Effect of Silicon Carbide Reinforcement on Wear and Tribological Properties of Aluminium Matrix Composites

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Abstract

Although Silicon Carbide (SiC) is a non-metal, however, it is highly wear resistant and also has good mechanical properties with low density, including strength at elevated temperature, thermal shock resistance and self-lubricating properties. The tribological properties of SiC reinforced composites depend mainly on the matrix, size and amount of reinforcing phase, heat treatment and fabrication techniques. The SiC reinforced aluminum matrix composites (AMCs) are new emerging material which can be tailored and engineered to obtained specific required properties for specific application. The main objective of this literature are the abrasive wear & tribological behaviour of SiC. The wear by abrasion is form of wear caused by contact between a particle and material having solid surface. Abrasive wear is the removal of material by the passage of hard asperities over a surface. Abrasion in any material is fast and severe sorts of wear and might lead to vital costs if not adequately controlled. In this paper an attempt has been made to provide a literature review on effect of intrinsic factors on wear behaviour of AMCs containing SiCp.

Keywords: *Metal matrix composites (MMCs), Aluminum matrix composites (AMCs), Silicon Carbide Particles (SiCp), Wear, Reinforcement, Abrasive*

1. Introduction

Aluminum alloys, like 2XXX, 5XXX, 6XXX and 7XXX alloy series are the most commonly utilized materials in composite fabrication and composites made from these are widely employed in the aerospace and automobile industries [1, 2]. AMCs are manufactured by incorporating reinforcement particles like SiC, B_4C, and Al_2O_3 with micron or nano-scale sized particles into matrix alloy [3]. Tribology such as frictional force is important during analysis of wear performance of materials [4]. Tribology is the study of interactions between surfaces in motion relative to each other. Friction, wear and lubrication are fundamental concerns that are related to this field [5]. It is well known that improvement in the wear resistance of aluminum matrix can be obtained by addition of ceramic particles such as SiC and $A1_20_3$ to the matrix alloys [6, 7, 8, 9]. Hashim et al. [10] reported that the distribution of the reinforcement material in the matrix must be uniform and the bonding between these should be optimized. AMCs made with SiC reinforcement particles has low density and weight, high strength at elevated temperature, high hardness and stiffness, along with improved wear resistance etc. in comparison to the base materials [11]. Particle-reinforced metal-matrix composites (MMCs) are used in brake and piston components in automobiles over the last few decades owing to their attractive friction and wear properties [7].MMCs, like most composite materials; provide improved properties over monolithic matrix, such as higher strength, stiffness, weight savings [12].Generally, fibrous or particulate are two important phases within the MMCs, which are distributed uniformly in a metallic alloy. Improvement in sliding wear resistance of MMCs is obtained by reinforcement of hard ceramic particles [13, 14]. This is due to the presence of hard particles in the matrix alloy, which protects the matrix from wear [15, 16]. Under sliding condition, the applied load is transferred from the soft matrix to the hard reinforcements, imparting high stress carrying capabilities to MMCs [17].

2. Silicon Carbide Particle (SiCp)

It is a compound of silicon and carbon and its chemical formula is SiC. It was originally produced by a high temperature electrochemical reaction of sand and carbon. Any acids, alkalis or molten salts up to 800°C do not attack SiC. In air, SiC forms a shield due to formation of silicon oxide layers at 1200°C and is able to be used up to 1600°C with no strength loss. SiC is highly wear resistant and also has attractive mechanical properties with low density, including strength at high temperature and ability to resist thermal shock. It is used in ceramics, abrasives, refractories, and other high-performance applications [18]. Wear resistance of aluminum alloys can be significantly improved by adding ceramic particles like SiC to the matrix material [6, 7, 19-22].

3. Wear

Gradual removal of a material from surfaces of solids is termed as Wear. The detached material becomes loose wear debris. Nowadays, wear particles are the subject of intensive studies [23-25]. The first experimental investigations of wear have been carried out by Hatchett [26] and Rennie [27]. Wear is the progressive loss of

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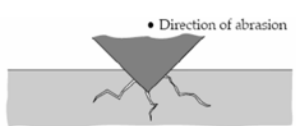
material due to rubbing action between a surface of solids and the contacting substance [28]. The wear damage may be in the form of micro-cracks or localized plastic deformation [29]. Wear of materials is the result of many mechanical, physical and chemical phenomena. Abrasive, adhesive, fatigue, fretting, erosion, oxidation and corrosion, these all are the different kinds of wear which have been recognized [30, 31]. Wear of solids is usually treated as the mechanical process except oxidation and corrosion**.** Wear by abrasive and the contact fatigue are the most important from the technological point of view.
Complete elimination of wear is very difficult, but it can be reduced. The simplest methods for reduction of friction and wear are as follows: lubrication, formation of sufficiently smooth surfaces, modification of near-surface materials of component rubbing against each other, corrects assembling of fitted component parts.

