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A comparative study of dry sliding wear behaviour of sillimanite and rutile reinforced LM27 aluminium alloy composites

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Abstract

The present work compares the dry sliding wear characteristics of sillimanite reinforced and rutile reinforced LM27 aluminium alloy based composites prepared by stir casting process. Particles in the size range of 1–32 μm were added in 5, 10, and 15 wt%. Microstructure, nanohardness, coefficient of friction, and wear rate characteristics were evaluated. Optical microscopy revealed uniform distribution of both sillimanite and rutile particles in the matrix. The hardness of sillimanite reinforced composites was superior to rutile reinforced composites. Further, the wear resistance of sillimanite reinforced composites was superior to rutile reinforced composites. However, coefficient of friction values of sillimanite particle reinforced composites were higher than the rutile particle reinforced composites. SEM-EDS analysis of wear track and wear debris revealed that abrasive wear and adhesion/delamination mechanisms were responsible for the wear of composites at low and high applied load conditions respectively.

1. Introduction

Aluminium alloys have exceptional strength to weight ratio but lack in tribological properties. In order to enhance the tribological characteristics and mechanical properties of these alloys, aluminium matrix composites (AMCs) have been developed. AMCs exhibit high strength, low density, high toughness, high corrosion resistance, high wear resistance, low thermal expansion and high thermal conductivity [1–6]. Because of these properties, AMCs find use in a variety of engineering applications viz. aviation, automobile, and defence [1, 3, 4, 7]. Some auto-components like pistons, cylinder liners, brake discs, brake drums etc are processed using AMCs [2, 8, 9]. AMCs are generally stir cast with ceramic particle reinforcements of SiC, TiC, B₄C, Al₂O₃, TiB₂ etc [6, 7, 10]. Most of the research to improve the wear characteristics of AMCs has concentrated on reinforcing the aluminium matrix with synthetic ceramic particles like SiC, TiC, B₄C, Al₂O₃, TiB₂ etc [2–4, 6, 7, 10]. However, synthetic ceramics are costly and increase the overall cost of processing of AMCs. To decrease the processing cost, aluminium matrix is reinforced with natural ceramic minerals like sillimanite, rutile, zircon, garnet etc. These minerals are cheap and abundantly available in the coastal areas of India. Natural minerals when reinforced in aluminium matrix help in improving the wear properties of AMCs [11–16]. Each natural mineral has unique characteristics viz. chemical composition, physical properties, thermal properties, and mechanical properties. Sillimanite (Al₂SiO₅) is an ore of aluminium, and hence, sillimanite particles tend to form good interfacial bonding with Al-Si matrix. In addition to this, sillimanite particles have low density, high hardness, and low coefficient of thermal expansion. Thus, during wear testing, AMCs reinforced with sillimanite particles will show a lower rise in temperature with reduced wear rate and coefficient of friction (COF) values [12, 17]. On the other hand, rutile has high thermal stability, high hardness, and is considered as a low friction material. Rutile particle reinforcement in AMCs leads to increase in load-bearing capacity of composites and results in high yield strength, low wear rate, and low COF values. Rutile reacts chemically with aluminium matrix at the interface. This helps in improving the wetting of matrix and reinforcement [11, 18]. Each specific mineral reinforcement improves the tribological properties of AMCs in a unique manner. Therefore, it was
decided to investigate the effect of two different mineral reinforcements on wear behaviour of piston grade Al-Si alloy based AMCs. To the best of our knowledge, wear behaviour of piston grade hypoeutectic Al-Si alloy based AMCs containing sillimanite or rutile particle reinforcement is not available in literature. In the limited studies on rutile or sillimanite particle reinforced AMCs, hypereutectic or eutectic Al-Si alloys have been used as the matrix material [11, 14, 19, 20]. Further, the average particle size of sillimanite/ rutile particles used in these studies lied in the range of 44–75 μm [21, 22]. The effect of reinforcing fine sized sillimanite/rutile particles on the wear behaviour of hypoeutectic Al-Si alloys has also not been studied. The present research is an attempt to overcome these limitations. In the present work, a hypoeutectic Al-Si alloy (LM27 alloy) was reinforced with sillimanite and rutile particles separately having particle size in the range of 1–32 μm. Dry sliding wear characteristics of the developed composites has been tested for their suitable application in automobile industries.

