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TRIBOLOGICAL BEHAVIOR OF WC- GR REINFORCED HYBRID COMPOSITES

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ABSTRACT

In the present investigation the sliding wear behavior of as-cast and T6 heat treated Al6061 alloy and WC-Gr reinforced hybrid composites were studied for different applied loads. Using liquid metallurgy technique, composites were synthesized for 1 - 4 wt% of tungsten carbide (WC) in steps of 1 wt% and 4 wt% of graphite (Gr) reinforcement. The cast composites were solution heat treated at 500-550 ^{0}C and artificially aged for 1,3,5 hrs at 175^{0}C. The results revealed that the strength and hardness of the composites improved significantly with heat treatment. The wear tests were conducted for different loads for a sliding distance of 3 km and sliding velocity of 2.62 m/s according to ASTM G-99 standard using pin-on-disc apparatus. The specific wear rate of heat treated composites gradually decreased with the increase in sliding distance and the maximum wear resistance was observed in 5 h aged Al6061-3wt%WC-4wt%Gr composites. The worn surfaces of the samples were studied under scanning electron microscope to understand the microscopic wear behavior.

Keywords: Heat treatment, Aging, Hardness, Wear rate, Sliding distance.

I. INTRODUCTION

Aluminum alloy possesses poor wear resistance. Whereas Aluminum Matrix Composites (AMCs) are known for better wear resistance and good mechanical properties. These composites are synthesized by liquid or powder metallurgy routes. The study of wear performance of these composites is a subject of strong interest, especially for their potential application in automobile components [1].

In AMCs high volume fractions of hard reinforcements favors for wear resistance, the wear rate of the counter body is found to be greatly enhanced by the abrasive action of the reinforcements. Carbides, oxides, nitrides and different intermetallics compounds have been used extensively as reinforcing particulates for AMCs [2]. The optimum properties of Metal Matrix Composites (MMCs) with enhanced performance depend up on the selection of the reinforcing phase and processing technique. Different reinforcement particles such as SiC, B C, Al O , TiC and Zirconia are the widely used in the manufacture of MMCs [3–6]. Limited attempts have been made to examine the effect of aging on sliding wear behavior of composites. According to several authors [7-10], over aged composites exhibit higher wear resistance when compared with that of the under aged composites. This difference is attributed to the relaxation of tensile stresses, compressive stresses induced in reinforcements during aging.

However Pan et al. [8] described this fact due to change in fractural path from particulate matrix interface to grain boundary. The thermal mismatch between the reinforcement and the metallic matrix during heat treatment results in the occurrence of higher dislocation density in the matrix alloy at the reinforcement interface [11]. This higher dislocation density significantly alters the precipitation kinetics and hence, the significance of solutionizing time in discontinuously reinforced composites extends not only to the complete solubility of secondary phase but also to the termination of dislocation generations in the matrix [12]. Li and Tandon [13] studied on A356-SiC composites and observed that aged samples exhibit marginally higher wear resistance than that of the as-cast one even though the hardness of

the composite is significantly higher than that of the alloy. Wear performance of the composite may not dependent on matrix hardness but also on other factors like sliding induced plastic deformation, stress relaxation in over aging, matrix particle interface characteristics and precipitation behavior [14]. From the literature it was found that, study on heat treated aluminum matrix hybrid composites is inadequate. The information on wear behavior of tungsten carbide and graphite reinforced aluminum matrix composite is not available. In this investigation the composites were synthesized by using liquid metallurgy technique with Al6061 as matrix alloy and tungsten carbide (WC) and graphite (Gr) as reinforcements. The wear behavior of synthesized composites was evaluated in T6 heat treated condition.

II. EXPERIMENTAL

2.1 Materials

The matrix used in the investigation consists of 0.84 Mg, 0.62 Si, 0.22 Cu, 0.03 Mn, 0.23 Fe, 0.22 Cr, 0.10 Zn, 0.1 Ti and balance Al in wt%. The reinforcement consists of 1-4 wt% of Tungsten carbide (WC) of 5 µm and 4 wt% of Graphite (Gr) of 10 µm size (Table 1). The process includes melting the alloy and adding the preheated reinforcement particles in the melt through mechanical stirring. The melt was casted in a permanent cast iron die in the form of cylinder of 200 mm length and 16 mm diameter.

