

Tribological and microstructural investigation of hybrid AA8011/ZrB₂-Si₃N₄ nanomaterials for service life improvement



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ABSTRACT

The effect of ZrB₂-Si₃N₄ particle reinforcement on the tribological behavior and microstructure of AA8011 alloy has been studied. ZrB₂-Si₃N₄ particles were varied from 0 wt% to 20 wt% with an interval of 5 wt%. Dry sliding pin-on-disc tests at a room temperature condition were conducted to investigate the wear performances of the aluminium alloy/ ZrB₂-Si₃N₄ composites. The tests were conducted at varying loads, from 20 to 40 N. The results depicted that the wear rates of the AA8011 alloy/ZrB₂-Si₃N₄ composites are lower than that of the AA8011 and further decreases with increasing ZrB₂-Si₃N₄ content. Also, the friction coefficient of the matrix alloy is higher than that of the composites and decreases with increasing ZrB₂-Si₃N₄ content. This established the unique efficacy of ZrB₂-Si₃N₄ effect on performance characteristics of aluminium series in application.

Introduction

Over the last few decades, aluminium alloy has distinguished itself to be the major primary material for most industrial and engineering applications due to its excellent intrinsic properties [1,2].

There are various alloys of aluminium ranging from 1xxx to 8xxx depending on the alloying constituents, these alloys possess different properties with diverse industrial applications. Recently, AA8011 containing Al-Fe alloys has emerged as a basic structural material in modern engineering applications which cut across transportation, construction, and the building where improved tensile strength, higher hardness, and good wear resistance materials are extremely required [3].

However, poor tribology, low hardness, and tensile strength are some of the challenges that militate against its wide range of applications [4,5].

To curb the above limitations, researchers all over the world have successfully employed the use of discontinuous second phase material which gives rise to matrix composites. These reinforcement materials include bio-waste such as (coconut shell ash, rice husk, bamboo ash, melon ash) etc. [5–8]. Industrial waste like red mud, fired clay etc [9]. Finally, the hard-ceramic reinforcement like the (oxides, carbides, borides, and nitrides) [10–12].

Metal matrix composites (MMCs) are characterized with

significantly enhanced properties because of the combinations between two or more chemically and physically distinct phases (continuous and discontinuous phases) [13]. The newly formulated composites possess suitable distinctive properties which cannot be found in any of the two separates phases.

The timely progression in industrial activities recently has amounted in an increased interest in composites containing low density and low cost of production. According to Sokoluk et al [25], light composite materials are very essential for reducing fuel consumption in automobile applications. Aluminium metal matrix composites (AMMCs) reinforced with ceramic particulates are competent primary materials with a unique combination of mechanical, physical and tribological properties which are scarce in monolithic alloys [14,15]. The intense studies of AMMCs are on the increase over the last few years due to its great attributes in the automotive, aerospace, marine and defense industries [16].

Several methods of developing AMMCs such as stir casting, powder metallurgy, squeeze casting, molten salt stirring method as stated by Pan et al. [26] and so on has been contributed by researchers. However, in a bid to develop materials with less cost effective and mass production, stir casting routes to emerge as the most popular method used by researchers. Stir casting method is preferred over all other techniques because of its simplicity, affordability, less expensive, and ability to achieve uniform distributions of particulates embedded in the matrix

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[17].

Research shows that the addition of hard ceramic reinforcement in the form of particles, fibres, or whiskers into the monolithic alloy invariably enhanced the mechanical and tribological behavior of composite materials. Series of research works on the wear performances of the AMMCs materials have been undertaken by several authors, Raju et al. [18] experimented the tribological properties of Al-Cu alloys and innovative Al-Cu metal matrix composites and concluded that the wear is drastically enhanced in relative to the Al-Cu base alloy. Chen et al [24] investigated the processing and properties of magnesium containing a dense uniform dispersion of nanoparticles. It was asserted from their report that reinforcing light weight magnesium with nanoparticles will improve the strengthening mechanism. Rao et al. [12] studied the dry sliding wear behavior of TiC-AA7075 metal matrix composites and reported that increase in the weight percent volume of TiC reduces the coefficient of friction and improve the wear resistance of the composite. Ramesh et al. [2] experimented the effects of TiO₂ on the wear behavior of Al6061-TiO₂ composite, they reported that the composites exhibited higher hardness and lower coefficient of wear. They further affirmed that an increase in the applied load resulted in massive volume loss but reduced wear coefficients.

