A Review on Sliding Wear Behaviour of Aluminium Matrix Composites with Hybrid Reinforcements for Automotive Applications

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The aluminium matrix composites, particularly with hybrid reinforcements are the advanced materials that have been widely used as a substitute material in the transport sector, to manufacture lighter-weight and higher-performance components. As these components are often subjected to sliding wear under working conditions, therefore several of these applications require enhanced frictional and wear resistance. The purpose of the current review is therefore aimed at highlighting the focus of the current research scenario, in the field of tribological behaviour of aluminium based hybrid composites, to explore the materials for automotive applications. A significant experimental data has been reported in this area, and it has been revealed that the materials possessing high wear resistance are associated with formation of a stable tribolayer on the wear surface and the fine equiaxed wear debris. The operating variables such as applied load, sliding distance and sliding speed, temperature, wearing surface hardness, reinforcement contents and morphology have been found as critical parameters in relation to the wear regime, encountered by the material during operation. An attempt has been made to present and review the various aspects relevant to sliding wear behaviour of aluminium alloys and the hybrid composites, with different combinations of reinforcements. Further, it has been found that the cost and the weight of the aluminium matrix composites can be considerably controlled, by addition of hybrid reinforcements, without compromising the tribological properties.

Keywords: sliding wear, aluminium composites, hybrid reinforcements, ceramics, and waste materials.

1. Introduction

Metal matrix composites (MMCs), like most composite materials, provide enhanced properties over monolithic materials, such as higher strength, stiffness and weight savings [1]. Generally, there are two phases in the MMCs, i.e. a fibrous or particulate phase, distributed in a metallic matrix. The MMCs reinforced with ceramic reinforcements have shown significant improvement in tribological properties, including sliding wear resistance [2,3]. This is due to the presence of hard phase in the metal matrix, which protects the matrix from wear [4,5]. Under sliding conditions, the applied load is transferred from the ductile alloy matrix to the hard reinforcements, providing higher stress bearing capabilities to MMCs [6].

The aluminium matrix composites (AMCs) are the type of MMCs, which offer flexibility in the design of a component, by selecting suitable matrix, reinforcements

and the processing route [7]. These materials have been emerged from the perpetual need of high-performance components for automotive applications. AMCs offer the promising perspective in assisting the automotive engineers to achieve improvement in vehicle efficiency. Recent developments in this field have confirmed that the properties of these composites can be tailored, by changing the fraction, size and type of reinforcing particles, to meet a particular requirement [8-10].

The silicon carbide (SiC) and alumina (Al₂O₃) are some of the hard ceramic reinforcements, which are added to aluminium matrix to improve its mechanical strength and wear resistance. However, the use of single reinforcement in aluminium matrix may sometimes compromise the values for physical or mechanical properties. First of all, these reinforcements are denser than the aluminium matrix, and they increase the weight of the AMCs. Secondly, ceramic particles are very hard, and they increase the wear rate of the mating

counter-faces, due to the abrasive action. Therefore, these reinforcements reduce the wear resistance of the tribosystem, while improving the wear resistance of the AMCs [11]. Thirdly, the increase in hardness of the composites due to presence of hard particles makes the machining of AMCs difficult. Thus, it is essential to identify the ways to retain the positive influence of ceramic particles, while the attending these problems, simultaneously. The use of secondary reinforcement is well suited for these applications and their addition can make the design of AMCs more flexible and reliable.

1.1. Hybrid aluminum matrix composites (HAMCs)

The applications of AMCs with multiple reinforcements (hybrid composites) are continuously growing, as they are considered as a better substitute for single reinforced composites. These composites combine the properties of the ceramics with that of the secondary reinforcements, to provide aggregate characteristics profile, not exhibited by any single material [12-16]. Recent research on hybrid composite has revealed that the presence of graphite particles can reduce the wear of the composites, while agro/industrial waste products can be added to provide materials for low cost and low weight applications [17,18]. The agro/industrial waste materials like red mud, fly ash, rice husk ash (RHA) and bamboo leaf ash (BLA) are some of the green reinforcements, which can be beneficially used as reinforcements in the aluminium matrix. But, the strength level achieved by reinforcing these particles into the aluminium matrix is too less to be used for high stress bearing applications [19-21]. This may be due to presence of silica (SiO_2), which has strength much lower than the aluminium matrix. Therefore, these materials can be considered as secondary reinforcements in aluminium matrix in addition the ceramics, to obtain the candidate materials for various automotive components [22]. In addition to this, two different ceramic reinforcements can also be combined to improve mechanical performance of the composites under certain conditions.

Keeping all these issues in mind, this paper presents various aspects related to the wear behaviour of HAMCs. The wear mechanisms of pure aluminium alloys, single reinforced composites and the HAMCs containing particulate reinforcement phases are also discussed and compared. In addition to this, the significant parameters which control the wear behaviour of the composites have been identified. The study will helpful in development of database for wear properties of the HAMCs, with the use of secondary reinforcement (to either alumina or silicon carbide).

1.1.1 Reinforcements type

The focus of the selection of suitable material for tribological applications is the desired type, quantity and distribution of the reinforcements (particles and fibers) in the matrix alloy [23]. Although, the fiber reinforcements provide the most cost effective

strengthening (in a given direction), but the particle reinforced composites are more attractive, due to their cost effectiveness, isotropic properties and their ability to be processed, using similar technology used for monolithic materials. The reinforcement particles which can be reinforced into the aluminium matrix are generally classified into two categories: hard particles like SiC , Al_2O_3 and silica (hardness up to 30 GPa), which are added to improve the wear resistance properties, or soft particles like graphite and MoS_2 (hardness below 2 GPa), which are used for solid lubrication purpose [24]. Therefore, by selecting the appropriate type of reinforcement particles, it is possible to improve the wear performance of the composites.

1.1.2 Processing methods

The characteristic profile for the composites with same composition and amount of the reinforcement can also be changed by selection of manufacturing technique and the processing method. Jayaseelan et al. [25] fabricated aluminium alloy specimen with 5% silicon carbide contents, using stir casting and powder metallurgy fabrication routes, and found that the stir cast specimen possessed superior strength levels than the sample made by powder metallurgy. Further, Zhou and Xu [26] found improvement in wettability, reduction of porosity and homogeneous distribution of reinforced particles with two step stir casting, and hence better tribological properties. The addition of magnesium along with reinforcing particles has also been found to influence the wear characteristics of the AMCs. Ahlatci et al. [27] reported that the addition of magnesium also helps in improvement of wettability of particles within the alloy matrix and therefore increases the wear resistance of the composites.

