Vol. 34, No 1 (2012) 36-43

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Wear Behaviour of Al-Si-Fe Alloy/Coconut Shell Ash Particulate Composites

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Keywords:

Al-Si-Fe alloy
Coconut shell ash
Wear and Microstructure

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A B S T R A C T

Wear behaviour of aluminium alloy (Al-Si-Fe) reinforced with coconut shell ash particles (CSAp) fabricated by stir casting process was investigated. The wear and frictional properties of the metal matrix composites was studied by performing dry sliding wear test using a pin-on-disc wear tester by varying the applied load from 10-50 N, speed 2.0 m/s and sliding distance 4000 m. The morphology of the worn out surface was determined by scanning electron microscope (SEM). The results show that the coefficient of friction increases with increasing load for the Al-Si-Fe alloy and the composites containing CSAp. It is observed that, as the applied load increases, the wear rate also increases but decreased with CSAp addition. This is because, whenever applied load increases, the friction at the contact surface of the material and rotating disc obviously increases. Hence, incorporation of the coconut shell particles in the Al-Si-Fe alloy matrix as reinforcement increases the wear resistance of the material.

1. INTRODUCTION

Metal-matrix composites (MMCs) have emerged as a class of materials capable of advanced structural, aerospace, automotive, electronic, thermal management, and wear applications. The performance advantage of metal matrix composites is their tailored mechanical, physical, and thermal properties that include low density, high specific strength, high specific modulus, high thermal conductivity, and high abrasion and wear resistance.

In general, the reduced weight and improved strength and stiffness of the MMCs are achieved with various monolithic matrix materials. In recent years there has been an increasing interest in composites containing low density and low cost reinforcements [1-3].

Among various reinforcements used like SiC, Al_2O_3 etc, Coconut shell ash is one of the most inexpensive and low density reinforcement available in large quantities as solid waste byproduct. Coconut shell is an agricultural residue from the coconut processing industry. Approximately, 15 Kg of coconut shell are obtained for 100 Kg of coconut. Coconut shell contains organic and inorganic material. The organic materials in coconut shell are 33.61 %

Cellulose, 36.51 % Lignin, 29.27 % Pentosans and 0.61 % Ash [3].

Synthesis of aluminum based lightweight composites by economic route of solidification processing has received considerable attention due to significant improvements in the tribological properties of such composites including sliding and abrasive wear resistance, and also, seizure resistance [4-6]. Aluminum based metal matrix composites (AMCs) are promising materials for automotive, aerospace, Deep Ocean, nuclear energy generation and other structural applications because of their low density, high stiffness and low wear rate [1, 7-8]. Research and development on various types of Al–Si-Fe alloy matrix composites have been actively carried out to reduce the weight of machines and to improve the tribological properties of such composites [3, 5]. In the present work, an attempt is made to utilize the abundantly available CSA as reinforcement in Al-Si-Fe alloy to improve the wear properties.

2. MATERIALS AND METHODS

2.1 Materials

The coconut shell used in this work was obtained from a coconut seller in Kaduna, Kaduna state of Nigeria. The photograph of the coconut shell is shown in Fig. 1.

(a) Coconut shell

(b) Crushed coconut shell

Fig. 1. Photograph of the Coconut shell

2.2 Equipment

Equipment used in this research are- electrical resistance furnace, X-ray diffractometer (XRD), Scanning electron microscope with energy dispersive spectrometer (SEM/EDS) Machine, X-ray fluorescent XRF, Pin on Disc machine.

2.3 Methods

2.3.1 The processing of the coconut shell (Carbonization)

The coconut shell was grinded to form coconut shell powder. The powder was packed in a graphite crucible and fired in electric resistance furnace at temperature of 1300 ^oC to form coconut shell ash (CSAp) (Fig. 2).

(a) Coconut shell powder

(b) Coconut shell ash

Fig. 2. Photograph of coconut shell ash

2.3.2 Mineralogical Characterization of the Coconut Shell ash

Mini Pal compact energy dispersive X-ray spectrometer (XRF) was used for the elemental analysis of the coconut shell ash. The system is controlled by a PC running the dedicated Mini Pal analytical software [9]. The sample for the analysis is weighed and grounded in an agate mortar and pressed in hydraulic press into a pellet. The pellet is loaded in the sample chamber of the spectrometer and a voltage of 30kv and current of 1 mA is applied to the X-rays to excite the sample for 10mins. The spectrum from the sample is now analyzed to determine the concentration of the elements in the sample.

