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STUDIES ON MECHANICAL PROPERTIES AND TRIBOLOGICAL BEHAVIOUR OF LM25/SiC/Al_2O_3 COMPOSITES

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Abstract

This paper involves the study of mechanical properties and wear characteristics of LM25/SiC/Al_2O_3 hybrid metal matrix composites. Composite specimens of reinforcements ranging from 0 to 30 wt-% were fabricated using liquid metallurgy route. Mechanical properties such as hardness and tensile strength were analysed for both unreinforced alloy and composite specimens. Wear characteristics of composite specimens were studied using Pin-on-disc tribometer. Wear experiments were conducted with load range of 10 N to 30 N and velocity range of 1 m/s to 3 m/s. The sliding distance was kept 1500 m for all wear experiment. Worn out surfaces of composites were analysed using Scanning Electron Microscope. From experiments it was found that, the mechanical properties and wear resistance increased as the weight percentage of reinforcement increased.

Keywords: Dry sliding, Metal matrix composites, Wear, Aluminium composites.

1. Introduction

Metal Matrix Composites (MMCs) are most promising in achieving enhanced mechanical and wear properties due to the presence of reinforced particles.The use of aluminium which is both light weight and corrosion resistant in various applications has been limited due to their inferior strength, rigidity and wear resistance. At present time, Aluminium Metal Matrix Composites ($AMMC_S$) are well recognized and steadily improving due to their advanced engineering properties, such as better wear resistance, high specific strength, low density and high stiffness. Among these, wear is one of the most commonly encountered industrial problems leading to the replacement of components and assemblies in engineering [1]. Wear reduces the operating efficiency by increasing material losses, fuel utilization and the rate of component replacement. Thus, assessment of the wear behaviour of composite material is essential [2, 3]. But no consistent wear behaviour of composites has been established so far. So, the wear behaviour of each composite has to be studied separately before using it in an application.

Studies on wear behaviour of aluminium-Silicon Carbide (SiC) composite show that increasing the volume percentage of SiC reduces the weight of aluminium alloy as well as wear rate [4]. It is inferred that when Al7075 alloy is reinforced with SiC of various volume fractions (manufactured by Powder Metallurgy), its wear resistance increased. The increase in wear resistance is generally due to formation of Mechanically Mixed Layer (MML) on the worn surface which is revealed by worn surface analysis. MML is formed due to turbulent plastic flow induced by shear instability (shear stress) in part of metal close to worn surface and this plastically deformed metal gets mixed with steel plate counterpart [5].

Rigney [6] further confirmed the formation of MML and found that it consists of components of composite material, steel and also oxide formed due to oxidation. Wear resistance increased with the increase in volume fraction of reinforcements since MML has the high hardness than the base metal composite. The wear characteristics of composites mainly depend on the structural, chemical and mechanical characteristic of MML. Wear increases abruptly when the protective MML is ruptured and also observed that thickness of MML increased as load increases till transition load, after that MML ruptures [7].

Aluminium based MMC containing up to 15 wt-% of SiC synthesised by stir casting method showed near uniform distribution of SiC particles in the matrix. Stir casting method is simple, economical and it provides near uniform distribution. When wear is monitored with Pin-on-disc tribometer, it is observed that resistance to wear increased with increase in wt-% of SiC particles. But wear has increased with increase in normal load and sliding velocity. Hardness of composites has increased with increase in SiC particles [8]. But, increase in wt-% of SiC makes component difficult to machine, also SiC particles detached from composite itself acts as an abrasive. So to obtain better wear properties, soft reinforcements can be added. When Al2024 is reinforced with SiC and graphite, hardness and wear resistance increased. But when graphite alone is used, wear rate increases due to decrease in fracture toughness and also due to removal of its lubricant layer [9]. The presence of graphite decreases the toughness of composite.

Kok [10] studied the wear resistance of Al/Alumina (Al_2O_3) composites and found that the wear resistance increased with increasing Al_2O_3 particle content and size and decreased with increasing the abrasive grit size and sliding distance. The wear resistance of composites with larger size particles are mainly due to hardness of the reinforced particles and the composites with smaller size particles are due to both strengthening of the matrix and hardness of the particles. Elango et al. [11] investigated the wear behaviour of LM25 and its composites reinforced with SiC and Titanium Dioxide (TiO_2). The results revealed that the reinforcement has improved the wear resisting property of LM 25 alloy.

Based on the above literature, LM25 alloy is selected as matrix; Al_2O_3 and SiC particles are selected as reinforcements with an average size of 10 – 15 μm. LM 25 is mainly used in cylinder blocks and cylinder heads. Hence an attempt has been made to improve the wear resistance of that alloy by incorporating hard reinforcements.

2. Fabrication of Composites

The alloy and composites are fabricated by liquid processing technique. Composite samples fabricated in this study are: (a) LM 25 alloy with 5 wt-% SiC and 5 wt-% Al_2O_3 (b) LM 25 alloy with 10 wt-% SiC and 10 wt-% Al_2O_3 (c) LM 25 alloy with 15 wt-% SiC and 15 wt-% Al_2O_3. Chemical composition of LM 25 alloy is given in Table 1. LM25 alloy is melted to a temperature of 700ºC in the furnace, and reinforcements are preheated to a temperature of 300ºC simultaneously. The reinforcements are preheated to improve the wettability, remove moisture and also to reduce the temperature gradient between molten metal and reinforcements. For composite with 10 wt-% of reinforcements, the measured quantity of SiC and Al_2O_3 are added to the molten metal with continued stirring action. The mixture is stirred for 3 minutes at the speed of 200 rpm to get uniform distribution and it is poured in the mould cavity. The same procedure is repeated for fabrication of composites with 20 wt-% and 30 wt-% reinforcements. The samples prepared are cylindrical in shape and are 30 mm in diameter and 120 mm in length.

Table 1. Chemical composition of LM 25 alloy.

Composition	Si	Fe	Cu	Mn	Mg	Cr
%	6.5-7.5	0.5	0.1	0.3	0.2-0.6	0.05

Composition	Ni	Zn	Sn	Ti	Pb	Ca	Al
%	0.1	0.1	0.05	0.2	0.1	0.05	balance

3. Studies on Mechanical Properties and Wear Behaviour

Experiments on wear behaviour, mechanical properties including hardness and tensile strength are conducted for unreinforced alloy and compared with those of composite specimen. The values of each experiment are the average of three trials. Test procedures used are briefly discussed in the following sections.

3.1. Tensile test

The specimens are prepared according to ASTM E8 Standards. The gauge is 24 mm long and having diameter of 6 mm. The total length of the specimen is 80 mm. The equipment used to test tensile strength is Universal Testing Machine (UTM).

3.2. Hardness test

The specimens are prepared according to ASTM E384 standards. The surfaces of specimens are polished using emery papers with 500 and 400 mesh size (3/0 and 4/0 grit size respectively). The specimens are then polished using velvet disc polishing machine to get fine finish. The hardness test is carried out in Vicker's micro hardness tester. The load of 100 gm for a period of 15 seconds is applied on specimens.

3.3. Wear test

Wear experiment is conducted using Pin-on-disc tribometer. The composite specimens are prepared according to ASTM G99 standards. The dimensions of cylindrical pin specimens are 12 mm diameter and 20 mm length for all the samples. The test is conducted in dry sliding conditions. The counter face rotating disc is made of EN-32 steel having hardness HRC65. Before and after each test, the weight of specimen has been measured and weight loss is calculated. The weight has been measured in a digital balance having least count of 0.1 mg. After each test, the disc is cleaned with acetone to remove debris. The sliding distance for all tests is kept constant at 1500 m. To conduct the wear experiment, 3 levels of load and 3 levels of velocity are considered. The load range is taken to be 10 N to 30 N, and sliding velocity range is taken to be 1m/s to 3 m/s (Table 2).

Table 2. Process parameters and levels.

