

The Effect Of Deformation On Wear Behaviour Of 5% Fly Ash Particle Reinforced Al-10Mg Alloy Matrix Nano Composites Synthesized By Stir Casting

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Paper History

Received: 20-January-2016

Received in revised form: 25-February-2016

Accepted: 28-February-2016

ABSTRACT

Aluminium alloy matrix composites attract much attention due to their lightness and moderate casting temperatures. Among the various reinforcements used in composite material, fly ash is one of the most inextensible and low density reinforcements available in large quantities as solid waste by-product obtained from combustion of coal in thermal power plants. The micro sized fly ash particles have been reduced to nano structured fly ash using High energy ball mill and the size was reduced from 53 μ m to 27 nm after 30 hours of milling. Cast Al-10 wt% Mg is used as matrix to yield improved strength. Composites were fabricated with Micro and nano structured fly ash particles reinforced with Al-10Mg alloy matrix by stir casting and experiments were conducted under laboratory conditions to assess the wear characteristics of Al- 5 wt% fly ash (micro sized) and Al- 5 wt% fly ash (nano structured) composites under different working conditions in pure sliding mode on a pin-on-disc machine. The composites were given different deformations by upsetting and the effect of deformation on wear behaviour is determined in the present investigations. The wear rate of the composites was decreased with deformation and for deformations beyond 30%, the wear rate was increased due to strain softening. The increased frictional thrust at higher load results in increased debonding and caused easy removal of material and hence the wear rate is increased with increase in normal load. The coefficient of friction in all the cases is decreased with the increase of normal load. This is attributed to the wear of the matrix from the pin surface leaving the particulates standing proud.

KEY WORDS: Fly Ash; Nano Composites; Ball Milling; Wear.

NOMENCLATURE

Al	Aluminium
Mg	Magnesium
Φ	Diameter
%	Percentage

1.0 INTRODUCTION

Nanoscience and nanotechnology has become the buzz-word in recent years. It has appeal of miniaturization; also, it imparts enhanced electronic, magnetic, optical and chemical properties to a level that cannot be achieved by conventional materials (Bhushan, 2004; Kohlar et al., 2004). A variety of ways have been reported to synthesize nano level materials such as plasma arcing, chemical vapour deposition, electro deposition, sol-gel synthesis, high intensity ball milling etc (Guozhong Cao, 2004). Among these methods, high-energy ball milling has advantages of being simple, relatively inexpensive to produce, applicable to any class of materials and can be easily scaled up to large quantities (Baraton, 2003). In this mechanical treatment, powder particles are subjected to severe plastic deformation due to the repetitive compressive loads arising from the impacts between the balls and the powder. This produces novel crystalline and amorphous materials with crystallite sizes at the nanometre scale (Koch, 2006). Metal matrix composites are advanced materials resulting from a combination of two or more materials in which tailored properties are realized. However the ductility of the MMCs deteriorate with high ceramic particle concentration (Akio et al., 1999). The particulate reinforced aluminium matrix composite are gaining importance because of their low cost with advantages like isotropic properties and the possibility of secondary processing

facilitating fabrication of secondary components. The particulate composite can be prepared by injecting the reinforcing particles into liquid matrix through liquid metallurgy route by casting (Koczak et al., 1993; Maity et al., 1993). Casting route is preferred as it is less expensive and amenable to mass production. Among the entire liquid state production routes, stir casting is the simplest and cheapest one.

Aluminium composites have emerged as advanced materials for applications like aerospace, automobile, defence and other engineering fields. Wear behaviour of aluminium matrix composite was studied by Rosenberger et al., in which the matrix alloy AA6061, was reinforced with Al_2O_3 , B_4C , Ti_3Al and B_2Ti in volume fraction ranging from 5% to 15%. The Al-fly ash composite has shown better wear resistance compared to unreinforced alloy upto a load of 80N and fly ash particle size and its volume fraction significantly affect the wear and friction properties of composites (Sudarsan et al., 2008).

