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INVESTIGATION OF TRIBOLOGICAL BEHAVIOR AND ITS RELATION WITH PROCESSING AND MICROSTRUCTURES OF AL6061 METAL MATRIX COMPOSITES

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ABSTRACT

The present study deals with the investigation of wear behaviour of Al6061MMCs and its relation with Processing & microstructure. Al 6061 MMC composite containing different weight percentages of A l2O3 & keeping 2 weight % graphite constant have been fabricated using a Vortex method (stir casting method). A pin-on-disc wear testing tribometer was used to carry out the dry sliding wear tests on both Aluminum 6061 alloy composites and Aluminium 6061 monolithic alloy over a load range of 10-50N and sliding velocity of 1.88–5.65 m/s for various sliding distances of 1-3km. The SEM micrographs taken for the micro structure analysis of the reinforced composite specimens produced by casting show that the graphite and Al_2O_3 particulates are uniformly distributed in the matrix. The SEM of wear surfaces showed that the large grooved regions and cavities with Al2O3 particles were found on the worn surface of the composite.

Also worn surface of the Al 6061composite is rougher than unreinforced Al6061 alloy, this indicates an abrasive wear mechanism results due to presence of Al_2O_3. Further, it was understood from the experimentation that the wear rate and coefficient of friction decreased linearly with increasing weight percentage of Al_2O_3. The wear rate increase as the sliding speed increases. The best results of minimum wear have been obtained at 8% weight fraction of Al_2O3

KEYWORDS: Aluminium 6061 Alloy MMC, Vortex Method, Dry Sliding, Friction, Wear

INTRODUCTION

Aluminium alloys is an important material for tribological applications due to it slow density, good capability to be strengthened by precipitation, good corrosion resistance and high thermal and electrical conductivity improved are usually reinforced by Al2O3, Sic, C,SiO2, B, BN, B4C. Therefore, the investigation of tribological behaviour of aluminum based materials is becoming increasingly important. Aluminum is the most popular matrix for the metal matrix composites (MMCs). In the present investigation, aluminum alloy 6061 was used as the matrix material. Aluminum 6061 alloy has the highest strength and ductility of the aluminum alloys with excellent machinability and good bearing and wear properties. Hartaj Singh et al have suggested various techniques for the development of Metal matrix Composites by reinforcing ceramic particulates as well as fibers.[1]

Vencl et al [2] experimented tribological tests results of Al-Si alloyA356 (EN-Al Si7Mg0.3), with and without 3 wt. % Al_2O_3 reinforcement. The reinforcement was in the shape of particles with 12 μm in diameter and the technology for producing of composite was compo casting Improvement of wear resistance for the composite material with 3 wt. % Al_2O_3 reinforcement was Significant for specific load up to 1 MPa. Sajjadi et al [5] and Muhammad Hayat Jotkho et al [4] have made an attempt to comparing mechanical properties of alloys contains less percentage of " Al2O3" as compared with alloy which contain the higher percentage " Al_2O_3" which shows some higher strength and ductility. The high percentage of " Al2O3" up to 15% in alloys decreases the tensile strength. The decrease in strength of alloys is due to increase the higher percentage of “Al2O3" in alloys. Micro structural characterization was investigated by optical (OP) and scanning electron microscopy (SEM). The aluminium alloy hard particle composite can successfully be synthesized by solidification process (stir casting or vortex technique). Aluminium composite so developed exhibit uniform distribution of the particle in the matrix and good interface bonding between the ceramic phase and the metallic matrix. The investigation reveals the. Both the composites fabricated with liquid metallurgy route. The structure and the properties of these composites are controlled by the type and size of the reinforcement and also the nature of bonding [28].

Das et al [3] Basavarajappa and Chandramohan et al [5] have demonstrated dry sliding wear behaviour, aluminum alloy reinforced with reinforced with SiCp-Graphite. The un-lubricated pins on disc wear test were conducted, to examine the wear behaviour of aluminum alloy and its composites. They reported that wear rate of graphite composites is lower than that of matrix alloy and SiCp reinforced composite.

Sharama et al [8] have studied liquid metallurgical technique. A pin on disc wear testing machine was used to carry out the tribological tests on both composites and matrix alloy over a load range of 10–50N and sliding velocities of 1.25–3.05 m/s for various sliding distances of 0.5–3 km.The wear resistances of Al6061 matrix, garnet particulate reinforced composites are superior to that of unreinforced matrix alloy. Hosking et al [10] reported an increase in the dry sliding wear resistance of 2014Al- Al2O3 with increasing weight percent and size of non-metallic particles.