1.2. Wear characteristics

The composite materials designed for wear resistance applications should be able to support heavy load, without undergoing any deformation or fracture during performance. They should also maintain controlled friction and wear over long periods, without severe surface damages as galling, scuffing or seizure. The MMCs reinforced with ceramic particulates can withstand severe wear conditions, because of their high strength [28,29]. The aluminum based MMCs possess good thermal conductivity along with reduced weight, due to which most widely preferred for these applications [30,31].

Stephens et al. [32] reported that the wear resistance normally increases with increase in the volume contents of hard ceramics and the particle size. The hard ceramic particles increase the strength and wear resistance of composites, but decrease their ductility [27,33]. The soft particles like graphite and TiO_2 acting as solid lubricants, decrease the coefficient of friction, the ductility and the strength of filled matrix [16,17]. Further, Deuis [4] reported that the materials possessing high wear resistance are influenced by the formation and

detachment of the oxide layer, on the surface of the composite under the load range used.

Although, HAMCs have the capability to offer excellent strength to weight ratio, while providing comparable wear properties, but a careful identification of the conditions through analysis and understanding of tribological parameters is a major issue for material selection and development. Moreover, contradictory results regarding the influence of the different tribological parameters on the performance of HAMCs can be found from previous investigations. Many investigators carried out experiments on the wear performance of HAMCs, against different counter surfaces under different parametric conditions. In the following section, the tribological behavior of HAMCs with different possible combinations of reinforcements have been discussed and reviewed.

2. Review and discussion

2.1. Reinforcing solid lubricants and ceramic particles

Table 1 presents the various investigations regarding influence of solid lubricant particles as partial reinforcement, into the aluminium matrix, with different type and size of reinforcements and operating parameters.

Suresha and Sridhara [34] found that the protective layer formed between the pin and the counterface, due to incorporation of graphite particles in the aluminium matrix. This behaviour may be due to the fact that the graphite particles acts as solid lubricants and reduce friction, while the ceramic particles are quite hard and produce abrasive action.

Suresha and Sridhara [34-37] reported that the wear of composites decreased with increase in the percentage

Table 1 Sliding wear investigations regarding influence of solid lubricant particles in HAMCs fabricated by stir casting method

Reference	Suresh et al. [34]	Kumar and Dhiman [38]	Elango et al. [42]	Radhika et al. [44]
Apparatus	Pin on disc	Pin on disc	Pin on disc	Pin on disc
Reinforcing Particles	SiC, Gr (Total 10% share)	SiC (7%) Gr (3%)	SiC (7.5%) TiO ₂ (0-5%)	Al ₂ O ₃ (9 mass%) Gr (3 mass%)
Size of Particles(μm)	SiC (10-20) Gr (70-80)	SiC (27-33) Gr (20-25)	SiC (25) TiO ₂ (50)	Al ₂ O ₃ (15-20) Gr (50-70)
Matrix type	LM25 (AlSi7Mg.5)	Al 7075	LM 25	AlSi10Mg
Counterpart	EN-31 Steel Ra =0.1 μm	EN 32 steel disc HRC 70	Hard steel HV 698	EN 32 steel HRC 65
Speed (m/s)	0.4-2.0	2-6	1.04 (fix)	1.5-3.5
Load (N)	15-75	20-60	29-49	20-40
Distance (m)	400-2000	2000-4000	150-475	700-2100
Mass/volume Fraction (%)	--	Response surface methodology	--	Taguchi method
%age Error	--	7	--	3.88-14
Parameters Influence	--	(1) load (2) speed, (3) distance	(1) load, (2) distance	(1) distance, (2) speed (3) load
Analysis	SEM graphs	ANOVA, SEM graphs, Regression equations	SEM, Graphs	ANOVA Regression eqn

Fig. 1 Variation of the wear with reinforcement content, sliding speed, load and sliding distance for Al/SiC/Gr hybrid composite [34]

Fig. 2 The specific wear rate of the unreinforced alloy and hybrid composite for all combination of load and sliding speed with respect to sliding distance [38]

of reinforcement and sliding speed, while with increasing load and sliding distance, the wear of the composites increased (Figure 1). With addition of solid lubricant i.e. graphite particles, the wear of the composite tends to decrease. On the other hand, the presence of silicon contents is responsible for increase in strength and the resistance to wear of composite. But, it reduces the machinability of parts, and increases the stiffness. In the study, the percentage of reinforcements for optimum wear conditions was evaluated to be 7.5%. The results obtained in this study are in line with that obtained by Stojanovic [16] i.e. the combined use of the both the hard and soft reinforcements lead to improvement of tribological and mechanical characteristics of aluminium alloys.

Kumar and Dhiman [38] fabricated hybrid composites to compare the specific wear rate of pure alloy (Al-7075), and the alloy (Al-7075) reinforced with 7 mass% of silicon carbide and 3 mass% of graphite. It was reported that the specific wear rate of the hybrid composite was lower than the pure alloy, for all combinations of operating parameters. Under low speed and low load conditions, the specific wear rate was reduced, due to formation of oxide layers, crushing of the silicon carbide particles and miniature lubricant layer formation in between work material and counter surface [39-41]. This type of the behavior was observed up to transition state, after which this trend was reversed, due to decrease in the role of the oxide layer. With an increase in the sliding distance, the specific wear rate of both the materials (alloy and composite) under investigation decreased up to transitional conditions, after which the trend was changed. The specific wear rate of these materials for all combinations of load and speed with sliding distance is shown in Figure 2.

The results obtained are in line with [16,34] that wear resistance of alloy increased with hybrid reinforcement. It was supported by the result that the Al-7075 alloy was seized during the test, while no such failure was observed for hybrid composites under investigations. A combination of different types of wear behavior was also observed for the both the materials i.e. abrasion, delamination and adhesive wear. By applying the Response Surface Methodology (RSM), the load was predicted as most influential parameter as far as specific wear rate of materials under test is concerned, followed by sliding speed and sliding distance.

