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Dry sliding behavior of aluminium alloy reinforced with hybrid ceramic particles

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Abstract
In the present work, aluminium alloy LM6 is reinforced with dual hybrid titanium dioxide and graphite particles and composites are prepared by stir casting process. Developed composites were characterized by microstructural analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS). Mechanical and tribological characterizations were carried out in terms of Vickers microhardness and dry sliding wear. Results revealed that the presence of reinforcements improves the microhardness significantly and hybrid composite containing 5% Gr + 10% TiO_2 produced highest microhardness of 164 Hv due to uniform dispersion of particles. Further, higher reinforcements led to agglomeration in matrix and cause anisotropy in composites, which lower the mechanical properties of material. Analysis of dry sliding wear tests revealed that with increase in reinforcement percentage, the wear rate linearly decrease and above 15% reinforcement levels, wear rate starts increasing. At higher loads, wear rate increased due to higher metal to metal contact but the Coefficient of Friction (COF) was decreased due to lubrication provided by graphite. Increase in sliding velocities initially decreases the wear rate, however at higher velocities wear rate increased exponentially. It was observed that the presence of graphite increases the lubrication properties whereas titanium oxide contributes to the overall improvement of mechanical strength of composites. The overall results reported enhanced strength of composites by addition of optimum reinforcements in aluminum matrix which can be utilized in many automobile applications.

Keywords: Aluminium, Hybrid Composite, Ceramic, Sliding Wear, Mechanical Properties, SEM.

1. Introduction

The applications of Aluminium Metal Matrix Composites (AMC's) has increased significantly in the recent years. This increase in AMC applications is supported by unmatched properties obtained by aluminium composites in terms of high strength to weight ratios, lower costs, higher wear and corrosion resistance, high hot hardness and higher stiffness coupled with lower weight [1-3]. AMC's are far much superior to aluminium alloys due to enhanced properties and ability to possess functional properties by variety of reinforcements. The acceptability of various ceramic reinforcements further enhances the domain of AMC composites which can be used in variety of applications including aerospace, automobile and structural applications [4-5]. Typical applications of lower density composites in aerospace and automobile applications triggered the interest of researchers in this field of AMC [6-8]. The various reinforcements added in the aluminium matrix to increase the functionality properties includes silicon carbide, graphite, zircon, fly-ash, rice husk ash, alumina, boron carbide, titanium carbide and boride, etc. [9-16]. Researchers [17-18] have studied various mechanical and tribological properties of single reinforced and hybrid reinforced aluminium metal matrix composites. However, selection of hybrid reinforcement is quite a difficult task and depends up on the properties to be enhanced. Kumar and Dhiman [19] reported that higher content of SiC reinforcement increases hardness significantly but this in turn affects the machinabilty of composites. It was reported that it is essential to maintain the advantageous influence of reinforcement on composite material. Further, various processing methods are available for processing of AMC which includes stir casting, powder metallurgy, diffusion bonding, infiltration process, chemical vapour deposition process, microwave processing [20-23] and many more. But stir casting is still one of the oldest, simple and economical processing methods for developing low melting point metal matrix composites such as aluminium and magnesium composites [24].

The work of Umanath *et al.* [25] analyzed the dry sliding wear performance of aluminium alloy reinforced with hybrid silicon carbide and alumina particles. It was reported that 15% hybrid reinforced composite shows significant improvement in wear resistance in comparison to 5% reinforced composites. The factorial technique for studying the wear behavior of hybrid aluminium composites was reported by Ravindran *et al.* [26]. It was reported that the loss of material and COF were mainly influenced by the applied normal load and sliding distance. It was reported that wear resistance of 5% SiC+5% graphite reinforced hybrid composite was superior to that of 5% SiC reinforced composites. It was concluded that addition of soft graphite with hard carbides increases the wear resistance. Niranjan and Lakshminarayanan [27] studied the wear behavior of in situ Al-TiB_2 composites and reported that wear properties of developed composites has improved significantly due to presence of fine TiB_2 particles which were uniformly dispersed in the aluminium matrix. Elango and Raghunath studied the wear properties of aluminium reinforced with hybrid SiC+TiO_2 ceramic particles. It was reported that TiO_2 reduces the wear rate and on further increasing the percentages wear rate decreases noticeably. Though lot of work is reported on TiO_2 as reinforcement for various applications including wear resistance and bio-medical applications, but very less detailed literature on the analysis on dry sliding behavior of Aluminium LM6 alloy reinforced with hybrid TiO_2+Gr particles is available.