Suresh et al [15] have observed that one of the important limitations in fabrication of aluminum matrix composites is the compatibility of reinforcement in the matrix. This is of prime importance in case of Al composites; as Al is covered with a thin layer of ox-ide which blocks the surface wetting and reacts with some ceramics to form inter metallic phases which tend to influence the final properties of composites. The tribological behaviour of self-lubricated aluminium/SiC/graphite hybrid composites with various amount of graphite addition synthesized by the semi-solid powder densification method [27]In the case of particle-filled MMCs, the mechanical properties are not significantly altered, but tribological properties show marked improvements. Soft solid lubricant particles such as graphite and mica improve antiseizing properties of A1alloys whereas hard particles like SiC, alumina, WC, TiC, zircon, silica, and boron Carbide greatly improves the resistance to abrasion of A1.alloys. [31]

MATERIAL AND EXPERIMENTAL PROCEDURE

Matrix and Reinforcement Materials Details

In the present investigation, Al 6061 alloy was chosen as the base matrix since its properties can be tailored through the coating process. The matrix Al6061 alloys were procured from Fen fee Metallurgical, Bangalore in the form of ingots. The reinforcing materials selected were alumina (Al_2O_3) & Graphite (Gr). To compensate the reduction in mechanical properties, primary reinforcement of alumina, average size of 25 microns in particulate form was chosen with varying its weight % from 2%,4%,6% & 8%. Alumina being hard and brittle in nature gets accommodated in soft ductile aluminum base matrix, enhancing the overall stiffness and strength. The graphite (2%), average size of 25 microns was chosen as the secondary reinforcement. There are sufficient literatures elucidating the improvement in wear properties through the addition of graphite. However there is also a decline in mechanical properties due to inclusion of graphite above 5 % [30]. The Chemical composition & reinforcement materials used are presented in Table 1 & 2.

Table 1: Chemical Composition of Aluminum 6061

Weight (%)	Mg	Si	Fe	Cu	Ti	Cr	Zn	Mn	Al
Al6061	0.8-1.2	0.40-0.80	0.70 max	0.15 -0.4	0.15 max	0.04-0.35	0.25 max	0.15	Bal

Table 2: Properties of Matrix and Reinforcement

Material	Elastic Modulus (Gpa)	Density (g/cc)	Hardness (HV)	Tensile Strength (Mpa)
Al6061	70-80	2.7	107	310
Gr	627	2.09	40	371
A l2O3	300	3.69	107	200-250

Fabrication of Al 6061 Metal Matrix Composite by Vortex Method

The liquid metallurgy technique was used to fabricate the composite specimens because it is the most economical route to obtain composites with discontinuous fibers or particulates. Wahab et al [11] enumerated that a stir casting process was successfully utilized for casting Al-Si matrix composites reinforced with AlN particles. The distribution of aluminum nitride particles surrounding Si phase has improved the hardness of the composites. Lackporosity exhibited in the microstructure of Al-Si matrix composite indicates there is a rather good particulate-matrix interface bonding. In-situ Al2O3 SiC, C having 20 wt%, 25 wt%, 30 wt% and 35wt% of powdered particulate were fabricated by liquid metallurgy (stir cast) method. Significant improvement in uniform distribution of particulates is noticeable as the wt % of the flake particles increases. [28]

Vortex method as shown in Figure.1. This approach involves mechanical mixing of the preheated reinforcement particulate containing Al2O3 & graphite into a molten metal bath and transferred the mixture directly to a shaped mould prior to complete solidification. This process has major advantage that the production costs of MMCs are very low. In this study, aluminium alloy 6061 with the theoretical density of 2.8g/cm3 was used as the matrix material while Al2O3 (alumina) & graphite particles with an average particle size of 25µ, and a density of 3.97 & 2.2 g/ cm3 respectively were used as reinforcement. 1.95 Kg calculated weight of Al 6061 ingot alloy is taken in the crucible and placed inside the induction furnace and the temperature is set up to 7500C. Alumina & Graphite particles were preheated at 4000C respectively and added to the melt through the vortex. The metals will melts at a temperature 650-6750C and automatic stirring was carried out for about 10 min at stirring speed of 300–350 rpm in order to create the necessary vortex. Mechanical stainless steel stirrer coated with aluminite (to prevent migration of ferrous ions from the stirrer material into the aluminum alloy melt). The graphite& alumina particles were added and the melt was thoroughly stirred and subsequently degassed by passing hexachloroethane (C2Cl6) solid degasser & the flux is removed manually. The Aluminum Metal matrix 6061 composite material is ready for further experimentation.

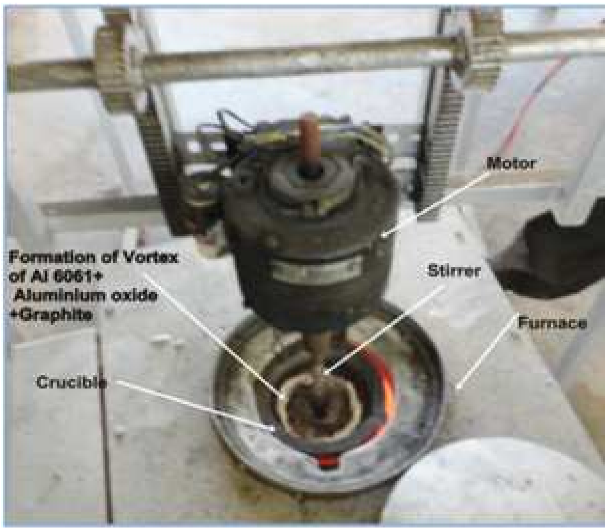


Figure 1: Al 6061 MMCs Casting Route by Stir Casting Method

Wear Test Eexperimental Set up and Procedure

Figure 2: A Photograph View of the Pin-on-Disk Type Wear Testing Machine

A pin-on-disc wear testing tribometer of Ducon make was used to investigate the dry sliding wear behavior of the Al 6061 MMC composite specimens. Dry sliding wear tests were conducted as per ASTM G99 standards. Wear specimen of 8 mm diameter and 30 mm length were machined from cast samples and then polished metallographically. 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 counterpart rotating against EN-32 (Hardness 65 HRC) steel disc by applying the load at room temperature as shown in figure-5 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 wear testing machine was microprocessor controlled, in which height loss and frictional force can be monitored simultaneously by a PC-based data logging system. The height loss data was converted into volumetric loss by multiplying it with area of cross section of the test pin. The wear rate was calculated by dividing volumetric loss with sliding distance.

