Wear Analysis of an Advanced Al–Al₂O₃ Composite Infiltrated with a Tin-Based Alloy

Mihail Kolev , Ludmil Drenchev and Veselin Petkov

Equipment and Technologies with Hydroaerodynamics Centre, Institute of Metal Science, Bulgarian Academy of Sciences, 67 Shipchenski Prohod Str., 1574 Sofia, Bulgaria; ljudmil.d@ims.bas.bg (L.D.); veselin.petkov@ims.bas.bg (V.P.)

* Correspondence: mihail1kolev@gmail.com

Abstract: In this study, a hybrid material is produced, and the effect of different loads varying from 40 to 60 N against an EN-31 steel counter disk on its wear behavior under dry sliding conditions at room temperature is studied. The tribological behavior is studied via the pin-on-disk method and analyzed using primary wear parameters, such as the coefficient of friction (COF), mass wear, and specific wear rate. The obtained results are compared with the results for B83 babbitt under the same wear test conditions. Microstructural observation with scanning electron microscopy (SEM) is performed along with X-ray energy dispersive spectroscopy (EDX) for chemical analysis conduction. The results from the wear experiments indicate that the hybrid material possesses a lower COF, mass wear, and specific wear rate as well as a higher wear resistance in comparison to the B83 babbitt specimen when subjected to the same test conditions. The results from the wear experiments indicate that by applying different loads of 40, 50, and 60 N, the hybrid material possesses a lower mass wear, specific wear rate, and COF specifically at a load of 40 N in comparison to the B83 babbitt specimen under the same test conditions. It was also observed that by increasing the load under dry sliding friction, the hybrid material increases its mass wear and specific wear rate.

Keywords: Al–Al₂O₃; tin-based babbitt; tribological behavior; mass wear; specific wear rate

Citation: Kolev, M.; Drenchev, L.; Petkov, V. Wear Analysis of an Advanced Al–Al₂O₃ Composite Infiltrated with a Tin-Based Alloy. *Metals* **2021**, *11*, 1692. <https://doi.org/10.3390/met11111692>

Academic Editor: Belén Díaz Fernández

Received: 8 September 2021

Accepted: 20 October 2021

Published: 24 October 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The fabrication of lightweight and high-strength composite materials has played a major part in improving environmental protection, reducing emissions, and enhancing the mechanical and tribological properties of products intended for use in industrial machinery and transportation manufacturing.

Due to their good low density, wear resistance, fatigue strength, high load-carrying capacity, thermal conductivity, excellent corrosion resistance, and overall low price when compared to other materials, aluminum metal matrix materials (AMMCs) have become one of the most common choices for materials used in a variety of industrial sectors [1–5]. To improve the strength and wear resistance of AMMCs, different types of reinforcing phases (RPs) are introduced. The most common RPs are silicon carbide (SiC) [6–8], alumina (Al₂O₃) [8–10], graphite [11], zirconium silicate [12], titanium carbide [13], and boron carbide [14]. Since its high thermal stability and brittle phase do not appear between the RP and the metal matrix, alumina can be viewed as a well-suited choice for reinforcement [15].

The volume loss of different AMMCs is influenced by the load and reinforcement size, according to various studies [15–17].

An investigation of the wear properties of composites obtained via powder metallurgy with AA7075 as the base alloy and reinforced with 5 wt% Al₂O₃ particles with sizes varying between 0.3 and 15 µm under dry sliding conditions concluded that the sample with the largest RP particle size demonstrated the best wear resistance. In addition to this data, using analysis of variance (ANOVA) has shown that the most significant parameter influencing volume loss is the load [15].

The wear properties of AMMCs obtained by a liquid processing method from AA242 reinforced with 30 vol% of alumina particles were investigated, and the results indicated that, when increasing the wear load, the wear rate increased and the coefficient of friction (COF) decreased due to the removal of the RP [16]. Due to its better thermal dissipation, the tribological performance under of an AA6061 composite reinforced with alumina sub-micron particles under dry sliding conditions indicated a lower wear rate when compared with grey cast iron [17].

Babbitt alloys are one of the most studied wear-resistant alloys and one of the most common materials intended for application in bearings [18–20]. Tin-based babbitts are casting alloys with a multiphase microstructure, most commonly characterized by SbSn and Cu_6Sn_5 intermetallic compounds and a solid solution matrix [21–25]. The tin-based babbitt is plastic and soft, carrying the particles of hard phases, which provide effective abrasion resistance [20–23]. Due to the presence of β -phase particles in tin babbitts with up to 20 wt% antimony, the hardness of these alloys has been observed to increase without deteriorating the sliding wear behavior [21,24]. The effect of antimony in tin-based white metals varying between 5 and 23 wt% on the amount of wear in lubricated wear testing has also been studied, with results indicating that 18 wt% antimony is the limit at which the wear resistance of the alloy is not affected [24]. Due to its low COF and high fracture toughness, cast commercial babbitt grades B88, B83, and B83C with tin bases are used as antifriction materials in a variety of engineering applications [26]. Also, due to its soft plastic base and large hard second-phase inclusions, and according to the Charpy rule, the tin-based babbitt possesses a low COF [23]. The production of dispersion-hardened heterogeneous tin-based babbitt composites leads to overcoming a drawback such as the low fatigue resistance due to the sharp angles of SnSb intermetallics [27]. A study suggests that the inclusion of 10 wt% of alumina reinforcement in Sn-Sb-Cu babbitt alloy improves the wear resistance of the material [28]. In another investigation, three types of hard particles with different densities and identical shapes such as Al_2O_3 , Cr_3C_2 , B_4C were blended with tin-based babbitt alloy and the results from the tribological tests indicate that combination of babbitt and alumina shows the lowest coefficient of friction [29].

