Materials Science-Poland, Vol. 24, No. 2/1, 2006

Dry sliding wear behaviour of Al 2219/SiC metal matrix composites

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The present study deals with investigations relating to dry sliding wear behaviour of the Al 2219 alloy, reinforced with SiC particles in 0–15 wt. % in three steps. Unlubricated pin-on disc tests were conducted to examine the wear behaviour of the aluminium alloy and its composites. The tests were conducted at varying loads, from 0 to 60 N and a sliding speeds of 1.53 m/s, 3 m/s, 4.6 m/s, and 6.1 m/s for a constant sliding distance of 5000 m. The results showed that the wear rates of the composites are lower than that of the matrix alloy and further decrease with increasing SiC content. As the load increases, cracking of SiC particles occurs and a combination of abrasion, delamination, and adhesive wear is observed. The samples were examined using scanning electronic microscopy after wear testing and analysed.

Key words: *MMC; Al-based MMC; SiC; casting; wear; abrasion*

1. Introduction

The adoption of lightweight and high-performance metal matrix composites (MMCs) for aerospace, automobile, and consumer-related industries have been hindered by high costs of producing components of even minimally complex shape. Casting technology may be the key to overcome this problem, although several technical challenges exist. Achieving a uniform distribution of reinforcement within the matrix is one such challenge, which directly influences the properties and quality of the composite materials. Discontinuously reinforced aluminium metal matrix composites (DRAMMCs) are a class of composite materials that have desirable properties, such as low density, high specific stiffness, high specific strength, a controlled co-efficient of thermal expansion, increased fatigue resistance, and superior dimensional stability

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at elevated temperatures [1, 2]. The most commonly employed metal matrix composite system consists of an aluminium alloy reinforced with hard ceramic particles, the latter usually being silicon carbide, alumina [3, 4] or soft particles such as graphite or talc [5, 6]. These composite materials exhibit different strengthening mechanisms in comparison to conventional materials or continuous reinforced composites [7]. Thus, much research, both experimental and analytical, has been done to gain a better understanding of the mechanical behaviour of these composites and their excellent wear resistance. With continual development in fabrication techniques, MMCs have been able to replace more conventional metallic monolithic alloys (e.g., aluminium) in applications where light weight and energy saving are important design considerations. The presences of hard reinforcement phases (particulates, fibres, or whiskers) have endowed these composites with good tribological (friction and wear) characteristics. These properties, along with good specific strength and specific modulus, make them good candidate materials for many engineering applications where sliding contact is expected. All mechanical components that undergo sliding or rolling contact, such as bearings, gears, seals, guides, piston rings, splines, brakes and clutches, are subject to some degree of wear. Wear is a surface phenomenon that occurs by the displacement and detachment of material, because it usually implies a progressive loss of weight and alteration of dimensions over a period of time.

An extensive review work on the dry sliding wear characteristics of composites base on aluminium alloys have been undertaken by Sannino et al. [8], and abrasive wear behaviour by Deuis et al. [9]. In their studies and discussions, the effect of reinforcement volume fraction, reinforcement size, sliding distance, applied load, sliding speed, hardness of the counter face and properties of the reinforcement phase which influence the dry sliding wear behaviour of this group of composites are examined in greater detail. Sliding wear rate and wear behaviour were reported to be influenced by various wear parameters [10–13]. Lim et al. [14] studied the tribological properties of Al–Cu/SiC metal matrix composites and reported that along with increasing their mechanical properties, wear resistance also increased drastically, which effects the counter face.

In view of the above description, an attempt has been made in this study to improve the dry sliding wear behaviour of Al 2219 reinforced with SiC particles (SiCp) at different loads and speeds, such that it will be more relevant and appropriate for severe environments.

2. Experimental details

2.1. Materials

The metal matrix material selected for the present investigation was based on the Al–Cu–Mg matrix alloy, designated by the American Aluminium Association as

Al 2219. This matrix alloy was chosen, since it provides an excellent combination of strength and damage tolerance both at elevated and cryogenic temperatures. The SiC particles which were used to fabricate the composite had an average particle size of 25 μm and average density of 3.2 g/cm^3. The amount of SiC particle reinforcement varied from 0 to 15 wt. % in three steps. The nominal chemical composition of the matrix alloy is given in Table1.

Table 1. Composition of Al 2219 (wt. %)

Element	Si	Fe	Cu	Mn	Mg	Zn	V	Ti	Zr	Al
Content	0.20 max.	0.30 max.	5.8–6.8	0.2–0.4	0.02 max.	0.10 max.	0.05–0.15	0.02–0.1	0.1–0.25	balance

2.2. