known as fluid film, plain, or sleeve bearings. The effectiveness and performance of the bearings have an impact on how well the systems and mechanisms work. Therefore, it is important to choose bearing materials carefully to ensure that these systems function properly and perform up to expectations. Compared to sliding-contact bearings, rolling-contact bearings have less friction. Sliding contact bearings must nevertheless be used. They are widely used, and each has a unique set of advantages. [15] Industrial machines, engines, automobiles, compressors, electric generators, gas and steam turbines, and other equipment employed in the gas, oil, electrochemical, and power industries employ journal bearings. According to Hamrock et al. [16], the kind of bearing, type of lubrication, and environmental factors all affect the material choice for bearing applications. Combinations of embeddability, compatibility, conformability, fatigue strength, and resistance to corrosion and cavitation erosion need to be present in the journal-bearing material. [17], [18]. There is not a single material that can meet all the criteria for a better bearing component. Therefore, a compromise or blend of the above stuffs are needed for any kind of optimal performance. It is not acceptable to rub the shaft and bearing materials together since this might result in localized welding that can score, seize, or scratch the bearing material. Compatibility is the name for this inherent tendency [19], [20].To lessen stress concentrations and preserve oil film thickness, the bearing material should experience a modest amount of deformation when the bearing assembly is slightly out of alignment. This ability is called conformability. Any abrasive damage can be reduced by embeddability to both the bearing and shaft [21], [22], [23], which has the capacity for embedding all the hard particles in the bearing material surface. The aforementioned three elements determine how well any bearing material can withstand scoring. While conformability and embeddability decrease inversely with hardness, compatibility is difficult to evaluate [24], [25]. Moreover, there are a few desirable and significant mechanical properties found in bearing materials, which are low coefficient of friction (COF), compressive strength, fatigue strength, good wettability, low thermal expansion coefficient, cost and availability, high thermal conductivity, sufficient elasticity, and hardness [26], [27]. The wear and frictional behaviour of journal bearings are significantly influenced by the lubrication of the moving parts [28], [29]. Extreme boundary lubrication, hydrodynamic or full film, boundary lubrication, or thin film, have been the three fundamental lubrication techniques [30]. In hydrodynamic bearings, a substantial lubricating film separates the mating surfaces. In boundary lubrication, a thin lubricating coating separates the mating surfaces [31]. Both of these techniques result in long-lasting lives.

## 2. Development of Bearing Materials and Current Trends

In fact, numerous varieties of materials are available, which are often specialised for an application. The bearing materials can be metallic or non-metal bearing materials. It is observed that metallic bearings are comprised of aluminium-based, white metals (based on lead and tin), porous metals, and bronzes (based on copper) [32], [33], [34], [35]. Ceramics, composite materials, and polymers are used to make non-metallic bearings. In addition, bearings can be categorised based on their geometry, with full round sleeves being referred to as "bushes" and half round sleeves being called "bearing."

### 2.1 Metallic bearings

Metals like gold, aluminium, copper, iron, silver, indium, lead, and tin are used as bearing materials [36]. For bearing applications, metals with a 70 BHN hardness can be employed [37].Bearing metals, white metals, or Babbitt metals are another name for alloys made of lead and tin that are used in bearings. The most widely used bearing materials were created by Isaac Babbitt in 1839 [38]. Due to environmental, legislation and health issues, the utilisation of lead-based bearing materials has decreased [39]. As a result, lead bearings are replaced in recent years by materials based on tin-based materials [40]. Tin Babbitt has good embeddability, conformability, and adhesion qualities, yet their weak fatigue strength constrains this application severely [34]. The babbitt alloys are generally produced by casting [41]. As a bearing surface, white metal is cast onto steel, bronze, cast-iron, and other metals to increase their fatigue strength. [32], [34].

The table 1 compares the metallic materials for bearing applications. Table 1 clearly shows that Babbit [42] possesses the most important properties for a good bearing material. One of the widely used compositions comprises

**Table 1** Various metallic materials for bearing applications [16], [32], [34]

| Property | Compatibility | Conformability | Embeddability | Fatigue strength | Corrosion resistance | Compressive strength | Density | Cost |
|---|---|---|---|---|---|---|---|---|
| Babbitt | High | High | High | Low | Moderate | Low | High | High |
| Al based | Moderate | Moderate | Moderate | Moderate | High | Moderate | Moderate | Moderate |
| Cu based | Low | Low | Low | High | Low | High | High | Moderate |
| Polymer based | Low | High | Moderate | Moderate | High | Moderate | Low | Low |

22-26% lead (Pb), 1-2% tin (Sn), and the remaining copper (Cu). Within these alloys, tin entirely dissolves in copper, creating a bronze matrix with lead islands [47]. This composition enhances the bearing mechanical properties, improving its performance as well as durability. Efforts are actively underway in recent studies to minimise or eliminate the use of lead in journal bearings [34].

### 2.2 Non-Metallic Bearings

Application in light-duty scenarios is found in non-metallic bearings where chemical durability, self-lubrication, and high-temperature resistance are used in space applications and food handling equipment [43]. Conformability, excellent vibration absorption, and corrosion resistance are some of their benefits, but their low melting points and high thermal expansion are some of their limitations. Composite bearings combining metal and polymer matrices improve strength and wear resistance [44]. These composites incorporate solid lubricants like carbon graphite and molybdenum disulfide to enhance their lubrication properties. Various fiber-reinforced plastic materials like carbon, E-glass, and stainless-steel fibres have PTFE, epoxy resin, and polyester resin as matrix materials [37]. These advancements reflect the continuous evolution of non-metallic bearing materials, which aim for optimal performance in various industrial applications.