The incorporation of nanoparticles as reinforcement in the babbitt alloys has been proven by various studies [30,31] as an improvement in tribological and mechanical properties in the nanocomposites. A study focused in investigating the influence of alumina nanoparticles on microstructural variation of tin-based babbitt as well as bimetallic microstructural interface suggest that the addition of 0.25 and 0.50 wt% alumina nanoparticles improves the mechanical and tribological properties and affects the morphology and distribution of Cu_6Sn_5 hard phase in the solid solution of the nanocomposite [30]. The results presented in another study of white babbitt coatings modified by carbon nanotubes show increase in the wear resistance of tested materials [31].

The aim of the present research is structural and chemical characterization of an advanced composite material in addition to the study of the effect of different loads on the tribosystem interaction parameters such as mass wear, specific wear rate, and coefficient of friction, of an advanced composite material with enhanced wear resistant properties under dry sliding conditions. The advanced composite consists of an aluminum- Al_2O_3 skeleton produced by a replication method, which is commonly utilized for the production of high-porosity metal materials with an open-cell structure and it is infiltrated by tin-based babbitt [20]. Analyzing the literature, the production and investigation of no such advanced composite material was found. The tribological characterization was conducted under different conditions, especially 40, 50, 60 N loads. These conditions were not presented in the literature by other authors investigating tin-based babbitt alloys reinforced with micro- or nanoparticles [27–31].

The combination of the low density, fatigue strength, high load-carrying capacity, thermal conductivity, excellent corrosion resistance, and overall low price of the AMMCs with the self-lubricating properties and load-carrying ability of the tin-based babbitt could represent a potential practical application for the manufacturing of sliding contact bearings.

This study is a continuation of our previous research [32,33], and the results of the observed tribological behavior of the advanced composites are compared with the results of the B83 babbitt with different loads and under the same dry sliding conditions.

2. Experimental

2.1. Production Method and Materials

The new hybrid material consists of a composite (aluminum– Al_2O_3), high-porosity, open-cell skeleton infiltrated by B83 babbitt. A replication method is used for the preparation of the skeleton [20,32–35]. It begins with the preparation of a sodium chloride (NaCl) leachable preform (space holder). The NaCl particles are mixed with 5 wt% water and 7 wt% Al_2O_3 particles. Then, the obtained mixture is processed by compacting it into a cylindrical steel cup under a pressure of 1.5 MPa. The moisture from the NaCl compacts (green compacts) is removed via drying in a furnace at $200\text{ }^\circ\text{C}$ for 2 h. The green compacts are sintered in a tubular furnace at $785\text{ }^\circ\text{C} \pm 1\text{ }^\circ\text{C}$ for 2 h, and the cooling of the obtained salt leachable preform is performed at room temperature. Thereafter, it is preheated before its fixation in die at $680\text{ }^\circ\text{C} \pm 2\text{ }^\circ\text{C}$ and infiltration by molten $\text{AlSi}_{10}\text{Mg}$ alloy. The infiltration is conducted using the squeeze casting method with an applied pressure of 80 MPa for 60 s. Then, the obtained composite is cooled down at room temperature, and the space holder is removed via dissolution in $70\text{ }^\circ\text{C}$ hot distilled water with an ultrasonic machine.

The last processing stage of the hybrid material is focused on B83 babbitt infiltration in the already-fabricated aluminum– Al_2O_3 skeleton using the squeeze casting method. The skeleton is preheated before its fixation in die at $680\text{ }^\circ\text{C} \pm 2\text{ }^\circ\text{C}$, and the B83 babbitt is infiltrated with a pressure of 80 MPa for 60 s. The obtained hybrid material is cooled down at room temperature.

Figure 1 describes the three stages of the production process of the hybrid material.

Figure 1. The production process of the hybrid material.

Sodium chloride particles with a size range of 430–850 μm are used as space holders to obtain the preforms (Figure 2a). The base alloy for obtaining an aluminum– Al_2O_3 skeleton with a complex geometry and thin walls is $\text{AlSi}_{10}\text{Mg}$ (see Table 1). The choice of this particular alloy is due to its post-processing flexibility, low weight, and very good mechanical

and thermal behavior. The reinforcing phase consists of Al_2O_3 particles with sizes varying between 10 and 30 μm (Figure 2b). The material utilized for the infiltration in the aluminum– Al_2O_3 skeleton is B83 babbitt with grade of B83 (Sn/Sb/Cu/Fe/Al/As/Pb/Zn/Bi) (see Table 2). The material used as the counter disk is EN-31 steel hardened to 62 HRC (see Table 3). Optical image of hybrid material test pin before conducting the wear tests is presented in Figure 2c.