2. Materials and method

This section focuses on the material selected for current research and various experimental details involved in the present work.

2.1 Materials

LM6 alloy of aluminium is selected as matrix material due to its wide acceptability in automobile and industrial use. The elemental composition of LM6 alloy is shown in Table 1, which shows that 89% of aluminium is present in pure form and is alloyed with silicon, iron, chromium, zinc and magnesium in lower percentages. Alloy was cleaned properly by using acetone prior to the melting.

Table 1: Elemental composition of LM6 aluminium alloy

Element	Mg	Mn	Si	Fe	Ni	Zn	Ti	Al
Wt %	0.01	0.3	10	0.4	0.05	0.08	0.02	Bal.

The reinforcements selected in the present study are titanium oxide and graphite. Fig. 1 show the morphology of powders and it is observed that TiO_2 particles are spherical whereas graphite is in flake form. These reinforcements were mixed in proper proportions to form hybrid powder of average particle size of 50 μm. The selection of these powders were carried out by proper literature survey which revealed that addition of soft reinforcement in terms of graphite can enhance the material tribological properties when mixed with harder phases such as titanium dioxide. The selection of reinforcement percentages was based on trial experiments and literature such that significant improvement in both mechanical and tribological properties can be achieved.

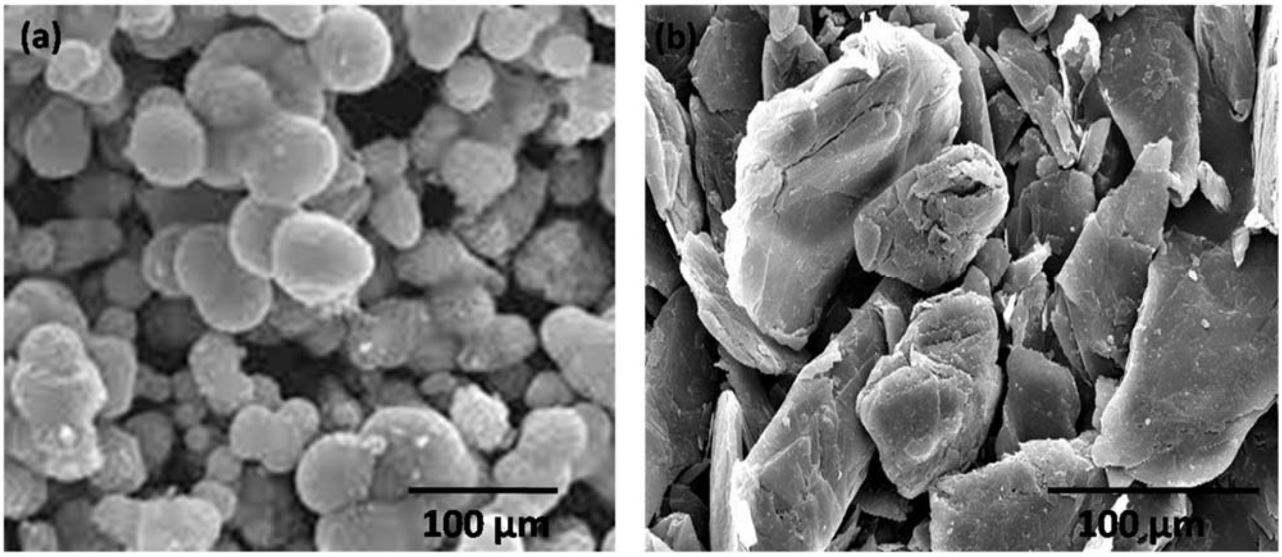

Fig 1: Typical SEM images showing the morphologies of (a) TiO_2 and (b) Graphite particles

2.2 Development of Aluminium Hybrid Composites

The aluminium hybrid composites were developed by stir casting process, which allows mixing of reinforcements manually in the molten metal. Stir casting is the oldest, economical and widely accepted casting technique [28]. The distribution of reinforcement in the aluminium matrix depends on many parameters such as stirring speed, wettability of reinforcements, cooling rate etc. In present work mechanical stirrer of graphite was used for stirring process such that vortex flow was achieved which allowed uniform mixing of reinforcement. Aluminium alloy was heated up to 850 ˚C such that alloy was melt and reinforcements were added to form molten slurry of composite. Again this slurry was heated and cooled with continuous stirring till slurry gets thicker. The different composites developed with varying reinforcements are shown in Table 2.