2.3.3 Specimen preparation

The metal matrix composite that was used in this study was produced at the Foundry shop of the National Metallurgical Development Centre, NMDC, Jos Nigeria. The specimens were produced by keeping the percentage of iron and silicon constant and varying the coconut shell ash particles (CSAp) from 3-15wt%CSAp. High purity aluminum wire free from dust and contamination and 7wt%Si was charged into a graphite crucible. The crucible furnace and heated to about 7500 ^{0}C till the entire alloy in the crucible was melted and 2wt % iron powder was added. The reinforcement particles (CSAp) were preheated to 800 ^{0}C for 1 hour before incorporation into the melt. Preheating of the particles is to improve wettability and harmonize the temperature. After the molten metal was fully melted, degassing tablets (hexachloroethane) was added to reduce porosity.

Simultaneously, 1wt% magnesium was added to the melt in order to enhance wet ability between coconut shell ash particles and the alloy melt. It was noticed that without the addition of magnesium, the particles of coconut shell ash were rejected. The stirrer made of stainless steel was lowered into the melt slowly to stir the molten metal at the speed of 500-700 rpm. The preheated CSAp particles were added into the molten metal. The stirring was continued for another 5 minutes even after the completion of the particle feeding. The mixture was poured into the mould which was also preheated to 500 ^{0}C for 30 minutes to obtain uniform solidification. Using this process 3-15wt%CSAp composites were produced.

2.3.4 Hardness Test

The hardness values of the samples were determined (ASTM E18-79) using the Rockwell hardness tester on "B" scale (Frank Well test Rockwell Hardness Tester, model 38506) with 1.56 mm steel ball indenter, minor load of 10 kg, and major load of 100 kg and hardness value of 101.2HRB as the standard block[10].

2.3.5 Wear Test

A pin-on-disc test apparatus was used to investigate the dry sliding wear characteristics of the composites as per ASTM G99- 95 standards [11-16]. The disc used is En-32 steel hardened to 62 HRC, 120 mm track diameter and 8 mm thick, with surface roughness of 10 lm Ra. The initial weight of the samples was measured using a single pan electronic weighing machine with an accuracy of 0.01 g. During the test, the pin is pressed against the rotating disc. The wear test was conducted by varying applied load 10 to 50 N with a constant speed of 2.0 m/s and sliding distance of 4000 m.

2.3.6 Microstructural Analysis

The microstructure of the cast samples and surface morphology of the wear debris were studied using a JOEL JSM 5900LV Scanning Electron Microscope equipped with an Oxford INCATM Energy Dispersive Spectroscopy system at the department of chemical and metallurgical engineering, University of Witwatersrand, Johannesburg South Africa. The samples were firmly held on the sample holder using a double-sided carbon tape before putting them inside the sample chamber. The SEM was operated at an accelerating voltage of 5 to 20 Kv [1].

3. RESULTS AND DISCUSSION

The XRF chemical composition of the coconut shell ash is represented in Table 1. XRF analysis confirmed SiO_2, Al_2O_3, MgO and Fe_2O_3 to be major constituents of the ash. Silicon dioxide, iron oxide and alumina are known to be among the hardest substances. Some other oxides viz. CaO, K_2O, Na_2O and MnO were also found to be present in traces.

Table 1. XRF analysis of Coconut shell ash.

Element	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	MnO	ZnO
%	15.6	0.57	12.4	0.52	16.2	0.45	45.05	0.22	0.3

The presence of hard elements like SiO_2, Al_2O_3 and Fe_2O_3 suggested that, the coconut shell ash can be use as particulate reinforcement in various metal matrixes since there is a light of chemical composition similarity with the XRF analysis of rick husk ash, bagasse ash and fly ash currently used in metal matrix composites [1, 13].

The hardness values of the developed composites increased with an increasing percentage of coconut shell ash particle additions. This is noteworthy that the hardness value of coconut shell ash is 95.05HB and the presence of the hard ceramic phase in the ductile matrix has resulted into the increase in the hardness of the composite (see Fig. 3). For example the hardness values increased from 63.50HRB at 0wt% to 78.60HRB at 15wt% coconut shell ash particles. These increaments are attributed to increase of the weight percentage of hard and brittle phase of the coconut shell ash particles in the aluminium alloy. This hardness of the coconut shell particles are obtained from the SiC, Al_2O_3, Fe_2O_3 and SiO_2 of the chemical made up of the particles. Also the presence of coconut shell ash particles in the alloy increases the dislocation density at the particles-matrix interfaces. This is as a results of differences in coefficient of thermal expansion (CTE) between the hard and brittle reinforced particles and soft and ductile metal matrix which results to elastic and plastic incompatibility between the matrix and the reinforcement [1, 6-8].