According to Elango and Raghunath [42] the aluminium matrix (LM25) reinforced with hybrid reinforcements (SiC and TiO_2) possess higher strength and wear resistance, as compared to the aluminium matrix. The results of the study are presented in Figures 3(a) and 3(b), and it can be observed that the wear resistance increased, when hybrid reinforcement were added into the Al-matrix. It was also revealed in the study that the aluminum alloy exhibits more wear followed by SiC reinforced Al-matrix composites and the hybrid composites. When contents of the TiO_2 were increased

in vol% for fixed particle size, the wear rate and coefficient of friction of the composites decreased, due to lubricating nature of TiO_2 . With an increase in the load, the wear behavior was changed from mild to severe, although this change for composites takes place at higher values, as compared to unreinforced alloy. It has been revealed that the wear rate decreased, as the sliding distance was increased. This behavior of the composites is due to microstructural homogeneity with greater porosity, and poor interfacial bonding between matrix and TiO_2 particles, which further leads to the formation of oxide layers on the surface of contact. This layer acts as a protection cover on the surface of composites, and thereby reduces the wear [43].

N. Radhika et al. [44] applied Taguchi's method to generate an experimental plan, for finding the wear

Fig. 3 Wear rate of unreinforced alloy and composites at applied loads of (a) 29.43 N, (b) 39.24 N [42]

performance of the hybrid composites (Al-Si10Mg + alumina + graphite). This method significantly reduces the number of trials that are required to model the response function, compared with the full factorial design of experiments [45,46]. By applying this technique, possible interaction between the factors that influences the wear behavior was identified. The results show that sliding distance (46.8%) has the highest influence on wear rate, followed by applied load (31.5%), and sliding speed (14.1%). For coefficient of friction, the sliding distance, applied load and sliding speed have contribution of 50%, 35.7% and 7.3% respectively. Further, the regression equations were

generated to establish correlation between the significant terms obtained from ANOVA analysis. The experimental values and computed values were compared and an error associated with dry sliding wear of composites varying from 3.88% to 14.1% was predicted. In this study, the wear rate was found to increase with increase in wear load, and decrease with increase in wear speed and sliding distance [16].

2.2. Reinforcing combination of ceramic particles

Table 2 shows the previous investigations, regarding influence of combination of different ceramic reinforcements into Al matrix.

Uvaraja and Natarajan [47] applied Taguchi

Table 2 Sliding wear investigations regarding influence of ceramics in HAMCs fabricated by stir casting method

Reference	Uvaraja et al. [47]	Kumar et al. [48]	Rajmohan et al. [54]
Apparatus	Pin on disc	Pin on disc	Pin on disc
Reinforcing Particles	SiC(5-15 mass%) B ₄ C(3 mass% fix)	SiC (0-15%) Zrcon (0-15%)	SiC (10 mass%) Mica (0-6 mass%)
Size of Particles(μm)	SiC (30-70) B ₄ C(5-20)	SiC (20-32) Zr (20-32)	SiC (25) Mica(45)
Matrix type	Al 7075	LM 13	Al356
Counterpart	EN-31 Steel HRC 62	EN 32 HRC 65	EN 32 steel HRC 65
Speed (m/s)	1.5-4.5	1.6 m/s fix	0.3-1.57
Load (N)	10-40	1 kg, 5 kg	9.81-49
Distance (m)	400-2000	0-2880	--
Mass/volume Fraction (%)	vol%(5-15) SiC	--	Mica (0-5 mass%)
Time (min)	5-15	--	--
Temp.(°C)	--	50-300	--
Techniques (modelling)	Taguchi method	--	R.S.M. method
% Error	6.9-9.23	--	5
Parameters Influence	(1) vol% SiC, (2) load (3) speed	(1)Load	(1) Load (2) mass% mica, (3) Speed
Analysis	ANOVA, SEM, Regression eqns.	SEM, Graphs	ANOVA, R ² -value

technique to evaluate wear performance of the HAMCs, with different combination of hard ceramic reinforcements (SiC and B₄C). The optimum conditions for minimum wear rate and coefficient of friction were evaluated, using the developed ANOVA and the results were verified by regression equations [45].

Percentage of reinforcement (30.99%) has been found as the most influential parameter, regarding the sliding behavior of the composites, followed by applied load (29.96%) and sliding speed (29.89%), as shown in Figure 4(a) and 4(b). The error obtained with the help of ANOVA for wear rate and coefficients of friction are 10.78% and 10.65% respectively. Multiple regression values for wear rate and coefficient of friction are found to be 0.865 and 0.866 respectively. The errors with maximum values of 11.76% and 9.23% were observed for wear rate and the coefficient of friction, respectively. These values confirm that the Taguchi's method can be successfully applied for evaluating the influence of various parameters on sliding wear behaviour of the composites. It is revealed from the study that the wear rate decreases with increasing values of speed, volume fraction and time, while it increases with increasing load [16].

To study the wear behavior of composites at high temperatures, Kumar et al. [48] fabricated five composites, namely A, B, C, D and E with different compositions of zircon sand and silicon carbide particles were used as hybrid reinforcements (up to 15 mass%), to obtain required wear properties [49,50]. The microhardness of these composites with different combinations of dual reinforcements has been presented in Table 3. The higher values of microhardness for hybrid composites show that the composites with better interfacial bonding between particle and alloy matrix can be obtained, by incorporating dual reinforcements in the aluminium matrix.