Table 2: Composition of various composites developed

S.No.	TiO_2 Wt%	Graphite Wt %	Total Reinforcement Wt %
1	0	0	0 (Pure LM6 Alloy)
2	5	0	5%
3	0	5	5%
4	5	5	10%
5	10	5	15%
6	15	5	20%

2.3 Characterization Techniques

The developed hybrid aluminium composites were characterized by relevant available techniques using metallurgical microscope, Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), Vickers microhardness and dry sliding behavior analysis. SEM, EDS and metallurgical microscope was used to analyze the microstructure and dispersion behavior, whereas microhardness and wear tests were carried out to study the mechanical characterizations such that effect of reinforcements on function properties can be evaluated. Table 3 presents the parameters selected for dry sliding wear behavior. All the tests were carried out at room temperature.

Table 3: Selected parameters for dry sliding wear tests

Parameters	Descriptions
ASTM standard	G99-05
Test setup	Pin on disc tribometer; Model: Tr20LE
Wear specimen	Rectangular samples of various composites (Ref. Table II) with initial roughness of 0.2μm
Counter disc	Material: EN31, Hardness: 72 HRc, Dia: 85 mm and Initial roughness 2μm
Sliding Distance (m)	2000
Sliding speed (m/s)	0.5-2.0 in steps of 0.5
Normal load (N)	1, 2, 3, 4, 5
Lubrication condition	Dry
Temperature	Room temperature (36 ˚C)

3. Results and discussion

This section represents the characterization results of hybrid aluminium composites developed with varying weight percentages of reinforcement's levels. The detailed results are as follows:

3.1 SEM/EDS Observations

The properties of any composite material depend upon the microstructures and dispersion of reinforcements in the matrix. The optical micrographs of composites containing 5% TiO_2 particles and 5% graphite particles are shown in Fig. 2 (a-b). The dispersion of reinforcements revealed uniform distribution in the LM6 matrix. The SEM image of LM6 composites containing hybrid reinforcement is shown in Fig. 3, which again revealed the uniformity in distribution behavior. At higher reinforcement levels, the agglomeration of TiO_2 particles was observed as shown in Fig. 4. This agglomeration of reinforcements can produce highly anisotropic behavior of the composite materials, which further tends to decrease the properties. The elemental distributions in the aluminium matrix were evaluated by Energy Dispersive X-Ray Spectroscopy and results of EDS analysis of composite containing 10% TiO_2 + 5% Gr are shown in Fig. 5.

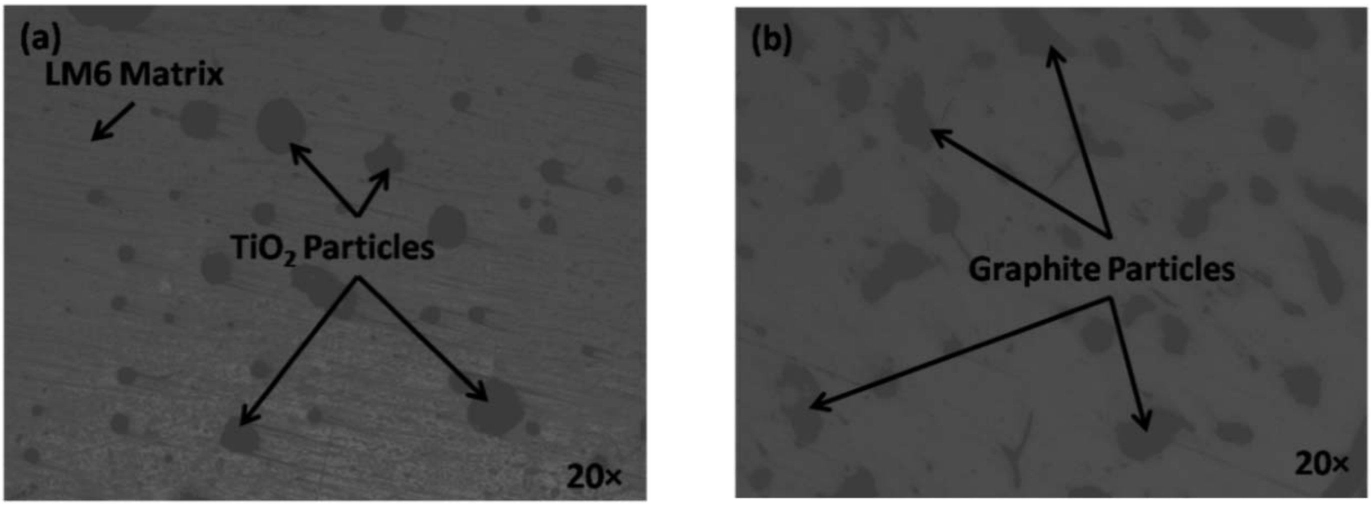

Fig 2: Optical micrographs showing the dispersion of (a) 5% TiO_2 and (b) 5% Graphite particles at 20 x magnifications