Fly ash is one of the residues generated in combustion, and comprises the fine particles that rise with the flue gases. Among various dispersoids used, fly ash is one of the most inexpensive and low density reinforcement available in large quantities as solid waste by-product during combustion of coal in thermal power plants. Fly ash particles are classified into two types, precipitator and cenosphere. Generally, the solid spherical particles of fly ash are called precipitator fly ash and the hollow particles of fly ash with density less than 1.0 g/cm^3 are called cenosphere fly ash. The precipitator fly ash, which has a density in the range of $2.0\text{-}2.5 \text{ g/cm}^3$ can improve various properties of selected matrix materials, including stiffness, strength and wear resistance and reduce the density. One common type of fly ash is generally composed of the crystalline compounds such as quartz, mullite, hematite, glassy compounds such as silica glass, and other oxides. Hence, composites with fly ash as reinforcement are likely to overcome the cost barrier for wide spread applications in automotive and small engine applications. It is therefore expected that the incorporation of fly ash particles in aluminium alloy will promote yet another use of this low-cost waste by-product and, at the same time, has the potential for conserving energy intensive aluminium and thereby, reducing the cost of aluminium products (Rohatgi, 1994; Rajan et al., 2001; Rohatgi et al., 1997). In view of the above said advantages with fly ash additions as reinforcements in MMCs, the present investigation makes an attempt to synthesize the Al-10Mg composites with stir casting route with micro and nano structured fly ash and focused to characterize the enhanced mechanical properties in terms of hardness, density and wear resistance for the newly developed Al-10Mg composite samples.

An attempt has been made to study the wear behaviour of the Al-Mg alloy Metal Matrix nano composite with nano structured fly ash as reinforcement. Emphasis is given in determining the effect of deformation on wear behaviour of these composites.

2.0 EXPERIMENTAL SET UP

2.1 Materials and High energy ball milling

Aluminium based metal matrix composites containing 5 wt% nano structured fly ash particulates were successfully synthesized by stir cast (vortex) method. Commercially pure aluminium with 99.5% purity obtained from NALCO is alloyed with 10% Mg and

is used as the matrix material and fly ash obtained from Visakhapatnam Steel Plant is used as the reinforcement in the present investigations. The chemical composition of the as received fly ash sample is depicted in Table 1. Fly ash sample of 1 Kg weight was taken in a graphite crucible and allowed to preheat in the muffle furnace at $1000 \text{ }^\circ\text{C}$ for 2 hours to find out the loss on ignition and it was found to be 2%. The Preheated fly ash was cooled to room temperature, washed in distilled water and dried. The dried fly ash has been sieved for 30 minutes using Rotap Sieve shaker and an average particle size of $53 \text{ }\mu\text{m}$ was obtained. The fly ash particles were then reduced to nano level using a high-energy planetary ball mill (Model: Fritsch Pulverisette 5) shown in Figure 1 available at Indian Institute of Technology- Madras, in a stainless steel chamber using tungsten carbide balls of $10 \text{ mm } \Phi$ size. The total duration of milling was 30 hours. The rotation speed of the planet carrier was 200 rpm and the ball mill was loaded with ball to powder weight ratio of 10:1. Toluene was used as the medium with an anionic surface active agent to avoid agglomeration. The milled sample powder was taken out at a regular interval of every 5 hours of milling and dried with mechanical drier.



Figure 1. Fritsch Pulverisette(5) – High Energy Ball Mill

Table 1: Chemical composition of as-received fly ash, wt. %

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O
58.15	30.05	6.15	1.45	1.05	1.53	0.4	1.18

2.2 X-Ray Diffraction studies

The fresh as well as milled fly ash powder was characterized with an X-Ray Diffractometer (Model: 2036E201; Rigaku, Ultima IV, Japan) and the sample preparation of XRD was done as per the standard practice at Department of Metallurgical Engineering, Andhra University College of Engineering, Visakhapatnam. The sample was tightly packed on a glass slit and precautions were taken to avoid manual contamination of the powder. The X-ray diffraction measurements are carried out with the help of a Goniometer model 2036E201 using Cu K α radiation ($K\alpha = 1.54056 \text{ \AA}$) at an accelerating voltage of 40 kV and a current of 20 mA. A steady decrease in the crystallite size was observed and it was found that the crystallite size has been reduced from $53\mu\text{m}$ to 27 nm in 30 hr of milling. The X-Ray diffractograms obtained at various time intervals of milling are shown in Figure 2. Three major phases were identified for all the milling times;

which are $Al_2Si_2Sb_2$, $Al_2Co_1O_4$ and $Al_2O_5Ti_1$.

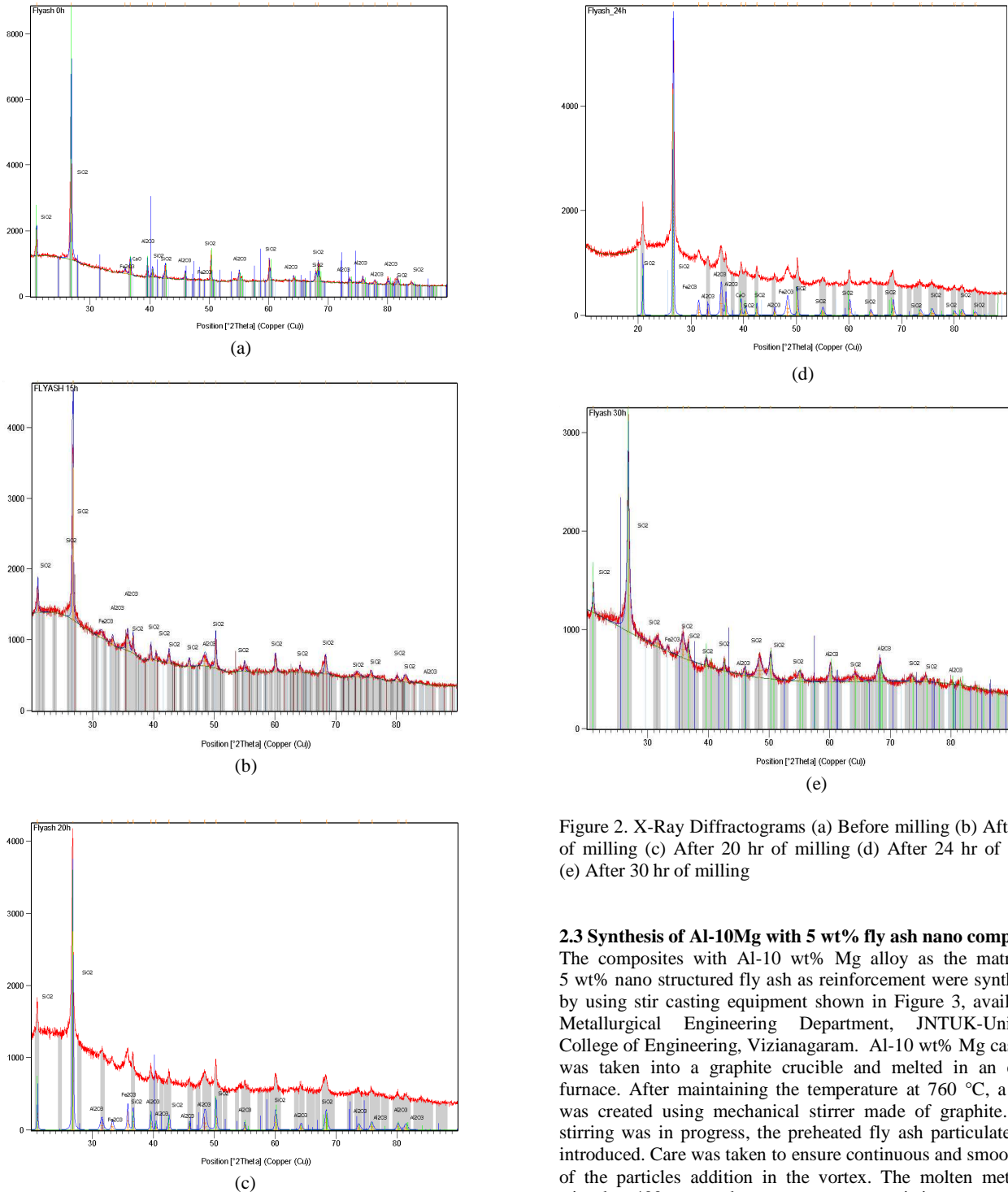


Figure 2. X-Ray Diffractograms (a) Before milling (b) After 15hr of milling (c) After 20 hr of milling (d) After 24 hr of milling (e) After 30 hr of milling

2.3 Synthesis of Al-10Mg with 5 wt% fly ash nano composites

The composites with Al-10 wt% Mg alloy as the matrix and 5 wt% nano structured fly ash as reinforcement were synthesized by using stir casting equipment shown in Figure 3, available at Metallurgical Engineering Department, JNTUK-University College of Engineering, Vizianagaram. Al-10 wt% Mg cast alloy was taken into a graphite crucible and melted in an electric furnace. After maintaining the temperature at 760 °C, a vortex was created using mechanical stirrer made of graphite. While stirring was in progress, the preheated fly ash particulates were introduced. Care was taken to ensure continuous and smooth flow of the particles addition in the vortex. The molten metal was stirred at 400 rpm under argon gas cover; stirring was continued for about 5 minutes after addition of fly ash particles to get the uniform distribution in the melt. During stirring small pieces of

magnesium (0.5 wt. %) were added to the molten metal to enhance the wettability of nano structured fly ash with melt. The melt with the reinforced particulates were bottom poured into preheated metal mould while stirring was in progress. Finger castings of 12mm x 120 mm were removed from the moulds after cooling and were homogenized at 100°C for 24 hours.



Figure 3. Stir Casting equipment

2.4 Wear Tests

Cylindrical samples of 10mm x 10mm were cut from the finger ingots and were upset to obtain 10%, 20%, 30% and 40% deformations. Wear Tests were conducted as per ASTM G-99 Standard under unlubricated condition in a normal laboratory atmosphere at 50-60% relative humidity and a temperature of 28-35°C on a Pin-on-Disc wear testing machine shown in Figure 4 at Metallurgical Engineering Department, JNTUK University College of Engineering, Vizianagaram. A hardened ground steel disc (En-32) having hardness 65 HRC and surface roughness (Ra) 0.5 µm is used in the wear testing machine. The disc rotates with the help of a D.C. motor having speed range 0-1000 rpm with wear track diameter 50 mm-80 mm, which could yield sliding speed 0 to 10 m/sec. Each test is carried for 5 hrs run and the mass loss in the specimen after each test is estimated by measuring the weight of the specimen before and after each test using an electronic weighing machine having an accuracy up to 0.01 mg. Care has been taken that the specimens under the test are continuously cleaned with woollen cloth to avoid entrapment of wear debris and to achieve uniformity in experimental procedure.



Figure 4. Pin on disc wear testing machine

3.0 RESULTS AND DISCUSSIONS

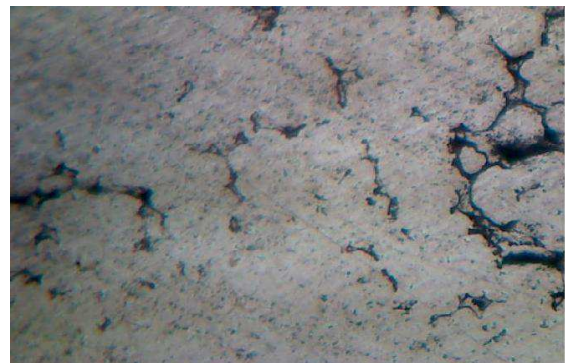
3.1 Microstructure of the composites

The polished samples were observed under optical microscope, shown in Figure 5 at Metallurgical Engineering Department, JNTUK University College of Engineering, Vizianagaram to ascertain the distribution of the reinforcement of fly ash.

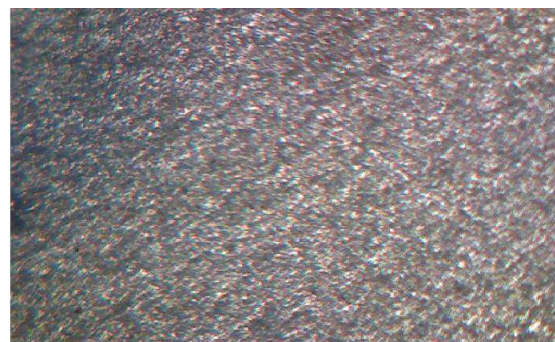


Figure 5. Optical Microscope

The optical micrograph of Al- 5Wt% fly ash shown in Figure 6 depicts that the distribution of Al-10Mg alloy matrix with fly ash reinforcement is uniform and the composite is free from voids and discontinuities.



(a) Al-Mg alloy+ 5% nano structured fly ash



(b) Al-Mg alloy+ 5% micro sized fly ash

Figure 6. Optical micrographs

3.2 Hardness tests

The hardness tests are conducted using Vickers hardness tester and the results are furnished in Table 2. The hardness of the composites with coarse grained fly ash particle reinforcement was significantly increased with increase in deformation under compression. This is due to the strain hardening that occurred in conventional coarse grained materials and is related to dislocation movements. On the other hand, the hardness measurements of the composites with nano fly ash particle reinforcement were not increased with increase in deformation under compression which is due to strain softening occurred under compression. It is consistent with the studies reported by KO et al (2005) on compression of fine grained aluminium alloys at room temperature.

Table 2. Vickers hardness measurements

Metal Matrix Composite	VHN				
	0% def	10% def	20% def	30% def	40% def
Al + 10% micro sized Flyash	86.91	82.91	89.269	94.1	91.32
Al + 5% nano structured Flyash	68.87	73.6	77.66	83.27	79.98

3.3 Effect of particle size on wear resistance of the composites

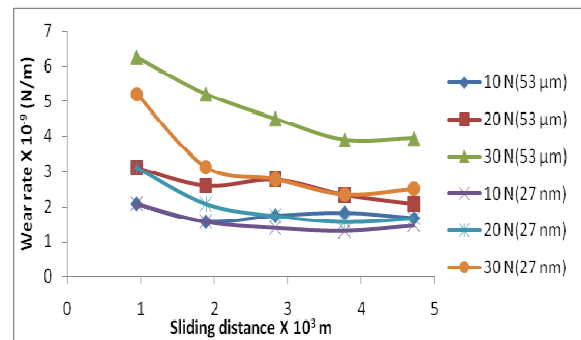
Wear rate was estimated by measuring the mass loss in the specimen after each test. The wear rate which relates to the mass loss to sliding distance (L) is calculated using the expression $Wr = \Delta m/L$, the Volumetric wear rate Wv of the composite is relate to density (ρ) and the abrading time (t), was calculated using the expression $Wv = \Delta m/\rho t$.

The friction force is measured for each pass and then averaged over the total number of passes for each wear test. The average value of co-efficient is calculated using the expression $\mu = F_f / F_n$, where F_f is the average friction force and F_n is the applied load. For characterisation of the abrasive wear behaviour of the composite, the specific wear rate is employed and is determined using the expression $Ws = Wv / Vs Fn$, Where Vs is the sliding velocity.

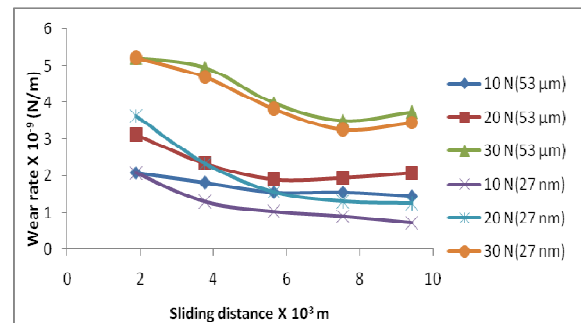
Wear tests are conducted on pure aluminium, Al-10Mg nano structured fly ash particle reinforced composites using various loads i.e., 10N, 20N, 30N and at different speeds of 200 RPM, 400 RPM, 600 RPM. The plots obtained were represented in Figure 7. It is evident that, at constant sliding speed and constant load the wear resistance of fly ash particle reinforced composites is increased compared to that of pure aluminum. The strengthening effects occurred in particulate reinforced composites increases the strength and hence the wear resistance. These effects include the transfer of stress from the matrix to the particulate, the interaction between individual dislocations and particulates, grain size strengthening mechanism due to a reduction in composite matrix grain size, and generation of a high dislocation density in the matrix of the composite as a result of the difference in thermal expansion between the metal matrix and particulates (Natarajan et al., 2006; Akhlaghi et al., 2009; Valdez et al., 2008). Significant increase in wear resistance is observed with the addition of nano

structured fly ash particles compared to that of micro structured fly ash particles in the composites. The surface properties of fly ash particles changes considerably with increased ball milling and hence the surface energy and inter atomic bonding will also increase. This might be the reason for the increase in wear resistance of nano particle reinforced composites.

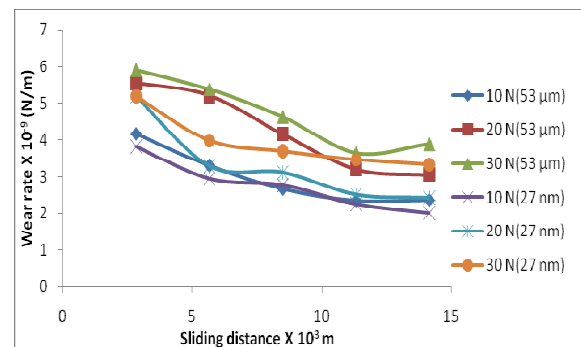
An increase in wear rate is observed with increase in normal load. This is because, the increased frictional thrust at higher load results in increased debonding and causes easy removal of material. The similar effect of normal load on volumetric wear rate has been observed by Cirino et. al. (1987) in the case of carbon epoxy composite.



(a)



(b)