Wear test was carried out for followings scenarios

- Five different applied loads of 10N, 20N, 30N, 40N & 50N for a total sliding distance of 2000m at a constant sliding speed of 3.76 m/s.
- Five different sliding velocities of 1.88 m/sec, 2.82 m/sec, 3.76 m/sec, 4.71 m/sec & 5.65 2 m/sec, against normal loads of 30 N for constant 2000m sliding distance

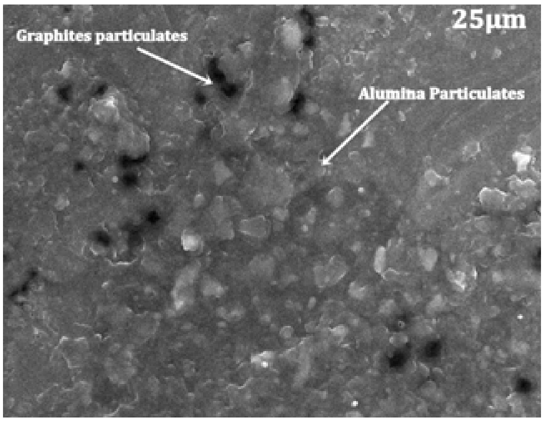
Five different sliding of 1000m, 1500m,2000m,2500m & 3000m a at constant sliding velocity 3.74 m/sec & 30 N load

RESULTS AND DISCUSSIONS

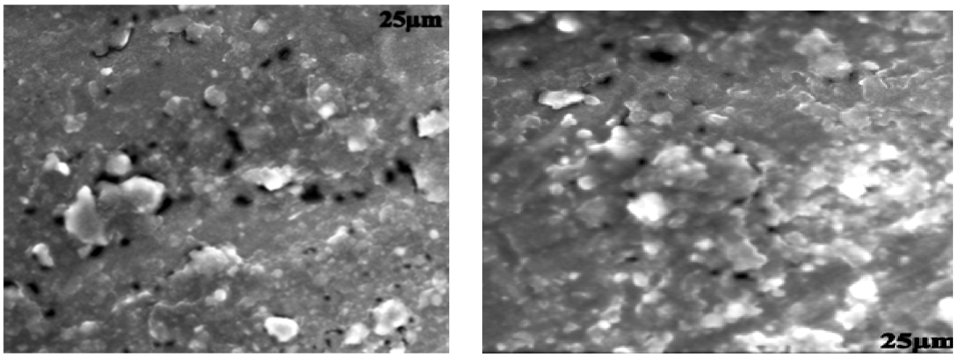
Microstructure Studies

After the Aluminum alloy 606/Gr/ Al2O3 fabricated by stir casting, the SEM micrographs were taken at IIT Bombay Al6061 alloy, Al6061 Metal matrix alloy composites shown in figure-3 reveal that there is fairly uniform distribution of Al2O3 & graphite particulates throughout the matrix alloy and good interface bonding between reinforcements& base metal. It is reported that higher hardness is always associated with lower porosity of the MMCs.

Also, it can be observed that there is good bonding between the matrix and the reinforcement particulates resulting in better load transfer from the matrix to reinforcement materials. The Particle clustering and agglomerations of porosity were observed in cast Aluminum composite 6061 -8% Al2O3



a) Al 6061 -2% Graphite-2% Al_2O_3



b) c): Al 6061 -2% Graphite-8% Al_2O_3

Figure 3: Microstructure Showing Good Interfacial Bonding between Al6061-Gr- Al_2O_3

Tribological Behavior of Aluminum 6061 Metal Matrix Composite

Numerous authors have investigated tribological properties of Al-based composite materials and have analyzed the influence of the type and properties of materials was analysed. Aluminium and its alloys: Al- Cu, Al-Si, Al-Mg-Si and Al-Zn were mostly used as the matrix, and SiC and Al2O3 of different size and volume fraction were mostly used as the reinforcements. Influence of additives (graphite) and surface roughness was analysed as well. [23].

Effect of Applied Load on Wear Rate

Applied load affects the wear rate of alloy and composites significantly and is the most dominating factor controlling the wear behaviour At constant speed, the wear rate of the Al 6061 composites and the matrix increases with increase in load. Similar observations were reported in the Influence of Particle Size on Dry Sliding Friction and Wear Behavior of Fly Ash Particle – Reinforced A 380 Al Matrix Composites [21]. The results indicate that the volume Content of particulates Al_2O_3 reinforcement has a marked effect on the wear rate. The wear rate of the composite specimens decrease with increasing weight percentage of Al_2O_3 particulate reinforcement. Similar to the results were observed by Amro and. AI-Qutub et al [6] expected, the wear rate of a Al 6061 Metal matrix composite specimen with a fixed eight percentage of reinforcement increases with Increasing applied load as shown in Figure-4.Adhesive wear was a predominant mechanism of wear followed by plastic deformation with increase of specific load [2].