## 3. Properties of Lead-Free Composites

### 3.1 Mechanical Properties of various Lead-free composites

Lead-free composites have gained prominence due to environmental concerns, highlighting the need for alternatives to lead-based materials. Typically, excellent mechanical properties like improved hardness, higher tensile strength, and superior wear resistance are exhibited by these composites. Extensively, research is performed with a variety of polymers, ceramics, and metallic alloys to achieve desirable properties. Lead-free FeS/Cu-Bi (FCB) copper matrix mixtures were developed with the help of ball milling and in situ Ni-coated FeS surface modification by Liu et al. [45]. It is found that the composites hardness increases from 50.5-64 HRB and the density of the composite rises from 5.82 g/cm$^3$ to 6.96 g/cm$^3$. Salleh et al. [46] utilised powder metallurgy techniques to develop different compositions of lead-free Sn-0.7Cu/Si3N4 composite. They examined the effects of Si3N4 particulates at rates of (0.5 wt%, 1.0 wt%, and 1.5 wt%) in the matrix. It was reported that the microhardness, ultimate shear stress, and maximum shear strain of the composite are all higher than the monolithic Sn-0.7Cu solder. The impact of mechanical alloying and surface modification on the tribological and mechanical properties of lead-free copper matrix composites using Bi and FeS powder as phases is lubricated for replacing the lead in CuPb alloy, which was developed by Liu et al.[47]. Ali et al. [48] conducted a study on the mechanical properties of lead-free composites, specifically focusing on impact toughness, hardness, and shear strength in Sn-1Ag-0.5Cu (SAC105) alloys containing Fe/Bi-bearing components. The addition of 1 wt.% Bi and 0.05 wt.% Fe led to a notable enhancement in hardness, increasing from 10.5 HV to 22.6 HV. Similarly, the shear strength experienced a significant rise, progressing from 17.8 MPa to 34.3 MPa as a result of the addition of Fe/Bi. Ma et al. [36] examined the effect of the addition of 0, 0.01, 0.03, 0.05, and 0.1 wt.% of Graphene Nano Sheets (GNSs) into Sn58Bi lead-free composites. The composite's tensile strength and hardness exhibited a respective increase of 14% and 38% with the incorporation of 0.1 wt.% graphene nanosheets (GNSs). Liu et al. [49] investigated the influence of graphene nanosheets on the mechanical properties of a Sn–Ag–Cu solder alloy. Their findings revealed that an increase in GNSs content resulted in enhanced ultimate tensile strength (UTS). Specifically, the UTS of SAC/0.03GNS reached 50.3 MPa, representing a 10% increase compared to the pure SAC solder with a UTS of 46 MPa .Chen et al. [50] investigated the impact of incorporating fullerenes (FNSs) nanoparticles into SAC305 lead-free solder. This incorporation was done at various weight fractions, specifically 0.05, 0.1, and 0.2 wt%, utilising the powder metallurgy technique. The results revealed a significant improvement of 12.1% in shear strength and 19.9% in microhardness with the addition of 0.2 wt% FNSs. Khodabakhshi et al. [51] used mechanical alloying to fabricate a lead-free s alloy (Sn-3.5Ag-0.7Cu or SAC alloy) with the incorporation of Ni-coated graphene nanosheets at a rate of 0.2 wt.%. It was observed that the incorporation of Ni-coated graphene nanosheets increases the tensile-shear strength by 65% and the ductility by 63%. Chellvarajoo et al. [52] investigated the impact of diamond nanoparticle reinforcement at rates of 0.5, 1.5, and 2.5 wt.% in lead-free SAC 305 composite. It was observed that the SAC 305 hardness increased by 77.5% with the incorporation of 0.5 wt.% diamond nanoparticles.

Chellvarajoo et al. [53] explored the impact of incorporating 0.5, 1.5, and 2.5 wt.% of Fe2NiO4 nanoparticles on the mechanical properties of SAC-305. Their investigation revealed that the addition of 1.5 and 2.5 wt.% of Fe2NiO4 nanoparticles resulted in a significant 56.82% increase in hardness. Xu et al. [54] employed mechanical mixing and ball milling techniques to incorporate different percentages of Ag-nanoparticle-modified graphene weight (Ag-GNSs) into Pb-free Sn-Ag-Cu (SAC) solder matrices. It was observed that the addition of 0.03%, 0.05%, 0.1% and 0.2% % wt. of Ag-GNSs increased the compressive strength by 6.5%, 10.6%, 9.35 and 4.2.%.

