MultiCraft

International Journal of Engineering, Science and Technology
Vol. 11, No. 1, 2019, pp. 1-9

INTERNATIONAL JOURNAL OF ENGINEERING, SCIENCE AND TECHNOLOGY

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Mechanical and dry sliding wear behavior of LM6/cenosphere composites

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Abstract

Cenosphere particles are potential discontinuous dispersoids used in metal matrix composites, since they are low-cost and low-density reinforcement available in large quantities as a waste by-product in thermal power plants.It helps in decreasing the density of the composites and increases the mechanical as well as the tribological behavior of the composites.In the present work, the influence of cenosphere on the microstructure, mechanical properties and dry sliding wear behavior of Al-Si12 matrix alloy was investigated. Wear tests were performed on the pin-on-disc wear tester at 0.5235, 1.0472, 1.5708 and 2.0944 m/s sliding velocity under loads of 5, 10, 15 and 20 N. The results revealed the homogeneous distribution of the cenosphere particles on the matrix alloy. The mechanical properties improved with increasing of cenosphere particles. The coefficient of friction of the matrix alloy and composites reduced and wear rate improved with increase in the load. Scanning electron microscopy (SEM) analysis indicated that specimens were worn out by abrasive, adhesive, and delamination wear mechanism.

*Keywords:*Al-Si12 matrix alloy, Cenosphere, Pin-on-disc wear tester, Dry sliding wear, Abrasive wear mechanism.

DOI: http://dx.doi.org/10.4314/ijest.v11i1.1

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1. Introduction

In the last few years, the metal matrix composites (MMCs) have emerged as the best material in the various industries due to its novel properties. Increasingly, MMCs are being used to replace the conventional materials in many applications, especially in the automobile industries (Rohatgi, 1994). But still, due to the cost factor, the MMCs are more expensive than the conventional materials. The cost factor limited the usage of the MMCs in various fields. Cost reductions can be achieved by the use of the less expensive reinforcements and simpler fabrication methods. The search of cheaper and inexpensive reinforcement has led to the use of cenosphere particles.

A cenosphere is a lightweight, inert, hollow sphere made largely of silica and alumina and filled with air or inert gas, typically produced as a byproduct of coal combustion at thermal power plants (https://en.wikipedia.org/wiki/cenosphere). Thus the addition of the waste cenosphere particles in aluminum MMCs will reduce the cost of the aluminum products.

Al-Si12 matrix alloy (http://www.cast-alloys.com/products/lm-chart.htm) has good casting characteristics. The alloy has good fluidity and hot tearing properties that make to produce thick and thin casting sections. It has a high strength which can be used for structural components in the automobile industry.

Casting is one of the most economical methods for fabrication of MMCs (Ghomashchi and Vikhrov, 2000). However, there are many drawbacks in conventional castings, such as porosity, hot tears, A and V segregates (Aldas and Mat, 2005). To overcome all these drawbacks, new casting techniques have been introduced. Among other casting methods, squeeze casting has more potential to create less defective cast components (Hashim*et al.*, 2001).

Extensive work has been done on Al MMCs by squeeze casting route. Many researchers worked on the various Al alloys MMCs. For instance, (Sukumaran*et al.*, 2008) worked on the Al 2024 alloy with 10 % of silicon carbide particles fabricated by squeeze casting method. Authors described the effect of squeeze pressure during solidification. They concluded that with a pressure of 100 MPa, a very fine microstructure was obtained with minimum casting defects. (Onat*et al.*, 2008) and (Onat, 2010) worked on the Al-4.5Cu-3Mg alloy with various volume % of SiC particles through the squeeze casting techniques. The researchers found that the hardness, tensile strength of the matrix alloy increased by squeeze casting. The squeeze castings resulted in fine microstructural cast component with minimum casting defects and increased in the tribological wear properties.

