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Development of Aluminium Based Hybrid Metal Matrix Composites for Heavy Duty Applications

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Abstract:

The present study deals with the investigation of dry sliding wear behavior of aluminium alloy based composites, reinforced with silicon carbide particles and solid lubricants such as graphite/antimony tri sulphide (Sb_2S_3). The first one of the composites (binary) consists of Al. with 20% Silicon Carbide particles (SiCp) only. The other composite has SiCp and solid lubricants: Graphite + Sb_2S_3 (hybrid composite) at solid state. Both composites are fabricated through P/M route using "Hot powder perform forging technology". The density and hardness are measured by usual methods. The pin-on-disc dry wear tests to measure the tribological properties are conducted for one hour at different parameters namely load: 30, 50 and 80N and speed: 5, 7 and 9m/s. The tested samples are examined using scanning electron microscope (SEM) for the characterization of microstructure and tribolayer on worn surface of composites. The results reveal that wear rate of hybrid composite is lower than that of binary composite. The wear rate decreased with the increasing load and increased with increasing speed. The results of the proposed composites are compared with iron based metal matrix composites (FM01N, FM02) at corresponding values of test parameters. These iron based metal matrix composites are also fabricated by P/M route using 'Hot powder perform forging technology'. The comparative study reveals that the proposed composites have lower friction coefficient, less temperature rise and low noise level; however they have little higher wear rate. It is concluded that the hybrid composite has acceptable level of tribological characteristics with blacky and smooth worn surface.

Keywords: *Al-MMC, Powder Metallurgy, Powder Forging, Heavy Duty applications.*

1. INTRODUCTION

Discontinuous reinforced aluminum metal matrix composites (DRAMMCs) are a class of composite materials having desirable properties like low density, high specific stiffness, high specific strength, controlled co-efficient of thermal expansion, increased fatigue resistance and superior dimensional stability at elevated temperatures etc. [1, 2]. These materials have emerged as the important class of advanced materials giving engineers the opportunity to tailor the material properties according to their needs. Essentially these materials differ from the conventional engineering materials from the viewpoint of homogeneity. In composites, controlled distribution of one or more reinforcement materials in continuous metal matrix phase is possible. Large majority of these composite materials are metallic materials reinforced with high strength, high modulus and brittle ceramic phases which can be either continuous in the form of fiber, discontinuous in the form of whisker, platelets or particulate reinforcements embedded in a ductile metallic matrix. In the last two decades, wear performances of DRMMCs reinforced with various reinforcements ranging from very soft materials like graphite, talc etc., to high hardened ceramic particulates like SiCp, Al_2O_3 etc., [3–6] have been reported to be superior to their respective unreinforced alloys. A good number of studies have been done on the Al/SiCp [4–6] and Al/Graphite [3, 7] individually. Traditionally, the external lubricant plays an important role in wear behavior. Though the wear behavior of Al/SiCp is good, the addition of natural lubricant like graphite enhances the self-lubricating capacity of the composites, which is essential in some of the applications where lubrication needs to be applied periodically, especially for wear parts which are difficult to access. Solid lubricant contained in the composite can be released automatically during the wear process and reduces the wear. The incorporation of graphite alone will give the desired solutions but various researchers have identified both experimentally and mathematically that the incorporation of graphite will reduce the mechanical properties of the composites [7], which is undesirable for the component used in structural and high-elevated temperature applications. The wear behavior of Al-alloy reinforced with SiCp-Graphite particles has been documented. As a result, combination of high-hardened SiC particles and soft graphite were used in the present work to investigate the wear behavior of the Al-alloy incorporated with SiCp and graphite particles for comparison with corresponding value of iron based metal matrix composites (Fe MMCs) [8].

2. MATERIALS

2.1 Disc

EN-32 steel disc has been used as brake rotor / brake drum with hardness of 60HRC, machined from a commercial passenger car brake rotor. The inner diameter, the outer diameter and thickness are 180, 140 and 15mm respectively. The surface is machined to an average roughness value of 1.5 µm (measured by P-6 stylus profile meter) which is same as the roughness value of sliding surface of the actual commercial brake rotor. The composition of the steel disc material is shown in Table 1.