Table 1 Material system for investigation

Matrix	Reinforcement (wt%)		Synthesized composite
	WC	Gr	
Al6061	0	0	Al6061 (Base alloy)
	1	4	Al6061-1wt%WC-4wt%Gr
	2	4	Al6061-2wt%WC-4wt%Gr
	3	4	Al6061-3wt%WC-4wt%Gr
	4	4	Al6061-4wt%WC-4wt%Gr

The hardness of the alloy and composites were measured in Brinell hardness tester (Model: TK8-3000, Make: Meta test) using a load of 500 kg. For hardness measurement, opposite sides of the samples should be parallel and polished. In each sample 03 indentations were taken and the average hardness value along with standard deviation was reported. For micro-structural examination, samples were cut from the cast disc and polished metallographically using standard metallographic technique and finally etched with Keller’s reagent. Etched samples were examined under scanning electron microscope.

2.2 Heat treatment

In 6xxx alloys the temperature for solution heat treatment is up to 500 to 550°C, because higher temperature leads to incipient melting, lowering the mechanical properties of the casting. The time at which the normal solution temperature must be long enough to homogenize the alloy. The alloy must ensure a satisfactory degree of solution of the precipitates. Aluminum with magnesium and silicon is heat treatable, at eutectic temperature of 500–550°C, the alloy will respond to heat treatment by age hardening. Cast alloys were given artificial aging treatment (T6) having a sequence of solution heat-treating, quenching and artificial aging. Solution heat treatment is carried out by heating the alloy into the a-single phase region followed by rapid cooling in T6 i.e. solutionised at 500–550 °C for 8 h followed by water quenching and aging at 170 °C, for 1, 3, 5 h and then cooled to room temperature. Due to precipitation, the strength and hardness was increased. The hardness was measured after the heat treatment using Brinell hardness testing machine and values were averaged over three measurements taken at different points on the cross section as shown in Table 2.

Table 2 Hardness of base alloy and composites

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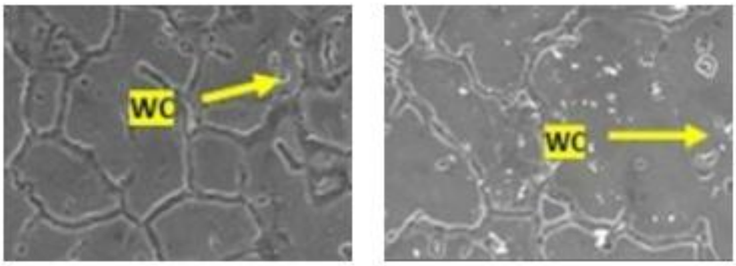
Material	BHN			
	as-cast	1*	3*	5*
Base alloy				
Al6061-1 wt%WC-4 wt% Gr	62±2	87±3	105±1	119±2
Al6061-2 wt%WC-4 wt% Gr	69±2	102±2	116±3	129±3
Al6061-3 wt%WC-4 wt% Gr	**76±1**	**111±1**	**126±3**	**142±2**
Al6061-4 wt%WC-4wt%Gr	60±2	80±2	96±2	107±2

*Ageing time (h)

2.3 Microstructures

Fig. 1(a) shows the microstructures of the as-cast composites represent primary aluminum grains and the precipitates of different intermetallic phases at the grain boundary. The microphotographs of the composites shows fairly uniform distribution of WC and Gr particulates Fig. 1(b) indicates the matrix grain size in heat treated composite are finer than the as-cast composite. The reduced size of the grain size shows the improved strength and hardness of the material. The good bonding between the matrix and reinforcement represents the reduced porosity.