Figure 2. Scanning electron microscope images of reinforcement and space holder: (a) NaCl particles in the range of 430–50 μm , after ref. [32] (adapted from [32], with permission from Springer Nature 2020); (b) alumina particles in the range of 10–30 μm , after ref. [32] (adapted from [32], with permission from Springer Nature 2020); (c) optical image of hybrid material test pin.

Table 1. $\text{AlSi}_{10}\text{Mg}$ alloy composition, wt%.

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Pb	Sn	Ti	Al
Composition, wt%	9.0–11.0	0.55	0.05	0.45	0.2–0.45	0.05	0.10	0.05	0.05	0.15	rest

Table 2. Tin-based alloy composition, wt%.

Alloy	Fe	Al	Cu	As	Pb	Zn	Sb	Bi	Sn
Composition, wt%	0.1	0.005	5.5–6.5	0.05	0.35	0.004	10–12	0.05	80.94–84.50

Table 3. EN-31 steel, wt%.

Alloy	C	Si	Mn	Cr	Si	Fe
Composition, wt%	0.90–1.20	0.10–0.35	0.30–0.75	1.00–1.60	0.20	rest

2.2. Characterization Methods

Test specimens from the hybrid material and B83 babbitt sliding against the EN-31 steel are used for determining the structural and tribological characterization. The results from both materials are compared and discussed.

Structural observations are determined via a scanning electron microscope (SEM), tabletop HIROX SEM SH-5500P (Hirox, Tokyo, Japan), and, for conducting the chemical microanalysis, X-ray energy dispersive spectroscopy (EDX), QUANTAX 100 Advanced–Bruker (Bruker, Germany).

The tribological properties of all the test specimen are determined with a Ducom Rotary (Pin/Ball-on-Disk) tribometer, model TR-20, made in India (Ducom, Bengaluru, India). A pin-on-disk tester was used to conduct dry wear tests on test specimens (pins with a spherical tip) that were 10 mm in diameter and 30 mm high. A 140 mm diameter counter disk of EN-31 steel hardened to 62 HRC (surface roughness: 1.6 Ra) was used and the following test parameter values were applied: 40, 50, and 60 N loads, $1.004 \text{ m}\cdot\text{s}^{-1}$ linear velocity, 7 min test duration, and 418 m sliding distance. Four tests were conducted for

each material and selected load. The COF is calculated using the data acquisition system of the tribological installation. The specific wear rate is calculated using Formula (1) [31]:

$$S_W = W \div L, \text{ kg} \cdot \text{m}^{-1} \cdot \text{N}^{-1} \quad (1)$$

$$W = \Delta_m \div D, \text{ kg} \cdot \text{m}^{-1},$$

where S_W is the specific wear rate, W is the wear rate, L is the normal force, D is the sliding distance, and Δ_m is the wear amount (mass loss of tested specimen).

3. Results and Discussion

3.1. Microstructure

Figure 3 shows SEM image with markers indicating different zones of the test samples in EDX analysis (Table 4) for infiltrated B83 babbitt before conducting tribological tests and Figure 4a–f shows SEM images with markers indicating different zones of the test samples in EDX analysis of wear surfaces of the hybrid material and B83 babbitt specimen at loads of 40, 50, and 60 N.

Figure 3. SEM image with marks highlighting different zones of EDS analysis of B83 babbitt before tribological tests.

Table 4. EDX analysis of selected zones from Figure 3 on the raw surface of B83 babbitt, mass norm., %.

No. Analysis	Sn	Sb	Cu	Al	Pb
1	61.69	7.68	30.12	0.24	0.27
2	65.51	8.50	24.67	0.36	0.96
3	80.18	14.57	3.43	1.82	—

Figure 4. Cont.

Figure 4. SEM images with marks highlighting different zones of EDS analysis of the following samples: (a) wear surface of B83 babbitt at a load of 40 N; (b) wear surface of hybrid material at a load of 40 N; (c) wear surface of B83 babbitt at a load of 50 N, after ref. [32] (adapted from [32], with permission from Springer Nature 2020); (d) wear surface of hybrid material at a load of 50 N, after ref. [32] (adapted from [32], with permission from Springer Nature 2020); (e) wear surface of B83 babbitt at a load of 60 N; (f) wear surface of hybrid material at a load of 60 N.

The microstructure of the surface of the B83 babbitt specimen before the start of tribological tests shows that the investigated alloy consists of numerous needle shaped Cu_6Sn_5 phases, Figure 3 and its chemical composition is presented in Table 4.

The wear scar and wear direction on the wear surface of the B83 babbitt at a load of 40 N are shown in Figure 4a. The iron content on the babbitt contact surface after the wear test is higher than on the raw babbitt surface due to the asperity contacts of the sample and the counter disk (see Table 5).