Sun *et al*. (2014) fabricated Aluminum Matrix Fly Ash (AMFA) Cenosphere composites using the stir casting technique and studied the effect of process parameters on composites. They also found that tensile strengths improved maximally by 50 % when the cenosphere content is 13 wt %. This type of composite is difficult to fabricate because of the abrasive nature of the alumina reinforcement. The wear resistance of the Al 7075 reinforced with B4C composite increases with the increasing amount of B4C particles (Baradeswaran and Perumal, 2013).(Prabu *et al*., 2006) studied the distribution of particles in a metal matrix (aluminium alloy–silicon carbide) based on stirring speed and stirring time and observed that increase in stirring speed and stirring time results in a homogenous distribution of the particles.(Lashgari *et al*., 2009) examined the influence of strontium on improving wear resistance in aluminium boron carbide stir cast composites with 10% reinforcement. They proved that adding strontium to aluminium boron carbide composites increase wear resistance. The addition of boron carbide in Al-Si-Mg alloy matrix yield improved mechanical properties. The boron carbide particles were uniformly dispersed in the aluminium matrix (Canute and Majumder, 2018). Kalaiselvan *et al*. (2011) examined the effect of boron carbide particles (20 µm) with varying weight fractions (2%, 4%, 6%, and 8%) in A359 alloy through stir casting method. The experimental results revealed that the A359/B4C/8p composites have high hardness and tensile strength.

So far from the earlier studies, it has been observed that studies on squeeze casting were carried out in cast aluminum alloys such as Al6061, AA603, Al2024, Al-Si8Cu3Fe, Al-Si7Mg, A357, A535 and A7010 (Ghomashchi and Vikhrov, 2000; Yue and Chadwick, 1996 and Sukaram*et al*., 2004). However, no work has been reported on the Al-Si12 matrix alloy with cenosphere by squeeze casting process. The present investigation is based on the microstructural studies, mechanical properties and tribological behavior of both the Al-Si12 matrix alloy and Al-Si12/cenosphere composites.

2. Experimental procedure

2.1 Materials:

In the present study Al-Si12 alloy is used as matrix it consists of Cu-0.1%, Mg-0.1%, Si-11.8, Fe-0.6%, Mn-0.5%, Ni-0.1%, Zn-0.1%, Pb-0.1%, Ti-0.2%, Sb-0.05%, Al-remainder. The reinforcement used in this study is cenosphere, procured from National Power Engineers, Kolkata, India. The size of the cenosphere particles are in the range of 30-200 µm, and the density is 0.6 g/cm^3.

2.2 Composite Fabrication:

The fabrication process of the composites may be found elsewhere (Bera*et al.*, 2017).

2.3 Experimental Tests:

The optical microstructure study is carried out in the ZEISS optical microscope (model- AX10). The samples are first polished in the belt polishing in order to get the required dimension of the samples then the samples are polished with the emery polishing paper with grades 1/0, 2/0, 3/0, and 4/0 respectively for 1-2 hours after that the samples are polished in the cloth polishing for 1-2 hours and finally polished in the diamond polishing with 3 µm diamond paste, until the scratches are removed from the required surface of the samples and the mirror-like surface obtained.

The hardness of the composites is measured in a LECO microhardness tester (Model –LM 248AT) with a Vickers diamond indenter under a load of 500 gf. The dwell time was 15 s, and the speed of indentation is50 µm/s. The mean of at least five tests is taken for each sample.

The theoretical density of the composites is measured using equation may be elsewhere (Agarwal*et al.*, 2017). The experimental density is determined with the Archimedes principle.

Table 1.Density and porosity of the matrix alloy and composites.

Sample Name	Theoretical density ($\circ_T$)	Experimental Density ($\circ_E$)	Porosity (%)
LM6 alloy	2.648	2.644	0.151
5wt.%c/s	2.655	2.642	0.489
7.5wt.%c/s	2.662	2.639	0.864
10wt.%c/s	2.669	2.635	1.273
12.5wt.%c/s	2.675	2.625	1.869

The dry sliding wear tests are carried out by pin-on-disc wear tester (Figure1). The pin-on-disc wear tester details may be found elsewhere (Bera and Acharya, 2017). The wear tests are carried under a dry condition at ambient condition. The dry sliding wear test is performed on a steel disc (EN 31) having of 120 mm, and a thickness of 8 mm is used as a counter surface. The average roughness (Ra %) of the steel disc is 1.2 µm. The test specimens are cylindrical pin shape with a dimension of 10 mm of diameter and 26 mm of height. The pins are made to slide on the steel disc with the various parameters as given in Table 2. Further details of the test details may be found elsewhere (Bera and Acharya, 2017). The wear rate and coefficient of friction values are calculated using ASTM formulas. The surface morphology of the worn out samples is performed on a SEM.