2. Materials and methods

2.1. Materials

LM27 alloy was used as the matrix material. Chemical composition of LM27 alloy is presented in table 1. Rutile (TiO$_2$) and sillimanite (Al$_2$SiO$_5$) mineral particles were used separately as ceramic reinforcements. Mineral particles were ball milled in a ball milling set-up. The powder obtained after ball milling was sieved using a sieve-shaker to obtain particle size of 1–32 μm. Table 2 presents the chemical composition of sillimanite and rutile particles (as provided by the supplier) which is nearly the same as obtained through EDS analysis as shown in figures 1(a)–(b).

2.2. Processing of composites

LM27 alloy composites were processed using stir casting process. Mineral reinforcement (rutile or sillimanite) were added in the weight percentage of 5, 10, and 15 wt%. For stir casting, LM27 alloy billet was cut into pieces and melted in a graphite crucible using an electric furnace. Temperature of the furnace was maintained at 750 ºC. Before being added to the molten aluminium, mineral particles were pre-heated to 350 ºC to allow any volatile substances present in the ceramic particles to escape. This also helped in reducing the temperature gradient obtained during addition of particles to the molten mass. Before addition of pre-heated particles, molten alloy was stirred at a speed of 630 rpm for 5 min to obtain the vortex. After 5 min, the speed of stirring was reduced to 250 rpm and ceramic particles were added to the molten charge. Finally, speed of stirring was again increased to 630 rpm to ensure that particles are distributed uniformly throughout the melt. Finally, the molten mass was poured into the cast iron mould and allowed to cool in air. After solidification, samples were prepared as per requirements of testing.

In the present study, sillimanite reinforced AMCs are designated as SRC and rutile reinforced AMCs are designated as RRC. Table 3 presents the designation of different composites processed in the present study.

2.3. Characterization

Optical microscopy was used to observe the dispersion of reinforced mineral particles in the LM27 alloy matrix. X-ray diffraction was used to determine the various phases formed in the processed composites. Further, the

| Table 1. Elemental composition of LM27 aluminium alloy. |
|----------------------------------|
| Element | Cu | Si | Mn | Zn | Mg | Sn | Ni | Fe | Ti | Pb | Al |
| wt%     | 1.5–2.5 | 6–8 | 0.2–0.6 | 1.00 | 0.35 | 0.1 | 0.3 | 0.5 | 0.2 | 0.2 | Balance |

wt%: Percentage weight.
* maximum amount.

| Table 2. Elemental composition of rutile and sillimanite minerals. |
|------------------|
| Name of mineral sand |
| Constituents present in the mineral sand |
| Ti | O | Al | Si | O |
| Percentage weight (wt%) | 46.25 | 53.75 | 33.79 | 17.76 | 48.46 |

Table 3 presents the designation of different composites processed in the present study.
wear track and wear debris obtained during wear testing were analysed using scanning electron microscopy (SEM) and electron dispersive spectroscopy (EDS).