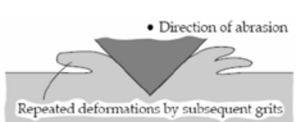
3.1 Abrasive wear

The abrasive wear of solids mainly influenced and controlled by its hardness. With reference to experimental evidence it is concluded that the wear rate of two body abrasions is linearly decreases as the hardness of material increases [32] and proportional to the normal load and size of abrasive particle for many pure metals [33]. However, the complex behavior has been observed for alloys [34-36]. The directly proportional relationship of wear resistance was observed in annealed pure metals with their hardness values but more complex for alloys [32, 37, 38]. It was originally thought that abrasive wear by grits or hard asperities closely resembled cutting by a series of machine tools. However, microscopic examination exhibits that the participation of sharpest grits are cause for cutting process. The particles may remove material by micro cutting, micro fracture, pull-out of grains individually or accelerated fatigue [39] as shown in Figure.

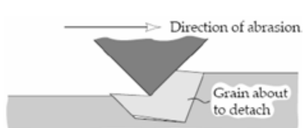
(a) Cutting



(b) fracture



(c) Fatigue by repeated ploughing



(d) Grain pull-out

Fig. Mechanism of abrasive wear [39]

4. Effect of Intrinsic Factors on Wear

Factors intrinsic to the material experiencing surface interaction are fall under intrinsic factors. The principal tribological parameters that control the wear performance of discontinuously reinforced aluminum (DRA) composites are intrinsic factors like reinforcement type [40,41], reinforcement size [40,42], size distribution [43,44], reinforcement shape [45,46], matrix microstructure [47], and finally reinforcement volume fraction [48,49].DRA composites generally exhibit enhanced wear performance when compared with unreinforced aluminum alloys [40-49].

4.1 Reinforcement type

Composites containing hard SiC, TiC, and $Al_2O_{3,}$ exhibited wear rate four to ten times lower than the unreinforced matrix alloy [50].Hosking et al. [40] reported that, at low load (0.5 N), SiC particulate are more effective than Al_2O_3 particulates in resisting wear.

G. B. Veeresh Kumar et al [51] studied the Al6061/SiC and Al7075/Al_2O_3 composites and concluded that the composites shows higher wear resistance**,** author also observed that there was significant improvement in wear resistance of composite by addition of SiC particles as compared to Al2O3 particles.

4.2 Reinforcement size

Size of reinforcing particles is the important factor which plays an important role in determining the tribological behavior of AMCs. Both, breakage of reinforcing particles and the ease of their removal from the base alloy, decide the wear resistance of composites and are affected by the size of reinforcement particle [52, 53].

Sahin et al. [54] investigated the abrasive wear performance of SiCp reinforced AMCs. The authors observed that for SiC emery paper, wear rate linearly increased with applied load, sliding distance and abrasive size while it decreased with sliding distance for Al_2O_3 paper.

Jokinen and Anderson [42] also observed that the DRA composite wear rate decreased with increasing SiC particle size for higher load (39.2 N), while at lower load (10 N), the DRA composite wear rate abruptly decreased from 5 to 13 µm and slightly increased from 13 to 29 µm particle size.

Alpas and Zhang [55] observed that DRA wear performance was consequently improved, though reinforcement size of SiC particles increases from 2.4 µm to 15.8 µm only at low load and for constant sliding speed of 0.2 m/s. Mondal et al. [56] reported that the AMCs suffer higher wear rate as compared to that of matrix alloy under 7N load and 80 µm abrasive particle size, when the SiC particles reinforcement size ranging from 50 to 80 µm.

S. Mahdavi et al. [57] studied the wear properties based on the size of SiC particles (19, 93 and 146µm). Wear behavior of Al6061/10vol%SiCp and Al6061/10vol% SiCp/5vol% graphite composites fabricated by In Situ Powder metallurgy (IPM) method were investigated using a pin-on-disk wear tester and finally authors concluded that all of the composite samples demonstrated lower wear rate, and lower friction coefficient as compared with the virgin alloy. SEM studies of the worn surfaces and wear debris revealed that in the unreinforced metallic matrix the important wear mechanism was the adhesive wear. However, in the Al/10SiCp composites, by increasing size of SiC particle from 19 to 146 µm the wear mechanism changed from adhesive to abrasive and delamination**.** Abrasive wear was the main wear mechanism for hybrid composites and was not affected by the SiC particle size.