TABLE 1 Composition of EN-32 steel disc

Constituent	C	Cr	Si	Mn	P	S	Mg	Fe
Percentage	0.45	0.25	0.27	0.65	0.04	0.04	.25	Balance

2.2 Test Pins:

The chemical formulation for preparation of aluminum metal matrix composites (Al-MMCs) is shown in Table 2. The Al-MMCs were manufactured through powder metallurgy route using "Hot Powder Preform Forging Technology" developed by Lenin et. al [8]. Proposed composites were fabricated by using of Al-alloy as matrix reinforced with silicon carbide particles (size 34µm) and solid lubricants (graphite and Sb_2S_3). The composition of powders (wt %) was mixed into two stages by mechanical alloying, followed by attrition and conical ball milling for two respectively and mixture filled in designed capsule. The capsule was heated up to 450 ^{O}C and soaked for one hour in tubular furnace. At this temperature, it was forged in channel die without application of inert gas or vacuum by friction screw press of 100 ton capacity. After forging, slabs were prepared by using of machining processes. They were reheated to 530 ^{O}C in muffle furnace and repressed in hydraulic press at 20 bar. Homogenization process was done at 530 ^{O}C for six hours.

TABLE 2 Chemical formulation of Al- MMCs (by wt. %)

Samples	Nature of composite	SiC_p (34µm)	Graphite (45 µm)	Sb_2S_3	Al alloy
Al01	binary	20	--------	-------	80
Al02	hybrid	10	6	3	81

3. EXPERIMENTAL DETAILS

3.1. Determination of Density (Archimedes Principle)

The basic method of determining the density of the specimen by measuring the ratio of mass and volume was used. In this paper the density of the specimens was estimated by Archimedes' principle is shown in Table 3.

TABLE 3 Physical and Mechanical properties of Al-MMC

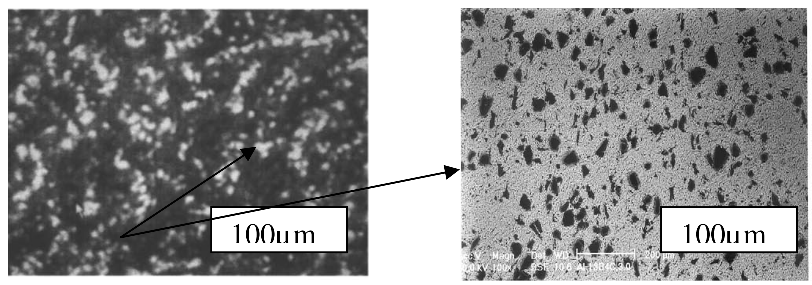
Test Pins	Density(ρ) gm/cc	Hardness (BHN)
Al01	2.80	89
Al02	2.73	83

3.2. Brinell Hardness Test

Test material was indented with a 10 mm diameter hardened steel ball subjected to a load of 15.25 kg applied for 10 to 15 seconds. The diameter of the indentation left in the test material is measured with a low powered microscope. Brinell harness number is calculated by dividing the load applied by the surface area of the indentation. The diameter of the impression is the average of two readings at right angles and the use of a Brinell hardness number table can simplify the determination of Brinell hardness structures. Brinell hardness number of test pins is shown in Table 3.