The oxides formed during sliding wear at a high load were fractured and comminute as sliding continued. Participating in the mechanical mixing process, the crushed oxides dispersed into the mixed surface layer, and acted as pinning points for grain boundaries in the ultrafine mixture in the wear debris and in the MML.[29] The present investigation have also shown that with an increase in the load, iron and aluminum oxides coexisted with the intermetallic phases. The wear rates were mild at low loads and increased gradually until the material experienced a transition from mild to severe wear as indicated by the sharp increase in the slope of the wear rate versus load curve. The severe wear manifested itself by massive surface damage and large scale aluminum transfer to the counterface accompanied by the generation of coarse debris particles, typically in the shape of plates with a shiny metallic appearance. These features were readily identifiable during the test by the naked eye [34]

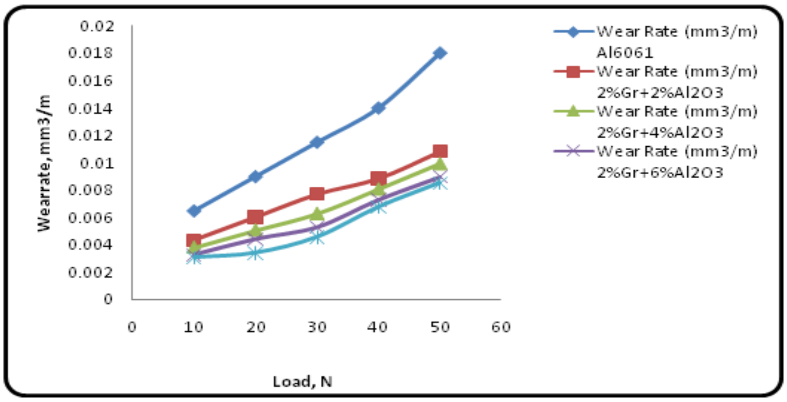


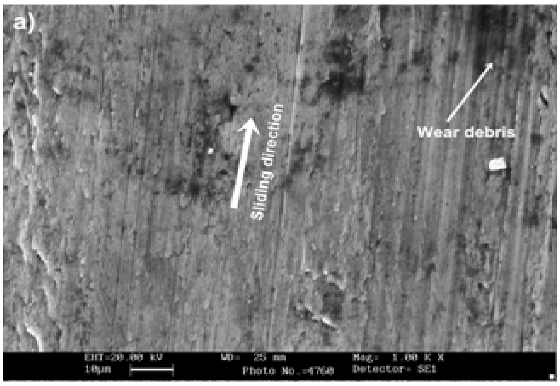
Figure 4: Indicate That the Wear Rate Increases with Increasing Applied Load for all the Composites

It is evident from experiment that at low applied load and sliding speed (3.76 m/s) the worn pin surface predominantly reveals fine and shallow grooves in the sliding direction. Such features are characteristics of abrasive wear, in which hard asperities of the counterface plough into the hybrid composite pin, causing wear by the removal of small fragments of material Al_2O_3 particles effectively act as load carrying members and coupled with the formation of lubricating graphite film, the overall wear rate is low . From SEM micrograph, at load 50N the exposed Al_2O_3 particles are fractured and get trapped between the steel counterface and the Al 6061 matrix. The fractured Al_2O_3 particles and sharp asperities on the counterface easily penetrate the graphite film and coarser and deeper grooves are formed and the wear rate increases. Similar finding were found by Veeresh Kumar et al [20]

From the figure-6, the SEM and it is very clear to observe the wear mechanisms for the formation of the wear debris and mechanically mixed layer- MMLs, it is clear that mechanical mixing played a vital role in the dry sliding wear in the range of loads used. Once the MML formed, it provided a surface protection before critical conditions were reached and then loose debris was detached or delaminated from the mixed layer, in agreement with the wear behaviour observations. It is clearly observed that the MMLs are between three and five times harder than the AA6061 alloy. Actually, the hardness of the MML is independent of the composite and the value is comparable to the hardness of the Steel counterface.[30]

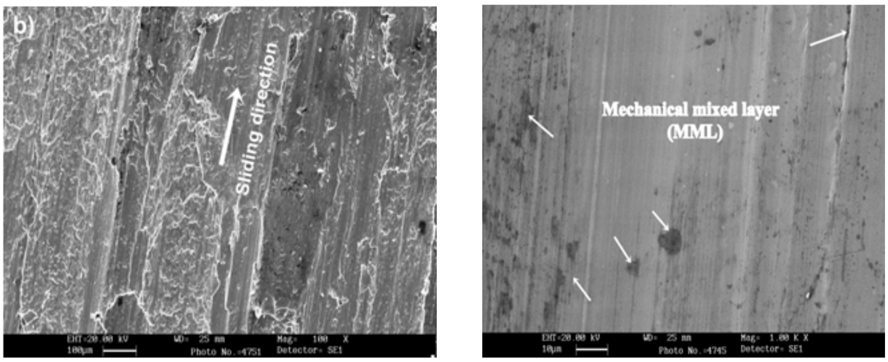
Effect of Sliding Speed

In this present study, Al6061+2%Gr+8%Al_2O_3 composition it gives the lower wear rate compared with the other composition. But in Al6061+2% Gr+2% Al_2O_3 composition, initially the wear rate was maximum because of at lower speeds Al_2O_3 particulates fracture and is removed. As speed increases the Al_2O_3 particulates undergo less fracture, this helps in retaining the amount of Al_2O_3 particulates. The accumulated Al_2O_3 particulates influence the wear resistance with increasing speed which is plotted in graph as shown in Figure-7

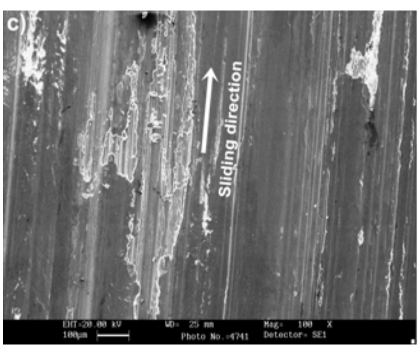


a) Pure Aluminum 6061Alloy

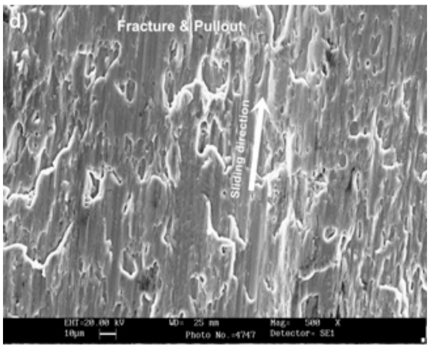
Figure 5: SEM Micrograph of the Worn Surface of Al 6061 Composite (L = 50N, S = 3.76 m/s)



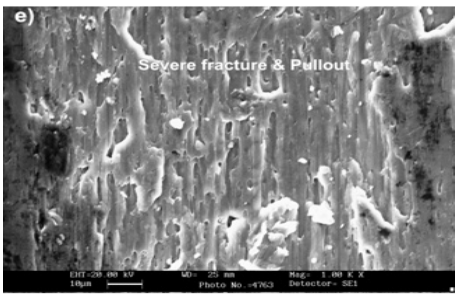
b) 2% Al_2O_3



c) 4% Al_2O_3



d) 6% Al_2O_3



e) 8% Al_2O_3

Figure 6: SEM Micrograph of the Worn Surface Showing MML Formation

Similar findings were obtained from Amro et al [6] wear rate is to decrease with increasing sliding speed, except for the case of 1.5 m/s (highest speed) for the 20% Al_2O_3 composite at 30-N load (highest load), where the wear rate increases with sliding speed. High load experiments (50 N) clearly show an increasing wear rate with the higher concentration of Al_2O_3 However, this needs further elaboration. the wear rate of the composite decreases with increasing sliding speed.

This can be atributed to the increase in the extent of oxidation of the aluminium alloy as a result of higher interfacial temperatures generated due to higher sliding speeds and the formation of MML (Mechanically mixed layer) containing thick oxide film and minute fractured fly ash particles. The graphite is squeezed out onto the surface by subsurface deformation and the subsequent transferring between and smearing onto the tribosurfaces result in the formation of the lubricating film there[20]. From Figure-8, SEM illustrate the wear regime, the wear rates decrease with increasing the test speed and reach a minimum value at a certain speed. At any constant load for a constant period of time (10 mins) the wear rate increases with increase in speed and clearly shows that fly ash improves the load bearing properties of A 380 alloy -during sliding. As the sliding speed increases from 2m/s to 4 m/s the wear rate of the composite also increases with speed which gives a direct relation between speeds and wear rate. Similar trend was observed in the study of dry sliding wear behaviour of particles reinforced with Al alloys [31]

It is obvious from figure-9, the wear rate of both unreinforced Al 6061alloy and the Al 6061 Metal matrix composites decreases as the sliding speed increases up to 600 rpm (3.76 m/s). At a speed of 750 rpm(4.71 m/s), only the wear trend of the unreinforced alloy changes from mild to severe, while the composites continue to show the same trend. At a speed of 5.65 m/s, the composite wear rate curve pattern changes to severe wear. The unreinforced alloy shows seizes at 900rpm (5.65 m/s), whereas as the composite does not. Further, the wear rate of the composite decreases as the amount of reinforcement. Heavy noise and vibration were observed during the process and transfer of the pin material to the disc was also observed