From the above literature survey, it was observed that a lot of experimental works has been carried out with ceramic particles such as silicon carbide, alumina and tungsten carbide as reinforcements. Research done with AA8011 alloy with hybrid silicon nitride and zirconium diboride reinforcement is still very novel. Hence an attempt is made to develop AA8011/ZrB₂-Si₃N₄ MMC and evaluate the wear performances and friction coefficient under varying parameters.

Materials and methods

Materials

Commercial aluminium AA8011 alloy pellet of purity 97.86% were obtained from aluminium rolling company ota, Nigeria with composition shown in Table 1. Zirconium Diboride (ZrB₂) Nano powder of 99.9% purity, 40–50-nm particle size and Silicon Nitride (Si₃N₄) 99.9% purity, particle size of 50-nm was used in this work. All the powders were supplied by Hongwu International Group, China. The masses of the ceramic powders (ZrB₂ and Si₃N₄) were measured in 50:50 wt proportion and mixed to achieve homogenous mixing before admixing with the molten AA8011. As reported by Fayomi et al. [19].

Composites development

The two steps stir casting route with the optimum process parameter was in place to develop the composite materials for this study. The proportion of the Si₃N₄-ZrB₂ and AA8011 required to produce AA8011/Si₃N₄-ZrB₂ composites containing 5–20 wt% reinforcement was pre-determined.

The Si₃N₄-ZrB₂ reinforcement was preheated at a temperature of 450 °C for 10 min to help remove moistures, impurities and improve wettability before being introduced into the vortex. The quantified AA8011 were charged into a graphite crucible furnace and heated to a temperature of 750 °C above its melting temperature to ensure complete melting of the material. The preheated Si₃N₄-ZrB₂ was introduced into the molten metal AA8011 and stirred with mechanical stirrer to achieve homogeneity of both the continuous and discontinuous phase. The developed composite was tilted into the sand molds. Unreinforced

Table 2

Material composition of the composites.

AA8011	ZrB ₂ + Si ₃ N ₄
100	0
95	5
90	10
85	15
80	20

AA8011 alloy was also prepared by casting for control experimentation. This process was done to prepare composites of different reinforcement particles as shown in Table 2. This is according to the work done by Fayomi et al. [19].

Wear testing

The tribological performances of the as-cast unreinforced and different hybrid reinforced aluminium composites were analyzed under dry sliding condition using Universal Tribometer S/N: RTEC 2441, USA. The pin-on-disc tribometer makes use of ball 250" (6,350 mm), E52100 Alloy steel, Grade 25. The machined composite samples of 15 mm diameter and 15 mm length were grinded and polished to obtain smooth surfaces. The composite samples were weighed to obtain the initial weight of the samples before commencing the test against hard steel alloy of 350 mm diameter. The tribological analysis was conducted at varying applied loads of 20 N, 30 N and 40 N keeping other parameters constant such as the sliding distance of 5000 m, constant time of the 60 s and velocity of 3 mm/s. In this experiment, the coefficient of friction, wear loss, wear volume, wear rate, wear resistance has been determined by the relationship below. The worn-out surfaces were examined using OPM.

$$\text{Wear volume}(V) = \frac{m}{\rho} \text{ in } (\text{mm}^3) \quad (2.1)$$

$$\text{Wear rate, } W = \frac{\text{wear volume}}{\text{Sliding Distance}} = \frac{V}{D} \text{ in } \frac{\text{mm}^3}{\text{m}} \quad (2.2)$$

$$\text{Wear resistance} = \frac{1}{\text{Wear rate}} = \frac{1}{W} = \frac{\text{m}}{\text{mm}^3} \quad (2.3)$$

$$\text{Coefficient of friction, } \mu = \frac{\text{Frictional Force}}{\text{Applied Load}} \quad (2.4)$$

m = mass loss (Initial mass – Final mass) in (g)

D = Sliding distance, in m

ρ = density, g/ mm³

Micro-structural study

The worn-out surfaces of the composite samples were exposed to microstructural analysis using an OPM to reveal the wear tracks that was obtained under the tribometer.