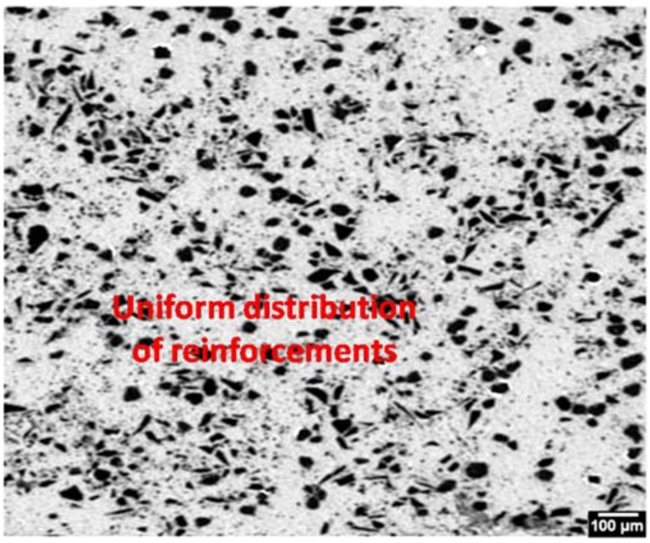

Fig 3: BEI SEM images showing hybrid composites with 15% (10%TiO_2+5%Gr) reinforcements

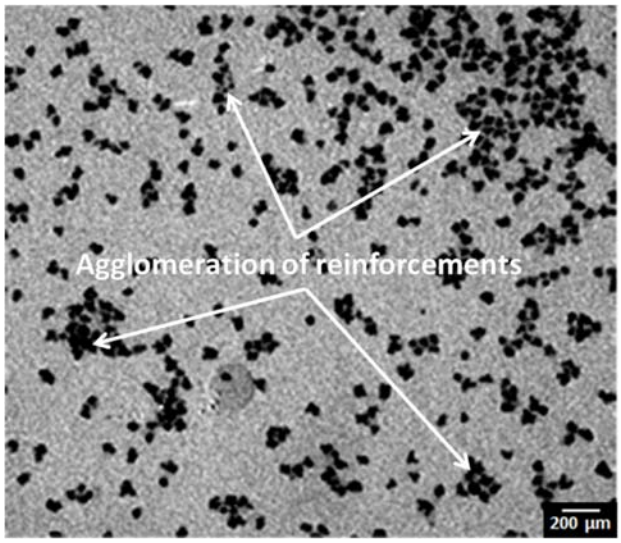

Fig 4: Typical SEM image showing agglomeration of particles at 20% hybrid reinforcement level

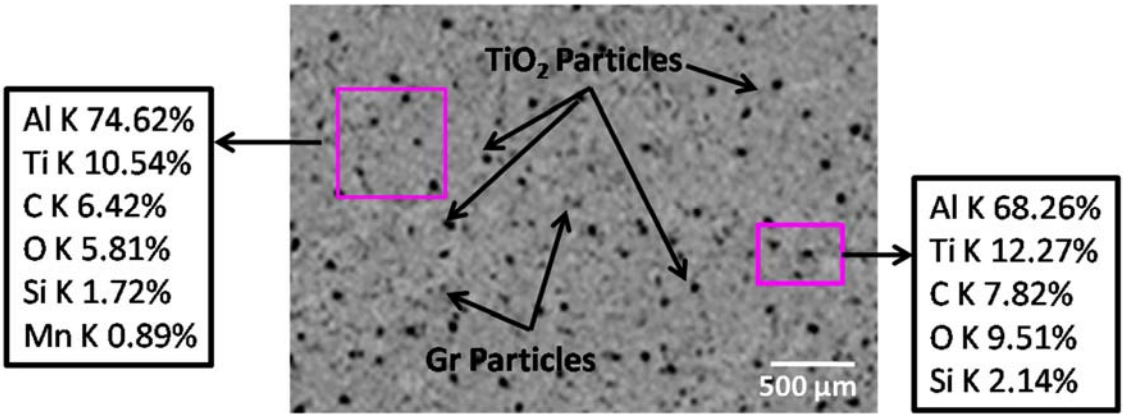

Fig 5: EDS analysis of 10%TiO_2+5%Gr hybrid composite

Results revealed that at various positions of composite aluminium was the main element followed by titanium, oxygen, carbon (due to presence of graphite), iron and magnesium. Presence of oxygen is due to the titanium dioxide reinforcement. The interface between the TiO_2 and aluminum matrix is shown in Fig. 6, which shows crack free interface without the presence of any pores and defects. Defects in the interfaces tend to lower the mechanical properties and hence it is one of the main parameters that affect the composite performance under loading.

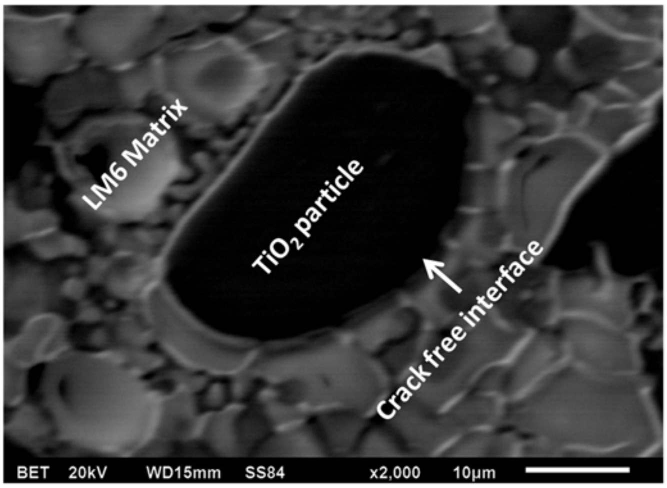

Fig 6: SEM image at higher magnification showing the interface between TiO_2 particle and LM6 matrix

3.2 Microhardness Studies

The hardness of any material directly influences the wear resistance properties. In the present study trial experiments were first conducted to check the influence of reinforcements on microhardness. Vickers microhardness tests were carried out at 100 gram load with dwell of 20 seconds. The results of Vickers microhardness are shown in Table 4, which revealed that the presence of TiO_2 particles significantly improves hardness in comparison to graphite.

Table 4: Results of Vickers microhardness of LM6 alloy and developed composites

S.No.	TiO_2 Wt%	Graphite Wt %	Vickers Microhardness (Hv)
1	0	0	78.2±8 (Pure LM6 Alloy)
2	5	0	112±18
3	0	5	96±10
4	5	5	138±25
5	10	5	164±28
6	15	5	138.4±45

Further, the influence of varying weight percentages of reinforcements is shown in Fig. 6, which show that hardness increases linearly with increase in TiO_2 weight percentage. It was found that at higher reinforcement levels, the variation in microhardness occurred which may be due to the agglomeration of reinforcements in matrix phase.

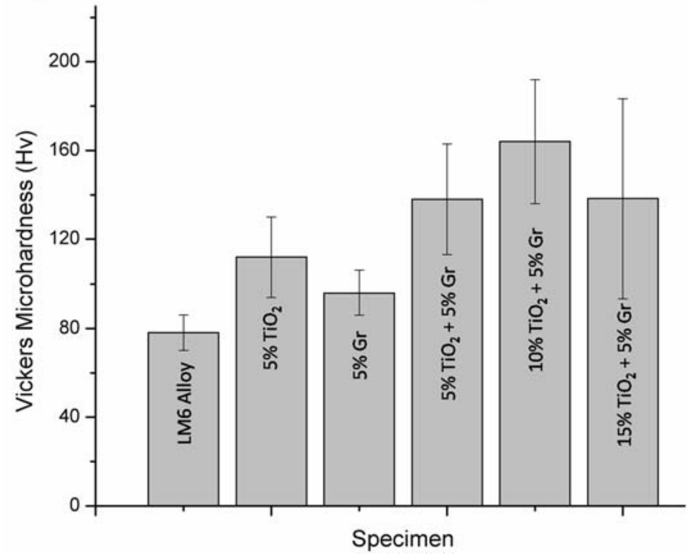

Fig 6: Effect of reinforcement weight % on Vickers microhardness of developed composites

This aggregation of particles causes differential hardened phases and hence causes higher variations. It can be clearly seen that the highest microhardness of 164±28 Hv is shown by the composite containing 10% TiO_2 + 5% Gr reinforcement. In comparison to the base alloy, the reinforced composite containing 10% TiO_2 + 5% Gr shows 109.7% higher microhardness. Further, to study the effect of microhardness on tribological properties, dry sliding wear tests were performed and results are reported in the next section.