3.3. Wear Testing of the Composites

A pin-on-disc test apparatus was used to investigate the dry sliding wear characteristics of Al-MMCs (Al01 and Al02) as per ASTM G99-95 standards. The wear specimens (30x7x7mm) were machined forged slabs, and polished for metallographic examination. The tests were conducted for one hour at different loads: 30, 50 and 80N and sliding speeds: 5, 7 and 9m/s at room temperature. The initial weight of the specimen was measured in a single pan electronic weighing machine with a least count of 0.0001g. During the test the pin was pressed against the counter part rotating against EN-32 steel disc by applying the load. A strain–gauged friction-detecting arm holds and loads the pin specimen vertically into a rotating hardened steel disc. The frictional traction experienced by the pin during sliding is measured continuously by PC-based data-logging system. After running through a fixed time period, the specimen were removed, cleaned with acetone, dried and weighed to determine the weight loss due to wear. The difference in the weight measured before and after the test gives the wear of the specimen. The wear rates were determined using the weight loss method. The frictional forces are recorded by mechanical transducer/load cell. Although the frictional forces vary with sliding time, an average value for the analysis was considered. Each test was conducted for a constant load and speed for one hour and similar tests were carried out for different speeds and loads to investigate the tribological behavior. Scanning Electron micrographs (SEM) of the prepared Al-MMC samples are shown in Fig.1. The distribution of particles throughout the matrix is found to be fairly uniform for both binary and hybrid samples.



(a) (b)

Fig.1. SEM micrographs of (a) Binary and (b) Hybrid MMC.

4. RESULT AND DISCUSSIONS

4.1 Effect of Load and Sliding Speed on Wear Characteristics:

Figs. 2(a) and (b) show the variation of wear rate (weight loss/min) with varying load and sliding speed for binary and hybrid composites. A drastic increment in wear rate of binary composite was observed with load increased from 50-80N. The wear rate shows little variation with increasing sliding speed over the load range 30-50N and for higher load range 50-80N, slight reduction is observed with increased in sliding speed from 07 to 09m/s (Fig. 2 (a). For hybrid composite, it is almost stable and minimum at sliding speed 05m/s and increased with increasing of speed from 05 to 09m/s (30-50N) and decreased for 50-80N (Fig. 2(b)). It has been concluded that wear resistance is improved with incorporation of SiC-particles with solid lubricants than that of binary Al-alloy.

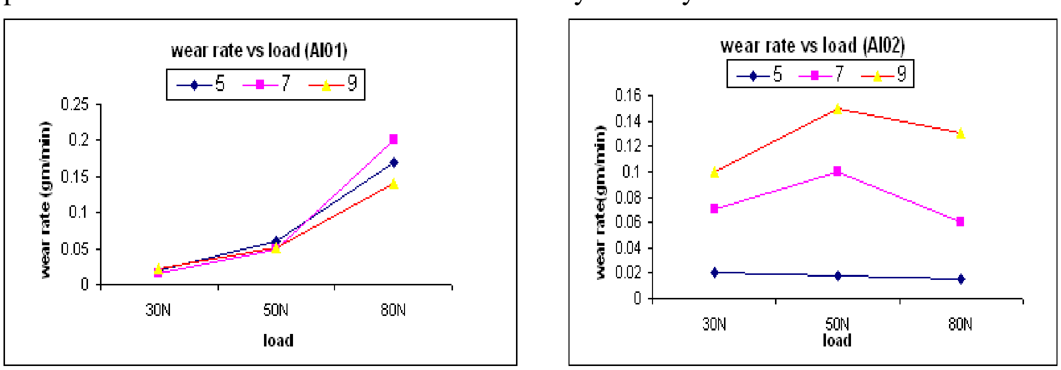


Fig. 2 Effect of load on wear rate of composites for different speeds: 05, 07 and 09m/s.

4.2 Effect of Load and Sliding Speed on Coefficient of Friction (COF):

Figs. 3(a) and (b) show the variation of coefficient of friction with varying the load and sliding speed. The COF of binary composite decreased linearly with applied load (30-80N) and speed (05-09m/s) (Fig. 3 (a)). It is observed that, the value of COF is high at low loads and tends to decease with increasing load, and nature of decline of COF with various sliding speeds is similar. For hybrid composite**,** the COF at low speed (05m/s) is higher with reduced sensitivity at lower load range (30-50N) (Fig. 3 (b)). At speed (07m/s), COF deceased with increased load from 30 to 50N and becomes stable for higher applied load range (50-80N). It is minimum at high speed (09m/s) and decreased with increased applied load from 30-80N. It has been concluded that coefficient of friction is stabilized with incorporation of solid lubricants for various sliding speeds and applied loads.