4.3 Reinforcement shape

Wear rate decreases linearly with reduction in the grain size, attributed to the grain boundary strengthening of Al leading to strain hardening. Such behavior may be attributed to the change in the grain shape from equiaxed to columnar ones [58].The SiC reinforcement in the AMCs is more fracture resistant compared to $A1_2O_3$ and Si. The SiC particles are harder compared to other reinforcements and will provide an effective barrier to subsurface shear by the motion of the adjacent counterpart [59] and this result is likely due to differences in particles shape [60].

Wang and Rack [45] invested the wear behavior of Al7091/SiC composites with two reinforcement shape, particulate and whisker respectively. Composite was prepared via powder metallurgy route. For steady state condition, he found that at low sliding velocity, wear rate of particulates and parallel oriented whiskers were found to be 3.23 X 10^{-3} mm^3/m and 3.64 X 10^{-3} mm^3/m respectively. While at high velocity wear rate was 1.63 X 10^{-3} mm^3/m and 1.11 X 10^{-3} mm^3/m respectively. On the basis of above results author concluded that steady state wear rate depends on reinforcement shape and sliding velocities and for low velocities particulates were more efficient. But for initial run in period, especially at high velocities wear rate was found to be 28.1 X 10^{-3} mm^3/m and 13.2 X 10^{-3} mm^3/m respectively. Author concluded that for high velocities, parallel oriented whisker were more efficient than particulates, also the reinforcement shape is affected by sliding velocities.

Modi et a1. [61] Showed that reinforcement/matrix interfacial strength and the second phase shape both greatly influenced composite wear rate. Composites reinforced with SiC particles revealed an improved wear resistance than those containing SiC fibres.

4.4 Reinforcement volume fraction (V_f)

It has been reported that for composite, resistance to wear increases with increase in V_f of the reinforcement [62, 63]. The wear performance of MMCs can be enhanced by increasing the V_f of the reinforcing ceramic phase by as much as 70% [64]. Also the dry sliding wear resistance increases with increase in particle V_f. At higher V_f , the friction coefficient was found higher and there was negligible effect of load on friction coefficient [65].

Venkataraman and Sundararajan [66] also studied sliding wear rate and friction as a function of reinforcement V_f. Composite pins composed of an aluminum matrix reinforced with a SiC particles varying from 0 to 40 vol. %, were slide against a hardened steel disc. Two loads (52 and 122 N) were studied at the sliding velocity of 1 m/s. From this research it was concluded that wear rate lowered with increasing reinforcement V_f.

Rana and Stefanescu [67] found a decreasing friction coefficient owing to reinforcement in an (Al-l.5 Mg)-SiC, with a friction coefficient of 0.63 for the unreinforced, 0.45 and 0.25 for the 12.5 and 15 vol.% SiC composite respectively. However, the reduction in friction coefficient by the presence of reinforcement was controlled by the sliding speed. Wang and Rack [68] noted that an increase in reinforcement V_f resulted in a higher counterpart wear rate for both the initial run-in and steady-state wear periods.

Mahdavi and Akhlaghi [69] fabricated Al6061/SiC/Gr hybrid composites using In situ Powder Metallurgy (IPM). In this method, powder metallurgy and stir casting fabrication methods are combined into an overall net shape forming process. SiC particles (0–40 vol. %) with an average size of 19 µm, along with uncoated Gr particles (9 vol. %), was introduced to the molten 6061 Al matrix. Then, the slurries were stirred and the powder mixtures were cold pressed in six different pressures (between 250 and 750 MPa) and sintered. Then composites were heat treated and their hardness and wear properties were investigated. Author finally concluded that the wear resistance of the hybrid composite containing 20 vol. % SiC and 9 vol. % Gr is superior to the virgin alloy and the other samples. Increase in the SiC content to 20 vol. %, after a distance of 1000 m, causes reduction in volume loss and wear rate about 88%. More increasing of the SiC fraction from 20 to 40 vol. % results to increase the volume loss and wear rate by 76% and the friction coefficient of all composites is less than that of the matrix alloy sample. The friction coefficient was reduced by increasing the SiC content up to 30 vol. %.

Iwai et al. [70] fabricated Al2024/SiCw composites via powder metallurgy method, with volume fraction of whiskers ranging from 0 to 16%, were investigated by pin-on-disk tester under dry sliding conditions. The test materials of a disk were rubbed against a steel counter face pin (0.45% carbon), at 40 N load and at sliding speed of 0.1 m/s. Authors reported that the wear resistance of an Al 2024 alloy increased with the additions of SiCw in both severe and mild wear. The sliding distance corresponding to the transition from severe to mild wear was observed to reduce with increasing $\mathbf{V_f}$.