Fan et al. [55] explored the impact of cobalt (Co) addition (0.5-2.0 wt.%) on Sn-0.7Cu solder and found that addition of 2.0 wt.% of CO increases the tensile strength by 25 Mpa-50 MPa. Saleh et al. [56] developed the lead-free composites with the addition of 10 % wt. to 40 wt% of Bi into Sn-Zn alloy. It was reported that the addition of 40 wt% of Bi increases the tensile strength to 299.9 MPa. Nasir et al. [57] explored the shear strength of SAC107 alloy reinforced with silicon nitride (Si3N4) particles at rate of 0, 0.25, 0.5, 0.75, and 1.0 wt.%. The introduction of 0.75% Si3N4 was found to enhance shear strength by 25.6%. Thomson et al. [58] developed the lead-free bearing material using bismuth, which was replaced by lead in the C93700 alloy. Bismuth was incorporated at rates of 5%, 10%, and 15%. The observation revealed that replacing lead with 15% bismuth resulted in the highest tensile strength, reaching 284 MPa. Additionally, Zhang et al. [59] investigated the impact of the ratio of graphene (Gr) to titanium (Ti) on the mechanical properties, microstructure, and interface structure of lead-free Cu40Zn. In addition, Cu40Zn-Gr-Ti and Cu40Zn-Gr composites' mechanical properties were divided into two groups. Within the Cu40Zn-0.5Gr group, an increase in titanium (Ti) content from 0.3% to 1.9% resulted in varied mechanical properties. The yield strength (YS) exhibited a range from 285 MPa to 326 MPa, ultimate tensile strength (UTS) ranged from 479 MPa to 525 MPa, elongation decreased from 21.3% to 13.5%, and hardness increased from 123 HV to 147 HV. Similarly, in the Cu40Zn-1.0Gr group, with Ti content increasing from 0.3% to 1.9%, YS ranged from 264 MPa to 316 MPa, UTS from 426 MPa to 493 MPa, elongation decreased from 17.1% to 8.6%, and hardness increased from 112 HV to 147 HV. It was reported that there is a rise in the number of nano Ti clusters and Cu2Ti4O particles with the increase in Ti content that leads to the mechanical properties' improvement. Imai et al. [60] investigated the properties and ease of machining of lead-free powder metallurgy Cu60-Zn40 brass alloys containing graphite. The extruded brass containing 0.5% graphite exhibited a remarkable 38% increase in machining speed and 95% of the ultimate tensile strength (UTS). Vetterick et al. [61] used powder metallurgy techniques to replicate the desired microstructure of leaded bronze. The research revealed that Cu-10Sn-3Bi composites exhibited a tensile strength of 420 MPa, while Cu-10Sn-10Pb composites achieved a tensile strength of 300 MPa. Notably, the tensile strength of lead-free Cu-10Sn-3Bi composites was observed to be 40% higher than that of Cu-10Sn-10Pb composites. Wang et al. [62] developed composite with Ni that was added into layers of graphite-lead free tin bronze on steel sheets surface by graphite and CuSn10 primary sintering mixed powders with poly vinyl alcohol (PVA) and nickel nitrate solution in the atmosphere of ammonia decomposition at the rate of 5, 8, 10, and 12 (vol%) gradually. It was observed that composites containing nickel comprise 5, 8, 10, and 12 (vol%) of graphite, and they have HB hardness values of 44.5, 41.3, 39.8, and 37.3 respectively. CuSn10Pb10 alloy has a hardness of 42.4 HB, which is higher than Ni-containing composites with 8, 10 and 12 (vol%) graphite. It was concluded that Ni can be added to help the graphite and CuSn10 matrix contact, which increases the hardness of composites. Jun et al. [63] reported that the composites are made using fibres coated with the same method, the density initially decreases while the hardness increases. However, as the volume of fibres in the composite increases, the hardness initially continues to rise before eventually decreasing. They found that of the hardness of the 9vol% fibre/Cu-4wt.%Sn-6wt.%Zn was better than the 12vol%. fibre /Cu-4wt.%Sn-6wt.%Zn. Zhang et al. [64] developed the lead-free Cu-FeS composites using power metallurgy. It was observed that the addition of FeS increases the hardness of the composites. The maximum increases in hardness were achieved with the addition of 7.5%, which was about 44% with the help of the rapid solidification method. Shen et al. [65] developed an in-situ nanoparticulate-reinforced Sn-Ag composite. It was discovered that adding those Ag3Sn nanoparticles helped the in-situ nanoparticle-reinforced Sn -Ag composite perform better mechanically. Pandher & Lawlor [66] investigated on the silver impact in lead-free alloy. It was reported that with high Ag alloys, there is more Ag3Sn intermetallic compound (IMC) in the bulk solder matrix and more mechanical strength, leading to the best temperature cycling reliability, Low Ag results in less Ag3Sn IMC in the bulk solder matrix and improved ductility, which improves performance under conditions of high strain rate.

Niranjaini et al. [67] It was found that adding 0.05% single-walled carbon nanotubes (SWCNT) increased both the yield strength and the ultimate tensile strength at all strain rates and temperatures. However, the observed rise in strength values at 75°C was only marginal. Sharma et al. [68] developed the Lead-free Sn-58Bi-$CeO_2$ composite using mechanical blending and melting. The $CeO_2$ was added at rates of 0 wt.%, 0.30 wt.%, 0.60 wt.%, and 0.90 wt.%. The outcome revealed that the tensile strength and ductility increases with addition of $CeO_2$.

Tables 2 and 3 present the various mechanical properties, like tensile strength and hardness, of the various lead-free composites developed by various researchers with different compositions.

The hardness of various lead-free composites, which ranges from 13.5 HV to 380 HV, is shown in Table 2. The kind and quantity of reinforcing particles determine the hardness of the composites. The hardness of the lead-free composites can be adjusted to match the journal bearing application demands. A bearing, for example, that is subjected to high loads will require a harder material than a bearing that is subjected to low loads.

The tensile strength of several lead-free composites is shown in Table 3, demonstrating their range of mechanical characteristics that are crucial for journal bearing applications. Due to the wide range of materials that are accessible, the tensile strength of the composites varies greatly. The tensile strength of a lead-free composite can be tailored to meet the specific requirements of a particular journal bearing application. For example, a bearing that is subjected to high loads will require a stronger material than a bearing that is subjected to low loads.

### 3.2 Tribological Properties of various Lead-free composites

The tribological properties play a vital role in the significance of lead-free composites, which is underscored