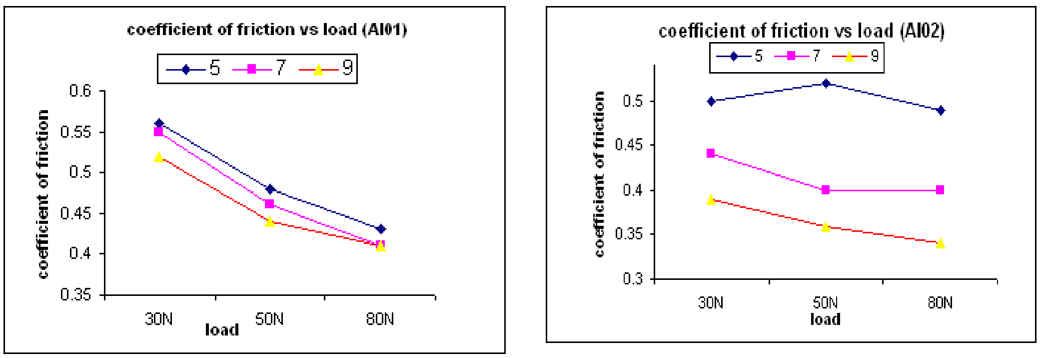
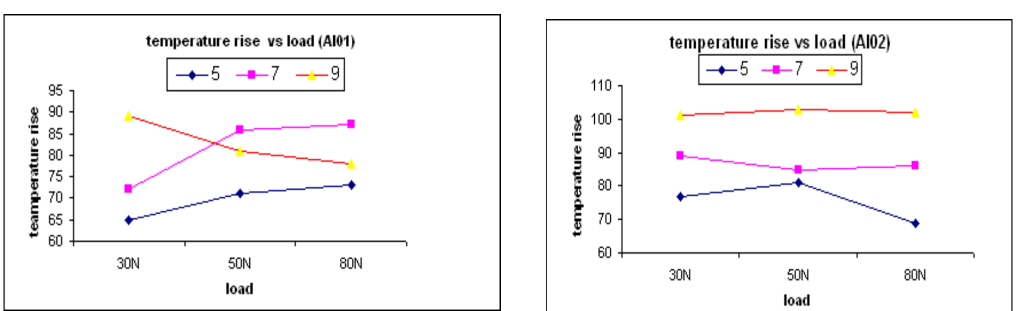


Fig. 3 Effect of load on coefficient of friction at different speeds: 05, 07 and 09m/s.

4.3 Effect of Load and Sliding Speed on Temperature Rise at Mating Surface

The temperature rise of binary composite at mating surface is increased over lower load range (30- 50N) for sliding speeds; 05 and 07m/s and decreased for sliding speed (09m/s**)** (Fig. 4(a)). Temperature rise of hybrid composite increased with sliding speed from 05m/s to 09m/s and stabilized at high speed (09m/s) for load range 30-80N (Fig. 4(b)). At speed (05m/s) it increased for load range 30-50N and decreased for load range 50-80N. It has been concluded that temperature rise for hybrid composite is more than temperature rise for binary composite.

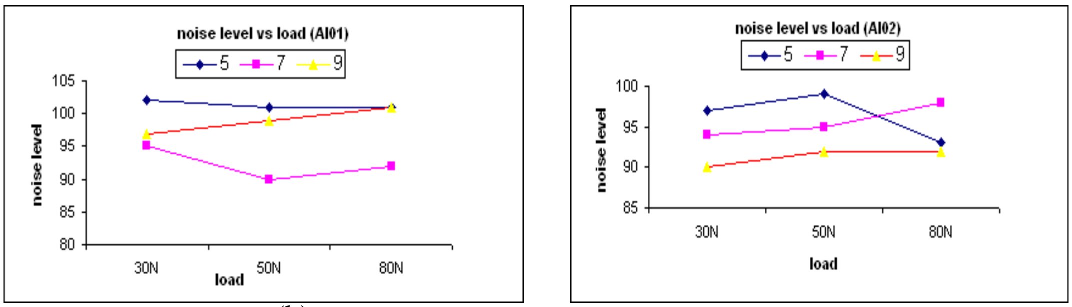


(a)

Fig. 4 Effect of load on temperature rise for different speeds: 05, 07 and 09m/s.

