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Effect of particle size on dry sliding wear behaviour of sillimanite reinforced aluminium matrix composites

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ABSTRACT

Present work describes the development of Al-Si/sillimanite reinforced composites via stir casting route. Sillimanite is abundant mineral available in coastal regions of India and has not been explored much as reinforced mineral for the development of composites. In the present work, dry sliding wear behaviour of LM30 aluminium alloy reinforced with sillimanite has been investigated. Composites reinforced with sillimanite in different weight percentage (3–18 wt percentage) and particle size range (fine: 1–20 µm, medium: 32–50 µm, and coarse: 75–106 µm) were prepared. Microstructural studies revealed uniform distribution of sillimanite particles in the matrix of composites. Nanoindentation taken at different phases indicated good bonding between reinforced particles and matrix. Fine particles (1–20 µm) reinforced composites containing 15 wt% sillimanite exhibited higher wear resistance which is 55% more compared to base LM30 alloy. Beyond this reinforcement level, wear resistance deteriorated because of agglomeration of the fine particles. Analysis of wear track and debris revealed that at low applied loads, abrasive wear was predominant whereas at higher applied loads, adhesive wear was dominating factor.

1. Introduction

Aluminium matrix composites (AMCs) reinforced with ceramic particles have drawn considerable attention in automobile, defence, aerospace, and other structural applications as fuel efficient advanced materials for different tribological applications [1–3]. These composites provide greater flexibility in tailoring the desired mechanical properties for different engineering applications [4,5]. Aluminium and its alloys act as a good matrix material for the development of particulate reinforced composites as they possess low density, high specific strength, high corrosion resistance and ease of fabrication with low cost [6–8]. Reinforcement of hard ceramic particles in the matrix of aluminium is done to improve the tribological properties [9,10]. AMCs can be used as wear-resistant material in various parts of automobiles (viz. brake drums, pistons, cylinder heads, and liners etc.) and pump bodies [11–17]. Several studies on reinforcement of pure ceramic particles viz. silicon carbide [16–18], silicon nitride [19,20], boron carbide [21–23], and alumina [24–26] to improve the wear characteristics are reported. In these studies the addition of pure single particle size ceramic powders to improve the wear resistance/mechanical properties (hardness, strength etc.) of AMCs has been done. However, pure ceramics being expensive leads to enhancement in the cost of the fabricated AMCs which is not desirable for large scale applications of the composites. To reduce the cost, reinforcement of minerals like sillimanite [11–15], garnet [27–29], zircon [17,30–32], and rutile [33–36] has been tried where the improvement in wear properties has been reported.

Reinforcement of sillimanite to improve the wear characteristics in aluminium matrix (LM6) has also been done [11–15]. However, in these work only one particle size range (50–150 µm) has been studied. Considering the fact that sillimanite has high hardness, high modulus, high corrosion resistance, low coefficient of thermal expansion, high resistance to creep deformation, high thermal shock resistance, and excellent thermal stability, a detail study on reinforcement of sillimanite has been planned. Moreover, sillimanite being an ore of aluminium will develop better wettability with aluminium matrix.

In the present work, LM30 aluminium alloy was used as the matrix material. LM30 is a piston grade alloy which finds applications in brake drums, pistons, cylinder heads, and liners in automobile sector and pump bodies. Such parts are in a state of constant wear and thus wear analysis is an important aspect which affects their performance. The present work reports on development of LM30/sillimanite composites and wear characteristics of these developed composites. In this study three different particle size range of sillimanite (1–20 µm, 32–50 µm, and 75–106 µm) has been selected. Finally, wear tracks and wear debris

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Table 1
Chemical composition of the as-received LM30 alloy.

Constituent Elements	Si	Cu	Fe	Mn	Mg	Zn	Cr	Ni	Ti	Ca	Pb	Sn	Sr	Al
wt%	17.74	4.10	0.533	0.106	0.523	0.262	0.034	0.023	0.0825	0.018	0.0832	0.031	0.0006	76.4

Table 2
Chemical composition of sillimanite.

Composition	Al_2O_3	SiO_2	ZrO_2	TiO_2	Fe_2O_3
wt%	58.60	38.54	2.20	0.26	0.40

were analysed to identify the wear mechanisms involved in the material removal process.

2. Materials and methods

2.1. Materials

An automobile grade LM30 aluminium alloy was used as the matrix material for preparing the AMCs. LM30 aluminium alloy was purchased from Emmes Metal Private Limited, Mumbai, India. Table 1 presents the composition (wt%) of the base material.

The aluminium matrix was reinforced with sillimanite (Al_2SiO_5). This ceramic mineral was supplied by Indian Rare Earths Limited, Mumbai, India. Table 2 presents the chemical composition of sillimanite.