Table 5. EDX analysis of selected zones from Figure 4a of the wear surface of B83 babbitt at a load of 40 N, mass norm., %.

No. Analysis	Sn	Sb	Cu	O	Fe	Pb	Al
1	83.49	9.73	2.65	2.44	0.85	0.56	0.28
2	86.26	8.50	3.66	0.20	1.01	–	0.37
3	84.32	8.68	2.86	3.18	0.73	0.23	–

On the SEM micrograph in Figure 4b, one can observe the pore walls of the skeleton, wear scar and wear direction on the wear surface of the hybrid material at a load of 40 N. The chemical composition given in Table 6 indicates two zones within the pore walls with high peaks of aluminum and smaller peaks of tin, oxygen, antimony, silicon, and iron, which is indicative for the progressive loss of babbitt material and the appearance of the skeleton. In the third indicative zone of the sample, the iron content is higher than the other two zones due to the adhesive wear, which results in detachment of a fragment from the counter disk.

Table 6. EDX analysis of selected zones from Figure 4b on wear surface of hybrid material at a load of 40 N, mass norm., %.

No. Analysis	Al	Sn	O	Sb	Si	Fe
1	53.27	28.03	6.16	3.34	7.11	2.09
2	54.55	29.34	8.52	3.66	2.85	1.09
3	14.24	58.01	9.12	8.28	1.50	8.85

The micrograph in Figure 4c shows a wear scar part of a large zone, due to the adhesive wear on the wear surface of the B83 babbitt at a load of 50 N. Its chemical composition given in Table 7 points to a higher content of iron and lower tin content compared to the

wear surface of the B83 babbitt at a load of 40 N. The SEM image presented in Figure 5a of the wear surface of the B83 babbitt at a load of 50 N shows that the intermetallics with greater distance between them are more frequent.

Table 7. EDX analysis of selected zones from Figure 4c of the wear surface of B83 babbitt at a load of 50 N, mass norm., %.

No. Analysis	Sn	Sb	Cu	O	Fe
1	77.35	8.70	12.25	3.08	2.37
2	83.78	11.23	2.86	1.53	0.60
3	80.04	10.06	4.72	3.30	1.88

Figure 5. Wear surface of B83 babbitt at a load of 50 N: (a) SEM image; (b) EDX pattern of intermetallic phase; (c) EDX pattern of Sn matrix.

Part of the wear track and the direction of the counter disk are visible in the SEM image shown in Figure 4d, which shows a hybrid material at a load of 50 N. The EDX analysis presented in Table 8 displays a zone with peaks of aluminum and oxygen, which indicates the presence of the alumina reinforcement incorporated into the aluminum alloy

skeleton. In the other zone of the chemical analysis, a slightly worn region due to the presence of tin and antimony peaks of the B83 babbitt alloy as well as an iron peak can be seen. The last indicates for transferred particles, which are detached from the counter disk and then they are incorporated into the B83 babbitt sliding surface.

Table 8. EDX analysis of selected zones from Figure 4d on wear surface of hybrid material at a load of 50 N, mass norm., %, after ref. [28].

No. Analysis	Al	O	Si	Sn	Fe	Sb	Cu
1	32.26	24.26	18.32	17.98	5.79	1.09	0.32
2	7.73	4.02	0.85	63.90	13.17	9.35	0.98

The SEM micrograph presented in Figure 4e shows few pores and a visible wear track zone possibly formed as a result of the synergetic effect of adhesive and fatigue wear on the contact surface of B83 babbitt at a load of 60 N. The iron peak in the wear track zone is lower compared to the one in the wear track zone of B83 babbitt at a load of 50 N (see Table 9).

Table 9. EDX analysis of selected zones from Figure 4e of wear surface of B83 babbitt at a load of 60 N, mass norm., %.

No. Analysis	Sn	Sb	Cu	O	Fe	Pb	Al	Si
1	80.28	13.16	3.56	1.51	0.54	0.42	0.27	0.26
2	81.14	11.70	4.09	1.55	0.68	0.38	0.27	0.18
3	77.23	15.00	4.28	1.93	1.12	0.39	0.03	–

The micrograph in Figure 4f shows few pores in the zone of the synergetic effect of adhesive and fatigue wear on the contact surface of the hybrid material at a load of 60 N. The highest peaks of Al as gathered from the EDX analysis given in Table 10 indicate the emergence of the aluminum skeleton from the pores shown on the micrograph. The presence of iron peaks in the analyzed wear track zones is the highest registered compared to the rest of the samples tested at different loads.

Table 10. EDX analysis of selected zones from Figure 4f of the wear surface of hybrid material at a load of 60 N, mass norm., %.