3.3. Dry Sliding Behavior of Composites

The parameters selected for studying the dry sliding behavior of developed composites are shown in Table 3, which shows that sliding distance, normal load and sliding velocities are varied at various levels. The output responses selected for dry sliding tests are wear rate and coefficient of friction.

3.3.1 Effect of Parameters on Wear Rate

Wear represents the material loss behavior of materials under sliding/rolling conditions and allows designers to study the interaction of materials under direct contact. It is one of the main parameters for development of parts having relative motion between them i.e. either sliding or rolling. If excessive losses of materials exist, then materials are said to have low wear resistance properties. A lot of research is going in this field such that high wear resistance materials are produced for applications in the field of surface engineering. The specimens prepared for dry sliding wear tests are shown in Fig 7, which are cylindrical pins in shape; having dimensions of Ø5×25 mm.

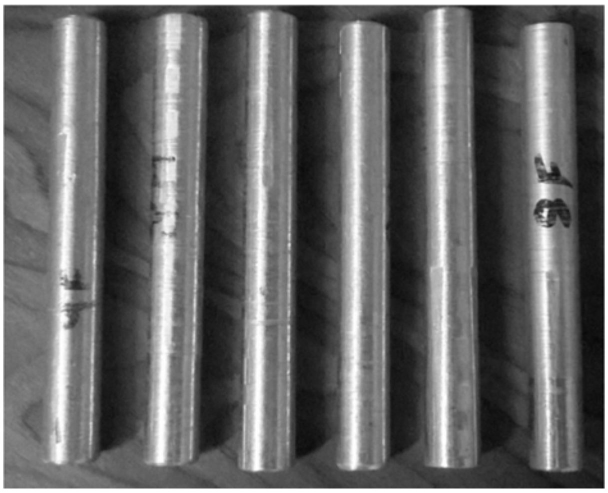

Fig 7: Cylindrical specimens prepared for dry sliding wear behavior

In the present work, specimens were slide dry against the hard counter face at various loading conditions. The results of wear rate at various loading conditions are shown in Figure 8. Results revealed that the wear rate of the aluminium alloy increased linearly with increasing the load and show less resistance to the wear.

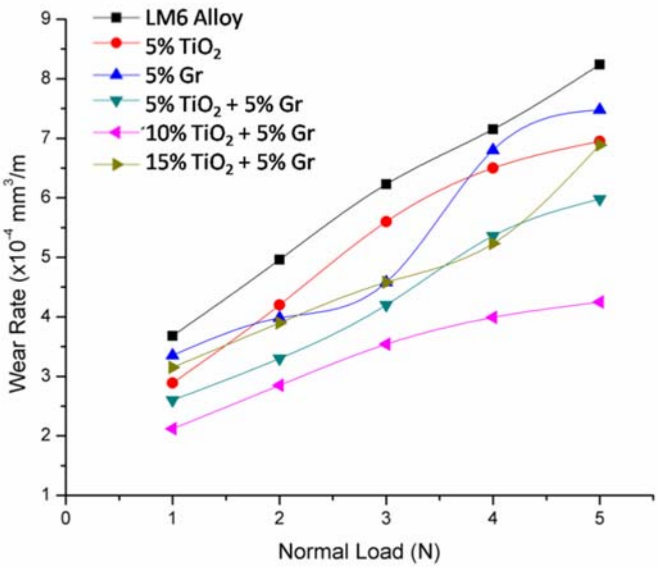

Fig 8: Results of wear rate of various specimens

This increase in wear with increasing the normal load is due to the increased friction between the mating surfaces. At higher loads, due to increased friction more heat is generated which causes localized welding and hence causes shearing of welded interfaces. The best resistance to the wear was shown by aluminium composite containing 10%TiO_2 + 5% graphite. This is due to the fact that highest hardness was observed in this composite which is directly related to the lower loss of material. For 5% Gr reinforced composite, wear rate increases up to 2N then decreases till 3N of load and again increases sharply. This is due to the lubrication property of graphite which lowers the wear rate, however at higher loading; this property is suppressed by smearing of tribo layers formed during sliding and causes metal to metal contact. Further, due to the strain hardening of wear out debris increases the hardness and causes three body wear phenomenon. This phenomenon result into higher wear rate at higher load. The wear behavior of highly reinforced composite was lower than the LM6 alloy, which may be due to the presence of hard and soft spots in the matrix. It was observed that agglomerated particles were subsequently removed from the surface at higher loads and deep craters were observed on the surface. This shows sudden increase in wear rate at 4N load. Further, grayish layer was observed in some samples. This layer is considered as tribolayer, which is formed by the presence of graphite in the composites. Graphite layers were formed during sliding under loading and moisture from the surroundings provides the lubricating properties. No tribolayer was present on the aluminium alloy surface; however uniform tribo layer was formed for 15% reinforced composite, which reduces the wear of composite. Other composites specimens revealed non uniform tribolayer due to differential hardening, which causes smearing of layers due to hard spots. Fig. 9 shows the optical micrographs showing the formation of uniform tribolayer and smearing of tribolayer at higher load.