(a) (b)

Fig. 1(a-b) Micrographs of as-cast and heat treated composites

2.4 Wear behavior

2.4.1 Sliding wear tests

Sliding wear tests were conducted in pin-on-disc wear testing apparatus (model: TR20-LE, Ducom Make, Bangalore, India) under varying applied loads (10 - 40 N) at a fixed speed of 2.62 m/s for a sliding distance of 3000 m against EN-31 steel disc of hardness HRC60. The pin samples were 25 mm length and 10 mm diameter. The surfaces of the pin sample and the steel disc were ground using emery paper (grit size 240) prior to each test. During sliding load is applied on the specimen through cantilever mechanism and the specimens brought in intimate contact with the rotating disc at a track radius of 100 mm. The samples were cleaned with acetone and weighed prior to and after each test. The wear rate was calculated from the weight loss measurement and expressed in terms of volume loss per unit sliding distance. Coefficient of friction was computed from the recorded frictional force and the applied load (i.e. the ratio of frictional force to the applied load). A set of three samples was tested in every experimental condition, and the average along with standard deviation for each set of three tests was measured. The applied load and sliding distance were recorded for the calculation of coefficient of friction and wear rate.

III. RESULTS AND DISCUSSION

3.1 Wear loss

At an applied load of 10 N, a wear loss of 3.5 mm3 in as-cast and 2.8mm3 in T6 heat treated 5 h aged alloy was observed. This shows the reduced volumetric wear loss of 20% in heat treated alloy. Fig. 2(a) shows the reduced wear loss with increase in aging time. Similar trend was observed in composites. In as-cast and heat treated Al6061-3wt%WC-4wt%Gr composite samples shown a wear loss of 2.5 mm3 and 1.55 mm3 respectively. This shows the reduced wear loss of 57% in the heat treated composite when compared with the base alloy. As the applied load increased the wear loss increases shown in Fig. 2(b-d) for the applied load of 20, 30 and 40 N. This shows the increased wear loss with increase in load for both the alloy and composites. At an applied load of 40 N, 33 % and 58% decrease in volumetric wear loss was observed in as-cast and heat treated composites when compared with the alloy in as-cast condition (Fig. 2(d)). From the analysis it was found that minimum wear loss was observed in Al6061-3wt%WC-4wt%Gr composites. The graphite acts as a solid lubricant, which reduces the volumetric loss. At higher loads the temperature of the sliding surfaces increases, which results in softening of the pin

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surface which is in contact with the disc, leading to heavy deformation and results in higher volumetric wear loss of the pin. Basavarajappa et al. [15] conducted dry sliding wear tests on hybrid aluminum matrix composites, reinforced with silicon carbide and graphite particles and showed that graphite particles are effective agents in increasing dry sliding wear resistance of Al-2219-SiCp composites. Gomez et al. [16] investigated the effect of graphite particles distribution on wear behavior of aluminum composites with 4.5 wt % of graphite content. They found that the presence of graphite particulate could improve the wear resistance in composites.

Gomez et al. [17] investigated the influence of heat treatment on the wear behavior of AA6092-SiC25p composites and highlighted the improvement in hardness due to T6 heat treatment, which lead to improved wear resistance of Metal Matrix Composites (MMCs). The graphite acts as a solid lubricant which is effective in enhancing the wear resistance of the composites. Also reduces the hardness of the composite [18].