No. Analysis	Al	Sn	Fe	Sb	O	Si
1	43.84	32.51	13.04	4.41	3.77	2.42
2	45.02	28.85	14.03	4.37	4.08	3.65
3	41.59	30.65	17.64	4.83	4.47	0.83

3.2. Tribological Characterization

The results of the effect of different loads on the coefficient of friction, mass wear, and specific wear rate of a hybrid material and B83 babbitt under dry sliding conditions are presented and compared in Figures 6 and 7. From the results shown in Figure 6 regarding the obtained COF, it can be seen that, with a load of 40 N, the hybrid material has a 11.2% decreased COF in comparison to the B83 babbitt. At the load of 50 N, the hybrid material has a 38.9% increased COF in comparison to the B83 babbitt. At the highest load of 60 N, the hybrid material has a 23.5% increased COF in comparison to the B83 babbitt. With a load increase of 25% from 40 to 50 N, the hybrid material exhibits an increased COF of 128.7% and a 3% decrease when the load continues to increase from 50 to 60 N. When the

load of 40 N increases by 25% for B83 babbitt, its COF increases 46.1%, and, when the load increases by 20% from 50 to 60 N, the COF increases by 9.5%.

Figure 6. Coefficient of friction of the hybrid material and B83 babbitt with respect to different loads of 40, 50, and 60 N and a distance of 418 m under dry friction conditions at room temperature.

Figure 7. Specific wear rate of the hybrid material and B83 babbitt with respect to different loads of 40, 50, and 60 N and a distance of 418 m under dry friction conditions at room temperature.

The results regarding the specific wear rate of both materials presented in Figure 7 indicate that the hybrid material at a load of 40 N exhibits a 52.2% decrease in comparison to the B83 babbitt. At a load of 50 N, the hybrid material exhibits a 72.3% decrease in its specific wear rate in comparison to the B83 babbitt. At a load of 60 N, the hybrid material exhibits a 33.3% decrease in its specific wear rate in comparison to the B83 babbitt. With a 25% increase of in the load from 40 to 50 N, the hybrid material exhibits a 63.6% increase in its specific wear rate, which remains the same at load of 60 N. When the load of 40 N for the B83 babbitt increases 25% from 40 to 50 N, its specific wear rate increases by 182.6%, and, when the load increases from 50 to 60 N, its specific wear rate decreases by 58.5%.

The results of the mass wear of both materials presented in Figure 8 show that at a load of 40 N, the hybrid material exhibits a 50.1% decrease in comparison to the B83 babbitt. At a load of 50 N, the hybrid material exhibits a 71.6% decrease in respect to its mass wear in comparison to the B83 babbitt. At a load of 60 N, the hybrid material exhibits a 31.1% decrease in its mass wear in comparison to the B83 babbitt. With a 25% increased load from 40 to 50 N, the hybrid material exhibits an increased mass wear of 98.9% and increases its mass wear with 19.5% from 50 to 60 N. When the load of 40 N for the B83 babbitt increases by 25% from 40 to 50 N, its mass wear increases by 249.4%, and, when the load increases from 50 to 60 N, its mass wear decreases by 50.7%.

Figure 8. Mass wear of the hybrid material and B83 babbitt with respect to different loads of 40, 50, and 60 N and a distance of 418 m under dry friction conditions at room temperature.

3.3. Discussion

The main focus of the present research is to study the effect of different loads on the interaction parameters of a tribosystem—such as the coefficient of friction, mass wear, and specific wear rate of a new hybrid material under dry sliding conditions. The results for this material are compared with those obtained for the B83 babbitt.

By applying different loads of 40, 50, and 60 N with a distance of 418 m and a linear velocity of $1.004 \text{ m} \cdot \text{s}^{-1}$ against an EN-31 steel counter disk, the hybrid material remains with decreased mass wear, specific wear rate and COF specifically at a load of 40 N in comparison to the B83 babbitt. The sharp-edged geometry of large SnSb intermetallics and the liquation process during the crystallization of the B83 babbitt increase its wear resistance against the harder steel counter disk, which attempts to tear the wear surface by its asperities from the running-in stage, the initial period of all experiments under dry sliding conditions [26]. The lower values of the COF at load 40 N are due to the occurrence of hard intermetallic particles resulting in decrease of adhesion, which was observed by Leszczyńska-Madej et. al. [21].

As a result of the friction between the surfaces of the hybrid material and the counter body, a zone of the aluminum- Al_2O_3 skeleton emerges and the contact zone of the aluminum- Al_2O_3 skeleton exert direct contact with the counterbody. During the increase of the load from 40 to 50 N, the count of these zones also increases, which is the reason for the increase of the COF. By increase of load from 40 to 50 N, the effective area of contact between the skeleton and counterbody remains practically without significant change.

As a result of the friction between the contact surfaces of the hybrid material and the counter body, a third body of wear debris emerged from the B83 babbitt, as well as debris from emerging walls of the aluminum- Al_2O_3 skeleton and iron appears (see Tables 6, 8 and 10). Due to this subsequently formed third body and the greater distance in between the precipitates the results from the COF tests at loads 50 and 60 N for the hybrid material vary and when compared with the B83 babbitt increase, as can be seen in Figure 5. Alcover, Jr. et. al. [36] associate the increase of COF with the greater refining of SnSb and Cu_6Sn_5 precipitates and Murata et al. [37] also associate the increase of COF with the increase of the distance between the precipitates or their small sizes.