Results and discussion

Wear behavior

Effect of load and percentage of reinforcement on wear rate and wear resistance

Fig. 1a revealed the progression in wear rate of the AA8011 and AA8011/Si₃N₄-ZrB₂ composites with varying compositions under an applied load of 20 N, 30 N and 40 N. it is evident from the figure below that the wear rate of the AA8011 and AA8011/Si₃N₄-ZrB₂ increases as the applied load increases from 20 N to 40 N under constant sliding distance and velocity. It is obvious that the rate of wear increases almost uniformly with the applied load, irrespective of the reinforcement

Table 1

Chemical composition of the aluminum alloy 8011 (AA 8011).

Mg	Si	Mn	Cu	Zn	Ti	Fe	Na	B	Pb	Al
0.47	0.46	0.09	0.14	0.22	0.01	0.61	0.01	0.01	0.01	97.86

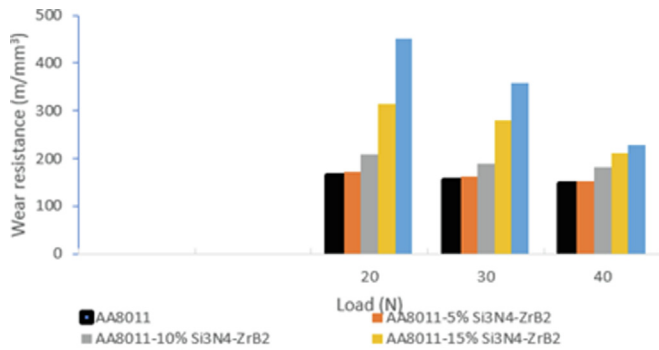


Fig. 1a. Variation of wear rate of AA8011 and AA8011/ Si₃N₄-ZrB₂.

of the composite [12,13]. However, the wear rate appears to reduce as the weight percent of the reinforcement increases. Looking from the figure, the wear rate of the unreinforced AA8011 at 20 N is 6.10×10^{-3} , as the load increase to 30 N the wear rate increases to 6.48×10^{-3} and then further increase uniformly to 6.86×10^{-3} at 40 N. Nevertheless, when AA8011 is reinforced with 5, 10, 15 and 20% Si₃N₄-ZrB₂, the wear rate reduces drastically. The results show that the wear rate decrease from 6.10×10^{-3} to 1.84×10^{-3} at 20 N, 6.48×10^{-3} to 2.40×10^{-3} at 30 N and 6.86×10^{-3} to 3.74×10^{-3} at 40 N respectively. AA8011 alloy reinforced with 20% Si₃N₄-ZrB₂ was observed to possess a low wear rate which invariably depict high wear resistance.

The continuous reduction in wear rate of AA8011/Si₃N₄-ZrB₂ composites may be ascribed to the higher load bearing capacity of Si₃N₄-ZrB₂ present due to its intrinsic mechanical strength. However, the gradual appreciation of the wear rate with an increased load applied resulted from the fact that as load increases, dry sliding contact heat is generated at the surface between the composite material (AA8011/Si₃N₄-ZrB₂) and the steel alloy used (pin-on-ball). Hence, the material strength decreases thereby exposing the material to severe wear at higher load applied. Si₃N₄-ZrB₂ is characterized by high hardness and tensile strength, it reduces the ductility of the soft base AA8011 when introduced into the melt pool of the molten metal. also, the strong interfacial bonding and complete wettability between the AA8011 and Si₃N₄-ZrB₂ resulted in the reduction of the proximity of particle worn-out which invariably decrease the wear rate. From the whole analysis, it can be deduced that the wear rate performances depend on the weight fraction of Si₃N₄-ZrB₂ and the applied load. This trend is in accordance with the work done by other researchers when they reinforced AMMCs with another ceramic particulate [20,21].

Fig. 1b present the variation of the wear resistance of the AA8011/ Si₃N₄-ZrB₂ as a function of the applied loads and volume fraction of the reinforcement, wear resistance is the direct reciprocal of wear rate. It is

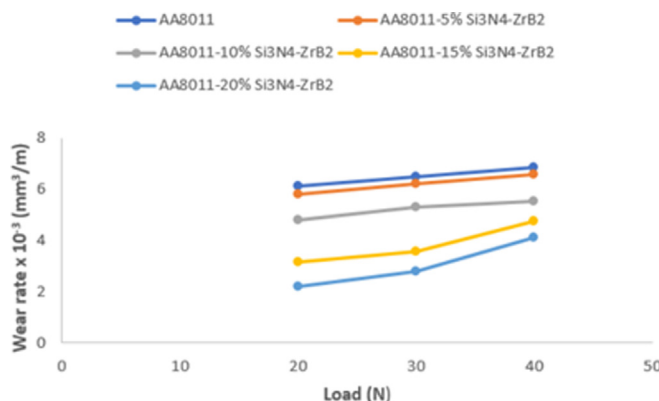


Fig. 1b. Variation of wear resistance of AA8011 and AA8011/ Si₃N₄-ZrB₂.