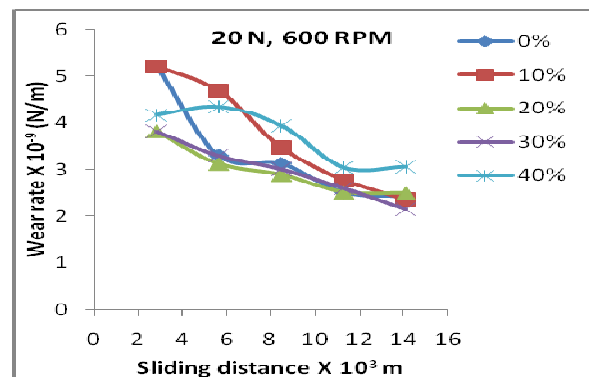
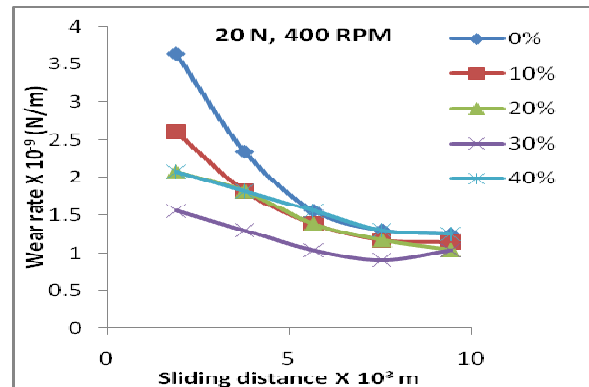
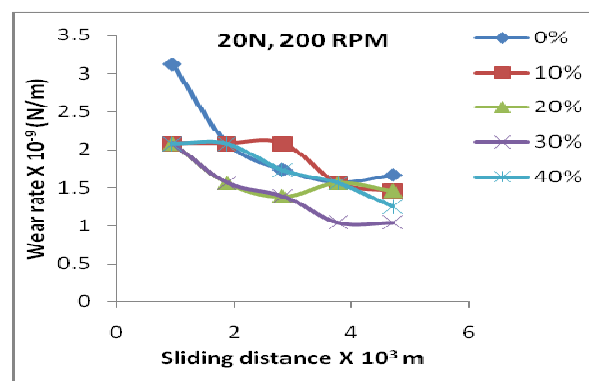
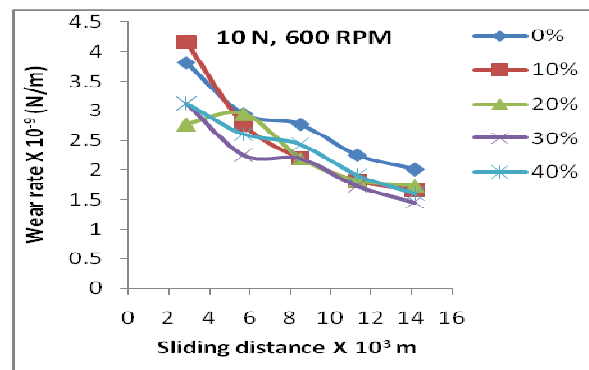
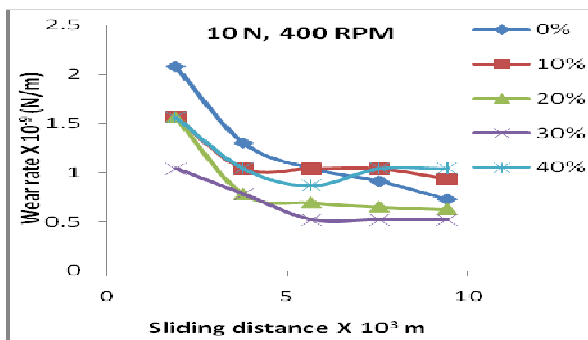
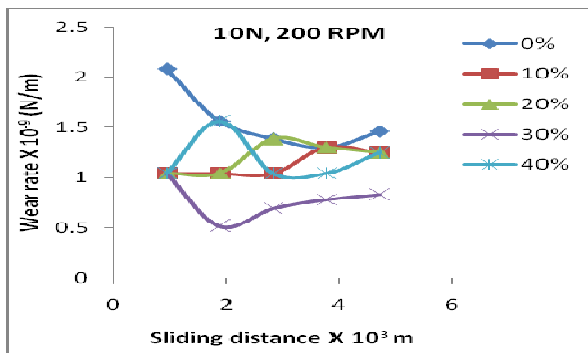


(c)

Figure 7. The effect of load and particle size on wear rate with sliding distance (a) 200 rpm (b) 400 rpm (c) 600 rpm

3.4 Effect of deformation on wear resistance of the composites

The hardness of Al-10Mg cast alloy and fly ash particle reinforced Al-10Mg alloy matrix composite was increased with increase in deformation. This might be due to the existence of strain hardening effects from matrix materials and also from the rule of mixture of composite strengthening (Callister, 2007). The coefficient of friction has been decreased with the increase of normal load for the alloy as well as the composite. This decrease in value occurs likely as a result of particulate standing above the surface making contacting area of the specimen smaller. In addition, this decrease in coefficient of friction may be attributed to the wear of the matrix from the pin surface leaving the particulates standing proud. A similar change in coefficients of friction has been observed by M.H. Korkut (2003) for the newly developed Al 2024/SiFe and Al 2024/SiFe/Al₂O₃ composites. The effect of deformation on wear rate with sliding distance at various loads and sliding velocities are depicted in Figure 8. The wear rate of the composite is decreased with deformation and for deformations beyond 30%, the wear rate is increased due to strain softening.