It was observed a great increase in the specific wear rate and mass wear for the B83 babbitt at load 50 N when compared with the test results for the same alloy at 40 and 60 N. Due to its inhomogeneous distribution and greater distance between the precipitates as can be seen in the SEM image of Figure 4, the B83 babbitt has shown non-relational results for mass wear and specific wear rate when tested at different loads [38]. Because of this, its wear rate and specific wear rate increased by increasing the load from 40 to 50 N and decrease by continuing to increase the load from 50 to 60 N. Thus, the obtained results for the B83 babbitt subjected to friction with the counter disk at a load of 50 N indicate

that the wear has occurred mainly in the adhesive wear region and the limited quantity of precipitates in that region were not enough to serve as reinforcing phase as in the case of the other two loads of 40 and 60 N.

We plan to continue our future work with production of hybrid materials by incorporating different RPs, such as SiC, B₄C, and TiC. We will also produce and test hybrid materials by employing hypereutectic alloy AlSi18 modified by phosphorus and nanodiamonds [39–41]. It is planned to determine the mechanical properties of hybrid materials in dynamic conditions. Efforts will be directed to elaboration of statistical models and study the tribological behavior of the obtained materials as a function of various testing parameters applying these models.

4. Conclusions

A method for the production of a new hybrid material is developed, and the effect of various loads—40, 50, 60 N—on parameters such as the coefficient of friction, mass wear, and specific wear rate under dry sliding conditions is studied. The novelty of the study lies in the self-lubricating properties and load-carrying ability of the B83 babbitt that could represent a potential practical application for the manufacturing of sliding contact bearings. The obtained results are compared with the results of B83 babbitt under the same test conditions. Based on the conducted wear experiments, the following conclusions can be summarized:

- By applying different loads of 40, 50, 60 N, the hybrid material maintains a decreased mass wear, specific wear rate, and COF specifically at a load of 40 N (11.2%) in comparison to the B83 babbitt.
- By increasing the load under dry sliding friction, the hybrid material increases its mass wear (98.9% from 40 to 50 N and 19.5% from 50 to 60 N) and specific wear rate (63.6% from 40 to 50 N and remains the same from 50 to 60 N).
- Due to the friction between the surfaces of the hybrid material and the counter body, a zone of the aluminum–Al₂O₃ skeleton emerges and the contact zone of the aluminum–Al₂O₃ skeleton exert direct contact with the counter body. During the increase of the load from 40 to 50 N the count of these zones also increases, which is the reason for the increase of the COF by 128.7%.

Author Contributions: M.K., L.D. and V.P. conceived and designed the experiments; M.K., L.D. and V.P. performed the experiments; M.K., L.D. and V.P. analyzed the data; M.K., L.D. and V.P. contributed tools; M.K., L.D. and V.P. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work is supported by the European Regional Development Fund within the OP Science and Education for Smart Growth 2014–2020, Project CoE National Center of Mechatronics and Clean Technologies, BG05M2OP001-1.001-0008-C01.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Haghshenas, M. Metal–Matrix Composites. In *Reference Module in Materials Science and Materials Engineering*; Elsevier: Amsterdam, The Netherlands, 2016.
2. Cooke, K. A comparative analysis of techniques used for joining intermetallic MMCs. In *Intermetallic Matrix Composites*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 221–241.