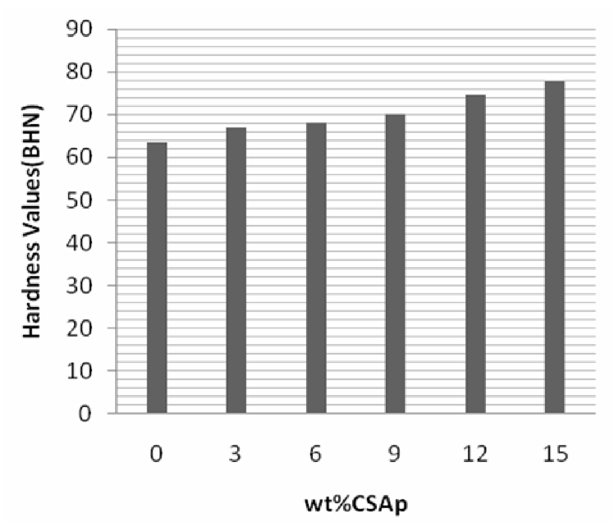

Fig. 3. Variation of Hardness values with wt% coconut shell ash

The microstructure of the aluminum alloy and that of the aluminum alloy with 9wt% coconut shell ash were analysed using Scanning Electron Microscopy/Energy Dispersive Spectrometer. The microstructure of the aluminum alloy is shown in Fig. 4. The structure reveals the eutectic phase containing Fe_3Si, Al_6Fe, in α-aluminum matrix [3].

The microstructure of the composites reveals small discontinuities and a reasonably uniform distribution of coconut shell ash particles in the aluminum matrix. The ceramic phase is shown as dark phase, while the metal phase is white (Fig. 4). Good retention of coconut shell ash particles was clearly seen in the microstructures of the composites. Good interfacial bonding was obtained by heating of coconut shell ash particulates prior to dispersion and addition of magnesium in small quantities during stirring improved wettability of coconut shell ash particles. These structures are in agreement with phases studied by other researchers [1, 8-9].

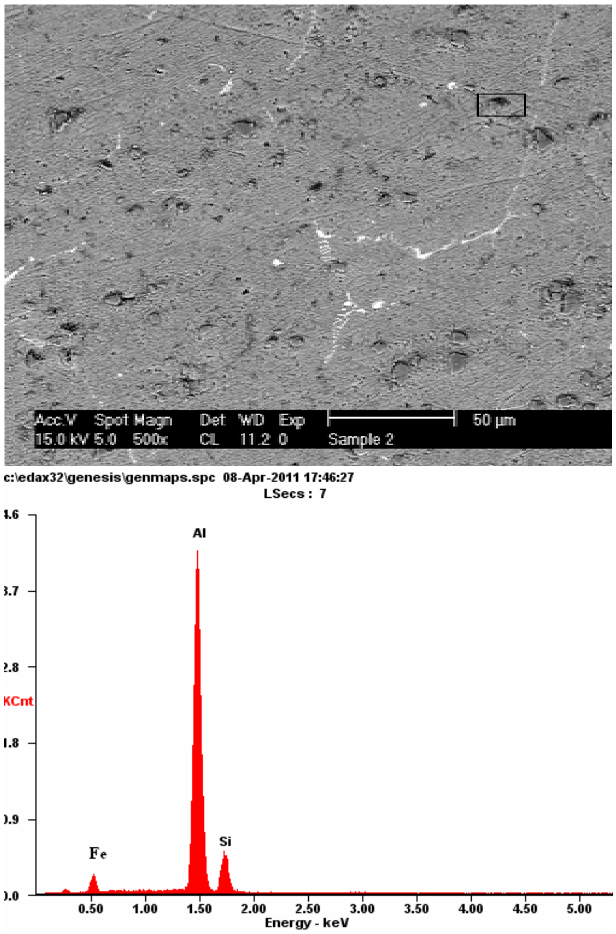

Fig. 4. SEM/EDS spectrum of the aluminum alloy.