2.2. Processing of composites

Stir casting process was used for fabrication of composites. The base alloy (LM30) was melted at 750 °C and stirred with a graphite stirrer for 2–3 min at 630 rpm. There after the stirrer speed was reduced to 250 rpm and sillimanite (Al_2SiO_5) was slowly added to the molten mass. This mixture was further stirred at 630 rpm for 8–10 min and was finally cast into a cast iron mould ($12 \times 12 \times 4$ cm^3) followed by air cooling. Single particle size reinforced composites containing different wt% of sillimanite (3–18 wt%, in a step size of 3 wt%) and also different particle size range (1–20 µm, 32–50 µm, and 75–106 µm respectively) was prepared by this process. In the present work, single particle size reinforced composites containing sillimanite particles of size 1–20 µm, 32–50 µm, and 75–106 µm were designated as SPS-F, SPS-M, and SPS-C respectively. Table 3 presents the details of various AMCs processed in the present work.

Specimens (base alloy as well as various composites) were prepared for optical microscopy through the standard metallographic procedure. Optical micrographs (Eclipse MA-100, Nikon Instruments, Tokyo, Japan) were obtained to evaluate the distribution of sillimanite in the matrix. To study the different phases present in the composites X-ray diffraction (XRD) patterns of base alloy and 15SPS-C composite was recorded using PANalytical X′pert PRO X-ray diffractometer with CuKα radiation (λ = 1.54 Å). Wear test was performed at different loads varying from 1 to 5 kg on a pin-on-disc wear testing machine (Wear and Friction Monitor TR-20 CH-400, Ducom Instruments, Bangalore, India). For the wear test, cylindrical pins of 10 mm diameter (as per ASTM G99 standards) were used. Wear tests of the base alloy and the composites were conducted under dry sliding conditions in ambient air against EN 32 steel disc having 65 HRC (832 HV) hardness and a sliding velocity of 1.6 m/s. The equipment is configured with the facility to measure the height loss (µm) of the specimen. Further, the volume loss of the specimen is calculated as the product of height loss and the contact area of the pin and disc. The wear results are presented as an average of three tests for a given wear test condition. After the wear test, worn out surfaces and debris were collected and analysed under a scanning electron microscope (JSM-6510LV, JOEL Ltd., Tokyo, Japan) to determine the wear mechanisms involved under different applied loads. Nanoindentations (TI 950 Tribo Indenter, Hysitron, Incorporation, Minneapolis, US) were taken at different phases of composites at a load of 1000 µN with a dwell time of 5 s. The nanoindentation results presented here are the average of test done on four specimen of similar category.

Table 3
Designation used for various AMCs processed through the stir casting route.

Weight percentage of sillimanite in AMCs (wt%)	Designation of Single particle size reinforced AMCs with sillimanite size as		
	Coarse (75–106 µm)	*Medium (32–50 µm)*	*Fine (1–20 µm)*
3.0	3SPS-C	3SPS-M	3SPS-F
6.0	6SPS-C	6SPS-M	6SPS-F
9.0	9SPS-C	9SPS-M	9SPS-F
12.0	12SPS-C	12SPS-M	12SPS-F
15.0	15SPS-C	15SPS-M	15SPS-F
18.0	18SPS-C	18SPS-M	18SPS-F

3. Results and discussion

3.1. X-ray diffraction analysis

Fig. 1a and b presents the X-ray diffraction (XRD) patterns of LM30 base alloy and 15SPS-C composite. Fig. 1a presents the peaks of aluminium and silicon present in the base alloy. The presence of sillimanite along with aluminium and silicon can be observed in 15SPS-C composite (Fig. 1b). Apart from these phases, aluminium silicate ($Al_2Si_4O_{10}$) was also observed in the composite. Aluminium silicate might have formed at the particle-matrix interface because of the reaction of sillimanite and LM30 alloy during casting.

3.2. Microstructural analysis

3.2.1. Base-LM30 matrix alloy

The microstructure of the starting material (LM30 aluminium alloy) typically comprised of Al-Si eutectic mixture and proeutectic (primary) silicon phase (Fig. 2). As the alloy solidifies primary silicon grows like a faceted structure followed by eutectic solidification. Higher magnification micrograph reveals that at some places structure is very fine compared to other places where primary α phase is also visible. Further, primary silicon morphology present in the matrix of eutectic was largely of polyhedral shape. The morphology of primary silicon phase considerably depends on solidification parameters viz. freezing rate, temperature gradient in the liquid, and composition of the liquid [37]. The cast structure of hypereutectic Al–Si alloy consists of a coarse and segregated primary silicon phase along with the needle like eutectic silicon (Fig. 2). Coarse primary silicon leads to a large scale reduction in the extrudability, machinability, strength, and ductility of the alloy. To achieve better mechanical and wear resistance properties from a hypereutectic Al-Si alloy, fine size of primary silicon along with its uniform distribution is necessary [37].

The notable structural feature of hypereutectic Al-Si alloy is the primary Si phase. Silicon phase is harder than other phases typically found in aluminium casting alloys. This hard phase is more abrasion resistant thus improves the wear resistance of hypereutectic Al-Si alloys