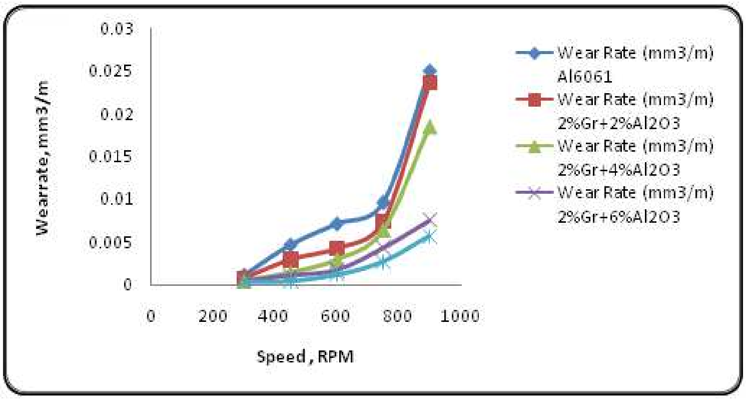
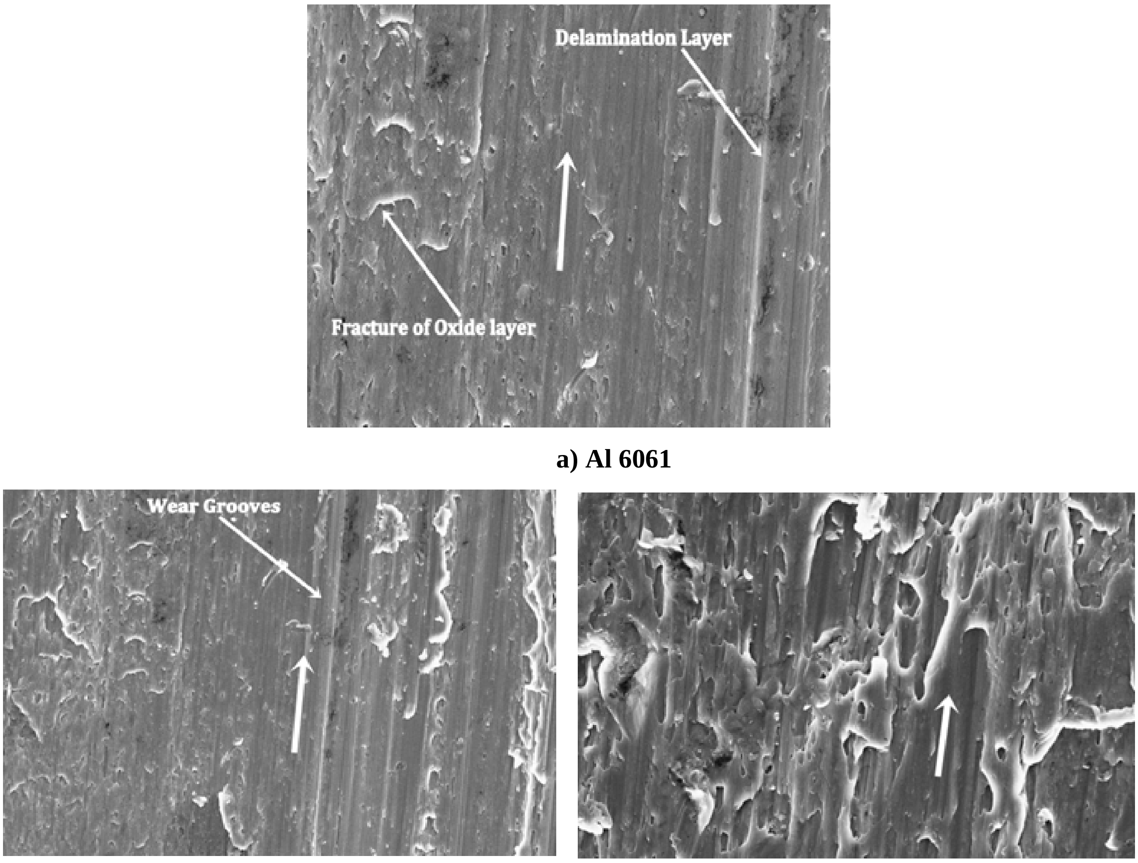


Figure 7: Indicate That the Wear Rate Decrease Creases with Increasing Speed



a) Al 6061

b) 4% Al_2O_3 **c) 8%Al_2O_3**

Figure 8: SEM Micrograph of the Worn Surface of Al 6061 Composite

(L = 30N, S = 3.76 m/s & Sliding Distance=2000m)

Effect of Sliding Distance

From figure-9, he wear rate were observed that the wear rate was maximum for un-reinforced Al 6061 as compared to composite. The addition of Al_2O_3 & graphite reinforced in Al 6061 alloy material which decreases the wear loss due to distribute the stress to the entire area and graphite material it acts as solid lubricator. It is observed from graph that Al6061 (8% Al_2O_3) composition which gives the lower wear rate as compared with the different % of Al_2O_3 Figure-10 show the wear track morphology of the specimens tested at a load of 30 N, sliding speed of 3.76 m/s, and a sliding distance of 2000 m, for unreinforced Al 6061, 4% and 8% of Al_2O_3 along with 2% Graphite reinforcement respectively. In the mild wear regime, volume loss due to wear increased linearly with the sliding distance indicating that wear progressed under the steady-state conditions. Severe wear initiated at increasingly shorter times (sliding distances) with increasing test load. [33] The wear rate of the unreinforced and composite specimens increases with increasing sliding distance. It is seen from the graphs that the wear rate of the unreinforced alloy specimens increases more rapidly with applied load compared with the composite alloy specimens. The graphs exhibit two regions which may be called ‘running-in’ and ‘steady state’ periods. During the running-in period, the wear rate increased very rapidly with increasing sliding distance. During the steady state period, the wear progressed at a slower rate and linearly with increasing sliding distance [33]