**Table 2.** Hardness of various Lead-free composites

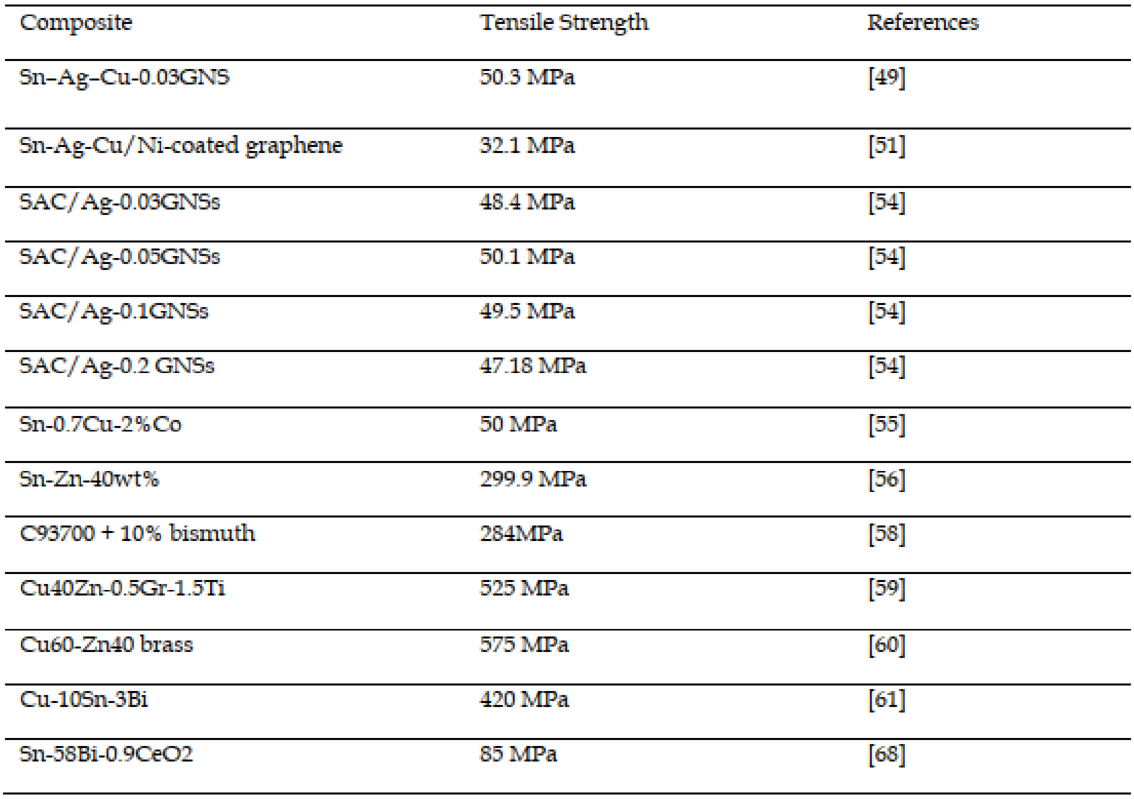
| Composite | Hardness | References |
|---|---|---|
| Sn–0.7Cu/Si3N4 | 14.94 HV* | [46] |
| FeS/Cu-Bi (FCB) | 64 HRB$^{\#}$ | [47] |
| Fe/Bi-bearing Sn-1Ag-0.5Cu (SAC105) | 22.6 HV* | [48] |
| 96.5Sn–3Ag–0.5Cu lead-free | 13.5 HV* | [50] |
| Cu40Zn-0.5Gr-1.9Ti | 147HV* | [59] |
| 5% Ni-CuSn10 composite | 44.5HB$^{\$}$ | [62] |
| 8% Ni-CuSn10 composite | 41.3HB$^{\$}$ | [62] |
| 10% Ni-CuSn10 composite | 39.8HB$^{\$}$ | [62] |
| 10% Ni-CuSn10 composite | 37.3HB$^{\$}$ | [62] |
| 9vol%. fibre/Cu-4wt.%Sn-6wt.%Zn | 100HV* | [63] |
| Cu-7.5wt.%FeS | 65HB$^{\$}$ | [64] |
| Sn–3.5Ag | 18.74HV* | [65] |
| Sn-58Bi-0.9$CeO_2$ | 28HV* | [68] |
| Fe-Cu+1%SN+1%MS2 | 380 HV* | [69] |

**$^{\$}$Brinell Hardness HB, $^{\#}$Rockwell B – HRB, *Vickers – HV**

by their tribological characteristics. Tribological studies delve into the friction, wear, and lubrication properties of these materials, ensuring their outstanding performance under varying operating conditions. These composites display superior tribological behaviour, effectively reducing friction and wear between moving components. [70] This diminished frictional resistance not only results in energy savings but also reduces heat generation within bearings, leading to more energy-efficient systems. [71].

Furthermore, certain lead-free composite formulations possess self-lubricating properties, reducing their reliance on external lubrication. This not only simplifies maintenance but also cuts down on operational costs.[72]. These advantages highlight the pivotal role of lead-free composites in enhancing the overall efficiency and reliability of machinery employing journal bearings. Also, the significance of lead-free composites extends to their adaptability and versatility. Ongoing research focuses on creating new composite formulations by combining different matrix materials and reinforcing agents to make these properties fit the needs of each application. This adaptability ensures that lead-free composites can be customised for various industrial sectors, ranging from automotive and aerospace to renewable energy and marine engineering. [73]. Liu et al. [70] developed a lead-free FeS/Cu-Bi (FCB) copper matrix that involves in situ Ni-coating of FeS powder followed by mechanical alloying with CuSn10 and Bi powder. The prepared composites were then sintered in an ammonia decomposition atmosphere. The FCB composites showed a 29% decrease in friction

**Table 3.** Tensile Strength of various Lead-free composites



| Composite | Tensile Strength | References |
|---|---|---|
| Sn–Ag–Cu-0.03GNS | 50.3 MPa | [49] |
| Sn-Ag-Cu/Ni-coated graphene | 32.1 MPa | [51] |
| SAC/Ag-0.03GNSs | 48.4 MPa | [54] |
| SAC/Ag-0.05GNSs | 50.1 MPa | [54] |
| SAC/Ag-0.1GNSs | 49.5 MPa | [54] |
| SAC/Ag-0.2 GNSs | 47.18 MPa | [54] |
| Sn-0.7Cu-2%Co | 50 MPa | [55] |
| Sn-Zn-40wt% | 299.9 MPa | [56] |
| C93700 + 10% bismuth | 284MPa | [58] |
| Cu40Zn-0.5Gr-1.5Ti | 525 MPa | [59] |
| Cu60-Zn40 brass | 575 MPa | [60] |
| Cu-10Sn-3Bi | 420 MPa | [61] |
| Sn-58Bi-0.9CeO2 | 85 MPa | [68] |

**Table 4.** wear rate and Coefficient of Friction of various Lead-free composites

| Composition | Reduction in friction coefficient | Reduction in wear rate (%) | Testing and characterisation | Apparatus | Lubrication | References | Observation |
|---|---|---|---|---|---|---|---|
| FeS/Cu-Bi (FCB) copper matrix | 29% | 73.2% | The size of the test samples 25 × 10 mm. The sliding distance 400 m, the applied load 5.0 N, the sliding speed 0.4 m/s, and the amplitude 20 mm. | Reciprocating ball-on- disc test device | Dry sliding wear tests | [70] | The tribological properties of the composites are greatly impacted by surface modification and mechanical alloying. |
| aluminium-nickel-copper (Al-C) | 30% | 45% | Friction testing pressure of 0.35 MPa, sliding speed of 5.5 m/s, The lubricant used was SAE 15W-40 | Pin on disc setup | Lubricated conditions | [74] | Surface texturing on the bearing surface significantly influences the wear rate. |
| phosphorous-aluminium-copper (Ph-C) | 70% | 50% | Friction testing pressure of 0.35 MPa, sliding speed of 5.5 m/s, The lubricant used was SAE 15W-40 | Pin on disc setup | Lubricated conditions | [74] | The better surface texturing of bearing surface influences the tribological properties. |
| Cu-FeS-Bi | 36% | 62%. | The diameter of specimen 35 and thickness 5 mm speed 0.25 m/s and load 330 N | HDM-20 end face friction and wear tester | Unlubricated conditions | [47] | The combined effect of surface modification & mechanical alloying influences the wear rate. |
| Cu-10Sn | 5.2% | NA | The pins loaded with 1745g , contact area of 12.88 $mm^2$ average contact stress between the pin and disk of 1.32MPa | Pin on disc setup | lubricated systems | [61] | The formation of highly networked boundary of hard, brittle intermetallic phase contributes to better coefficient of friction. |
| C90300 -13% graphite | 25.5% | NA | Loads of 44, 88, and 176 N for 30 minutes at a linear speed of 1 m/s. | Pin on disc setup | Unlubricated conditions | [77] | The better coefficient of friction is due to existence of graphite components in the matrix of copper-graphite pins. |
| PTFE + Organic Powder + Inorganic Compounds (Ca) | 13% | NA | Bush Size D20xL20xt1.5 mm Specific Load 4.9 MPa Velocity 6.0 m/min | Pin on disc setup | no lubrication | [78] | Addition of Ca contributes to better coefficient of friction. |

coefficient and 73.2% reduction in wear rate.

Sharma et al. [74] forged two lead-free bearing materials, such as phosphorous-aluminium-copper (Ph-C), and aluminium-nickel-copper (Al-C), and their tribological properties were evaluated. In addition, surface texturing was employed to improve the journal bearing performance. It is observed in the result that , when compared to the conventional lead bronze (Pb-C) material, the lowest specific wear rate (SWR) and friction coefficient were exhibited by the Ph-C material. In fact, there is an improvement of 30%-70% in the frictional coefficient and 45%-50% in SWR. Gao et al. [75] studied the tribological behaviour of a coating made of tin and bronze with tribology alloy (T-401) particles added to make it more flexible.

The coating was applied to the inner surface of a bushing used in aerospace engines using the high-velocity oxygen fuel (HVOF) thermal spray technique. Liu et al. [47] studied how mechanical alloying and surface modification change the mechanical and tribological properties of copper matrix composites that don't contain lead. This investigation involved the use of Bi and FeS powder as lubricating phases to substitute lead in the CuPb alloy.In conclusion, the average friction coefficient and wear rate decreased from 0.44 to 0.28, and 62 % respectively. The lead-free bearing material was developed by Thomson et al. [58] utilising bismuth as an alternative to lead in the C93700 alloy. Miyajima et al. [76] investigated the friction and wear characteristics of an Al–Sn–Si alloy coated with MoS2 under lubricated conditions using a reciprocating friction tester. The application of a MoS2 layer on the surface of the Al–Sn–Si alloy resulted in a notable reduction in friction, with an approximate 70% decrease in the area displaying the lowest friction coefficient. It was concluded that the presence of the MoS2 layer limited the wear depth to less than 1/10th compared to the uncoated Al–Sn–Si alloy. Mushtaq et al. [69] employed Powder Metallurgy (PM) techniques to produce lead-free Fe-Cu based powders. They introduced elements like tin, molybdenum disulfide, and Nanoboron nitride (BN) to improve both the tribological and mechanical properties of the material. The results showed that the material with 2.5 wt.% of Sn exhibited the highest hardness value. Vetterick et al. [61] used powder metallurgy techniques to replicate the desired microstructure of leaded bronze. They found that the average COF of the Cu-10Sn-10Pb valve plate material was 0.18, that of the Cu-10Sn-3bi was 0.19, and the average COF for each of the tin-infiltrated samples was 0.17.It was concluded that the composites containing nickel with a 10 vol% graphite concentration are optimal. Its wear rate and friction coefficient are 0.12 and 1.210- 4 mg/m. Kestursatya et al. [77] examined the friction coefficient of the C90300 alloy reinforced with 13% graphite. In contrast, the friction coefficient of the C90300 alloy ranged from 0.47 to 0.36. It was concluded that the C90300 alloy reinforced with 13% graphite reduces the coefficient of friction by 25.5%.

Jun et al. [63] examined the tribological properties of lead-free copper-based composites by incorporating carbon fibre into the tin bronze matrix, replacing part of the tin and all of the lead. They explored various factors, such as fibre volume, load, and sliding speed, in wear tests. The findings indicated that the wear resistance of the composite containing 9% vol% fibre /Cu-4wt.%Sn-6wt.%Zn was better than the traditional Zn-3wt.% % Pb tin bronze. Zhang et al. [64] developed the lead-free Cu-FeS composites using powder metallurgy. By employing a block-on-ring testing apparatus, the friction and wear characteristics were assessed for dry sliding with and without oil immersion. It was noted that under dry sliding conditions, the frictional coefficient and wear volumes both exhibited a decrease with an increased concentration of FeS in the composite.

Nakajima et al. [78] developed a lead-free polymer-based bearing for automotive applications using organic powder and inorganic compounds (Ca). The coefficients of friction for PTFE + Pb + others, PTFE + Organic Powder + Hard Particle, and PTFE + Organic Powder + Inorganic Compounds (Ca) were 0.29, 0.27, and 0.25. It was observed that the coefficient of friction of the lead-free PTFE + organic powder + inorganic compounds (Ca) bearing was 13% less than that of the lead base bearing. Some of the prominent tribological properties of the various lead-free composites as collected from the existing studies are presented in table 5.

Mechanical alloying and surface modification significantly reduce wear rates in lead-free composites, as shown in various journal bearings. The FeS/Cu-Bi [70] copper matrix showed a reduction of 73.2% in wear rate, while phosphorous-aluminum-copper and aluminum-nickel-copper composites also showed reductions. [74] The combined effect of surface modification and mechanical alloying resulted in a 62% reduction in wear rate. [47]

Lead-free composites have shown significant friction coefficient reductions in journal bearings, with surface modification and mechanical alloying resulting in significant improvements. Factors such as the type of reinforcing particles, mechanical alloying process, and bearing surface modification influence the reduction in friction, with FeS/Cu-Bi demonstrating a 29% reduction. [70] The addition of Ca compounds to PTFE resulted in a 13% reduction, while C90300 with graphite showed a -13% reduction, indicating improvement. [77], [78]. There are numbers of factors such as amount or type of used reinforcing particles, mechanical alloying process and bearing surface's surface modification influence the reduction in friction and wear.

### 3.3 Micro-structural characteristics of various Lead-free composites

One important microstructural property of lead-free composites is their grain size. Grain size is the average size of the grains in a material. Smaller grain sizes typically result in stronger and tougher materials. Lead-free composites can be engineered to have very small grain sizes, which contributes to their excellent mechanical properties [79], [80].

Another important microstructural property of lead-free composites is their distribution of phases. Lead-free composites are typically made up of two or more phases, one of which is a matrix material and the other of which is a reinforcing material. These phases distribution may have a significant impact on the composite's mechanical properties. Lead-free composites can be engineered to have a variety of different phase distributions, depending on the desired properties. Table 5 shows the Micro-structural characteristics of some lead-free composites.

Figure 1 demonstrates the SEM micrographs of the worn surfaces of Tin/bronze composites. The distribution of graphite was generally uniform, with occasional agglomerates observed in composites containing 20 µm graphite particles. Tribological tests were carried out using the pin-on-disk method under specific conditions. The CuSn10/graphite composite, with a graphite particle size of 45 µm and containing 0.4% Ti, exhibited the lowest friction coefficient and minimal wear on the steel ball. In addition, low wear and friction coefficients ware demonstrated by the other composites within the CuSn10 matrix. In contrast, the CuSn10PTi2/graphite 20 µm composite, with increased titanium and phosphorus content, exhibited the highest friction coefficient and the loss of counter-sample weight due to the hard phases' existence in the composite structure. The wear track's SEM microscopic analysis confirmed that the composite materials produced exhibited comparatively low wear.

Figure 2 shows the copper-based diamond composites'

**Table 5.** Micro-structural characteristics of various lead-free composites

| Composite | Matrix material | Reinforcing material | Grain size | Phase distribution | References |
|---|---|---|---|---|---|
| Tin/bronze composite | Tin/bronze | Graphite | 10-20 µm | Uniformly distributed graphite particles in a tin/bronze matrix | [81] |
| Copper-based composite | Copper | Bismuth and iron sulfide | 10-20 µm | Bismuth and iron sulfide particles distributed in a copper matrix | [82] |
| Aluminum-based composite | Aluminum | Silicon carbide | 10-20 µm | Silicon carbide particles distributed in an aluminum matrix | [83] |

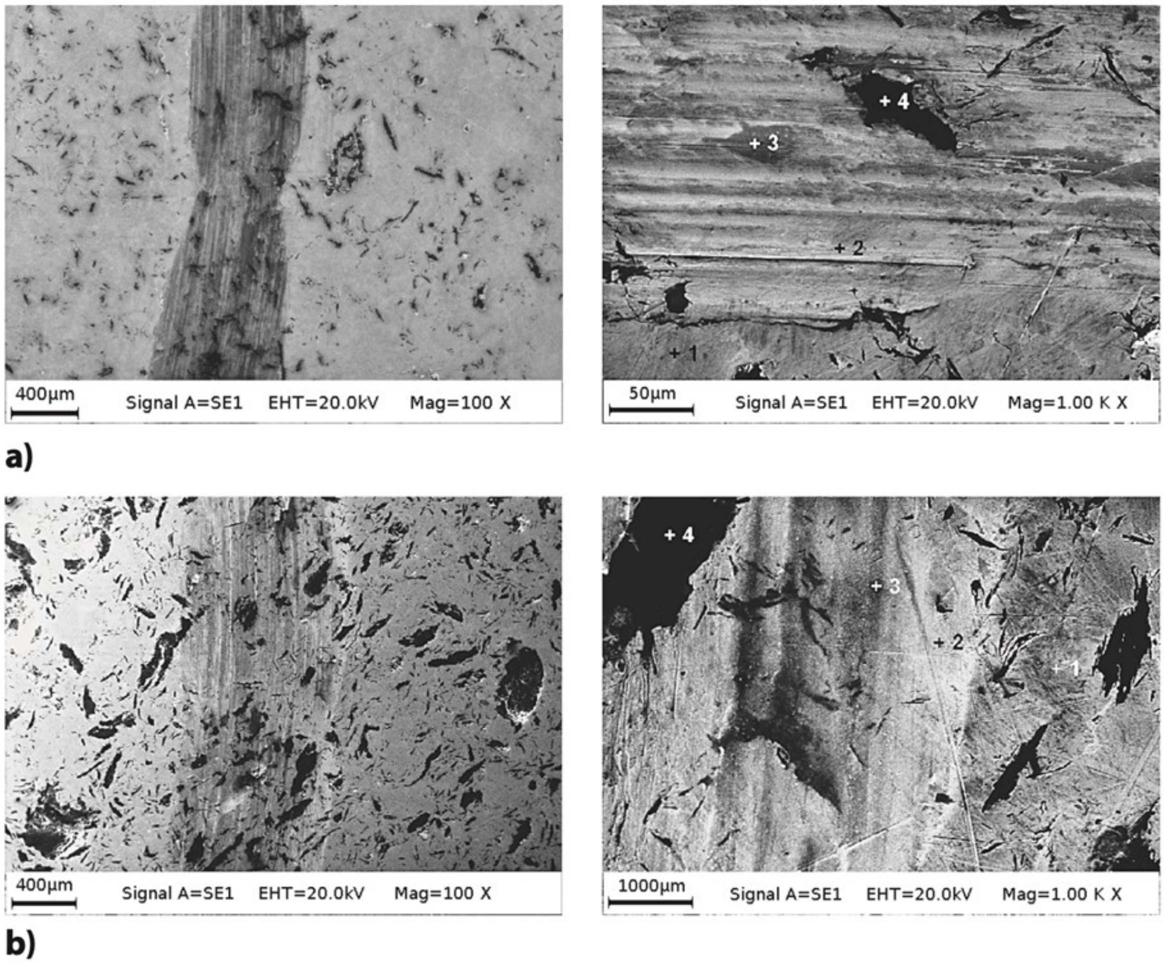


**Figure 1.** SEM micrographs of the worn surfaces of: (a) CuSn10Ti0-4/graphite (b) CuSn10Ti1-5/graphite (45 µm) composite after interaction with a steel ball [81]