Parameters	Levels		
Load (N)	10	20	30
Sliding Velocity (m/s)	1	2	3
Reinforcement (wt%)	10	20	30

4. Results and Discussions

Tensile test, micro hardness test and wear test are performed and their results are summarized below.

4.1. Tensile test

It is found from Table 3, there is increase in tensile strength between alloy and 10 wt-% reinforcement composites. With further increase in wt-% of reinforcements, the tensile strength increases. This is due to increase in resistance to deformation by adding the reinforcements. The presence of hard reinforcement (Al_2O_3 and SiC) in soft aluminium matrix generates dislocations due to thermal mismatch which causes an increase in dislocation density. This increase in dislocation density contributes to an increase in tensile strength of the composites as reinforcement increases and similar trend is observed in the case of aluminium/ Al_2O_3/graphite hybrid metal matrix composites [12]. The steep increase in 30 wt-% reinforced composite is due to more dislocation density. This happens due to dispersion of Al_2O_3 and SiC particles which create hinderance to dislocation motion.

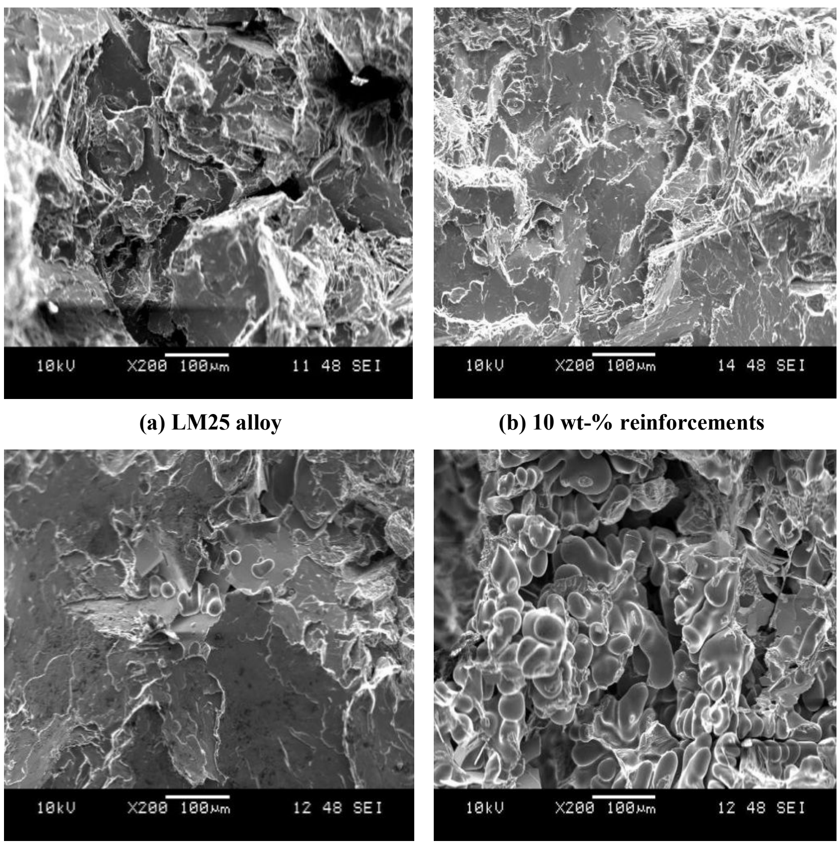
Table 3. Results of tensile test.

Composition (wt% Reinforcement)	Tensile Strength (MPa)
0	110.2
10	119.8
20	123.4
30	158.4

4.2. Fracture surface analysis

The fracture surface analyses for specimens are done and their micrographs are shown in Fig. 1.