2.4. Materials testing
The polished samples used for optical microscopy were used to perform the nano-indentation tests also. Nano-indentation testing was performed at three distinct phase regions in composites: (a) matrix region, (b) reinforcement region, (c) and interface region. For nano-hardness testing, 1 mN load was applied for a dwell time of 5 s. Further, wear tests and friction tests were performed on a pin-on-disc wear set-up. These tests were carried out for different applied load conditions of 1 kgf, 3 kgf, and 5 kgf. For each applied load, sliding speed and sliding distance were kept constant at 1.6 m s$^{-1}$ and 3000 m respectively. For wear testing, samples were prepared according to ASTM G99 standard and were taken in the form of cylindrical pins of 8 mm diameter and 90 mm length. Wear/friction tests were performed on Wear Monitoring Set-up, TR-20 CH-400, Ducom Instruments, India. During testing, pins were made to slide against a hardened EN31 steel disc having hardness of 63 HRC. The steel disc had a diameter of 165 mm and thickness of 8 mm. A linear variable differential transformer (LVDT) sensor attached to the Wear Monitoring Set-up recorded the reduction in length (height) of the cylindrical pin. This reduction in height was then multiplied by the cross-sectional area of pin to obtain total loss in volume of sample. Finally, the total loss in volume obtained at a particular sliding distance was divided by its respective sliding distance to obtain the wear rate of samples at a particular sliding distance. Surface roughness tester (Surf test SJ-400, Mitutoyo, Japan) was used to measure the surface roughness of the steel disc and

![Figure 1. EDS analysis of (a) rutile particles, and (b) sillimanite particles.](image)

Table 3. Designations used for various AMCs processed in the present research.

| Weight percentage of mineral particles reinforced in AMCs (wt%) | Sillimanite reinforced AMCs | Rutile reinforced AMCs |
|---------------------------------------------------------------|-----------------------------|------------------------|
| 5                                                             | SRC-5                       | RRC-5                  |
| 10                                                            | SRC-10                      | RRC-10                 |
| 15                                                            | SRC-15                      | RRC-15                 |
composite samples. The value obtained for the disc was $25 \pm 2 \, \mu m$; however, composites showed values in the range of $20 \pm 2$–$25 \pm 3 \, \mu m$. During wear tests, the rise in temperature of pin surface at the contact area was monitored using a temperature gun. The representative value of each experimentally determined parameter (e.g. wear rate, surface roughness etc) is an average of three values obtained for a particular experimental condition.

3. Results and discussion

3.1. Microstructural characterization

The as-cast LM27 alloy shows presence of primary $\alpha$-Al phase and eutectic mixture of Al-Si in the microstructure (figure 2). It is well reported that during the solidification process, initially, the nucleation and growth of dendrites consisting of primary $\alpha$-Al phase occurs, as shown in figure 2(a). At the eutectic temperature, growth of eutectic aluminium and eutectic silicon phase takes place. In eutectic nucleation, the silicon phase grows in a random direction to form flakes or needle type structure as shown in figure 2(b). Around this silicon phase, aluminium precipitates out to form the eutectic mixture [23, 24].

Optical micrographs of SRC composites and RRC composites at 5 wt% and 15 wt% of reinforcement level are presented in figures 3(a)–(f). Addition of both types of reinforcements to the LM27 base alloy resulted in uniform distribution of minerals throughout the matrix. During the solidification process, the entrapment of mineral particles in the solid wave front of the matrix material depends upon the thermodynamic and kinetic criteria of the solid-liquid interface. According to thermodynamic criteria, Gibb’s free energy required for engulfment of mineral particles in the solid wave front should be less than zero. However, for the wave front of $\alpha$-Al, it is reported that $\Delta G$ is greater than zero [3, 25]. Therefore, mineral particles (sillimanite/rutile) are pushed away from the solidification wave front of primary $\alpha$-Al phase. This can be observed in micrographs where the mineral particles are mostly entrapped in the vicinity of Al-Si eutectic mixture i.e. away from the primary $\alpha$-Al phase (figure 3). However, in case of SRC composites, some sillimanite particles were also observed at the inter-dendritic regions of $\alpha$-Al as shown in figures 3(a)–(b) and (e). This indicated that the velocity attained by sillimanite particles due to pushing interface was high as compared to the velocity of solid wave front (of primary aluminium) which caused entrapment of sillimanite mineral particles at the inter-dendritic regions i.e. in vicinity of primary $\alpha$-Al phase also [3, 25]. For RRC composites, rutile particles were present only in the vicinity of Al-Si eutectic mixture. Rutile particles caused variations in Si morphology as can be observed in figures 3(c)–(d) and (f)). Moreover, it can be observed that presence of rutile particles resulted in refinement of silicon phase (as shown in figure 3(d)). Thus, presence of rutile particles in RRC composites (a) changed the Si morphology from needle type to globular, and (b) restricted the grain growth of silicon phase.