Table2. Parameters of the dry sliding wear tests of the matrix alloy and composites

Test parameters	Units	Values
wt.% c/s	%	5,7.5,10,12.5
Load	N	5,10,15,20
Track radius	mm	50
Sliding velocity	m/s	0.5235,1.0472,1.5708,2.0944
Temperature	°C	Ambient

Figure 1. Experimental set up of pin-on-disc wear tester.

3. Results and discussion

3.1 Effect of cenosphere on hardness:

The hardness results of Al-Si12/cenosphere composites are given in Table 3. As can be seen in Table 3, cenosphere particle increases the hardness of the composites. The hardness of the composites increased due to the uniform distribution of the cenosphere particles on the Al-Si12 alloy matrix. The increase in hardness of the composites can also by the load transfer effect, thermal mismatch of the reinforcing particles and matrix. Due to this when load applied on materials the load transfer from softer matrix to harder particle so hardness increases. The hardness increases with the Hall-Petch theory and Orowon mechanism.

Table 3.Hardness value of the matrix alloy and composites.

Sample Name	Hardness
LM6 alloy	69.12
5wt.%c/s	74.24
7.5wt.%c/s	79.61
10wt.%c/s	84.25
12.5wt.%c/s	90.10

3.2 Effect of cenosphere on density:

The theoretical and experimental densities of the composite along with the corresponding porosity are presented in Table 1. It is observed from the table 1 that the actual and obtained density values are different. It also reported that the porosity of the composites increased with the addition of reinforcing particles. The similar results have been reported by various authors such as (Hanumaanth and Irons, 1993; Kok, 2000, and Ghosh and Ray, 1988). The variation in the results is due to the difference in the size and shape of the reinforcement and matrix, and entrapment of air bubbles during the stirring of the molten material inside the furnace.

Table 4. Mechanical properties of the matrix alloy and composites.

Sample Name	**Tensile strength (MPa)**	**Young's Modulus (GPa)**
LM6 alloy	112	55
5wt.%c/s	120	62
7.5wt.%c/s	130	67
10wt.%c/s	142	73
12.5wt.%c/s	155	81

3.3 Effect of cenosphere on Tensile strength:

The Tensile strength of the composites is presented in Table 4. From Table 4 it is observed that tensile strength and Young's modulus of elasticity of the composite increases as the cenosphere content increases. The 12.5 wt. % composites have the higher tensile strength and Young's modulus of elasticity than other composites.

3.4 Effect of cenosphere on microstructure:

Figure 2 represents microstructures of Al-Si12 matrix alloy and Al-Si12 /cenosphere composite. It can be seen that microstructure of composite (Figure 2a and b) consists of primary silicon, eutectic silicon, alpha aluminum (α-Al) and cenosphere particles. The SEM micrograph shows the uniform distribution of cenosphere particles. One of the very important factors in the Casting of the materials is the cooling rate. In sand casting, the cooling rate is slow, results in the segregation of the reinforcing particles at the interdendritic zone. But in squeeze casting cooling rate is high, resulting in uniform distribution of the reinforcing particles throughout the matrix (Sukumaran*et al*., 2008, and Onat, 2010). In the present study, as solidification rate in squeeze cast composites was very high, Therefore agglomerations have not been observed.

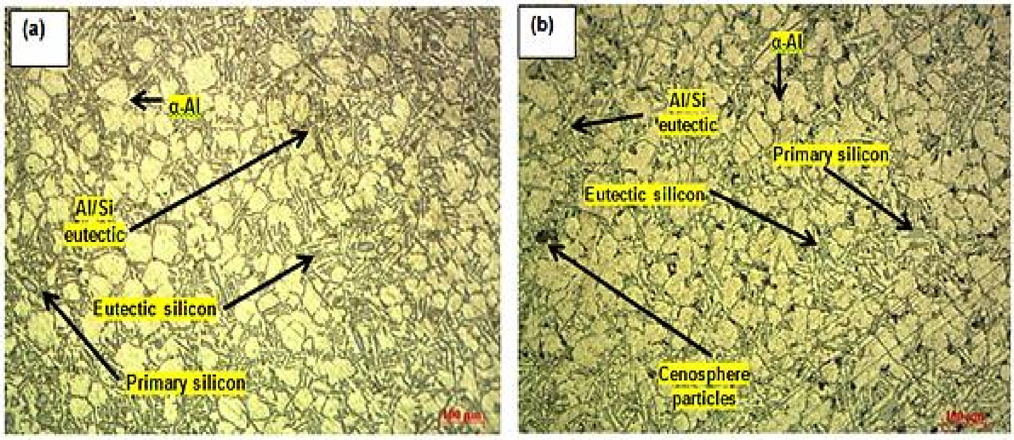

Figure 2. Optical micrographs of (a) Al-Si12 matrix alloy (b) Al-Si 12/cenosphere composite