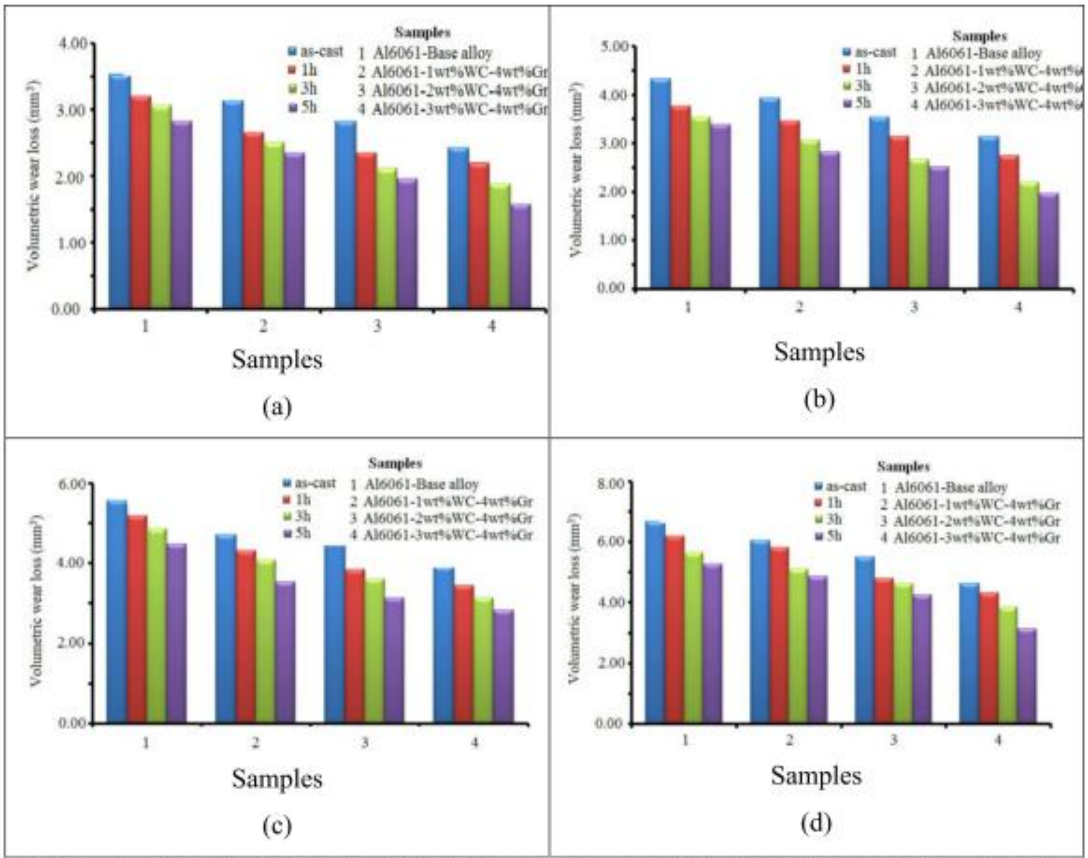
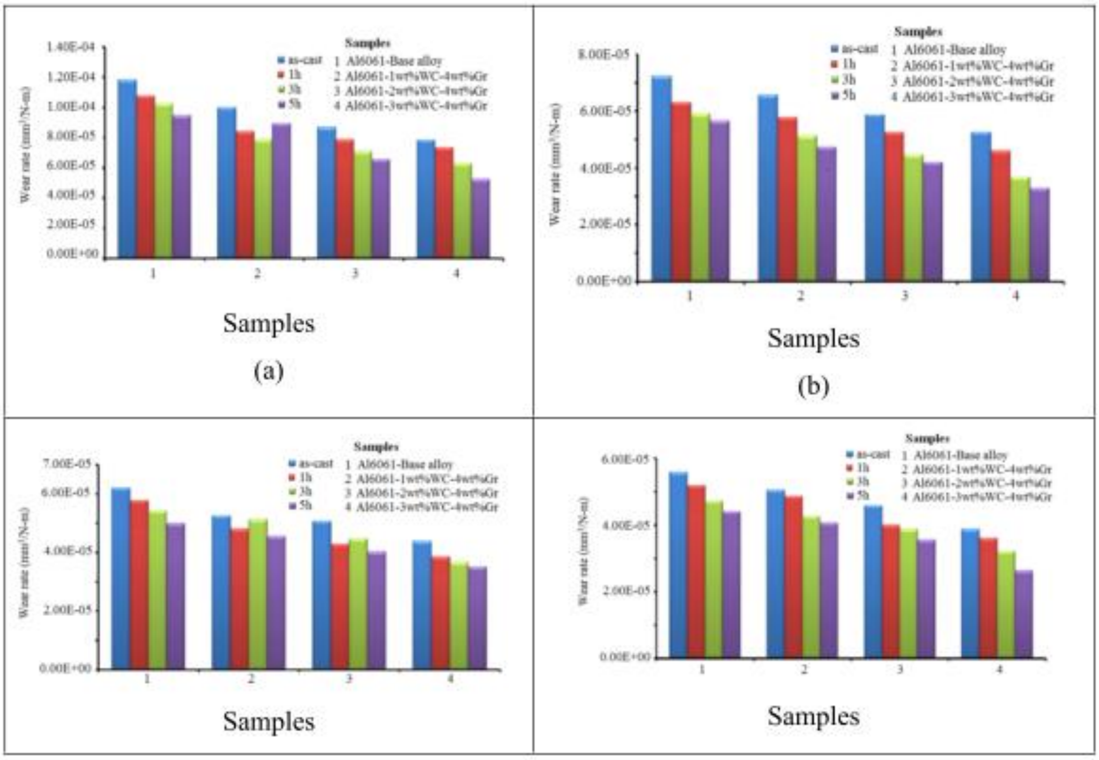