3.2. XRD analysis

The presence of different phases in the composites were analysed using x-ray diffraction technique. Figures 4(a)–(b) presents the XRD spectrum of SRC-15 and RRC-15 composites. The observed phases in SRC-15 composite were aluminium, silicon, sillimanite, and aluminium silicate as shown in figure 4(a). Presence of aluminium silicate is attributed to the occurrence of interfacial reaction between sillimanite and silicon (of alloy matrix) [13, 14]. For RRC-15 composite, XRD pattern showed presence of aluminium, silicon, and rutile phase as shown in figure 4(b). In
addition to these, peaks of aluminium copper (AlCu3 and AlCu) and aluminium titanium silicate (Al4Ti2SiO12) phases were also observed. It was assumed that interfacial reaction between aluminium, silicon, and rutile resulted in formation of Al4Ti2SiO12. The presence of intermetallic compounds formed by Al and Cu i.e. AlCu and AlCu3 signified that rutile particles were acting as activators for nucleation of intermetallics. The interfacial reactions may be presented as follows:

\[
4\text{Al}_2\text{SiO}_3 + 4\text{Si} \rightarrow 2\text{Al}_4\text{Si}_4\text{O}_{10} + 4\text{Al}
\]  

(1)

\[
4\text{Al} + \text{Si} + 6\text{TiO}_2 \rightarrow \text{Al}_4\text{Ti}_2\text{SiO}_{12} + 4\text{Ti}
\]  

(2)

3.3. Nano-hardness testing

Figures 5(a)–(c) presents the load-depth curve for LM27 base alloy, SRC-15 composite, and RRC-15 composite. For composites, indentation was obtained at the three distinct phase regions i.e. matrix, interface and

Figure 3. Optical micrographs of AMCs for (a) SRC-5 at 100×, (b) SRC-5 at 200×, (c) RRC-5 at 100×, (d) RRC-5 at 200×, (e) SRC-15 at 100×, and (f) RRC-15 at 100×.
reinforcement region. Nano-hardness values obtained at different phase regions of composites is presented in table 4.

Reinforcement of mineral particles to the LM27 alloy matrix increased the dislocation density and hence enhanced the hardness of matrix. The increase in dislocation density was attributed to the difference in coefficient of thermal expansion (CTE) between matrix and reinforcement [4]. More is the difference in CTE value (of matrix and particles), higher is the dislocation density. The coefficient of thermal expansion for LM27 alloy, sillimanite, and rutile is $18.95 \times 10^{-6} \, ^\circ C^{-1}$, $2.1 \times 10^{-6} \, ^\circ C^{-1}$ [26] and $9.3 \times 10^{-6} \, ^\circ C^{-1}$, respectively [27]. As sillimanite particles and LM27 alloy have a relatively greater difference in CTE value, hence higher dislocation density will be observed in SRC composites. For this reason, SRC-15 composite showed a higher value of nano-hardness at the interface and matrix regions as compared to RRC-15 composite. From XRD analysis, it was observed that due to interaction between matrix and reinforcement, some interfacial reactions occurred in the composite system. The products formed due to these reactions were hard intermetallic compounds [13, 14]. Hence, hardness value of interface region was higher than the matrix region. The high nano-hardness values obtained at interface region signified good interfacial bonding between matrix and reinforcement. It was noted that sillimanite particles made stronger interfacial bonding with matrix as compared to rutile particles.