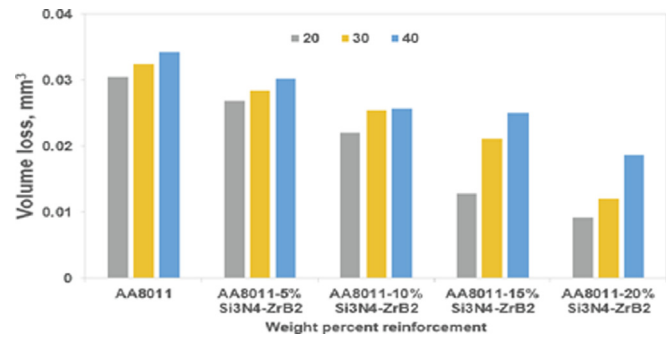


Fig. 2. Variation of wear volume loss with an increase in the percentage of reinforcement of AA8011 and AA8011/ Si₃N₄-ZrB₂.

evident from the graph that AA8011 is enhanced by the addition of Si₃N₄-ZrB₂ and the improvement increases with increase in volume fraction of Si₃N₄-ZrB₂. From the graph, the composite with 20% reinforcement possessed the highest potency of wear resistance but decreases with the increasing load applied. This improvement in the wear resistance of the developed AA8011/Si₃N₄-ZrB₂ composite could be attributed to the combined effect of composite grain modification during fabrication, individual strengthen properties of the ceramic material (Si₃N₄ and ZrB₂), load-bearing capacity of the hard Si₃N₄-ZrB₂ material and the strong intermetallic bonding at the grain boundary between matrix and reinforcement. The strengthening property of Si₃N₄-ZrB₂ was discussed by Fayomi et al. [18–20].

Effect of load and percentage of reinforcement on volume loss

The result of the wear volume of AA8011/Si₃N₄-ZrB₂ and as-received matrix material as a function of the concentration of Si₃N₄-ZrB₂ was presented in Fig. 2. It can be observed that the addition of volume fraction of Si₃N₄-ZrB₂ decreases the volume loss of the composites. it is worthy of note that less volume loss is recorded at a lower load of 20 N with value ranging from 0.0305 through 0.0269, 0.0221, 0.0129, 0.0092 (mm³) for 0%, 5%, 10%, 15%, and 20% respectively. At increased load of 30 N the volume loss increases ranging from 0.0324 through 0.0284, 0.0255, 0.0211, 0.0120 (mm³) for 0%, 5%, 10%, 15%, 20% respectively and finally at highest applied load of 40 N the value progress to 0.0343, 0.0303, 0.0251, 0.0187 (mm³) 0%, 5%, 10%, 15%, 20% respectively.

In general, the volume loss of the composite material increases as the applied load increases. However, in each of the applied load, the present of the reinforcement decrease the volume loss. It can be inferred from Fig. 2 that the as-cast matrix AA8011 possessed high volume loss and the rate of material pull-off increases with increase in load applied. The ductile soft nature of AA8011 could be responsible for the aggressive worn out of the material in relative to load applied. The lower value of the composite wear volume loss could be attributed to the presence of the inherent strengthening mechanism of the Si₃N₄-ZrB₂ reinforcement. More so, the strong interfacial bonding and refinement of Si₃N₄-ZrB₂ in the AA8011 could lead to low volume loss during dry sliding [17–19].

Effect of load and percentage of reinforcement on the coefficient of friction

Fig. 3 presents the regression plot of the coefficient of friction with varying loads (20 N, 30 N, and 40 N) and the percentage weight composition of the reinforcements (AA8011 reinforced with 0, 5, 10, 15 and 20% of Si₃N₄-ZrB₂). It can be deduced from the graph that the incorporation of Si₃N₄-ZrB₂ ceramics into the primary AA8011 matrix decreases the coefficient of friction as the volume fraction increases regardless of the normal load applied (20 N, 30 N, and 40 N). From Fig. 3, the average coefficient of friction of the developed composites (AA8011/Si₃N₄-ZrB₂) is in the range of 0.12–0.290 and it is lesser than that of the as-cast material (AA8011) which ranges from 0.33 to 0.66.