The electron transmission microscopy was used to make the analysis of the interfaces between coconut shell ash particles and the matrix. The presence of the considerable amount of silicon and iron in the matrix alloy ensured the formation of the required bonds between the components of the composite examined (see Fig. 5). Interfaces between the particles and the matrix, as free from intermediary phases and any precipitates, had an adhesive character of component bonding. Moreover, they were characterized by a high cohesion (without micro-cracks) and strength of bonding.

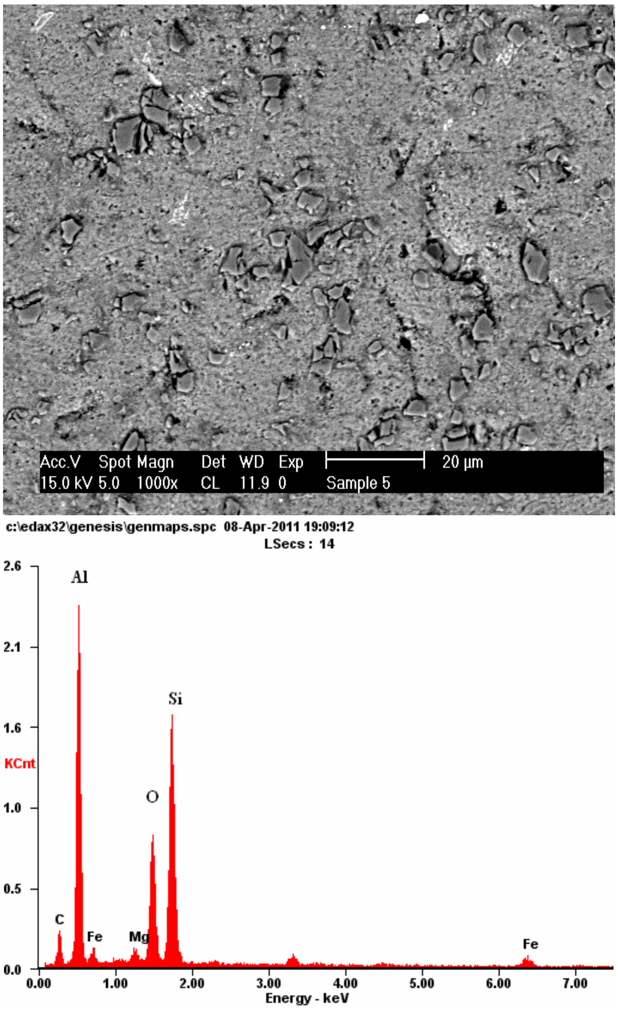

Fig 5. SEM/EDS spectrum of the aluminum alloy with 9wt%CSAp.

The microstructure of the composite clearly shows a uniform distribution of coconut shell ash in the aluminium alloy matrix. In the composites examined, no effects of unfavourable phenomena were observed, which frequently form in the structures of cast composites, such as the sedimentation or flowing out of the reinforcing phase, as well as the formation of particle agglomerates or gas blisters. This showed that there was good interfacial bonding between coconut shell ash particles and matrix, good interfacial.

The SEM microstructures of the worn surfaces are shown Fig. 6-7.

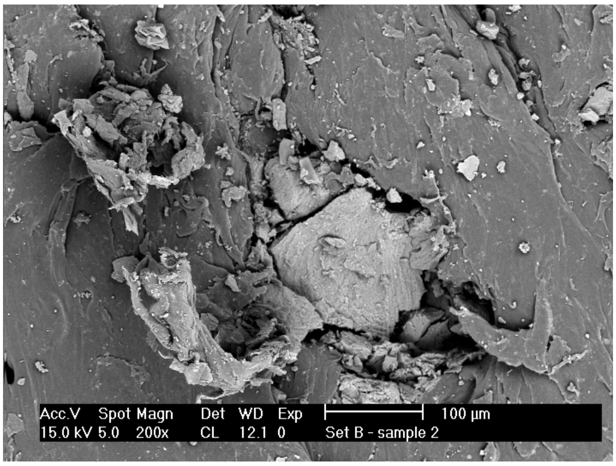

Fig. 6. SEM spectrum of the Worn surface of the aluminum alloy at 50N, 2.0m/s and 4000m.