Figures 5(a) and 5(b) shows the variation of the wear rate with change in temperature for dual and single reinforced composites, at the loads of 1 kg and 5 kg. The results show that when the temperature was increased

Fig. 4 (a) Main effect plot for means wear Rate, (b) Contribution % age of wear and friction coefficient [47]

from 50°C to 200°C at low load i.e. 1 kg, the wear behaviour was changed from mild to severe conditions whereas at higher load i.e. 5 kg, the oxide layers were observed to be formed, due to which the wear rate increases up to 150°C, and thereafter it decreases at

Table 3 Comparison and microhardness of five composites fabricated for investigation [48]

Composite	Total 15%wt reinforcement		Microhardness		
	SiC	ZrSiO ₄	Particle	Interface	Matrix
A	--	15	735.03	129.42	69.85
B	11.25	3.75	730.28	138.31	93.06
C	7.5	7.5	695.08	117.23	70.83
D	3.75	11.25	677.23	127.21	71.28
E	15	--	724.21	129.31	76.03

Fig. 5 Wear rate of composites versus temperature with (a) 1 kg load, (b) 5 kg load [48]

200°C temperature for all the composites. This behaviour of the composites is due to the reason that the pin protects the wear surface, due to formation of oxide layer [51]. Beyond this temperature, the transition from mild wear to severe wear takes place. The detachment of the oxide layer from the wear surface takes place, due to delamination mechanism [52]. The micrographs of the worn surfaces and debris were also studied, and it was found that with increase in temperature up to 250°C, the surface cracks were formed. Due to this, the delamination of the subsurface layers takes place, which further lead to the void nucleation and crack propagation. This mechanism results in the material removal from the wear surface in the form of plate like debris.

The depth of wear tracks on the surface increases up to a load of 5 kg due to material removal by micro cutting and microcracks were also observed in the subsurface area of the wear surface. In overall, it was found in the study that the dual reinforced composites show improved wear resistance at higher temperatures, as compared to single reinforced composites. Silicon carbide particles are more effective than zircon sand particles as reinforced in LM13 alloy, in improving the wear resistance. Composite-B (11.25% SiC and 3.75 Zircon sand) shows the highest value for micro hardness,

out of all the five composites. This will result in better wear performance under sliding conditions, due to better interface between the reinforcement particles and matrix, at all temperatures at loads of 1 kg and 5 kg.

The results also confirm that to obtain composites with better wear properties, it is necessary to have good interfacial bonding. Chawla and Shen [52] reported that direct strengthening arises in metal matrix composites, as a result of the transfer of load, from the weaker matrix to the harder and stiffer particulates, through the matrix particulate interface. When the hard particles get separated from the interface, it will results in an increase in wear rate of composites, due to reduction in the microhardness.

T. Rajmohan [54] used surface response methodology, to analyze the influence of various parameters on the wear loss of the HMACs. The aim of the study was to evaluate the controllable parameters that will results in optimization of response, by satisfying all the constraints [55]. The analysis of variance was carried out, and the predicted values were found to be very close to the experimental results, which show the validity of the applied method. As the sliding velocity was increased the wear loss decreased reasonably, while the wear loss was increased with increase of load. Results indicate that due to incorporation of mica particles, the wear loss reduced, while the density increased. The results of the ANOVA indicated that load is the main parameter influencing the wear loss of composites, followed by mass fraction of mica. It is inferred from the study that as the load was increased, the wear behaviour of the composites changed from abrasion to delamination [56,57].

2.3. Reinforcing agro waste material and ceramic particle

The wear properties of various HMACs fabricated by incorporation of agro/industrial waste materials, along with ceramic particles (either silicon carbide or alumina), as investigated by various authors are presented in Table 4.

Alename et al. [58] investigated the wear behaviour of HMACs partially reinforced with agro industrial waste ashes. The aim of the work was to explore the possibilities of developing low cost materials. Al-Mg-Si alloy matrix was reinforced with rice husk ash (RHA) and silicon carbide (SiC), in weight ratios of 0:1, 1:3, 1:1, 3:1, and 1:0, to prepare 5, 7.5 and 10 mass% of the reinforcements. For 5 mass% reinforcement phase, the hybrid composites with 1:3 weight ratios of RHA and SiC were having least coefficient of friction, while the hybrid composites with 1:1 and 3:1 weight ratios of RHA and SiC were having coefficients of friction comparable to that single reinforced composites (either SiC or RHA). The results indicate that the use of RHA as a complementary reinforcement in hybrid composites do not degrade the coefficient of friction, and therefore the wear resistance properties. Thus, RHA can be significantly used to produce low cost composites. The

Table 4 Sliding wear investigations regarding influence of agro-industrial waste in HAMCs fabricated by stir casting method

Reference	Alaneme et al. [58]	Alaname et al. [61]
Apparatus	Tribometer	Tribometer
Reinforcing Particles	SiC, RHA total (5, 7.5, 10 mass%)	Al ₂ O ₃ (6-8 mass%) RHA (2-4 mass%)
Size of Particles (µm)	SiC (28) RHA (50)	Al ₂ O ₃ (28) RHA (50)
Matrix type	Al-Mg-Si	Al-Mg-Si
Counterpart	--	Hard Tungsten Carbide Ball
Load (N)	25	25
Time (minutes)	0-16	0-16
Parameters Influence	mass% RHA	mass% RHA
Analysis	SEM, Graphs	SEM, Graphs

Al based alloy matrix, as usual, had the highest coefficient of friction among all the materials. For 7.5 mass% (RHA & SiC) reinforcement phase, the hybrid composites developed in different weight ratios also showed comparable coefficient of friction with SiC reinforced composites.

When the hybrid composites were fabricated with 10 mass% reinforcement phase, it was observed that the coefficient of friction decreased with higher RHA contents, when compared with other hybrid composites grade, means an increase in the wear resistance of composites. The results are also supported by the SEM graphs of the wear surface, which show the sign of adhesive wear mechanism due to accumulation of wear debris in most of the cases under investigation. The higher values for coefficient of friction results from adhesive of these wear debris on the surface of these composites [59,60].

According to Alename et al. [61], rice husk ash (RHA) and alumina (Al₂O₃) can be successfully used as hybrid reinforcements to develop HAMCs. The RHA was added in 2,3 and 4 mass% with alumina, to develop 10 mass% of reinforcement phase in Al-Mg-Si alloy matrix. The coefficient of friction was used to investigate the wear properties of the hybrid composites. The composites developed by reinforcing alloy matrix with 10 mass% alumina had least coefficient of friction, i.e. lower wear rate as compared to hybrid composites,

and its value remained constant for the whole time (i.e. 1000 seconds) under investigations. It is also supported by the results for the hardness for all the composites, which is highest for single reinforced (Al-Mg-Si matrix-10 mass% Al₂O₃) composite. Thus, it will undergo less plastic deformation as compared to the hybrid composites, and hence it will show lower friction coefficient [59].