Figure 1(a) shows the accumulation of microscopic and macroscopic voids of varying sizes and shapes randomly distributed throughout the fracture surface resulting in ductile void growth. Hybrid composite samples containing brittle reinforcements are surrounded by a relatively soft ductile matrix and hence brittle mode of failure occurred, Figs. 1(b), (c) and (d). As aluminium alloy deforms with increasing tensile load, the load is no longer transmitted effectively to the reinforcements and thus fracture surfaces shows mixed mode of failure comprising features of both brittle and ductile failure. As wt-% composition of reinforcement increases, the brittle nature of composite increases with corresponding decrease in ductile nature. This conversion is an advantage in the aspect of wear behavior. The voids which indicates the brittle nature is more in 30 wt-% reinforcements as shown in Fig. 1(d).



(a) LM25 alloy **(b) 10 wt-% reinforcements**

(c) 20 wt-% reinforcements **(d) 30 wt-% reinforcements**

Fig. 1. SEM micrographs of fracture surface.

4.3. Hardness test

Vicker's hardness values of composites are provided in Table 4. As the wt-% of reinforcement increases, there is an increase in hardness value of the material from base alloy, due to presence of Al_2O_3 and SiC. It can also be identified that Al_2O_3 and SiC particles have higher hardness than LM25 alloy. The matrix deforms plastically to accommodate the volume expansion due to incorporation of hard reinforcement particles. With increasing reinforcement content, the dislocation density increases further, causing the hardness values to increase further. Similar behavior is observed by Singla et al. [13] in the case of SiC MMCs. The improvement in the hardness of the composites with increasing reinforcement content can also be attributed to the higher hardness of Al_2O_3 and SiC particles and also due to strong interfacial bonding in between the Al alloy and SiC and Al_2O_3 interfaces.

From the results of mechanical properties, it is observed that the properties are improved for the composites than unreinforced alloy. Hence it is decided to carry out the wear test for the composite samples.

Table 4. Hardness value (HV) of material.

Composition (wt-% Reinforcement)	Vickers Hardness (HV)
0	88
10	98
20	99
30	106

4.4. Wear test

Total of 27 experiments are conducted based on Taguchi's L_{27} orthogonal array and the results are tabulated in Appendix A, Table A.1. Wear rate are in the order of 10^{-3}.

4.4.1. Effect of sliding velocity on wear rate

Figure 2 shows the effect of sliding velocity on wear rate at load of 30 N. As the velocity increases, wear rate decreases which is due to reduce in contact time between composite specimen and counter face of Pin-on-disc tribometer. This is also due to the fact that an increase in sliding velocity leads to an increase in the extent of oxidation of the aluminium alloys as interfacial temperature increases. This rise in temperature during wear is measured using a thermocouple inserted into a hole drilled in the samples. This adherent oxide layer (protective layer) prevents direct contact between the sliding interfaces, thereby decreasing the wear rate. This protective oxide layer covers the entire surface of the pin and becomes thicker as the sliding speed increases and reduces the wear rate. There is approximately 20% decrease in wear rate for 2 m/s and 50% decrease in wear rate for 3 m/s when compared with sliding velocity 1 m/s. It is also observed that wear resistance increased as wt-% of reinforcement increased and similar behaviour is observed as the wt-% of Al_2O_3 content increased in the case of aluminium/alumina/graphite hybrid composites [14].

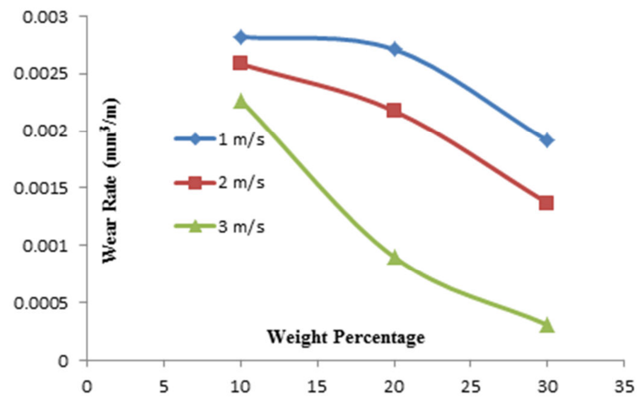


Fig. 2. Effect of sliding velocity on wear rate.