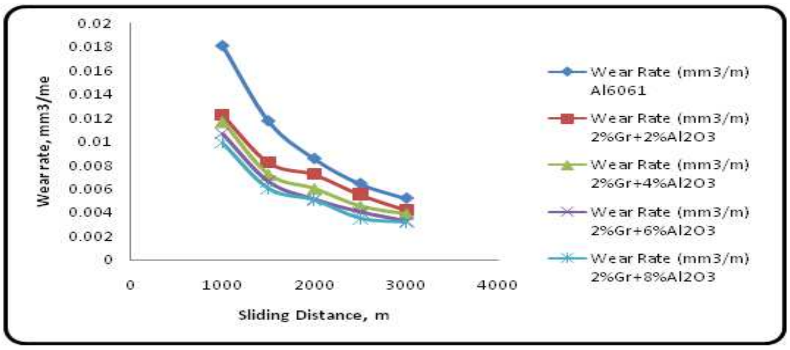


Figure 9: Indicate That the Wear Rate Decrease with Increasing Sliding Distance

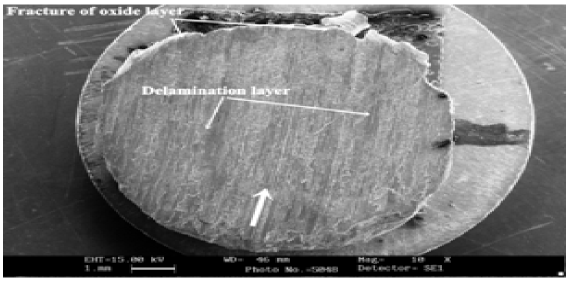
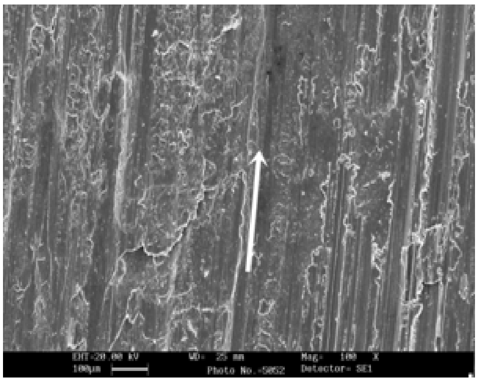
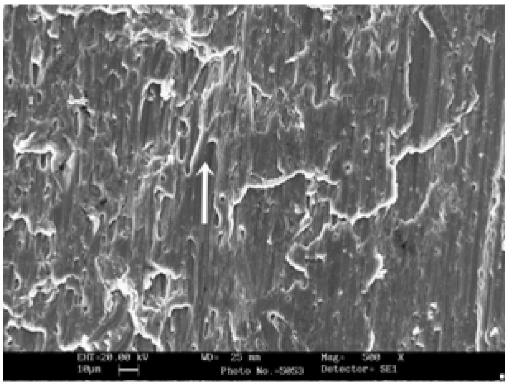


Figure 10: SEM Micrograph of the worn Surface of Al 6061 Composite (L = 30N, S = 3.76 m/s & Sliding Distance=1000, 2000 & 3000m) a) Al 6061





a) b) 4% Al_2O_3 **c) 8% Al_2O_3**

The micrograph shows the interaction of Al_2O_3 particles with the surface of hard disc, such that the initial formation of the lubricant layer can be observed and the Al_2O_3 particles are projecting outside. The cracking of particles is also seen to initiate at a particular location. A large deformation and cracking of the surface can be observed in the specimen containing 8% reinforced composite, in which voids and particle clustering occurred.

A large amount of plastic deformation was observed on the surface of the unreinforced alloy. In the case of composites containing 4 % Al_2O_3, & 8% Al_2O_3, the worn out surfaces are not smooth. Grooves were formed by the reinforcing particles. On these surfaces, areas showing a fractured appearance can be observed.

Coefficient of Friction

Friction coefficient is the ratio between the force developed and the applied force. Friction values for matrix and composite material were in expected range for light metals in dry sliding conditions, with remark that composite material, for the applied load range, showed slightly higher values comparing to the matrix material.[2] Wear resistance of the composites increases with increase in percentage of fly ash. [31].The friction coefficient of composites with coarse fly ash particles is higher compared to those of fine particles. The friction coefficient of fly ash particles exhibits increasing trend with increase in particle size. Higher coefficients of friction in the case of composites containing hard particles may be due to the formation of tribofilm at the interface between pin and disk. Composites decreases with increase in fly ash

The Coefficient of Friction of unreinforced Al6061 & reinforced Al6061 composite were studied for five applied loads 10N.20N, 30, 40 & 50 N and five different composite specimens with varying weight percentage of particle reinforcement of are shown in figure-12 .It is found that the coefficient of friction is maximum at a load of 10 N for both the matrix alloy Al6061 and its composites. However the Al_2O_3 (8%) weight fraction reinforced composite possesses the lowest coefficient of friction at this load and the friction coefficients are reduced by 41% in the range of 0.5–0.85 it can be noticed in figure -11 .