microstructural properties, focusing on the volume fraction and diamond particle size effects. Smaller diamond particles led to the formation of sharp polygonal carbides on the diamond surface, while larger particles resulted in uniform carbide coverage. The size of diamond particles significantly influenced thermal conductivity, with larger particles enhancing density and thermal conductivity. However, recent studies predominantly used diamond particles between 100 µm and 300 µm due to cost and improved bonding between particles and copper. Additionally, the diamond volume fraction played a crucial role. Increasing the fraction initially enhanced thermal conductivity but caused a decrease at high fractions (above 40-70%) due to reduced copper filling between particles. To achieve copper-based diamond composites with optimal thermal conductivity, it is suggested to target a diamond volume fraction within the range of 50% to 60%. Additionally, there is an observed decrease in the coefficient of thermal expansion as the diamond volume fraction increases. Current research mainly focuses on diamond fractions between 50% and 70%, although ultra-high pressures could allow fractions exceeding 70% or even reaching 90%. Breakthroughs in this field may require new shaping methods.

Figure 3 illustrates the aluminum-based ceramic-reinforced composite materials' microstructure that were prepared through low-energy mechanical alloying. The extension of alloying time resulted in a reduction in crystal size, and this effect was most pronounced in the sample with a 6% Zn ratio alloyed for 10 hours. Also, longer alloying times made the lattice strain higher, except for the sample that had a 9% Zn ratio. This suggests that Zn affects the lattice stress. Notably, the samples containing 6% Zn displayed the highest inclination to form alloys, while the addition of 9% Zn was not effective in reducing lattice strain. Furthermore, optical microscopy and elemental analysis supported these findings, confirming the enhanced homogeneity and alloying tendency in the sample with 6% Zn and a 10-hour alloying time. Overall, the study demonstrated that extending the alloying time and incorporating 6% Zn resulted in favourable microstructural changes, including reduced crystal size and improved alloy formation tendency.

## 4. Challenges in implementation of lead-free composites

The current engineering landscape makes it difficult to use lead-free composites for journal bearings. Some of the major challenges are;

Finding eco-friendly alternatives with similar or better

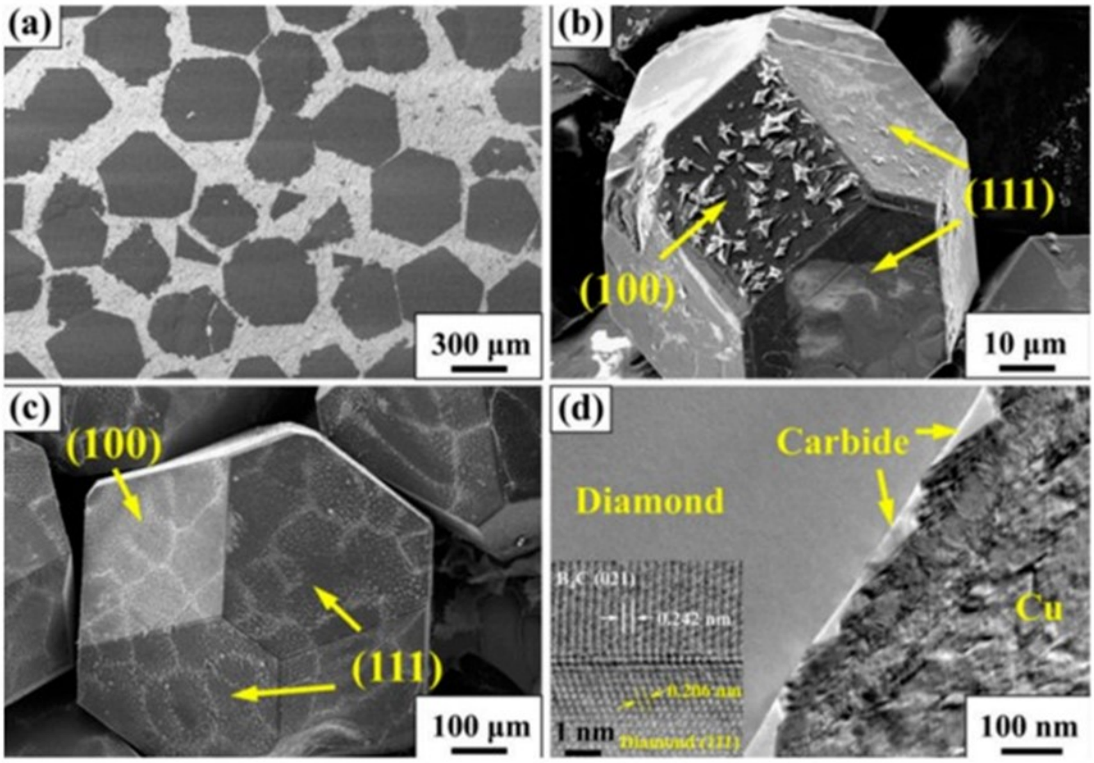


**Figure 2.** Microstructures of copper-based diamond composites by alloying B element in copper matrix: (a) The backscattered electron image; the extracted diamond particles with particle size matrix: (a) The backscattered electron image; the extracted diamond particles with particle sizes of (b) 66 μm and (c) 701 μm; (d) the copper/diamond interface image. [82]

mechanical and tribological properties makes replacing lead-based materials difficult [84], [85]. For heavy loads and fast sliding rates, materials with low friction and high wear resistance are essential. Engineering applications with heavy loads and rapid sliding require these materials for optimal performance and durability [86] . Design complexities and lubrication requirements must be carefully analysed to integrate new materials into engineering systems without affecting performance or durability [87], [88]. Lead-free journal bearings must balance performance and cost-effectiveness [89], [90]. Alternative materials' lifecycle environmental impacts must be addressed [96]. In order to comply with international laws and standard resource findings, the production, use, and disposal of materials should be considered with the product to determine the environmental footprint. [91] . To promote accountability and responsibility, it enforces business ethics and laws requiring rigorous testing and certification of lead-free materials [92]. The importance of education and knowledge distribution to promote industry adoption and integration of innovative solutions requires current information for engineers and manufacturers [93]. These efforts drive innovative and advanced solutions. Continuous research solves problems, advances, and keeps industries competitive in a changing world [94].