4.4 Effect of Load and Sliding Speed on Noise Level

From Figs. 5(a) and (b), it has been found that incorporation of complementary solid lubricants, the noise level is suppressed with reduced dampening and vibration. It is increased with load at sliding speeds; 07 and 09m/s and decreased for speed; 05m/s. It has been observed that at high sliding speed, the nose level is lower with slight variation for hybrid composites (Fig. 5(b)) than that of binary composites (Fig. 5(a)). It is concluded that solid lubricant incorporation in composites plays an important role in suppressing the noise level.



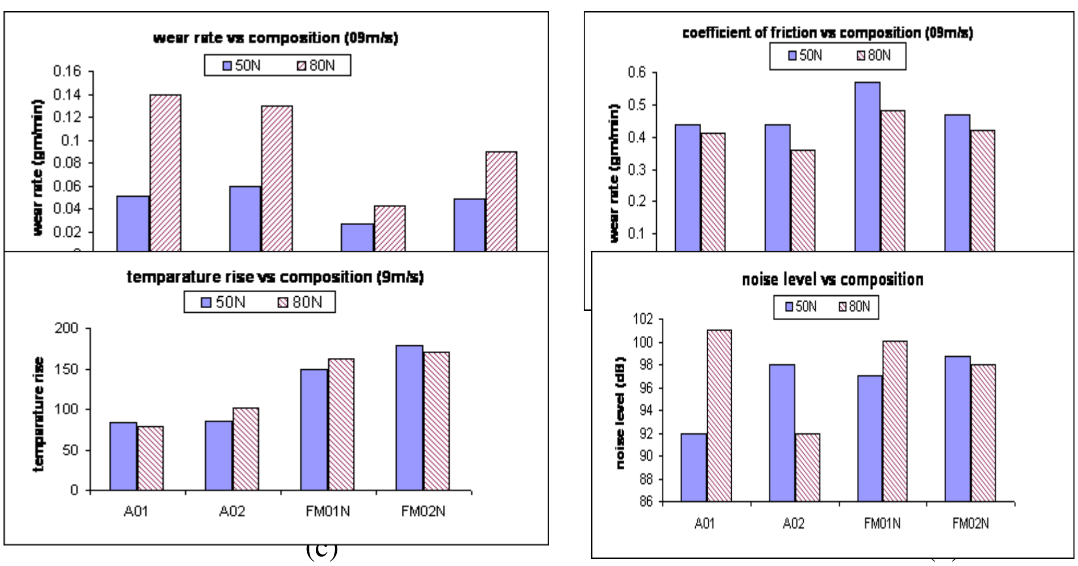
(b)

Fig. 5 Effect of load on noise level of composites for different velocities: 05, 07 and 9m/s.

4.5 Comparative Study of Al-Based Composites with Fe-Based Composites:

Wear rate, coefficient of friction, temperature rise and noise level of aluminum based composites have been compared to corresponding values of iron based composites [8] at different loads for a sliding speed; 09m/s. It has been found that the wear rate of aluminum based composites (Al01, Al02) is more than that of iron based composites (FM01N, FM02N). The variation of wear rate at high load for Al based composites is of opposite nature to the Fe-based composites Fig. 6 (a). The coefficient of friction for Al-based composites is lower than that of coefficient of friction for Fe based composites at lower as well as higher loads, but nature of variation with load is similar Fig. 6 (b). The temperature rise at mating surface is much lower in case of Al-based composites than iron based composites Fig. 6 (c). The nature of temperature rise with load is not similar for both types of composites. For composites: Al02 and FM01N, it is increased with load and decreased for composites: Al01 and FM02N. The noise level is lower for Al-based hybrid composite than that of Fe based composite at higher load. It is slightly higher for Al-based binary composite at higher load applied Fig.6 (d). It has been concluded that the proposed Al-based composites with lower wear resistance have better tribological characteristics than Fe- based composites.