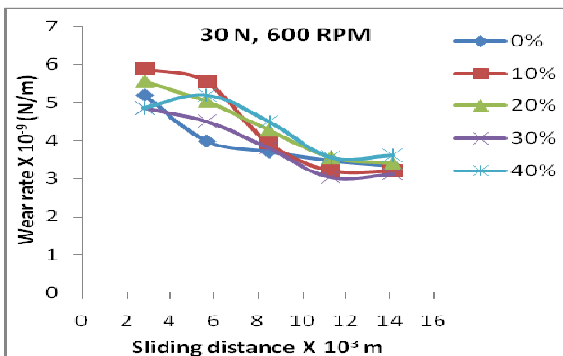
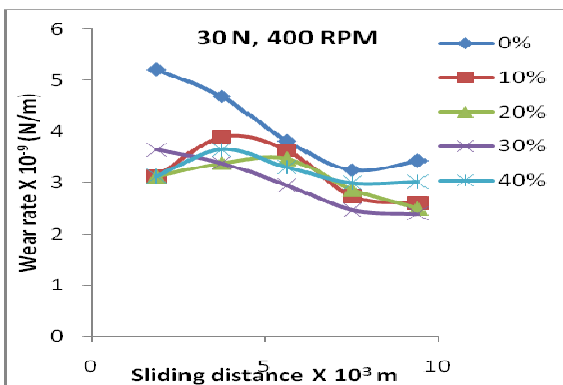
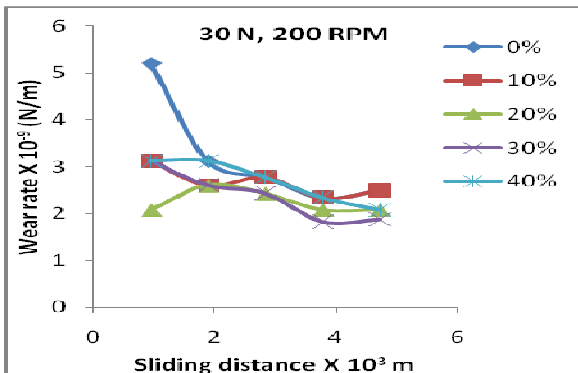
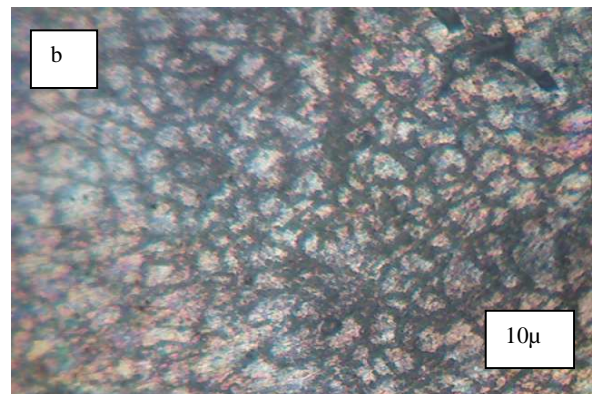


Figure 8. The effect of deformation on wear rate with sliding distance

Cracks have appeared for the same sliding speed with increased load and these might have helped in chipping of fly ash particles. With increase in applied load although the amount of cavitations appears to be low but deep cracks and grooves are clearly visible in the optical micrographs at higher loads. The optical micrographs depict that when the sample is rubbed, against steel wheel, at low sliding speed and low applied load hard particles might have chipped off and the grains of Al-Mg alloy matrix are grown into bigger sizes with increase in applied load and the matrix appears to be smeared along the direction of the sliding. This might have been caused also due to embrittlement of hard particles during sliding.



(a)



(b)

3.5 Microstructural observation:

The worn-out surfaces of some selected specimens after the wear test are observed under optical microscope and are shown in Figure 9.1 and 9.2. It is observed that cavities are formed in the matrix of the composite and have aligned parallel to the direction of sliding during slow sliding velocity i.e. at 200 RPM. The amount of cavities is reduced with increase in sliding velocities and minimum cavities are observed with sliding velocity of 600 RPM. In some regions, the substructures are aligned parallel to the sliding direction. The worn surfaces at higher sliding speeds are relatively smoother than at lower sliding speeds.