Figure 4. XRD spectrum of (a) SRC-15 composite and (b) RRC-15 composite.
3.4. Wear analysis

Figures 6(a)–(g) presents the wear behaviour of LM27 base alloy and various AMCs with change in sliding distance and applied load. Figure 6(a) presents the wear graph for LM27 alloy. Figures 6(b)–(d) and (e)–(g) present the wear graphs of SRC and RRC composites with reinforcement levels of 5 wt%, 10 wt%, and 15 wt% respectively. It was observed that addition of mineral particles to the base alloy enhanced the wear characteristics of the latter. Mineral particles are harder as compared to the base alloy. During the wear test, mineral particles mostly bear the load, and thus, resist the wear of composites. Secondly, the hard ceramic particles improve the hardness of base alloy \cite{3, 7}. Further, the bonding of reinforced particles with the matrix material also plays a significant role in improving the wear properties of composites. Formation of strong interfacial bonding delays the removal of particles from the matrix (during wear testing) which allows particles to withstand the load for a longer period. However, in case of weak bonding, the particles are easily removed and allow the matrix to come in direct contact with steel disc. This causes material removal at a higher rate \cite{5}. SRC composites showed a lower wear rate in comparison to RRC composites. Sillimanite particles improved the hardness of matrix and
Figure 6. Wear rate as a function of sliding distance for (a) as-cast LM27 alloy, (b) SRC-5 composite, (c) SRC-10 composite, (d) SRC-15 composite, (e) RRC-5 composite, (f) RRC-10 composite and (g) RRC-15 composite under different applied loads.
obtained a strong interfacial bonding with matrix. Hence, the load-bearing capacity of SRC composites was higher than RRC composites.

During the initial stages of wear, asperities of the two counter surfaces are in point contact. This results in high-stress concentration at the point of contact and increases the wear rate. With increase in sliding distance, the asperities deform and decrease the wear rate \[2, 3\]. The deformation of material results in strain hardening of the matrix which further reduces the wear rate \[10\]. Further, the gap between asperities is filled by the debris formed during the wear test. The entrapment of worn-out debris between the two counter surfaces results in formation of mechanically mixed layer (MML). MML is a mixture of wear debris of counter surfaces and their oxides. It prevents metal to metal contact between Al matrix and steel disc which also helps in reducing the wear rate \[2, 3\].

Sillimanite reinforced composites displayed higher hardness and stronger interfacial bonding in comparison to rutile reinforced composites. Hence, sillimanite reinforced AMCs showed better wear resistance than rutile reinforced AMCs.

For both, the base alloy and various AMCs, the wear rate increased with increase in applied load. At low load conditions (1 kgf), the point contact between sliding surfaces leads to ploughing action. This ploughing action results in generation of cracks. These cracks merge with one another and remove material from the pin surface \[3, 9\]. The MML formed by worn debris is more stable under low load conditions \[7\]. Thus, lower wear rate was observed at low load conditions. With increase in load to 3 kgf, the wear rate of base alloy as well as various AMCs increased. However, the quantum of increase in wear rate was lower for composites as compared to base alloy. At high load conditions (5 kgf), the materials undergo severe plastic deformation and experience high frictional force. Due to high frictional force, a significant rise in temperature was observed at the contact surface of pin and disc as shown in figure 7. This results in softening and oxidation of worn debris and pin surface.

Due to oxidation of the pin surface, an adherent layer of oxides on the surface of pin (MML) was formed which prevents the exposure of matrix material to the counter surface. The increase in applied load makes the MML unstable and exposes the pin surface to steel disc. Due to frictional heating, the material beneath the oxide layer becomes soft, and hence is not able to bear the load and gets removed easily \[2, 7\].

Due to the relatively lower hardness of rutile, RRC AMCs were subjected to relatively higher ploughing action compared to SRC AMCs. The hard sillimanite particles with good interfacial bonding restricted crack

Table 5. Improvement in maximum wear rate of AMCs over the base alloy.

| S. No. | Type of AMC | 5 wt% | 10 wt% | 15 wt% |
|-------|-------------|-------|--------|--------|
| 1.    | SRC         | 17    | 36     | 49     |
| 2.    | RRC         | 8     | 31     | 40     |

Figure 7. Temperature changes at the pin surface with respect to sliding distance during wear testing at a constant applied load of 5 kgf for LM27 alloy, SRC-15 composite, and RRC-15 composite.
propagation in SRC composites. However, for RRC composites, the cracks generation and propagation was higher. In addition to this, RRC composites showed a higher rise in temperature during wear testing (figure 7). This led to softening of matrix and higher wear rate in RRC composites.