Pramila Bai et al. [71] studied the wear behaviour of A356-Al-SiCp composite under dry sliding condition and revealed that, as the weight percentage of SiC particle increased from 15 to 25, improvement in wear resistance of the composite were observed. Ma et al. [72] are under the opinion that at high sliding speeds, 50% SiCp reinforced composite exhibits lower wear rates compared with 20% SiCp reinforced composite and unreinforced A390 alloy.

Ramachandra and Radhakrishna [73] synthesized AMC (12% SiC) by using vortex method. Dry sliding tests revealed that with increase in SiC content, improvement in abrasive wear resistance and hardness of AMCs was observed. But wear has increased with increase in sliding velocity and normal load and higher micro hardness also observed near the vicinity of SiC particle.

4.5 Wettability

Wettability is the ability of the liquid to spread on a solid surface and shows the intensity of intimate contact between them [74].According to oh et al.[75] good bonding/wetting between the solid and liquid is important for the formation of satisfactory bonds between them during casting of Al-SiC composites.

D.J. Lloyd et al. [76] concluded that wettability of the second phase in the matrix and bonding strength are related to one another and compared with respect to wear performance, friction coefficient and micro-hardness value of MMCs. The decrease in the coefficient of friction and improved wear resistance are due to uniform distribution of the particle in the metallic alloys, which is due to the better wettability of the reinforcing particles with the matrix.

4.6 Heat treatment

The alloy and composites exhibit improved wear resistance after heat treatment due to improved hardness [77]. In case of cast alloy, the value of wear rate was higher than that of the heat treated alloy and composite. During the process of wear, the cracks are generally occurred at the metallic alloy and reinforcement interfaces. Heat-treated alloy and composite showed improved strength and hardness that resulted in lower tendency for crack nucleation and showed improvement in wear resistance [78, 79].

Gomez and Barrena [80] concluded that the highest wear resistance was obtained for T6 thermal treatment condition. The studies revealed that the maximum hardening of the matrix was obtained when the composite material was solubilised at a temperature of 560^0C for 3 hours, quenched in ice water at 0^0C and ageing done at 175^0C for 7 hours. It was found that greater hardness of the matrix was achieved after T6 heat treatment for 7 hours and therefore it was the one, which gave the higher wear resistance to MMCs.

Wang and Rack [81] fabricated Al2124/SiC composites by powder metallurgy route, considering different volume fraction of reinforcement (0,10,20).Wear test was conducted on pin on disc wear tester at 14.2N load and variable sliding speed. Authors reported that the abrasive wear performance of over aged Al2124/SiC composites was slightly higher than for under aged composites, but for both over and under aged composites author observed same hardness values.

Pan et al. [47] prepared Al2124/20 vol. %.SiCp composite by powder metallurgy method. Wear test was conducted on pin on disc wear tester at normal load of 168N and constant sliding speed of 2 m/s and reported that there was better wear resistance of the overaged 2124 Al-SiC composite due to less pullout of SiC particulates.

Improvement in strength of Al6061 metal matrix composites may be achieved by using T6 age hardening heat treatment. Improved hardness after heat treatment should be higher in the composites containing fewer amounts of reinforcements. For each composite sample containing different percentages of reinforcing particles have optimum aging time**.** Formation of dislocation in the reinforcement–matrix interface is caused due to the mismatch of coefficients of thermal expansions in Al alloy and reinforcing phases. As the dislocation density increases diffusion of the alloying components also increases that result to higher nucleation and growth rate of the precipitates [82–84]. The aging tendency is also speed up by the possibility of heterogeneous nucleation of metastable phases on the SiC particles [83]

5. Conclusion

Al-SiC composites have tremendous potential for tribological applications. One of the main reason for selecting SiC as reinforcement is its good wear resistance property. But for the most effective results, influence of intrinsic factors and SiC distribution in the matrix must be taken into consideration during fabrication. This review presents the views, experimental results revealed and conclusions made over the past few decades by numerous investigators in the field of SiC reinforced AMCs. All the factors have considerable effect on the tribological performance of AMCs. From the literature it can be concluded that the SiC reinforced AMCs have better wear resistance than the unreinforced alloys. Addition of ceramic reinforcement particles (SiCp) enhances the wear resistance of the matrix alloy. The amount of reinforcement and size is a strong function for increase in wear resistance of composite. The improvement in wear rate observed with abrasive size as well as with SiC content but, decreases as the size of reinforcement increases. For constant particle size, the wear rate decreases linearly with increase in SiC content. Hardness of composite increases with reinforcement content, whereas wear rate decreases. This attributes that the hardness of the materials play a very important role in controlling their wear resistance. Increasing in reinforcement volume fraction led to reduced ductility and yield strength of composites but, with lower amount of reinforcement, material shows different behavior under the condition of wear.

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