4.4.2. Effect of load on wear rate

Figure 3 shows the wear rate at various load conditions at sliding velocity of 1 m/s. As the load increases, the coefficient of friction increases and thus frictional force increases. This in turn increases the temperature of material and results in increase in wear rate. A similar behaviour has been observed by Sudarshan and Surappa [15] in the case of A356/ flyash composites. Wear rate increases 200% for load 20 N and wear rate increases 400% for load 30 N when compared with 10 N. Thus, influence of load is high on wear rate. Also, as the wt-% of reinforcement increases, the wear rate decreases. This is due to the fact that with an increase in wt-% of reinforcements, contact area of reinforcements with the steel counterface increases, thereby improving the wear resistance.

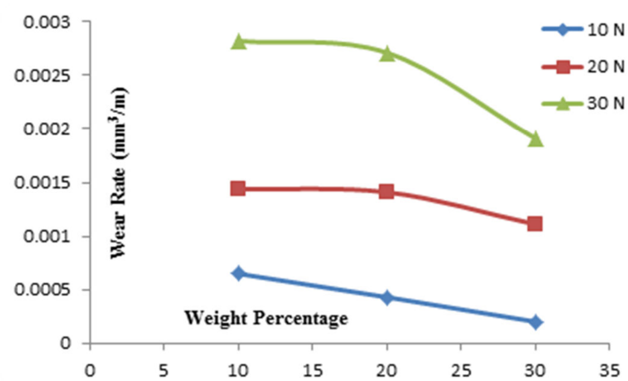
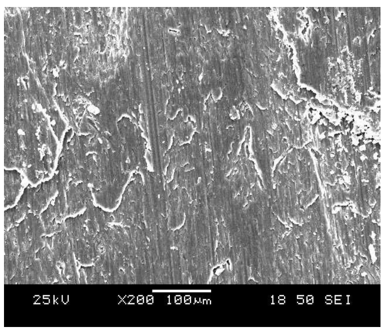


Fig. 3. Effect of load on wear rate.

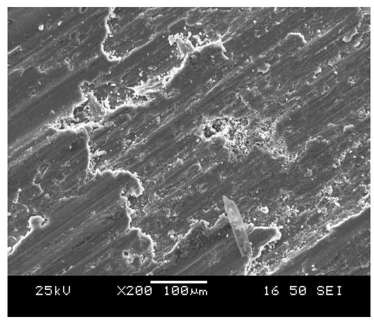
4.5. Worn–out Surface Analysis

Figure 4 shows the Scanning Electron Microscope (SEM) photographs of worn-out surfaces of composites at various load conditions. The presence of wear debris indicates the adhesive and plastic shearing of the asperities had occurred during the wear test [16]. In Al-based composites with SiC and Al_2O_3 reinforcements, the reinforcements act as abrasive against the counter face, increasing counter face wear. In addition, reinforcement liberated as wear debris acts as a third-body abrasive to both the composite and counter face surfaces.

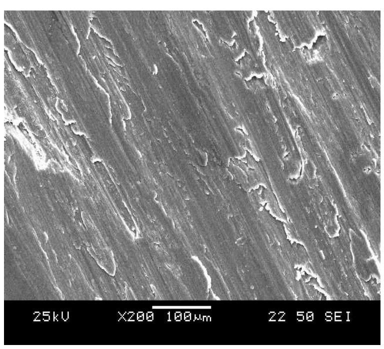
At 30 N load, degree of grooves formed at the worn surface are quite larger and undergo severe plastic deformation leading to severe wear compared to 10 N load. This can be seen by comparing SEM micrographs Figs. 4(b) and (c). At low load (10 N), the worn surfaces reveal predominantly fine and shallow grooves in the sliding direction and the extent of damage on wear surface is also relatively less, Fig. 4(b). As the load increases to 30 N, the size and amount of wear debris also increases. When the induced stress exceeds the fracture strength of the reinforcement particles, particle fracture occurs. Number of grooves as well as the extent of delamination also increases due to increase in the amount of fractured particles which abrade the soft matrix surface, Fig. 4(c). Material transfer from pin to the disc also occurs due to the abrading action of the fractured Al_2O_3 and SiC particles against steel disc. All these factors results in an increase in wear rate. Thus it can be concluded that the wear mechanism changes from abrasive wear to severe delamination wear as the load is increased.