The wear mechanism of the composites was observed to transform from predominant abrasive wear to adhesive wear with increase in RHA mass%. Detailed examination of wear tracks of single reinforced Al-Mg-Si matrix-10 mass% Al₂O₃ composite reveal the features associated mainly with abrasive mechanism. In case of Al-Mg-Si/8 mass% Al₂O₃/2 mass% RHA hybrid composite, the presence of abrasive wear is clearly evident from the formation of long grooves inside the wear tracks, while the signs of adhesive wear can be concluded from the patches of removed materials, which are glued to the worn surfaces [60,62]. For the case of Al-Mg-Si/6 mass% Al₂O₃/4 mass% RHA hybrid composite, the predominant wear mechanism is adhesive, which is responsible for increase in coefficient of friction with time. The wear rate increased with time, due to the fact that the pieces of worn surfaces get welded to the surface of aluminium composite, and adhere the sliding motion of the hard tungsten pin against the surface.

2.4. Influence of mechanically mixed layer (MML)

During the sliding of wear surface against the hard pin, the frictional contact takes place and high temperature is developed at the surface. The metal present in the specimen reacts with the oxygen of atmosphere to form their respective oxides. These oxides form a continuous film over the entire wear regime and reduce the wear rate from the surface. This oxide layer is known as mechanically mixed layer (MML) and influences the wear behaviour of composites. This layer has hardness much higher than the hardness of aluminium composites.

According to Rajmohan et al. [54], wear loss starts decreasing, when the sliding speed is increased beyond a limit, known as transitional speed, due to increase in temperature and softening of the Al/SiC/mica hybrid composites. The similar type of results were also obtained in other investigations i.e. the formation of MML reduces the wear rate [38,42,47,48]. The formation of the oxide layer avoids the metal to metal contact at normal load and normal speed conditions, and hence reduces the coefficient of friction. Under severe load and velocity conditions, these films get deformed and the contact between two metals starts. Thus, the oxide films reduce the interaction between the asperities, and avoid adhesive wear. Due to this, the wear loss is

less for mica reinforced hybrid composites even at high loads.

The results obtained are in agreement with the results of Srinivasan et al. [63], who also found that the presence of oxide films reduces wear. These films are distributed uniformly throughout the worn surface, and on further sliding it is converted into wear debris. Basavarajappa et al. [16] have observed that the wear rate of Al 2219/SiC/Gr hybrid composites, decreases as the speed increases up to 4.5 m/s. The iron particles present in the counterface gets oxidized, to form a protective layer, during sliding conditions against the hard SiC particles. According to Li and Tandon [64], the wear rate of the Al-composites is influenced by the presence of MML in the load range used. Due to presence of the MML, the transition of mild to severe wear can be delayed. Once this layer is removed from the wear surface, the direct contact takes place between the wear surface and the counterface. The MML cannot be formed again, which leads to reduction of frictional force [65]. The observations indicate that the MML formed with material comes from three sources: the counterface, the matrix and the particles.

The process of formation and separation of the MML can be confirmed from the micrographs of the worn surfaces. The SEM examination of the worn

Fig. 6 Wear surface of hybrid composite with 3% mica reinforcement under (a) load of 49.05 N and sliding speed of 1.57 m/s, (b) under load of 9.81 N and sliding speed 0.837 m/s, (c) under load of load 28.43 N and sliding speed of 0.381 m/s [54]

surfaces of mica reinforced hybrid composites at different loads and velocities is presented in Figures 6(a) to 6(c) [54]. These micrographs show numerous long grooves and these craters on the worn surfaces with increase of load to 49.05 N, at sliding speed of 1.57 m/s. The rows of furrow and delamination are the signs of plastic deformation. The wear tracks clearly indicate the presence of MML on the wear surface, which suggests that the sliding motion between hard pins and wear surface generates heat, and influences the wear rate. These films are uniformly distributed throughout the worn surface, and eventually broke off, to form wear debris. The frictional heat during the wear contributes to oxidation of finer debris more easily than the coarser ones.

The results of the previous investigations reveal that the formation of MML on the wear surface of unreinforced alloy and the HAMCs delays the transition of wear behaviour from mild conditions to severe conditions, under dry sliding conditions [38]. However, the MML is stable under low loads and sliding velocities and unstable under higher loads and sliding velocities for unreinforced alloy. But in the case of HAMCs, the MML is stable even under higher loads and velocities. This may be due to the presence of hard ceramic reinforcements in the HAMCs, which increases the hardness of the MML at higher temperatures. Due to this, the detachment of the MML gets delayed and it will ultimately lead to superior wear properties of the HAMCs as compared to matrix alloys, for all combination of operating parameters.

3. Future prospects of HAMCs

3.1. Material selection

In future, every organisation is concentrating on development of equipments and machine components, which consumes least possible energy. To achieve this target, there is need of lighter and smarter materials. HAMCs have come as a solution to this very specific material requirement. Currently, the efforts are made to develop HAMCs, with use of high quality and low cost/weight reinforcements from industrial waste. The alternative materials produced from solid wastes will exhibit good market potential, to fulfil the requirements in various applications due to environmental friendliness, cost effectiveness and energy efficiency [66]. For example, red mud is one of the most inexpensive and low density reinforcement available in large quantities as solid waste by-product, during production of aluminum from bauxite. Hence, composites with red mud as reinforcement are likely to overcome the cost barrier for wide spread automotive and small engine applications. The use of aluminium as a matrix material will reduce energy consumption, because it is a lighter material. Red mud as a complementary reinforcement will overcome the cost barrier, while the SiC will provide the requisite strength

to the aluminium matrix.

3.2. Wear performance

The HAMCs have shown the capability to offer more flexibility, in the design and manufacturing of automotive components, such as brake rotors, engine blocks, cylinder liners, pistons, gears, valves, pulleys, suspension parts etc. Therefore, the need of hour is to explore these materials for sliding wear applications. This can be achieved by finding the wear characteristics of these materials under the influence of different controllable parameters, as they exert a very strong effect on the wear of composites [67]. The wear of composites against the counterface can also discussed depending on the characteristics of worn surfaces, the wear debris and tribo-induced layers [68]. These findings can contribute to evaluation of tribological properties of these composites, based on a large variety of experimental data, obtained with different wear test methods. The database regarding the wear performance will enhance the applications of HAMCs for various automotive components, under sliding wear conditions.