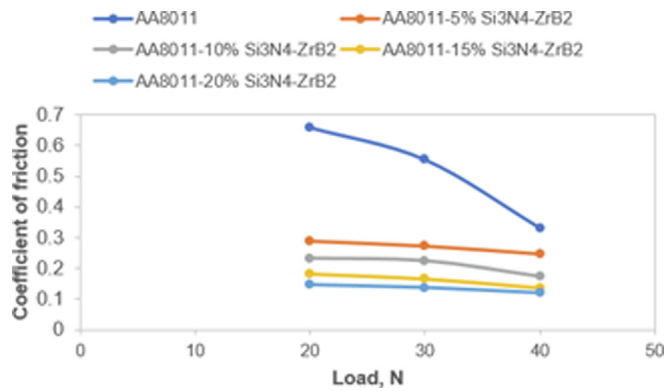


Fig. 3. Variation of the coefficient of friction of AA8011 and AA8011/Si₃N₄-ZrB₂.

However, the friction coefficient (μ) of the developed composites decreases with an increase in the amount of the hybrid Si₃N₄-ZrB₂ particles present. It is worthy of note that the coefficient of friction property of AA8011/Si₃N₄-ZrB₂ composite is determined by the addition of Si₃N₄-ZrB₂ with high hardening characteristics, and this could be due to the outcome of the process parameter employed in two-step stir casting route such as wettability without reaction at the interface boundary between the matrix and particulates, uniform distribution of Si₃N₄-ZrB₂ in the melt pool of molten AA8011 [12–15]. The present of ZrB₂ as part of the strong ceramic compound that makes up the hybrid composition with a high melting point and high hardness has been proven to drastically reduce the friction coefficient [22]. Pan et al. [27] reported that increase in loads will invariably lead to more severe surface deformation but decrease in noise because of friction which act as a medium for surface tuning [23].

In general, the overall decrease in the coefficient of friction as a function of the applied load and percentage composition of the reinforcement could be attributed to the surface roughing that arises because of the increasing applied load resulting in a larger amount of wear debris [13–20].

Morphological investigation of worn-out surface

Figs. 4–6 present the outcome of the optical microstructure of the worn surfaces of the AA8011 and AA8011/Si₃N₄-ZrB₂ composite when subjected to different applied load 20 N, 30 N and 40 N. The micrographs of AA8011/0% Si₃N₄-ZrB₂, 5% Si₃N₄-ZrB₂, and 20% Si₃N₄-ZrB₂ under the same varying applied load and other constant parameters were selected for simplicity, nevertheless, the similar justification holds

for another developed composite material.

Fig. 4a and b reveal the micrograph of the un-reinforced AA8011 alloy under the applied load of 20 N and 40 N respectively. From Fig. 4a at a load of 20 N, a minimal quantity of material was observed to be dislodged from the as-cast surface, however, a transfer of mild to severe wear was evident in Fig. 4b due to an increase in applied load to 40 N. It is worthy of note that the unreinforced AA8011 alloy display great plastic deformation under increased load due to the abrasive action where the wear tracks show layers with compacted wear debris and microcracks, this can be attributed to the ductile nature of the primary material (AA8011) with intrinsic low hardness as shown in Fig. 4a and b [19–22].

Fig. 5a and b present the micrograph of the composites reinforced with 5% Si₃N₄-ZrB₂ under the dry sliding wear condition with an applied load of 20 N and 40 N respectively. A distinctive shallow groove was observed in the microstructure, this groove increases with increase in load along the sliding direction. The images review a fine scratch on the worn sample at a low load of 20 N but transformed into a well identify grooves at a higher load of 40 N. there is no evidence of fragmentation, delamination or craters. The scratches observed in the microstructure instead of deep grooves depict the presence of reinforcement, the hard hybrid ceramic particulates of Si₃N₄-ZrB₂ act a solid lubricating thin-film which act against the contact between pin and sample, thereby increasing the wear resistance of the composite [7,9,23].

Fig. 6a and b show the wear tracks of the composites reinforced with 20% high weight fraction of Si₃N₄-ZrB₂. It can be observed from the image in Fig. 6a under the applied load of 20 N that increase in the percentage of particulates drastically reduce the amount of material dislodging from the composite surface revealing slight scratches and smooth surface compared to the one revealed by other percentage composition and as-cast alloy. At a higher load of 40 N in Fig. 6b the distinct groove and scratches were seen to be parallel to the dry sliding direction of the wear mechanism. It is not out of context if stated that the solid lubricating film of hard hybrid Si₃N₄-ZrB₂ with strong mechanical strength at the higher volume fraction of 20% forms a thick thin film layers resulting in prevention of metal to metal contact leading to small material worn out [4–6].

Generally, abrasive wear is observed to be the main wear mechanism that occurs in this study. It is worthy of note that the plowing action of the asperities on the surface of the (AA8011/ Si₃N₄-ZrB₂) composite and unreinforced alloy (AA8011) under an increased applied load amounted to the dislodging of such material inform of grooves. The rate of wear/wear volume loss increases with an increase in load, this is because of the frictional heat generated by contact pressure during the sliding relative motion [17]. The heat generated under high

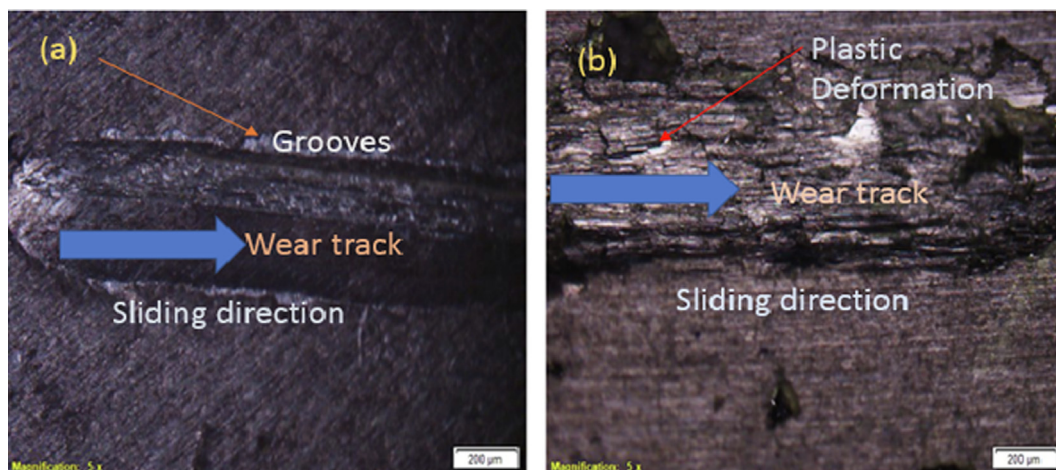


Fig. 4. Optical micrograph of the AA8011 alloy particles at an applied load of (a) 20 N (b) 40 N.

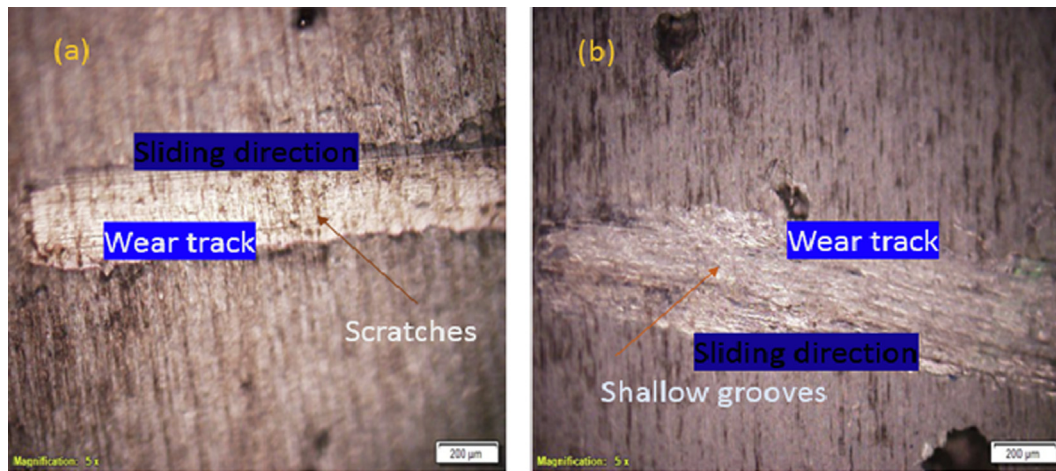


Fig. 5. Optical micrograph of the AA8011 alloy reinforced with 5% $\text{Si}_3\text{N}_4\text{-ZrB}_2$ particles at an applied load of (a) 20 N (b) 40 N.