It is obvious from the figure-12 for Al6061 alloy and all reinforced composites, with the increase in the applied load & percentage of weight fraction of Al_2O_3, the friction coefficient decreases. The variation in the coefficient of friction with Sliding Distance for Al6061 alloy and its hybrid composites. Al6061 alloy possesses lower coefficient of friction when compared with the hybrid composites studied. A maximum of 40% and 50% reduction in the coefficient of friction of the hybrid composite is observed at a maximum load of 49.05 N when compared with the matrix alloy.[33]

This improvement in the anti-frictional behavior of the hybrid composite can be mainly attributed to the excellent lubricating property of Al_2O_3 reinforcements.

The coefficient of friction of both Al6061alloy and its composites decreases with increased loads.

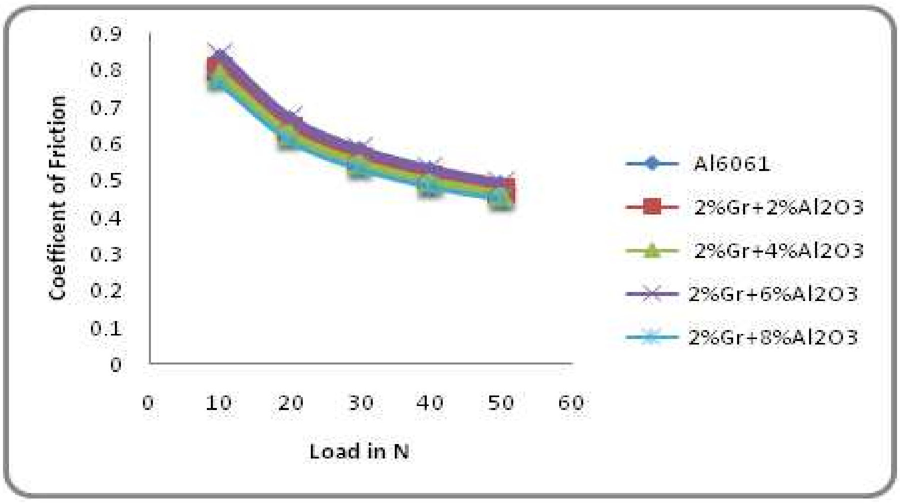


Figure 11: Indicate Coefficient of Friction of Both Al6061alloy and its Composites Decreases with Increased Loads

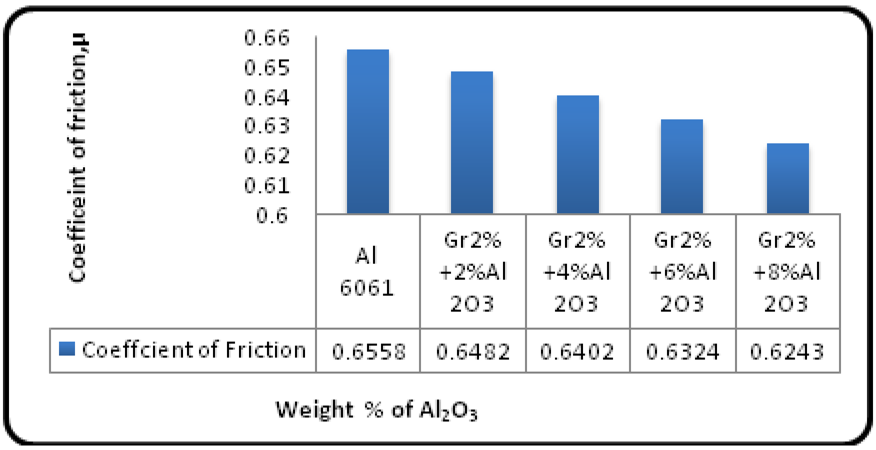


Figure 12: Indicate Coefficient of Friction of Both Al6061alloy and its Composites Decreases with Increased Loads

CONCLUSIONS

- The SEM of Aluminum 6061 composites produced by stir casting method shows that the fair uniform distribution of graphite and Al_2O_3 particles in the metal matrix.
- The incorporation of Al_2O_3 and graphite particles as reinforcements improved the tribological behavior and caused a reduction in the wear rate of Aluminum 6061 composites during the dry sliding process.
- The SEM of the worn surfaces of the Aluminum 6061 composites shows the worn surface of the composite alloy is generally much rougher than that of the unreinforced alloy. This indicates an abrasive wear mechanism which is essentially a result of hard Al_2O_3 particles exposed on the worn surface.
- The wear rate decreased with increase of sliding speed and Al_2O_3 percentage. At higher sliding speeds, MML and a lubricating film of graphite were formed between the pin and the Counterface, and they reduced the chance of direct metallic contact which helps to reduce the wear rate.
- The wear changes from severe abrasive wear to mild oxidative wear at high Sliding speeds. SEM illustrated the three types of wear namely, abrasion, delamination and adhesion. Low loads resulted in abrasion dominant wear. Higher loads resulted in delamination dominant wear with some adhesion at higher loads
- Coefficient of friction varies inversely with weight percentage of reinforcement, sliding speed and load. Coefficient of friction decreases with increase in percentage Al_2O_3, load and speed

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