Fig. 2(a-d) Effect of volumetric wear loss on applied load (1) 10 N (2)20 N (3) 30 N (4) 40 N

3.2 Wear rate

The specific wear rate of as-cast alloy is higher than heat treated alloys (Fig. 3(a)). The specific wear rate of the as-cast and heat treated composite was decreased when compared with the base alloy (Fig. 3(b-d)). With increase in aging time the specific wear rate decreases in both the alloy and composites. The incorporation of WC particles in an aluminum alloy increases the load bearing capacity, hence specific wear rate of aluminum alloy was reported to be decreased with increase in applied load. The reduced wear rate was observed in as-cast and heat treated AMCs with increase in WC reinforcement as shown in Fig. 3(b-d). The improvement in hardness of the composites represents the reduced wear rate as reported by researchers [21, 22]. The minimum wear rate was observed for all loading conditions in T6 heat treated, 5 h aged Al6061-3wt%WC-4 wt%Gr composites.

At lower loads (10 N) the contact resistance is high, due to which mild wear occurs. The rubbing surfaces form the fine wear debris which mainly consists of aluminum and iron oxides. The WC particulates act as load bearing and abrasive elements between the composite and disc. The worn surface of the composite leads to the formation of iron rich layers. The composite exhibited smaller plastic deformation and damages due to cavitations and de-cohesion taking place along the sliding direction of the surface at medium loads (20 & 30 N). Formation of the iron oxide was lesser at medium loads than that of lower loads. Presence of aluminum oxide was seen at the morphological surface. The worn surface does not show the presence of exposed particulate at medium loads due to rise in temperature, the matrix becomes soft and particulates were pushed in to the matrix. The trailing edge particle comes out when the surface becomes softer due to frictional heat



(c)	(d)

Fig. 3(a-d) Effect of wear rate on applied load (1) 10 N (2) 20 N (3) 30 N (4) 40 N

The lager particles still act as abrasive elements because the layer is not so thick at medium wear rates. At higher loads (40 N) the contact resistance was low, leads to severe wear. The wear rate in as-cast and heat treated composite decreases. Wear debris includes coarse metallic particles of the surfaces and Gr particles, which act as abrasive particles between the specimen and disc. The oxide film formed on the wearing surface prevents the metal to metal contact. The hard brittle oxide formed on aluminum provides protection against wear. The temperature of the sliding surfaces increases which leads to higher wear rates.

The hard particulates of WC reinforcement restrict the composites from getting soft. The presence of graphite in the matrix improves its oil spreadability over the contact surface, thus reducing the tendency to score or seize. Graphite consists of carbon atoms arranged in a layer like structure, displays a very low coefficient of friction while sliding on another clean surface. Ma et al. [19] found that at low loads, as particles act as a load bearing constituents, the direct involvement of aluminum alloy in the wear process is prevented. Metallographic observation at low loads indicated that there was less chemical interaction of the composite with the counter face due to smaller true contact area [20].

3.3 Worn surfaces

Worn surface of as-cast and heat treated composite at an applied load of 10 N shown in Fig. 4(a-b). It shows continuous wear groves and relatively smoother surface when compared with the heat treated composite. The rubbing surfaces showing fine wear debris which mainly consists of aluminum and iron oxides. The rubbed surface seems to be polished. The WC particulates act as load bearing and abrasive elements between the composite and disc. The worn surface of the MMCs leads to the formation of iron rich layers. The worn surface shows the white patches of iron oxide and exposed particles on the worn surface. At an applied load of 20 and 30 N the surfaces exhibits wear grooves, exposed WC particles and accumulation of wear debris at the boundary of WC particle (Fig. 4(c-d)). The composite exhibits smaller plastic deformation and damages due to cavitations and de-cohesion taking place along the sliding direction of the surface. Formation of the iron oxide was lesser at medium loads than that of lower loads. Presence of aluminum oxide was seen at the morphological surface.