For a given applied load and sliding distance, the wear rate of SRC composites was lower than RRC composites. Table 5 presents the improvement in maximum wear rate of composites over the base alloy at an applied load of 5 kgf and sliding distance of 3000 m.

3.5. Coefficient of friction
Table 6 shows the COF values for base alloy and various AMCs under different applied loads. For a given applied load, the base alloy (LM27) showed maximum COF value. Further, for the AMCs, at a given reinforcement level and applied pressure condition, rutile reinforced AMCs mostly showed lower COF value than the sillimanite reinforced AMCs.

For the base alloy, the interaction of pin surface with steel disc at asperities level was relatively more (as compared to composites) because of the absence of hard mineral particles in the matrix. As a result, steel disc asperities penetrated more into the base alloy surface as compared to composites. Higher is the digging, higher is the frictional force required to keep the counter surfaces in motion, and hence, higher was the COF value for the base alloy. In case of composites, COF value depends on hardness of the reinforcement, formation of the transfer film, and temperature rise during the wear test. RRC composites showed greater rise in temperature as compared to sillimanite reinforced composites (figure 7) because of lower thermal conductivity of rutile as compared to sillimanite. The thermal conductivity of rutile is 12.23 mcal cm⁻¹ s⁻¹ °C⁻¹ whereas that of sillimanite particles is 21.73 mcal cm⁻¹ s⁻¹ °C⁻¹ [28]. Due to higher thermal conductivity of sillimanite, heat dissipation rate of SRC composites was higher than RRC composites, and hence, temperature rise of SRC composites (at the contact surface) was lower than that in RRC composites. This resulted in more softening of RRC composites for a given applied pressure-reinforcement level condition. Thus, the frictional force required for removal of material was lesser for RRC composites, resulting in lower COF values than SRC composites [2, 29]. Further, sillimanite particles have higher hardness as compared to rutile particles (as shown in table 4). As a result, sillimanite particles do not deform plastically but rather penetrate more in the counter surface (i.e. disc) as compared to rutile particles. This increases the surface to surface friction and results in higher COF value for SRC composites.

3.6. Wear track and wear debris analysis
Figures 8(a)–(d) and 9(a)–(d) present the SEM micrographs of wear track/wear debris of SRC-15 and RRC-15 composites respectively for the extreme applied load conditions of 1 kgf and 5 kgf. For both the composites, the wear track obtained at 1 kgf load showed formation of narrow grooves and presence of worn debris on the surface. Grooves formed on the worn surface represent ploughing action caused by sharp asperities [3, 9]. Further, presence of worn debris on the wear track shows formation of a stable MML [7]. For SRC composite, some small sized craters were observed at low load conditions of 1 kgf (figure 8(a)). However, for RRC composites, minimal craters were observed (figure 9(a)). As the applied load increased to 5 kgf, the grooves obtained on the surface of both, SRC and RRC composites, became wider and also a large delaminated area was observed. For SRC composite, lesser delaminated area with wider grooves was observed (figure 8(b)). However, for RRC composite, larger delaminated area with some deep grooves was observed (figure 9(b)). The rise in temperature in RRC composites during wear test was observed to be higher than in SRC composites (figure 7). It is reported that rise in temperature leads to higher plastic deformation of matrix material and causes localized bonding of counter surfaces [6, 30]. Since, RRC composite suffered higher temperature rise, it showed larger delaminated area than SRC composites (figure 9(b)).
Figures 8(c)–(d) and 9(c)–(d) present the wear debris of SRC-15 and RRC-15 composites respectively. Wear debris for both, SRC and RRC composites, showed presence of features like micro-cut, flake-like debris etc under 1 kgf and 5 kgf applied load conditions. Presence of flake-like debris was attributed to merging of cracks generated during wear testing. For 1 kgf applied load, debris were mainly constituted of the flake like shape (figures 8(c) and 9(c)). Grooves on debris were also observed. Grooves on debris signified that the material initially underwent abrasive wear. Further, micro-cut debris were present due to removal of ductile aluminium by the ploughing action [13]. For the applied load of 5 kgf, apart from the flake like debris, other features like corrugated debris, fractured debris, and oxides on debris were also observed (figure 8(d)). Corrugated debris are a result of repetitive nature of stress during continuous sliding [13]. Similarly, fractured debris were observed because high loads lead to fracture of particles [13]. Further, higher loads increase the temperature of counter surfaces resulting in their oxidation. This leads to formation of oxides on the debris.

Finally, figures 10–11 present the EDS analysis of wear track and wear debris of SRC-15 and RRC-15 composites respectively under applied loads of 1 kgf and 5 kgf. Wear track of pin surface showed presence of iron and carbon (figures 10(a) and 11(a)). Due to high hardness of SRC composites, more iron content was present on their wear track as compared to RRC composites. The presence of iron on the wear track showed that material was removed from the steel disc and got attached to the pin surface under the action of applied load. This meant that wear debris comprised of materials removed both from the pin surface as well as the steel disc, and thus resulted in the formation of a stable MML. EDS of wear debris showed presence of iron and carbon along with Al, Si, O, and Cu (figures 10(c) and 11(c)). This showed that mechanical blending of wear debris had occurred under applied load conditions.

At higher load, rise in temperature was observed leading to localized welding between the counter surfaces. This resulted in transfer of material between the surfaces [30]. Due to this, high amount of Fe and C was present on the wear track of SRC-15 and RRC-15 composites (figures 10(b) and 11(b)). The high amount of carbon on the wear track may have acted as a lubricating agent which helped in reduction COF at higher load conditions.
Since debris were formed due to removal of adhesive material under the applied load, the wear debris showed presence of iron and carbon (figures 10(d) and 11(d)).

4. Conclusions

This research presented a comparative study of sillimanite reinforced composites and rutile reinforced composites processed using stir casting process. The following are the main conclusions to be drawn from the present work.

- Microstructural investigations revealed that mineral particles were uniformly distributed in the matrix material. Addition of mineral particles resulted in refinement of Si phase present in the LM27 alloy. RRC composites showed more refinement as compared to SRC composites.
- Hardness of SRC composites for the different phase regions was higher than RRC composites. High value of hardness obtained at the interface of sillimanite and matrix material signified a strong interfacial bonding between particles and matrix in the processed AMCs.
- SRC composites showed superior wear characteristics in comparison to RRC composites. The maximum improvement in wear rate observed for SRC-15 and RRC-15 composites was 49% and 40% respectively over the base alloy.
- RRC composites exhibited lower COF values than the SRC composites. This signified that addition of rutile particles resulted in higher lubricating effect than the sillimanite particles. This was attributed to the transfer of higher amount of carbon from counter surface to pin surface (which acted as a lubricating agent) in RRC composites.
SEM-EDS analysis of wear track and wear debris revealed that at low load conditions (1 kgf), wear was mainly of abrasive nature, whereas at high load conditions (5 kgf), wear mechanism responsible for wear of composite was adhesion and delamination.

Figure 10. EDS analysis of SRC-15 composite for (a) worn surface at 1 kgf, (b) worn surface at 5 kgf, (c) wear debris at 1 kgf, and (d) wear debris at 5 kgf.
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Figure 11. EDS analysis of RRC-15 composite for (a) worn surface at 1 kgf, (b) worn surface at 5 kgf, (c) wear debris at 1 kgf, and (d) wear debris at 5 kgf.

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