## 5. Conclusions

This comprehensive review of the behaviour of lead-free composites in journal bearings underscores the significant advancements made in seeking environmentally friendly alternatives to conventional lead-based materials. It emphasises the pressing necessity for sustainable engineering solutions aligned with global environmental objectives. The investigation illuminates the promising tribological and mechanical properties of lead-free composites, offering valuable insights for industries seeking reliable and eco-conscious bearing materials. However, it also highlights the intricacies of current challenges, emphasising the imperative for further research and innovation. The analysis reveals a noticeable gap in the study of lead-free composites' applications in journal bearings. Bridging this disparity between laboratory findings and real-world engineering demands necessitates assessing these materials' performance in practical industrial settings, considering variables like variable loads, speeds, and lubrication conditions. There is a clear imperative for in-depth studies focusing on the long-term durability and real-world applicability of lead-free composites in journal bearings. Systematic optimization studies concentrating on the composition of lead-free composites are also indispensable. Moreover, comprehensive comparative analyses are urgently needed to evaluate the performance of these composites across various operating conditions. This multifaceted approach is essential for advancing the understanding and implementation of lead-free composites in journal bearings, thereby fostering sustainable engineering

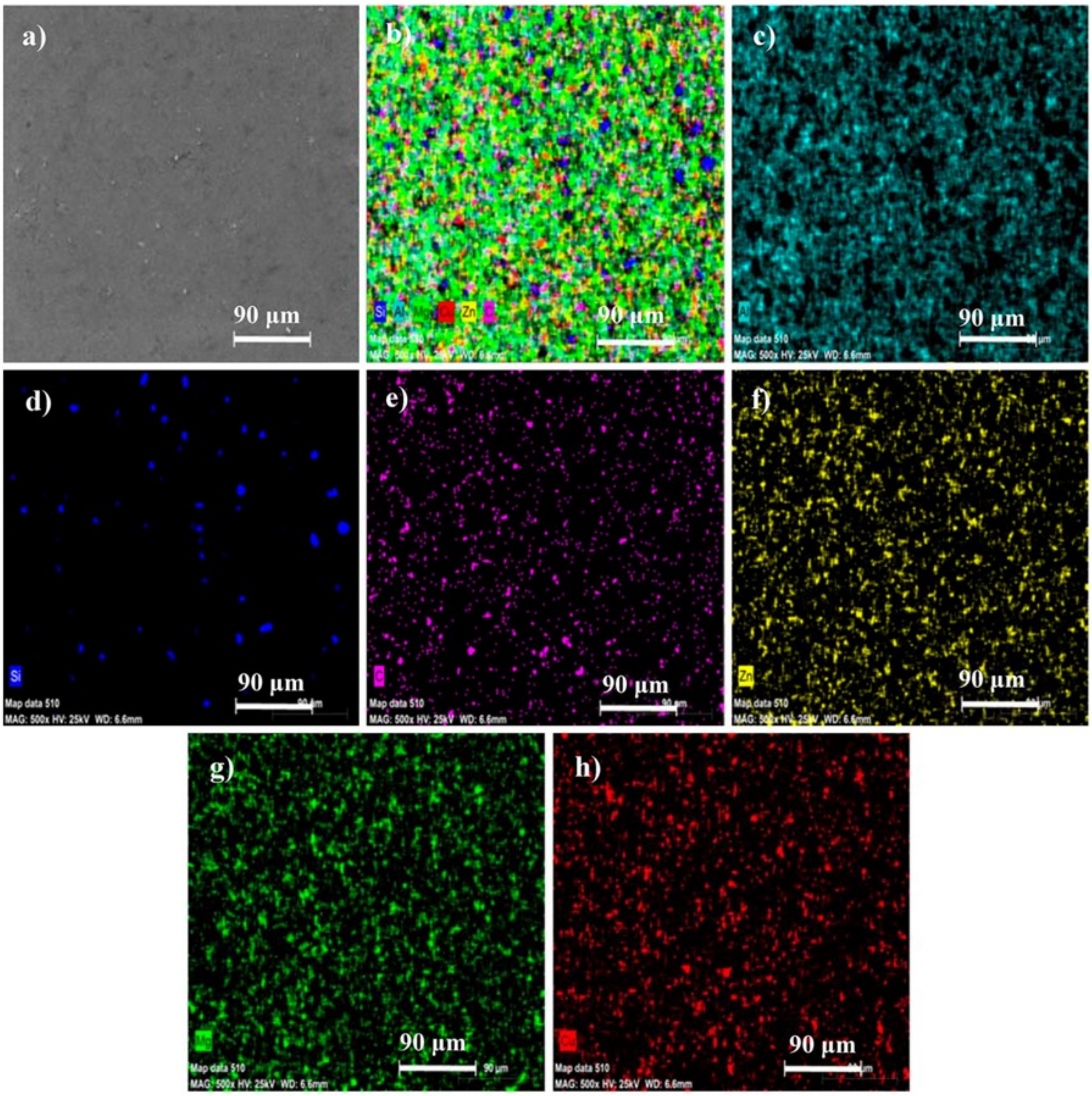


**Figure 3** SEM images of aluminum-based ceramic-reinforced composite of the sample containing 6% Zn a) Sem image b) All elements c) Al particles d) Si particles e) C particles f) Zn particles g) Mg particles h) Cu particles [83]

practises in line with environmental conservation goals.

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