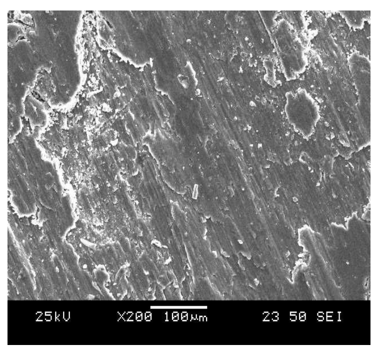
(a) L – 30 N, S – 3 m/s, R – 10 wt-%



(b) L – 10 N, S – 3 m/s, R – 30 wt-%



(c) L – 30 N, S – 3 m/s, R – 30 wt-%



(d) L – 30 N, S – 2 m/s, R – 10 wt-%

Fig. 4. SEM micrographs of worn-out surface.

The amount of grooving in the worn surfaces of the composites is reduced with increased wt-% of reinforcement indicating lower material removal. This is evident when comparing SEM micrographs Figs. 4(a) and (c). As the reinforcement of Al_2O_3 and SiC content increases, the depth and number of grooves on the surface of the pin decreases, thus increasing the wear resistance. The change in wear mechanism from severe to mild wear can also be attributed to an increase in reinforcement content. Roy et al. [17] have observed that a reduction in the severity of plastic deformation due to the incorporation of hard reinforcement (TiAl and Al_2O_3) in an aluminium matrix. It is observed that an improvement in hardness was due to incorporation of hard reinforcements, resulting in increased wear resistance.

As the speed increases, the contact time between the specimen and the counter face is very less and this results in lower material removal. This is evident by comparing SEM micrographs Figs.4(a) and (d). As the wear proceeds, a work hardened layer consisting of iron from the counterface, aluminium and aluminium oxide from the specimen is formed on the surface of the pin and thus the wear mechanism changes from delamination wear to mild oxidative wear. Deuis et al. [18] in the case of Al/SiC composites have observed that a MML was present on the worn surface of MMCs and this layer exhibited hardness approximately six times more than that of the bulk composite.

5. Conclusions

Mechanical properties and wear characteristics of LM25 alloy with SiC and Al_2O_3 is studied. It is concluded that, composites with 30 wt-% of reinforcement have higher tensile strength and hardness than LM25 base alloy. Wear rate of composites decreases with increase in wt-% of reinforcement. By increasing the applied load, wear rate increases and by increasing the sliding velocity, wear rate decreases with constant sliding distance. The amount of grooving in the worn-out surfaces of the composites is reduced with increased wt-% of reinforcement indicating lower material removal.

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Appendix A

Table A.1. Results of wear rate.

Experiment No.	Load (N)	Sliding Velocity (m/s)	Reinforcement (wt-%)	Wear Rate (mm^3/m)
1	10	1	10	0.000649
2	10	1	20	0.000430
3	10	1	30	0.000202
4	10	2	10	0.000672
5	10	2	20	0.000495
6	10	2	30	0.000407
7	10	3	10	0.000585
8	10	3	20	0.000383
9	10	3	30	0.000325
10	20	1	10	0.001439
11	20	1	20	0.001411
12	20	1	30	0.001113
13	20	2	10	0.001746
14	20	2	20	0.001664
15	20	2	30	0.000603
16	20	3	10	0.001028
17	20	3	20	0.000834
18	20	3	30	0.000450
19	30	1	10	0.002822
20	30	1	20	0.002712
21	30	1	30	0.001912
22	30	2	10	0.002587
23	30	2	20	0.002176
24	30	2	30	0.001368
25	30	3	10	0.002272
26	30	3	20	0.000900
27	30	3	30	0.000306