3.5 Influence of applied load on coefficient of friction:

Figure 3 shows the variation of the coefficient of friction of the Al-Si12 matrix alloy and composites with load at 0.5235 m/s sliding velocity. It can be seen that the coefficient of friction of the matrix alloy and composites decreased with increasing load. The friction coefficient decreases with increase in the wt. % c/s. Rana et al., (1989) studied the friction coefficient existing between an Al-1.5%Mg alloy reinforced with SiCp. They concluded that the friction coefficient decreased with an increase in the volume fraction of SiC particles. Saka et al., (1985) examined friction and wear in Cu reinforced with Al_2O_3 particles. They revealed that the friction coefficient decreased with increase in alumina content. A similar observation was reported by Zhang et al., (1994). The decrease in coefficient of friction with the increase in load can be due to an increase in load, the temperature of the contact surface increases and softens the surface of the pin. So, the friction coefficient decreases. There may be another reason that when the load increases, more wear of pin surface occurs, and the wear debris stuck in between pin and counter surface and acts as roller ball. Therefore, the coefficient of friction decreases.

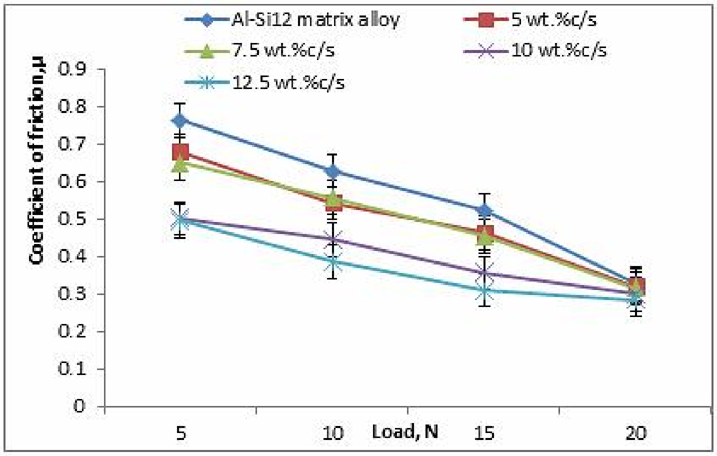

Figure 3. Variations in coefficient of friction with loads

3.6 Influence of applied load on Wear rate:

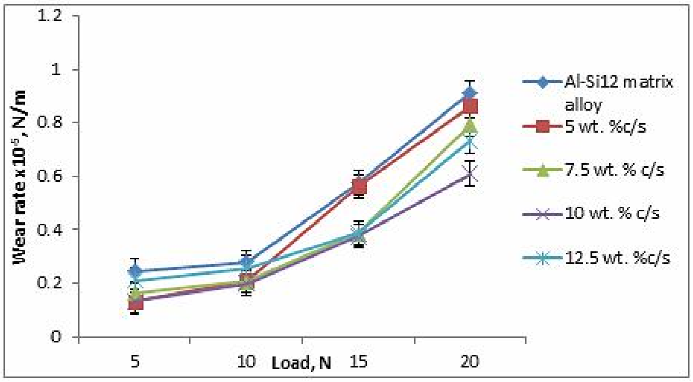

Figure 4. Variations in wear rate with loads

Figure 4 presents the variation of wear rate of matrix alloy and composites with load at 1.0472 m/s sliding velocity. The wear rate increased with the increase in the load. This is an agreement with studies of some researchers (Basavarajappa*et al*., 2006; Sahin and Ozdin, 2008, and Das *et al*., 2008). A similar observation was examined by Alpas*et al*., (1992), and Moustafa, (1995). This can be attributed due to following reasons-first one- At low load, mild wear was examined, but as the load increased beyond 10 N, the severe wear occurred. The severe wear is characterized by huge surface damage and results in the production of large wear debris (Figure 7a). Huge noise and vibration are detected during the process, and the transfer of the specimen material to the disc is observed. The second one- During the initial stage of abrasion, abrasive is in contact with the matrix, has less hardness as compared to angular silica sand (abrasive) particles. At that particular instance, the ratio Ha (hardness of the abrasive particle)/Hs (hardness of the surface) is much more than unity, resulting in severe matrix damage and the rate of material removal is very high. Thus, the specific wear rate is more. When the load increases, cenosphere particles get in contact with abrasive particles, Ha/Hs ratio is a little more than unity; as a result, cenosphere particles provide better resistance to the process of abrasion and reduce the wear rate.

3.7 Influence of Sliding velocity on Specific wear rate:

Figure 5 represents the variation of SWR of matrix alloy and composites with sliding velocity. The SWR first decreased with increasing sliding speed up to 1.5708 m/s and then increased with further increasing sliding velocity. This is because, at slow sliding velocity, the sliding surface is covered with oxide like mechanically mixed layer (MML) formed at the sliding interface and minimized direct metallic contacts. This resulted in a lower wear rate. At very high-velocity thermal softening of the matrix and localized melting on the interface, surfaces are reported. This causes the breakdown of the MML and allows more direct metallic contact during sliding, and cenosphere particles became dislodged, and suddenly huge wear resulted.

The same results were found by many researchers (Deusis*et al*., 1996; Wang and Rack, 1991; Lim *et al*., 1992, and Kwok *et al*., 1994), and author Subramanian, (1991) investigated the dry sliding wear behavior of an Al-12.3%Si alloy. He concluded that the wear rate of the alloy decreased with increasing sliding speed up to a critical speed, beyond which it increased.

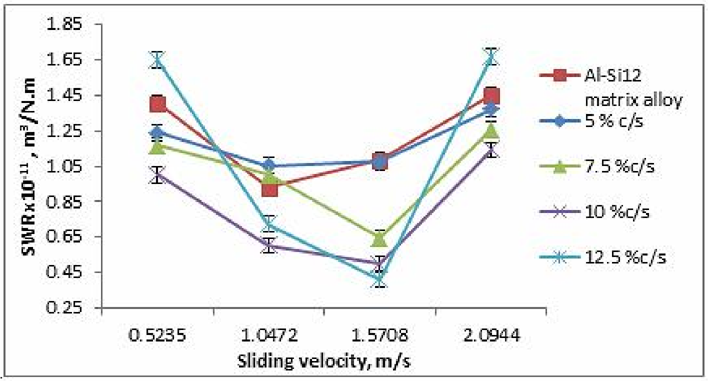

Figure 5. Variation in SWR as a function of sliding velocity

3.8 Morphology of the worn surface:

Figure 6-9 shows the worn surface morphology of the matrix and composites at different load. The sliding direction for all SEM morphology is represented by an arrow.

At low load, the SEM micrograph of matrix alloy (Figure 6a) consists of grooves, smaller and bigger size of wear debris. The grooves are of varying sizes, mainly wide and deep. The wear debris is accumulated along the edge of the grooves. The grooves are parallel to the sliding direction. But for the same load, the worn morphology of the composite (Figure 6b) contains grooves with no wear debris. These grooves are very shallow and narrow. The wear rate of the matrix alloy is more than composite at the same load. This is due to the Archard law (Archard *et al.*, 1953), According to the law, the wear rate of the material inversely proportional to the hardness of the material. The composite has a higher hardness than matrix alloy due to cenosphere particles.

At a load of 10 N, the morphology of the matrix (Figure 7a) consists multiple of small wear debris along the sliding direction of the grooves. It is shown in Figure 7(b) that the grooves are very wide and deep with some craters. The grooves reveal the presence of abrasive wear mechanism and the craters resemble the delamination. The delamination wear mechanism is more prominent at higher load. It results in craters and propagation of cracks on the wear surface (Figure 7b, 8-9).

At a load of 15 N, the morphology of the matrix (Figure 8a) has very long and wide crack along the sliding direction with wide grooves. This deep crack is due to breakage of the matrix during sliding. When we observe the Figure 8(b), it is clearly seen that the worn composite surface has shallow grooves with a small transfer of material and crater. The transfer of material reveals the adhesive wear.