4. Conclusions

Review of the prior investigations on the tribological properties of HAMCs provides several conclusions, regarding the influence and interaction of the reviewed parameters and the wear performance characteristics of the composites:

- The incorporation of solid lubricant particles as partial reinforcement in aluminium matrix increases the wear resistance of composites, while the use of agro/industrial wastes like rice husk ash as a partial reinforcement has also shown great promise for wear resistance applications. It also confirmed that the combination of hybrid ceramic reinforcements can also offer better or comparable tribological properties, under optimized controllable parameters.
- The wear rate, wear loss, coefficient of friction and morphology of the wear surfaces can be used to measure the wear performance of the composites. Under low load and low speed conditions the abrasion of the wear surface takes place, while at their higher values the adhesion or thermally activated severe wear starts, which is responsible for the wear tracks on the surface. Further, the sub surface cracks i.e. delamination of the composites can leads to the failure, due to formation of microcracks in the subsurface.
- Although material parameters, like normal load and sliding distance appear to be the principal interacting parameters, but it may be expected that the sliding velocity indirectly affects the subsurface behaviour through subsurface crack propagation, friction and temperature change.
- The techniques like Taguchi method, surface response methodology can be successfully applied,

to find the influence of controllable parameters, on the wear performance of the HAMCs. The wear rate generally increases with increase in the load and the sliding distance, while it decreases with increase in velocity and percent reinforcements. The change in this trend may be due to the formation and separation of the oxide layers.

- Evaluation of tribological performances of HAMCs needs to consider both reinforced part and unreinforced counterpart performances, for achieving a true tribosystem optimization.
- HAMCs possess better wear performance than the unreinforced alloys, and the improvement of wear resistance provided by hard ceramic reinforcement are more effective at elevated temperatures (150°C and 250°C), than at environmental temperature.
- Finally there is an immense potential, scope and opportunities for the researchers, in the field of prediction and improvement of tribological properties of the HAMCs. Although, utilization of low cost/waste reinforcement materials will remain a challenge for future, but the adequate database regarding the wear behavior of hybrid composites can help to enhance their applications in automotive industry. This can be achieved by conducting experimentation on these materials under different working conditions and analyzing the results for optimum conditions.

References

- [1] Chawla, N. and Chawla, K. K., "Metal Matrix Composites," Springer-Verlag, New York, 2005, 401.
- [2] Sannino, A. P. and Rack, H. J., "Dry Sliding Wear of Discontinuously Reinforced Aluminium Composites: Review and Discussion," *Wear*, 189, 1-2, 1995, 1-19.
- [3] Sinclair, I. and Gregson, P. J., "Structural Performance of Discontinuous Metal Matrix Composites," *Material Science and Technology*, 13, 9, 1997, 709-726.
- [4] Deuis, R. L., Subramanian, C. and Yellup, J. M., "Dry Sliding Wear of Aluminium Composites- A Review," *Composite Science and Technology*, 57, 4, 1997, 415-435.
- [5] Suresha, S. and Sridhara, B. K., "Effect of Addition of Graphite Particulates on the Wear Behaviour in Aluminum-Silicon Carbide-Graphite Composites," *Materials and Design*, 31, 4, 2010, 1804-1812.
- [6] Chawla, N. and Shen, Y., "Mechanical Behavior of Particle Reinforced Metal Matrix Composites," *Advanced Engineering Materials*, 3, 6, 2001, 357-370.
- [7] Surappa, M. K., "Aluminium Matrix Composites: Challenges and Opportunities," *Sadhana*, 28, 1-2, 2003, 319-334.
- [8] Gurcan, A. B. and Baker, T. N., "Wear Behaviour of AA 6061 Aluminium Alloy and its Composites," *Wear*, 188, 1-2, 1995, 185-191.
- [9] Taha, M. A., "Practicalization of Cast Metal Matrix Composites," *Materials and Design*, 22, 6, 2001, 431-441.
- [10] Ahlatci, H., Candan, E. and Cimenoglu, H., "Effect of Particle Size on the Mechanical Properties of 60 Vol.% SiCp Reinforced Al Matrix Composites," *Zeitschrift fur Metallkunde*, 93, 4, 2002, 330-333.
- [11] Song, J. I. and Han, K. S., "Effect of Volume Fraction of Carbon Fibers on Wear Behavior of Al/Al₂O₃/C Hybrid Metal Matrix Composites," *Composite Structures*, 39, 3-4, 1997, 309-318.
- [12] Dolata-Grosz, A. and Wieczorek, J., "Tribological Properties of Hybrid Composites Containing Two Carbide Phases," *Archives of Materials Science and Engineering*, 28, 3, 2007, 149-155.
- [13] Rooy, E. L., "Aluminum and Aluminum Alloys, Metals Handbook," ASM International, 1988, 15, 770.
- [14] Chen, R., Iwabuchi, A., Shimizu, T., Mifune, H. and Shin, H. S., "The Sliding Wear Resistance Behavior of NiAl and SiC Particles Reinforced Aluminum Alloy Matrix Composites," *Wear*, 213, 1-2, 1997, 175-184.
- [15] Mahendra, K. V. and Radhakrishna, K., "Characterization of Stir Cast Al-Cu-(fly ash + SiC) Hybrid Metal Matrix Composites," *Journal of Composite Materials*, 44, 8, 2010, 989-1005.
- [16] Basavarajappa, S., Chandramohan, G., Mukund, K., Ashwin, M. and Prabu, M., "Dry Sliding Wear Behavior of Al 2219/SiCp-Gr Hybrid Metal Matrix Composites," *Journal of Materials Engineering and Performance*, 15, 6, 2006, 668-674.
- [17] Stojanovic, B., Babic, M., Mitrovic, S., Vencel, A., Miloradovic, N. and Pantic, M., "Tribological Characteristics of Aluminium Hybrid Composites Reinforced with Silicon Carbide and Graphite- A Review," *Journal of Balkan Tribology Association*, 19, 1, 2013, 83-96.
- [18] Lancaster, L., Lung, M. H. and Sujan, D., "Utilization of Agro-Industrial Waste in Metal Matrix Composites: Towards Sustainability," *World Academy of Science, Engineering and Technology*, 7, 1, 2013, 25-33.
- [19] Prasad, S. D. and Krishna, R. A., "Production and Mechanical Properties of A356.2/RHA Composites," *International Journal of Advanced Science and Technology*, 33, 2011, 51-58.
- [20] Prasad, S. D. and Krishna, R. A., "Tribological Properties of A356.2/RHA Composites," *Journal of Material Science and Technology*, 28, 4, 2012, 367-372.
- [21] Zuhailawati, H., Samayamutthirian, P. and Mohd Haizu, C. H., "Fabrication of Low Cost