3. Hossain, S.; Rahman, M.; Chawla, D.; Kumar, A.; Seth, P.P.; Gupta, P.; Kumar, D.; Agrawal, R.; Jamwal, A. Fabrication, microstructural and mechanical behavior of Al-Al₂O₃-SiC hybrid metal matrix composites. *Mater. Today Proc.* **2020**, *21*, 1458–1461. [\[CrossRef\]](#)
4. Sharma, A.K.; Bhandari, R.; Aherwar, A.; Rimašauskienė, R.; Pinca-Bretotean, C. A study of advancement in application opportunities of aluminum metal matrix composites. *Mater. Today Proc.* **2020**, *26*, 2419–2424. [\[CrossRef\]](#)
5. Surappa, M.K. Aluminium matrix composites: Challenges and opportunities. *Sadhana* **2003**, *28*, 319–334. [\[CrossRef\]](#)
6. Surya, M.S.; Gugulothu, S.K. Fabrication, Mechanical and Wear Characterization of Silicon Carbide Reinforced Aluminium 7075 Metal Matrix Composite. *Silicon* **2021**, 1–10. [\[CrossRef\]](#)
7. Schmidt, A.; Siebeck, S.; Götze, U.; Wagner, G.; Nestler, D. Particle-Reinforced Aluminum Matrix Composites (AMCs)—Selected Results of an Integrated Technology, User, and Market Analysis and Forecast. *Metals* **2018**, *8*, 143. [\[CrossRef\]](#)
8. Krishna, S.A.M.; Shridhar, T.N.; Krishnamurthy, L. Research significance, applications and fabrication of hybrid metal matrix composite. *Int. J. Innov. Sci. Eng. Technol.* **2015**, *2*, 227–237.
9. Stojanovic, B. Application of aluminium hybrid composites in automotive industry. *Teh. Vjesn. Tech. Gaz.* **2015**, *22*, 247–251. [\[CrossRef\]](#)
10. Bhaskar, K.V.; Sundarrajan, S.; Rao, B.S.; Ravindra, K. Effect of reinforcement and wear parameters on dry sliding wear of aluminum composites—A review. *Mater. Today Proc.* **2018**, *5*, 5891–5900. [\[CrossRef\]](#)
11. Rajkumar, K.; Santosh, S. Effect of Nano and Micro Graphite Particle on Tribological Performance of Aluminium Metal Matrix Composites. *Appl. Mech. Mater.* **2014**, 592–594, 917–921. [\[CrossRef\]](#)
12. Jenix Rino, J.; Sivalingappa, D.; Koti, H.; Daniel Jebin, V.D. Properties of Al6063 MMC Reinforced With Zircon Sand and Alumina. *IOSR J. Mech. Civ. Eng.* **2013**, *5*, 72–77. [\[CrossRef\]](#)
13. Nayim, S.T.I.; Hasan, M.Z.; Seth, P.P.; Gupta, P.; Thakur, S.; Kumar, D.; Jamwal, A. Effect of CNT and TiC hybrid reinforcement on the micro-mechano-tribo behaviour of aluminium matrix composites. *Mater. Today Proc.* **2020**, *21*, 1421–1424. [\[CrossRef\]](#)
14. Yuvaraj, N.; Aravindan, S. Vipin Fabrication of Al5083/B4C surface composite by friction stir processing and its tribological characterization. *J. Mater. Res. Technol.* **2015**, *4*, 398–410. [\[CrossRef\]](#)
15. Aydin, F. The investigation of the effect of particle size on wear performance of AA7075/Al₂O₃ composites using statistical analysis and different machine learning methods. *Adv. Powder Technol.* **2021**, *32*, 445–463. [\[CrossRef\]](#)
16. Ahmad, F.; Lo, S.J.; Aslam, M.; Haziq, A. Tribology Behaviour of Alumina Particles Reinforced Aluminium Matrix Composites and Brake Disc Materials. *Procedia Eng.* **2013**, *68*, 674–680. [\[CrossRef\]](#)
17. Baig, M.M.A.; Al-Qutub, A.M.; Allam, I.M.; Patel, F.; Mohammed, A.S. Tribological Performance of Sub-Micron Al₂O₃-Reinforced Aluminum Composite Brake Rotor Material. *Arab. J. Sci. Eng.* **2021**, *46*, 2691–2700. [\[CrossRef\]](#)
18. Wu, H.; Bi, Q.; Zhu, S.; Yang, J.; Liu, W. Friction and wear properties of Babbitt alloy 16-16-2 under sea water environment. *Tribol. Int.* **2011**, *44*, 1161–1167. [\[CrossRef\]](#)
19. Adams, M.L. *Bearings: Basic Concepts and Design Applications—Section II: Bearing Design and Application*; CRC Press: Boca Raton, FL, USA, 2017; pp. 131–239. ISBN 9781138049086.
20. Stanev, L.; Mihail, K.; Ludmil, D. Tribological Characterization of Aluminum/Babbitt Composites and their Application to Sliding Bearing. *Arch. Foundry Eng.* **2020**, *20*, 31–36. [\[CrossRef\]](#)
21. Leszczyńska-Madej, B.; Madej, M.; Hrabia-Wisnios, J. Effect of Chemical Composition on the Microstructure and Tribological Properties of Sn-Based Alloys. *J. Mater. Eng. Perform.* **2019**, *28*, 4065–4073. [\[CrossRef\]](#)
22. Lashin, A.; Mossa, M.; El-Bediwi, A.; Kamal, M. Study of some physical properties of the rapidly solidified Sn-Sb-Cu-Zn alloys. *Mater. Des.* **2013**, *43*, 322–326. [\[CrossRef\]](#)
23. Korshunov, L.G.; Noskova, N.I.; Korznikov, A.V.; Chernenko, N.L.; Vil'Danova, N.F. Effect of severe plastic deformation on the microstructure and tribological properties of a babbitt B83. *Phys. Met. Met.* **2009**, *108*, 519–526. [\[CrossRef\]](#)
24. Ishihara, S.; Tamura, K.; Goshima, T. Effect of amount of antimony on sliding wear resistance of white metal. *Tribol. Int.* **2010**, *43*, 935–938. [\[CrossRef\]](#)
25. Zhang, D.; Zhao, F.; Li, Y.; Li, P.; Zeng, Q.; Dong, G. Study on tribological properties of multi-layer surface texture on Babbitt alloys surface. *Appl. Surf. Sci.* **2016**, *390*, 540–549. [\[CrossRef\]](#)
26. Valeeva, A.K.; Valeev, I.S.; Fazlyakhmetov, R.F. Effect of structure of B83 babbitt on its wear. *J. Frict. Wear* **2014**, *35*, 311–315. [\[CrossRef\]](#)
27. Kalashnikov, I.E.; Podymova, N.B.; Karabutov, A.A.; Bolotova, L.K.; Kobeleva, L.I.; Kolmakov, A.G. Local elastic moduli of particle-filled B83 babbitt-based composite materials prepared by powder metallurgy techniques. *Inorg. Mater.* **2016**, *52*, 429–434. [\[CrossRef\]](#)
28. Tasgin, Y. Effect of MgO, Al₂O₃ and FeCr₂O₄ on microstructure and wear resistance of Babbitt metal (Sn-Sb-Cu). *Mater. Res. Express* **2018**, *6*, 046548. [\[CrossRef\]](#)
29. Tillmann, W.; Abdulgader, M.; Hagen, L.; Hüning, S. Embedding Behavior of Ceramic Particles in Babbitt Coatings and Its Effect on the Tribological Properties of Low-Pressure Cold Sprayed Coatings. *Coatings* **2020**, *10*, 769. [\[CrossRef\]](#)
30. Ramadan, M.; Alghamdi, A.S.; Subhani, T.; Halim, K.S.A. Fabrication and Characterization of Sn-Based Babbitt Alloy Nanocomposite Reinforced with Al₂O₃ Nanoparticles/Carbon Steel Bimetallic Material. *Materials* **2020**, *13*, 2759. [\[CrossRef\]](#)
31. Aleshin, N.P.; Kobernik, N.V.; Mikheev, R.S.; Vaganov, V.E.; Reshetnyak, V.V.; Aborkin, A.V. Plasma-powder application of antifrictional babbitt coatings modified by carbon nanotubes. *Russ. Eng. Res.* **2016**, *36*, 46–52. [\[CrossRef\]](#)