At a higher load of 20 N, the worn surface of Figure (9a and b) has very deep and wide craters with a huge transfer of material. This is due to adhesive and delamination wear mechanism. The adhesive wear is the transfer of the material from the interface surfaces during the relative motion due to bonding between the interface contacting surfaces. The wear debris comes out from the wearing surface resulted in the hard protective layer called as tribolayer (Jiang *et al.*, 1995). This layer is also known as MML. At lower load, the tribology is stable, but when load increases the thermal softening of the matrix causes a breakdown in the tribolayer, resulting in more wear rate.

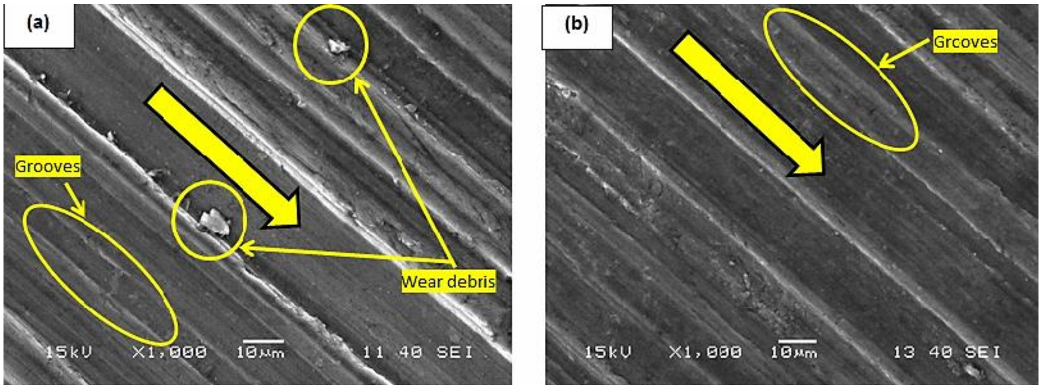

Figure 6.SEM morphology of (a) matrix alloy (b) composite at 5N load and 0.5235 m/s sliding velocity

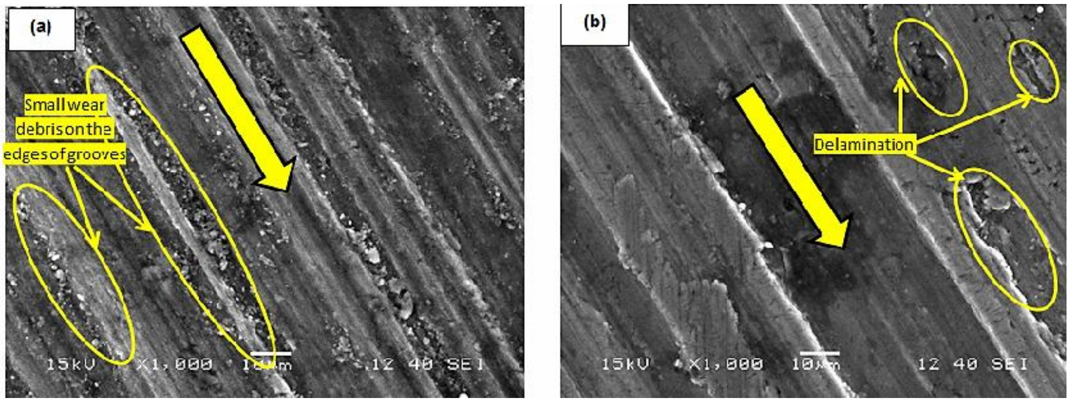

Figure 7.SEM morphology of (a) matrix alloy (b) composite at 10N load and 1.0472 m/s sliding velocity