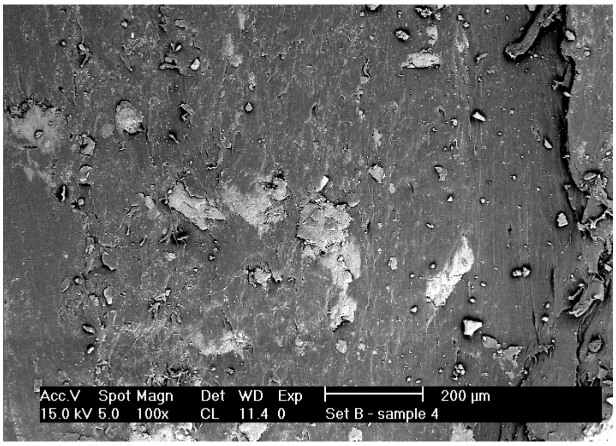

Fig. 7. SEM spectrum of the Worn surface of the aluminum alloy with 9wt%CSAp at 50N, 2.0m/s and 4000m.

From Fig 6-7, it can be seen that the aluminium alloy with no CSAp reinforcement form a good thin and uniform transfer film (see Fig 6). In the case of aluminium alloy with CSAp reinforcement (see Fig. 7) there appears to be some disruption of transfer film for CSAp which have affected the wear rate performance. The worn surface of the materials could be described as classical rachetting wear, as defined by [1, 14-16]. The transition in wear rate observed for many MMCs is faster and is believed to be the result of voiding/cracking between the reinforcement and the matrix, both of which lead to fragmentation and delamination of the surface [3]. Plate 3, revealed particles cutting and void formations due to chips out of matrix are seen, also there is evidence of Al-Si-Fe alloy removal and deep furrows in the structure.

The propagation of crack along transverse as well as longitudinal direction is well visualized. Furthermore, crushed and fragmented particles were noticed in the Fig. 7. The worn surfaces in some places reveal patches from where the material was removed from the surface of the material. The parallel grooves suggest abrasive wear as characterized by the penetration of the hard coconut shell ash particle into a softer surface, which is an important contributor to the wear behavior of Al-Si-Fe/CSAp composites. It is possible that the scored grooves might have been formed due to the action of the wear-hardened deposits on the disc track. Similar observations were observed in another research [1, 3].

The results of the wear rate and coefficient of friction are shown in Fig. 8-9. From the Figures it was observed that the wear rate increases with decreased in the weight percentage of coconut shell ash particles. Also increased in applied load resulted to increasing the wear rate of the samples, at lower value of the load accounts f o r lower wear rate (see Fig. 8). But at higher applied load, the samples got well spread with lesser particles getting exposed and breakage of CSAp takes place which is attributed to the extensive loss of the material due to fragmentation of CSAp and their detachment from the test material due to the non-availability of a medium to hold them.

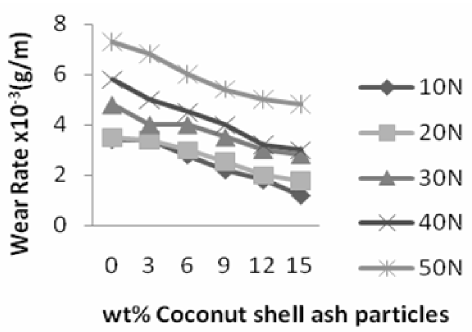

Fig. 8. Variation of Wear rate with wt% of Coconut shell ash particles

The beneficial effect of the reinforcement on the wear resistance of the Al-Si-Fe alloy composites is observed to be the best at low load and reduces with increase in applied load applied. With higher load contact temperatures become high and plastic deformation occurs with consequence of very high wear. Also when applied load are increased seizure was accompanied by a sudden increase in wear rate, heavy noise and vibration were also noticed. This type of seizure has been referred to as galling seizure [5-7]. The wear mechanism reported was oxidation at lower loads and adhesion and delamination at higher load [8-9]. This observation is at par with the one observed by Aigbodion and Hassan [1], on bagasse ash reinforced aluminium alloy composites who reported that the beneficial effect of particle reinforcement was gradually reduced with increasing load.

Also with increased load, the friction and wear will increase due to the critical surface energy of the MMCs. Furthermore, this is explained as the frictional heat raised the temperature of the friction surfaces. It is well known that wear process involve fracture, tribochemical effects and plastic flow. Transitions between regions dominated by each of these commonly give rise to changes in wear rate with load. Furthermore, this result is closely related to structure characteristics, and chemical effects occurred in frictional processes as well as transfer film formation on the counterface (see Figs. 8-9).