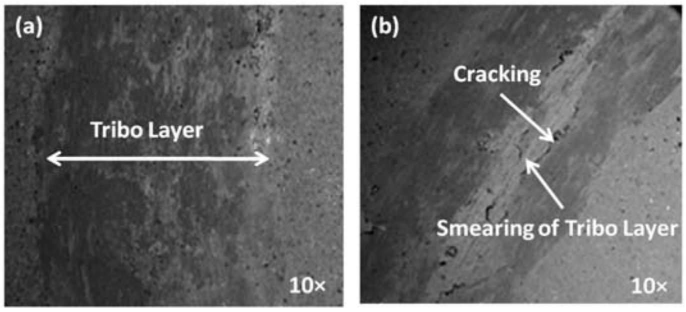

Fig 9: (a) Formation of tribo layer at 3N load and (b) smearing of tribo layer at 5N load

3.3.2 Effect of Parameters on Friction Behavior

The effect of normal load on the variation of the Coefficient of Friction (COF) is shown in Fig. 10. It is observed that initially COF is higher in the initial stages due to interlocking of surfaces and higher frictional force required to slide the surface over one another.

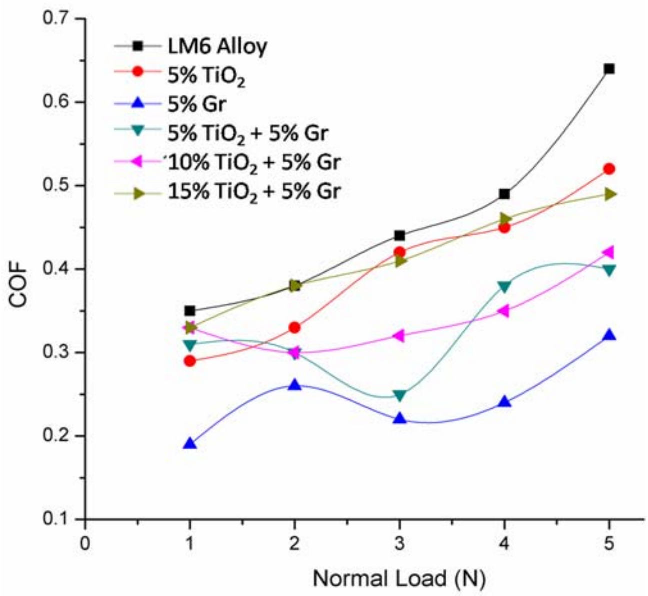

Fig 10: Variation of COF with respect to normal load applied

With an increase in the normal load, the COF increases in linear trend for LM6 alloy except for specimens containing graphite. The curve flattens and lowers on further increasing the load due to the steady state gained and the lubrication provided by graphite tribo layer. This transition of COF curve is due to the shift of metal to metal contact towards tribo contact. It is observed that composite containing 5% graphite shows the lowest COF even less than 0.18. The aluminium alloy shows higher COF due to the absence of tribo layer formation and increased metal to metal contact. Further, higher reinforced composites at higher loads causes smearing of non-uniform tribo layer and causes more metal to metal contact and increases COF. The variation of COF with an increase in sliding speeds is shown in Fig. 11.