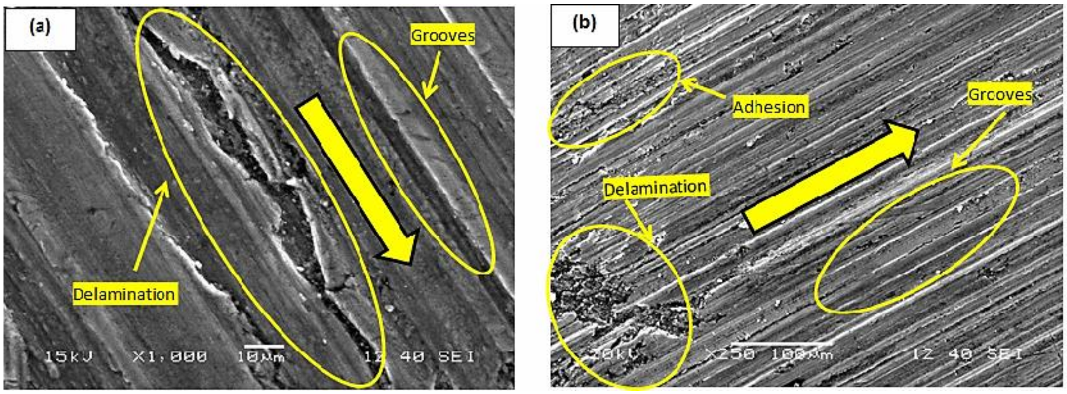

Figure 8.SEM morphology of (a) matrix alloy (b) composite at 15N load and 1.5708 m/s sliding velocity

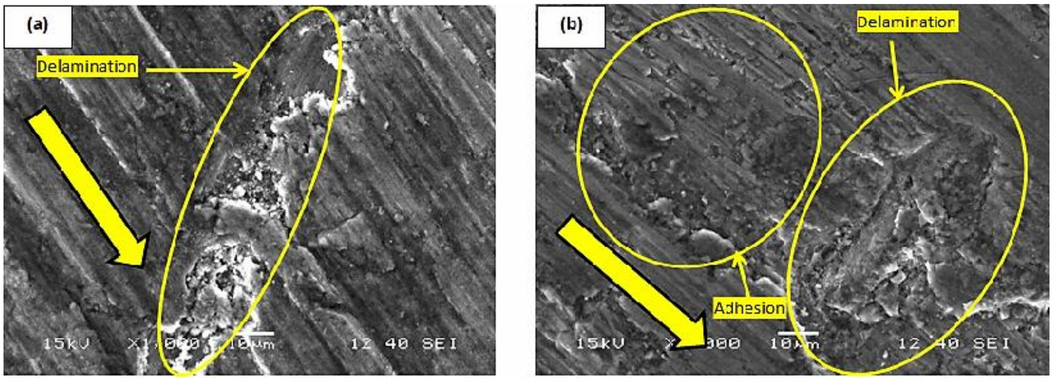

Figure 9.SEM morphology of (a) matrix alloy (b) composite at 20N load and 2.0944 m/s sliding velocity

4. Conclusions

The Al-Si12/cenosphere composites can be successfully fabricated by Squeeze casting method. The cenosphere particles are uniformly distributed in the matrix alloy with no agglomeration. Thereare no segregations of reinforced particles. Microstructures of the composites contain primary phase and eutectic regions. The squeeze casting process resulted in refining microstructure in squeeze cast matrix alloy and composites. The hardness of the Al-Si12 matrix alloy increases with the addition of the cenosphere. The hardness value increases from 69.12 to 90.10 VHN. The porosity increases with the increase in the cenosphere content in the Al-Si12 matrix alloy. The Al-Si12 matrix alloy has the minimum porosity of 0.151 % and the 12.5 wt. % c/s has the highest porosity of 1.869 %. The coefficient of friction of the matrix alloy and composites decreased with increase in load. The Al-Si12 matrix alloy has the highest friction coefficient as (0.8-0.4) and composite with 12.5 wt. % c/s has the lowest with (0.5-0.3).The wear rate increases with increase in the load. The matrix alloy has the highest wear rate of 0.9 x10^{-5} N/m, whereas the wear rate of

10 wt. % c/s is 0.55 x10^{-5} N/m. The SWR first decreased with increasing sliding speed up to 1.5708 m/s and then increased with further increasing sliding velocity. The SEM analyses of the worn out samples indicates the presence of abrasive wear mechanism, adhesive wear mechanism, and delamination wear mechanism.

Nomenclature

wt. %	Weight percentage
SEM	Scanning electron microscope
VHN	Vicker's Hardness number
SWR	Specific wear rate
MML	Mechanical mixed layer
Ha	hardness of the abrasive particle
Hs	hardness of the surface

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Received August 2018
Accepted October 2018
Final acceptance in revised form November 2018