32. Stanev, L.; Kolev, M.; Drenchev, L.; Krastev, B. Fabrication Technique and Characterization of Aluminum Alloy-Based Porous Composite Infiltrated with Babbitt Alloy. *J. Mater. Eng. Perform.* **2020**, *29*, 3767–3773. [\[CrossRef\]](#)
33. Stanev, L.; Kolev, M.; Drenchev, L. Enhanced Tribological Properties of an Advanced Al–Al₂O₃ Composite Infiltrated With a Tin-Based Alloy. *J. Tribol.* **2021**, *143*, 064502. [\[CrossRef\]](#)
34. Soubielle, S.; Diologent, F.; Salvo, L.; Mortensen, A. Creep of replicated microcellular aluminium. *Acta Mater.* **2011**, *59*, 440–450. [\[CrossRef\]](#)
35. Hutchings, I.; Gee, M.; Santner, E. Friction and Wear. In *Springer Handbook of Materials Measurement Methods*; Czichos, H., Saito, T., Smith, L., Eds.; Springer: Berlin, Heidelberg, 2006; pp. 701–703.
36. Junior, P.R.C.A.; Pukasiewicz, A.G.M. Evaluation of microstructure, mechanical and tribological properties of a Babbitt alloy deposited by arc and flame spray processes. *Tribol. Int.* **2019**, *131*, 148–157. [\[CrossRef\]](#)
37. Murata, A.; Tanigawa, Y.; Matsuoka, T.; Sakaguchi, K.; Watanabe, H.; Mukai, T. Effect of Precipitate Morphology on Tribological Properties in AZ91 Alloy. *J. Soc. Mater. Sci. Jpn.* **2005**, *54*, 90–96. [\[CrossRef\]](#)
38. Valeeva, A.; Valeev, I.S.; Fazlyakhmetov, R.F.; Pshenichnyuk, A.I. On the mechanism of running-in during wear tests of a babbitt B83. *Phys. Met. Met.* **2015**, *116*, 509–511. [\[CrossRef\]](#)
39. Dochev, B.; Velikov, A.; Panov, I.; Diyakova, V.; Kuzmanov, P.; Manolov, V. Microstructure and Mechanical Properties of a Hypereutectic Alloy AlSi18, Modified by a Nanodiamond and Phosphorus. *Int. Sci. J. Machines. Technol. YEAR XIII. Mater.* **2019**, *13*, 504–506.
40. Panov, I.; Dochev, B.; Manolov, V.; Velikov, A.; Dyakova, V.; Kuzmanov, P. Influence of a P modifier, a nanosized SiC modifier, and a combination of them on the mechanical properties of a hypereutectic aluminium-silicon alloy AlSi18. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *878*, 012061. [\[CrossRef\]](#)
41. Panov, I.; Dochev, B.; Manolov, V.; Velikov, A.; Diyakova, V.; Kuzmanov, P. Investigation of the potential of simultaneous modification of hypereutectic aluminum-silicon AlSi18 alloy with conventional and nano-modifier. *IFAC-PapersOnLine* **2019**, *52*, 488–493. [\[CrossRef\]](#)