At an applied Load of 40 N (Fig. 4(e)) smoother worn surface with protruded WC particle, accumulation of wear debris at the boundary of the WC particle and filling up of the valleys between WC particles with compacted wear debris was observe. Wear debris includes coarse metallic particles of the surfaces and Gr particles, which act as abrasive particles between the specimen and disc. The oxide film formed on the wearing surface prevents the metal to metal contact. The hard brittle oxide formed on aluminum provides protection against wear. It is clearly evident from the graph that there exists a transitional load at which there was a sudden decrease in wear rate.

At higher loads (40 N) the aluminum oxide film becomes thicker and continuous, covering the entire surface. This aluminum oxide film acts as a sliding surface. At critical velocity, the thin films were detached and wear rate was decreased. A thick film is plastically deformed approaching a molten state which allows particles to move upward in to the matrix without bearing any load at the beginning. The particles move upward and become dense and stop further movement. Thus dense surface acts as a harder surface, and due to increase in hardness the composites bear the higher transition.

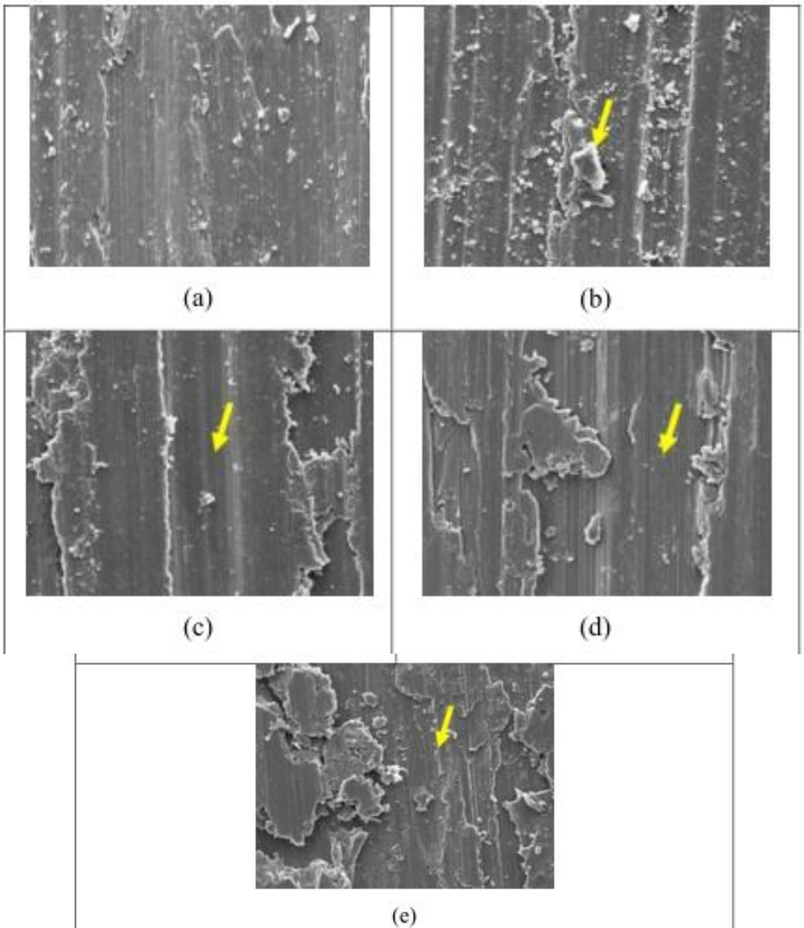


Fig. 4 Worn surface of the composites at different applied loads (a) as-cast (b) 10 N (c) 20 N (d) 30 N (e) 40 N

Alpas and Zhang [96] while investigating the wear of particle reinforced MMCs under different applied load conditions identified three different wear regimes. At low load (regime I), the particles support the applied load in which the wear resistance of MMCs are in the order of magnitude better than aluminum alloy. At regime II, wear rates of MMCs and aluminum alloy were similar. At higher load and the transition to serve wear (regime III), the surface temperature exceed a critical value. The higher loads the wear debris were size of the order of micrometers, at lower loads it is of the order of a few hundred micrometers as the load was increased the proportion of metallic wear debris increased. At the highest load the worn surface of the materials is described as classical rachetting wear [165].