It was found from Fig. 1(a), (b) that wear rate of hybrid composite during run-in period is more than that of binary composite. The asperities of both the pin and counter face which are in contact with each other are subjected to relative motion under the influence of applied load. Initially both the surfaces are associated with a large number of sharp asperities and contact between the two surfaces takes place primarily at these points. In the present case also, the asperities on the pin are having a large number of reinforcements. Under the influence of applied load and speed, the asperities in each surface come in contact with each other and they are either plastically deformed or remain in elastic contact. As the asperities are very sharp in nature, the effective stress on these sharp points may be more than the elastic stress and then all these sharp asperities are plastically deformed at their contact points except the partially projected points of the reinforcement. The plastically deformed surface will fill the valley of the material both in pin and the counter face during the course of action and there is a possibility of fracture of a few asperities on both the surfaces leading to very fine debris. The asperities of the sliding pin surface come in contact with the steel disc surface and work hardening of the matrix material takes place under the applied load and speed [9]. The SiC particles, which are very strong in compression, are pushed back in to the soft Al alloy initially instead of fracturing. During the initial run-in period in all the cases, the wear rate is more because of the fact that the few of highly projected SiC broken particles from the pin will act as debris and plough the surface particularly the Al-particles. In the resent investigation a new observation has been marked that the wear rate during the run-in period is so less and insensitive to sliding speeds. It shows the formation of strong adhesion of SiC with matrix material in binary composite than that of hybrid composite. As a result it is confirmed that incorporation of SiC and solid lubricants and applied technology play an important role to improve the wear characteristics of composites in wear dominant applications. In the case of hybrid composites the stress on the surface of the pin at high load and speed (>50N and > 05m/s) is almost uniform and contact between the pin and the counter face is intact. The initial wear is less in hybrid composites with the protecting layer, known as tribolayer, formed in SiCp composite-graphite smears and forms a protecting layer such that the wear rate is still less compared to SiCp composites. The decreasing trend of the wear rate when sliding speed is increased is due to the formation of protective oxide film [Fe_3O_4] along with the lubricating films of Graphite. At higher speed (>05m/s) due to increase in the temperature, the surface of the material becomes smooth that promotes local yielding and the wear mechanism changes from abrasion to delamination wear. Hence the graphitic composite has lesser wear rate for a particular speed and load compared to all other classes of composites under study.



Figs. 6 Comparison of proposed Al based composites with corresponding values of Fe-based composites [8] at loads: 50 and 80N for sliding speed: 09m/s.

5. CONCLUSIONS

The following conclusions can be drawn from this work.

1. Incorporation of graphite particles in the aluminium matrix as a second reinforcement. decreases the wear rates of the composite compared to SiCp reinforced composite.

2. Coefficient of friction is stabilized with incorporation of solid lubricants in composition of composite at solid state for various sliding speeds and applied loads.
3. Temperature rise for hybrid composite is more than that of temperature rise for binary composite but it is significantly lower than iron based composites.
4. Incorporating solid ingradients in aluminium powder play an important role to reduced the noise level.
5. Wear rate decreases as the sliding speed increases up to transition speed and load, due to work hardening of the surface, formation of Iron oxide, crushing of the SiC particles and smearing of Graphite.
6. Seizure occurred for wrought aluminium based alloys, but no seizure occurred for Al/ SiCp and Graphitic powder composites under the present study. Combination of abrasion, delamination and adhesive nature of wear was observed.
7. Proposed aluminium based composites with lower wear resistance have better tribologocal characteristics than iron based composites.

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