At higher loads, the oxide debris is expected to get better compacted to form transfer layer and spread over a larger area of the sliding surface. However, the wear rate under such circumstances takes place also by flaking of the transfer layer during sliding, apart from the processes of adhesion, micro-cutting and abrasion. At higher loads, the wearing process could be more aggravated by the transfer layer flaking off as indicated by the presence of a chunky sheet of oxide agglomerates in the wear debris as observed in Figs. 8-9.

Al-Si-Fe alloy and the composites containing CSAp have been examined for their friction behaviour determined by the variation of coefficient of friction during tests of dry sliding wear under different loads as shown in Fig. 9.

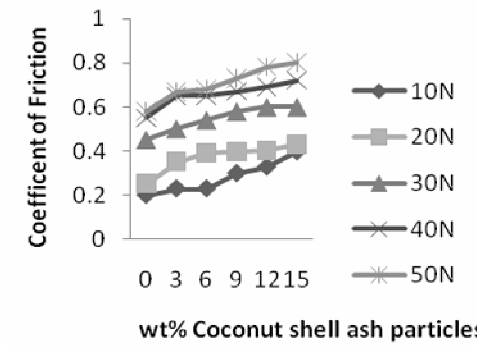

Fig. 9. Variation of Coefficient of Friction with wt% of Coconut shell ash particles.

The friction force rises in the initial period and then fluctuates around a mean during dry sliding. The mean has been determined from the individual values of coefficient of friction excluding the initial rising part, and it has been observed that the mean coefficient of friction increases with increasing load for the Al-Si-Fe alloy and the composites containing CSAp as shown in Fig. 9. At a higher load, the frictional force increases with greater dissipation of energy leading to a higher temperature at contact which resulting in higher of coefficient of friction with increasing load. But higher coefficient of friction with increasing CSAp content in the composite is surprising as these particles are supposed to create weak junctions with the asperities of the counter face because of low oxide-metal interfacial energy and also, contribute in the formation of a greater cover of transfer layer which should make relatively weak junctions. Therefore, the only inescapable conclusion is that ploughing of the sliding surface and micro-cutting during three body wears is contributing to higher frictional forces in composites containing more hard oxide particles.

The coconut shell ash particles composite exhibited the higher wear resistance under different applied load, for example the wear rate at 3wt%CASp are 3.5 x10^{-3} g/m and 7.2 x 10^{-3} g/m at 10 N and 50 N respectively. This behaviour can be attributed to the presence of CSAp on the counter surface, which acts as a transfer layer and effective barriers to prevent large-scale fragmentation of Al-Si-Fe matrix. This is also evident from the small size of the wear debris particles as determined by SEM analysis (see Fig. 7). The addition of hard ceramic particles improves the resistance to seizure. The coconut shell ash particulate allows considerable thermal softening effects without having adverse effects on the wear behavior [1, 9]. The reinforcement also causes higher hardness and less coefficient of thermal expansion of the Al-Si-Fe alloy matrix (see Fig. 3). The presence of the ceramic particles provides a higher thermal stability, increased abrasion and sliding wear resistance at high load and delays the transition from mild to severe wear [12-16].

The wear rate increased with increasing applied load while it decreased with increasing volume fraction of the CSAp material. This may be due to the reason that addition of ceramic content resulted in a pronounced drop in ductility accompanied by an increase in hardness which may further increase the wear resistance of the composites, because the hardness values of a materials is inversely proportional to the ductility. At any load, wear rate decreases with increase in addition of CSAp and improves the load bearing properties of Al-Si-Fe alloy matrix during sliding. The addition of CSAp restricts the flow or deformation of the matrix material with respect to load. It is observed that, as the applied load increases, the wear rate also increases. This is because, whenever applied load increases, the friction at the contact surface of the material and rotating disc obviously increases.

4. CONCLUSIONS

From the above results and discussion the following conclusions are made:

1. The presence of the coconut shell ash particles in the matrix alloy results in a much smaller grain size in the cast composites compared to the matrix alloy.
2. The hardness values of the developed composites increased with an increasing percentage of coconut shell ash particle additions.
3. The coefficient of friction increases with increasing load for the Al-Si-Fe alloy and the composites containing CSAp.
4. The wear mechanism reported was oxidation at lower loads and adhesion and delamination at higher load.
5. It is observed that, as the applied load increases, the wear rate also increases. This is because, whenever applied load increases, the friction at the contact surface of the material and rotating disc obviously increases.
6. The incorporation of the coconut shell particles in the Al-Si-Fe alloy matrix as a reinforcement increases the wear resistance of the material.

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