3.4 Friction coefficient (μ)

The variation of friction coefficient (□) with sliding distance is shown in Fig. 5. It shows the friction coefficient of the heat treated composite specimen is lower than that of the as-cast composite. The coefficient of friction is related to the interaction of asperities between the counter surfaces. Which is in micro scale varies within the specific range throughout the test period. This may result in fluctuation on friction coefficient within a narrow range in each of the material with sliding distance. In the composite, the reinforced WC particles support the load, reduces the contact area between the pin and counter disk surface, decrease the friction coefficient [23, 24]. This is probably one of the reasons for the observed enhancement in wear resistance of the composite.

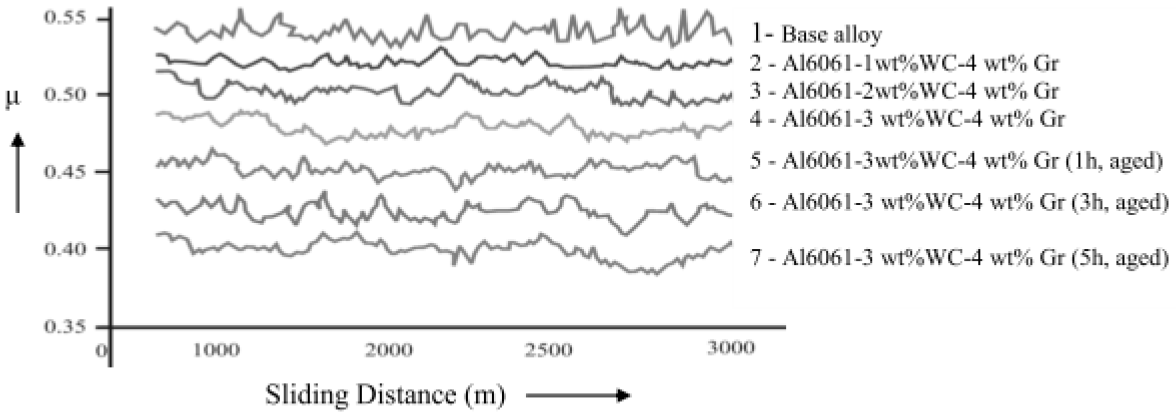


Fig. 5 Variation of friction coefficient with sliding distance

With reference to earlier investigations the higher formation of Fe rich layer on the worn surface may contribute to lower the coefficient of friction [25]. The formed layer on the worn surface of the pin is stable and substantially harder than the bulk material largely because it contains a fine mixture of Fe phase, Al and graphite. During the initial stages of sliding, the WC and Gr particulates present in the composite pin plough into the steel disk and thus create a debris mostly containing iron. Iron may be present either as iron or as iron oxide. It is reported that iron might get oxidized during this process and oxide layers, in particular Fe O layers 2 3 generated during wear, act as solid lubricants and help to reduce the wear rates [26]. Rohatgi et al. [27] studied friction and wear of Gr reinforced metal matrix hybrid composite. In larger graphite volume fractions, wear rates were very low and were independent of sliding velocity, which is due to graphite film stability. Skolianos and Kattanis [28], reported that the coefficient of friction of composite decreases with increase in wt% of reinforcement in SiC particle reinforced Al–405 % Cu/1.5% Mg alloy composites.

4.0 Conclusions

From the investigation the following conclusions were drawn.

- Addition of WC and Gr particles increases the wear resistance and mechanical properties.
- The wear resistance of the composite was considerably higher than that of the base alloy and increases with increasing WC particles up to 3 wt%.
- The hard WC particles resist against abrasive action and protect the surface, with increasing WC content the wear resistance increases.
- The results revealed the higher wear resistance in heat treated Al6061-WC-Gr composite when compared with base alloy. Hence these composites are suitable for applications in automobiles.
- Coefficient of friction of the alloy and composites varied marginally with sliding distance. Lower coefficient of friction was observed in composites.

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