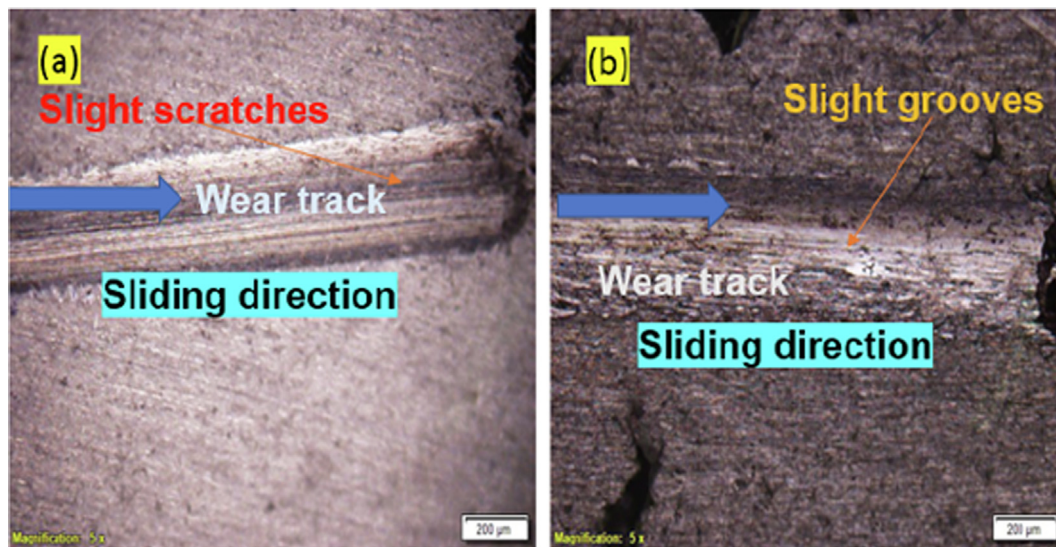


Fig. 6. Optical micrograph of the AA8011 alloy reinforced with 20% $\text{Si}_3\text{N}_4\text{-ZrB}_2$ particles at an applied load of (a) 20 N (b) 40 N.

pressure of load permit easy penetration of the pin into the material, this permeability birthed more volume loss of the material, and give way to wear mechanisms such as plastic deformation, micro-cracks, and cutting. However, the present of $\text{Si}_3\text{N}_4\text{-ZrB}_2$ in the composite help to militate against excess loss of materials from the composite surface. $\text{Si}_3\text{N}_4\text{-ZrB}_2$ possess an inherent mechanical strength which increases with the percentage volume composition, this hardness features help to withstand the frictional heat generated at high contact load thereby reducing the wear rate. This is like the work reported by Selvan et al. [19,22,23].

Conclusions

The hybrid composite of AA8011/ $\text{Si}_3\text{N}_4\text{-ZrB}_2$ has been successfully fabricated through two-steps double stir casting process and subjected to wear analysis, the following conclusions were derived from the tribological investigation;

- The rate of wear of the AA8011/ $\text{Si}_3\text{N}_4\text{-ZrB}_2$ decreases with increase in volume fraction of the hybrid; the unreinforced AA8011 possessed more of wear rate value, while the composite with AA8011/20% $\text{Si}_3\text{N}_4\text{-ZrB}_2$ reinforcement has a low wear rate.
- The wear rate increases with increase in applied load due to the frictional heat generated at high pressure of load.

- Addition of Si_3N_4 and ZrB_2 as hybrid reinforcement increase the wear resistance by forming a thick thin protective film layer between the two bodies under the sliding wear.
- The friction coefficient was observed to be high in unreinforced alloy and decreases with an increase in percent reinforcement of $\text{Si}_3\text{N}_4\text{-ZrB}_2$.
- The evaluation of the worn-out surface microstructure reveals abrasive, micro-cracks, plastic deformation, and slight delamination wear mechanisms.

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