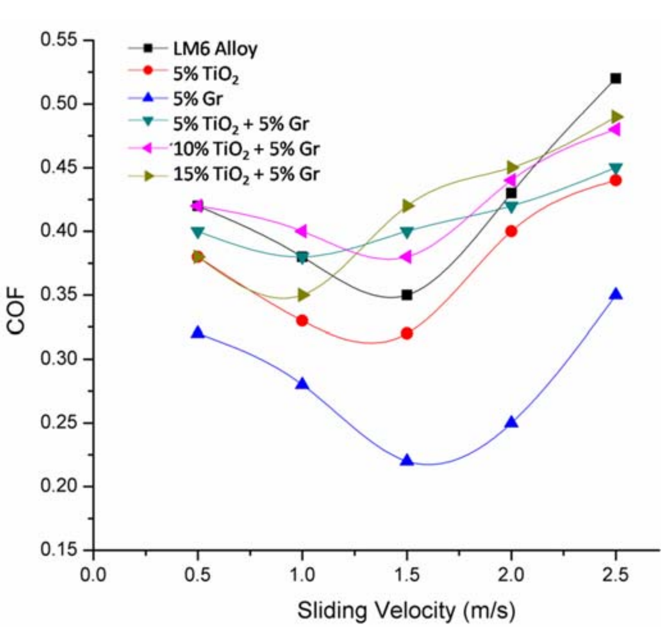

Fig 11: Effect of sliding velocity on COF

It was observed that at lower sliding speeds, the COF is higher, which further reduces on increasing sliding speeds and at higher sliding speeds COF starts increasing. This behavior is due to the fact that at lower sliding speeds, higher amount of heat is generated at particular area due to higher contact time. This causes localized welding of projected surfaces and increases COF. On increasing the sliding speeds, the graphite gets adsorbed on the counter disc and allows the formation of tribo layer. Moreover, at moderate sliding speeds the contact time reduces and there exist a balance between the heat generated and the heat dissipated, which lowers the COF. However, at higher speeds the heat generation increases due to accumulation of heat and causes the smearing of tribo layers. Composite with 5% graphite shows lower COF and highly reinforced composite shows higher COF due to higher heat accumulation and three body abrasive wear. Due to the agglomeration of reinforced particles in the matrix causes dislocations and particles causes higher wear which smears the tribo layers to increase the COF.

3.4 Wear Mechanism

The worn out samples after wear tests were studied using SEM to find out the modes of wear and mechanisms involved in the wear. Fig. 12 shows the SEM image of worn aluminium alloy and 15% reinforced aluminum.

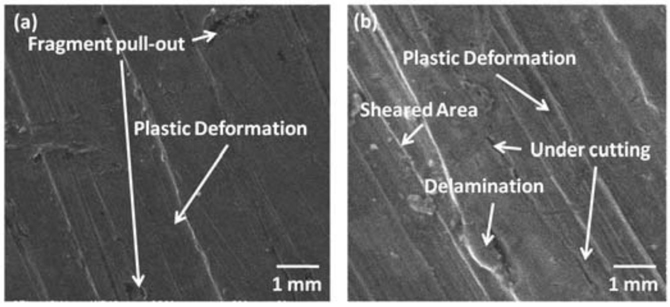

Fig 12: SEM images of (a) 15% reinforced composite and (b) LM6 aluminium alloy

SEM micrographs shows that lower debris were produce by the composite surface and few dislocations and delaminations were observed owing to higher hardness and lubrication provided by graphite. This produced finer surface of composite after sliding wear tests whereas, the surface of aluminium alloy shows the mixed mode of wear phenomena's involving delamination, plastic deformation of surface, cracking, ploughing and micro cutting. Due to lower hardness and absence of tribo layer in aluminium alloy, metal to metal contact occurred and caused higher abrasion and wear due to localized welding of surfaces.

4. Conclusions

The present work was based on the development of HAMCs with the additions of different reinforcements in terms of varying weight percentages of titanium dioxide and graphite. Developed composites were characterized by microstructural analysis, mechanical testing in terms of microhardness and study of dry sliding behavior. Following points can be concluded from the work carried out:

- The microstructural analysis revealed that uniform distributions of reinforcements were observed up to 15% of reinforcements (10% TiO_2+5% Graphite). The SEM images revealed quality interface was observed between reinforced particles and aluminium matrix.
- At higher reinforcement levels, agglomeration was observed in the matrix which is due to the increased particle-particle interactions.
- The Vickers microhardness tests revealed that composite with 10%TiO_2 +5%Gr shows highest microhardness value of 164±28 Hv, which is ~1.09 times better than base alloy. Highly reinforced composites shows higher variations due to the agglomeration of particles and the average value was lower than the 15% reinforced composite.
- Tribological studies revealed that hardest composite revealed least wear and the presence of appropriate amount of graphite (5%) leads to uniform tribo layer. At higher loads and higher sliding velocity, the formed layer gets smeared; resulting in increased COF and wear rate of composites.
- Increase in normal load increases the wear rate linearly of base alloy, whereas developed composites shows resistance to wear. Significant improvement in wear rate was observed in 15% reinforced composite. Presence of graphite tribo layer reduces the metal contact and lower valued of COF was observed due to lubrication provided by graphite.
- Overall results indicate the significant improvement in microhardness and wear resistance of LM6 alloy with the addition of hybrid reinforcements.

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