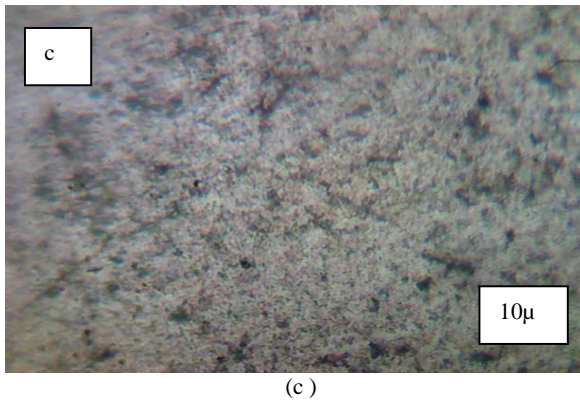


Figure 9.1 Optical micrographs of nano fly ash reinforced Al-10Mg alloy matrix composite after wear tests at 10N load (a) 200 RPM (b) 400 RPM (c) 600 RPM

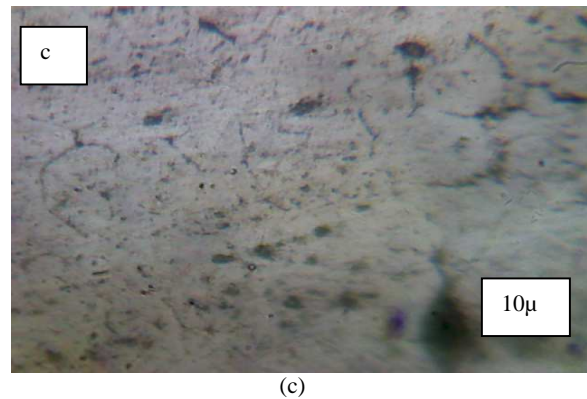
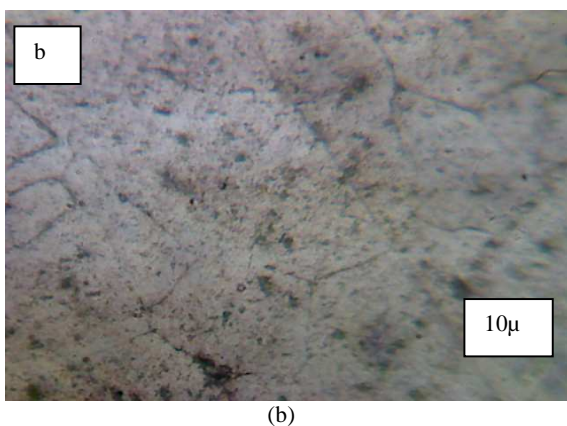
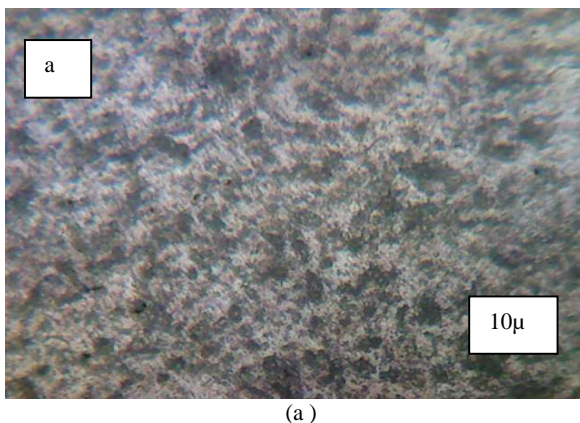


Figure 9.2 Optical micrographs of nano fly ash reinforced Al-10Mg alloy matrix composite after wear tests at 600 RPM speed (a) 10N (b) 20N (c) 30N



4.0 CONCLUSION

The following conclusions can be drawn from the present investigations:

The nano structured fly ash is successfully synthesized by high energy ball milling and the crystal size is reduced from $53\mu\text{m}$ to 27 nm in 30 hours.

The hardness of the composites with coarse grained fly ash particle reinforcement was significantly increased with increase in deformation under compression. On the other hand, the hardness measurements of the composites with nano fly ash particle reinforcement were not increased with increase in deformation under compression which is due to strain softening occurred under compression.

The wear rate was decreased with increase in deformation and at higher sliding velocities, increase in wear rate is observed due to strain softening at deformations beyond 30%.

The increased frictional thrust at higher load results in increased debonding and caused easy removal of material and hence the wear rate is increased with increase in normal load.

The coefficient of friction in all cases is decreased with the increase of normal load. This is attributed to the wear of the matrix from the pin surface leaving the particulates standing proud.

The microstructural observation of the worn out sample has revealed the formation of cavities in the matrix of the composite at slow sliding velocity i.e. at 200 RPM. The amount of cavities is reduced with increase in sliding velocities and minimum cavities are observed with sliding velocity of 600RPM.

At higher loads, deep cracks and grooves are observed in the optical micrographs. From the micrograph, it is seen that some cracks are originated at the grain boundaries of aluminium. This might be due to strain hardening of aluminium during sliding with the applied load and due to pulling up of hard fly ash particles from the aluminium grain boundaries. With increasing the applied load this effect is more pronounced because of embrittlement of hard particles during sliding.

ACKNOWLEDGEMENTS

The authors sincerely express their thanks to the UGC for extending the financial support for carrying the research work.

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