- Aluminium Matrix Composite Reinforced with Silica Sand,” *Journal of Physical Science*, 18, 1, 2007, 47-55.
- [22] Noguchi, M. and Fukizawa, K., “Alternate Materials Reduce Weight in Automobiles,” *Advanced Materials and Processes*, 243, 6, 1993, 20-26.
- [23] Miyajima, T. and Iwai, Y., “Effects of Reinforcements on Sliding Wear Behavior of Aluminium Matrix Composites,” *Wear*, 255, 1-6, 2003, 606-616.
- [24] Krishnamurthy, L., Sridhara, B. K. and Budan, D. A., “Comparative Study on the Machinability Aspects of Aluminium Silicon Carbide and Aluminium Graphite Composites,” *Materials and Manufacturing Processes*, 22, 7-8, 2007, 903-908.
- [25] Jayaseelan, V., Kalaichelvan, K., Kannan, M. and Vijay, A. S., “Extrusion Characteristics of Al/SiC by Different Manufacturing Process,” *International Journal of Applied Engineering Research*, 1, 1, 2010, 194-199.
- [26] Zhou, W. and Xu, Z. M., “Casting of SiC Reinforced Metal Matrix Composites,” *Journal of Materials Processing Technology*, 63, 1-3, 1997, 358-363.
- [27] Ahlatci, H., Kocer, T., Candan, E. and Cimenoglu, H., “Wear Behaviour of Al/(Al₂O₃p/SiC_p) Hybrid Composites,” *Tribology International*, 39, 3, 2006, 213-220.
- [28] Zhan, Y. and Zhan, G., “Graphite and SiC Hybrid Particles Reinforced Copper Composite and Its Tribological Characteristic,” *Journal of Material Science Letters*, 22, 15, 2003, 1087-1089.
- [29] Mata, M and Alcalá, J., “The Role of Friction on Sharp Indentation,” *Journal of the Mechanics and Physics of Solids*, 52, 1, 2004, 145-165.
- [30] Vencl, A., Rac, A. and Bobić I., “Tribological Behaviour of Al-Based MMCs and their Application in Automotive Industry,” *Tribology in Industry*, 26, 3-4, 2004, 31-38.
- [31] Surappa, M. K., Prasad, S. V. and Rohatgi, P. K., “Wear and Abrasion of Cast Al-alumina Particles Composites,” *Wear*, 77, 3, 1982, 295-302.
- [32] Stephens, J. J., Lucas, J. P. and Hosking, F. M., “Cast Al-7 Si Composites: Effect of Particle Type and Size on Mechanical Properties,” *Scripta Metallurgica*, 22, 8, 1988, 1307-1312.
- [33] Umanath, K., Selvamani, S. T. and Palanikumar, K., “Friction and Wear Behaviour of Al6061 Alloy (SiC_p + Al₂O₃p) Hybrid Composites,” *International Journal of Engineering Science and Technology*, 3, 7, 2011, 5441-5451.
- [34] Suresha, S. and Sridhara, B. K., “Wear Characteristics of Hybrid Aluminium Matrix Composites Reinforced with Graphite and Silicon Carbide Particulates,” *Composites Science and Technology*, 70, 11, 2010, 1652-1659.
- [35] Suresha, S. and Sridhara, B. K., “Effect of Addition of Graphite Particulates on the Wear Behaviour in Aluminium-Silicon Carbide-Graphite Composite,” *Materials and Design*, 31, 4, 2010, 1804-1812.
- [36] Suresha, S. and Sridhara, B. K., “Effect of Silicon Carbide Particulates on Wear Resistance of Graphitic Aluminium Matrix Composites,” *Materials and Design*, 31, 9, 2010, 4470-4477.
- [37] Suresha, S. and Sridhara, B. K., “Friction Characteristics of Aluminium Silicon Carbide Graphite Hybrid Composites,” *Materials and Design*, 34, 2012, 576-583.
- [38] Kumar, R. and Dhiman, S., “A Study of Sliding Wear Behaviors of Al-7075 and Al-7075 Hybrid Composite by Response Surface Methodology Analysis,” *Materials and Design*, 50, 2013, 351-359.
- [39] Dieter, G. E., “Mechanical Metallurgy SI Metric Edition,” McGraw-Hill Book Company, UK, 1988, 739.
- [40] Asif, M., Chandra, K. and Misra, P. S., “Development of Aluminium Based Hybrid Metal Matrix Composites for Heavy Duty Applications,” *Journal of Minerals and Materials Characterization and Engineering*, 10, 14, 2011, 1337-1344.
- [41] Pai, B. C., Ramani, G., Pillai, R. M. and Satyanarayana, K. G., “Review-Role of Magnesium in Cast Aluminium Alloy Matrix Composites,” *Journal of Materials Science*, 30, 8, 1995, 1903-1911.
- [42] Elango, G. and Raghunath, B. K., “Tribological Behavior of Hybrid (LM25Al + SiC+ TiO₂) Metal Matrix Composites,” *Procedia Engineering*, 64, 2013, 671-680.
- [43] Ravikiran, A. and Surappa, M. K., “Effect of Sliding Speed on Wear Behaviour of A356 Al-30 wt.% SiC_p MMC,” *Wear*, 206, 1-2, 1997, 33-38.
- [44] Radhika, N., Subramanian, R. and Prasat, S. V., “Tribological Behaviour of Aluminium/ Alumina/ Graphite Hybrid Metal Matrix Composite using Taguchi’s Techniques,” *Journal of Minerals and Materials Characterization and Engineering*, 10, 5, 2011, 427-443.
- [45] Taguchi, G. and Konishi, S., “Taguchi Methods, Orthogonal Arrays and Linear Graphs, Tools for Quality Engineering,” Dearborn, MI: American Supplier Institute, 1987, 35-38.
- [46] Chauhan, S. R., Kumar, A., Singh, I. and Kumar, P., “Effect of Fly Ash Content on Friction and Dry Sliding Wear Behavior of Glass Fiber Reinforced Polymer Composites-A Taguchi Approach,” *Journal of Minerals and Materials Characterization and Engineering*, 9, 4, 2010, 365-387.
- [47] Uvaraja, V. C. and Natarajan, N., “Optimization of Friction and Wear Behaviour in Hybrid Metal Matrix Composites using Taguchi Technique,”

- Journal of Minerals and Materials Characterization and Engineering, 11, 8, 2012, 757-768.
- [48] Kumar, S., Panwar, R. S., and Panday, O. P., "Effect of Dual Reinforced Ceramic Particles on High Temperature Tribological Properties of Aluminum Composites," *Ceramics International*, 39, 6, 2013, 6333-6342.
- [49] Kumar, S., Sharma, V., Panwar, R. S. and Pandey, O. P., "Wear behavior of Dual Particle Size (DPS) Zircon Sand Reinforced Aluminum Alloy," *Tribology Letters*, 47, 2, 2012, 231-251.
- [50] Panwar, R. S. and Pandey, O. P., "Analysis of Wear Track and Debris of Stir Cast LM13/Zr Composite at Elevated Temperatures," *Materials Characterization*, 75, 2013, 200-213.
- [51] Okafor, E. G. and Aigbodion, V. S., "Effect of Zircon Silicate Reinforcements on the Microstructure and Properties of as Cast Al-4.5Cu Matrix Particulate Composites Synthesized Via Squeeze Cast Route," *Tribology in Industry*, 32, 2, 2010, 31-37.
- [52] Martinez, M. A., Martin, A. and Llorca, J., "Wear of SiC-Reinforced Al-Matrix Composites in the Temperature Range 20-200°C," *Wear*, 193, 2, 1996, 169-179.
- [53] Chawla N. and Shen Y., "Mechanical Behavior of Particle Reinforced Metal Matrix Composites," *Advanced Engineering Materials*, 3, 6, 2001, 357-370.
- [54] Rajmohan, T., Palanikumar, K. and Ranganathan, S., "Evaluation of Mechanical and Wear Properties of Hybrid Aluminium Matrix Composites," *Transactions of Nonferrous Materials Society of China*, 23, 9, 2013, 2509-2517.
- [55] Rajaram, G., Kumaran, S. and Srinivasa Rao, T., "High Temperature Tensile and Wear Behaviour of Aluminum Silicon Alloy," *Materials Science and Engineering A*, 528, 1, 2010, 247-253.
- [56] Surappa, M. K. and Sudarshan, "Dry Sliding Wear of Fly Ash Particle Reinforced A356 Al composites," *Wear*, 265, 3-4, 349-360.
- [57] Rajmohan, T. and Palanikumar, K., "Modeling and Analysis of Performances in Drilling Hybrid Metal Matrix Composites using D-optimal Design," *The International Journal of Advanced Manufacturing Technology*, 64, 9-12, 2012, 1249-1261.
- [58] Alaneme, K. K., Adewale, T. M. and Olubambi, P. A., "Corrosion and Wear Behaviour of Al-Mg-Si Alloy Matrix Hybrid Composites Reinforced with Rice Husk Ash and Silicon Carbide," *Journal of Material Research and Technology*, 3, 1, 2014, 9-16.
- [59] Onat, A., "Mechanical and Dry Sliding Wear Properties of Silicon Carbide Particulate Reinforced Aluminium-Copper Alloy Matrix Composites Produced by Direct Squeeze Casting Method," *Journal of Alloys and Compounds*, 489, 1, 2010, 119-124.
- [60] Alidokht, S. A., Abdollah-zadeh, A., Soleymani, S. and Assadi H., "Microstructure and Tribological Performance of an Aluminium Alloy Based Hybrid Composite Produced by Friction Stir Processing," *Materials and Design* 32, 5, 2011, 2727-2733.
- [61] Alaneme, K. K. and Olubambi, P. A., "Corrosion and Wear Behaviour of Rice Husk Ash-Alumina Reinforced Al-Mg-Si Alloy Matrix Hybrid Composites," *Journal of Materials Research and Technology*, 2, 2, 2013, 188-194.
- [62] Lagiewka, M., Konopka, Z., Zyska, A. and Nadolski, M., "Examining of Abrasion Resistance Of Hybrid Composites Reinforced with SiC and C(Gr) Particles," *Archives of Foundry Engineering*, 8, 3, 2008, 59-62.
- [63] Srinivasan, M., Loganathan, C., Kamaraj, M., Nguyen, Q. B., Gupta, M. and Narayanasamy, R., "Sliding Wear Behaviour of AZ31B Magnesium Alloy and Nanocomposite," *Transactions of Nonferrous Metals Society of China*, 22, 1, 2012, 60-65.
- [64] Li, X. Y. and Tandon, K. N., "Microstructural Characterization of Mechanically Mixed Layer and Wear Debris in Sliding Wear of an Al-Alloy and an Al-Based Composite," *Wear*, 245, 1-2, 2000, 148-161.
- [65] Rao, A. K. P., Das, K., Murty, B. S. and Chakraborty M., "Microstructure and the Wear Mechanism of Grain-Refined Aluminum During Dry Sliding Against Steel Disc," *Wear*, 264, 7-8, 2008, 638-647.
- [66] Safiuddin, M., Jumaat, M. Z., Salam, M. A., Islam, M. S. and Hashim, R., "Utilization of Solid Wastes in Construction Materials," *International Journal of the Physical Sciences*, 5, 13, 2010, 1952-1963.
- [67] Rajeev, V. R., Dwivedi, D. K. and Jain, S. C., "Effect of Experimental Parameters on Reciprocating Wear Behavior of Al-Si-SiC_p Composites under Dry Condition," *Tribology Online*, 4, 5, 2009, 115-126.
- [68] Miyajima, T., Sasayama, S., Honda, T., Fuwa, Y. and Iwai, Y., "Effect of Hardness of Counterface on Dry Sliding Wear of Aluminum Matrix Composites against Steels," *Tribology Online*, 7, 1, 2012, 24-32.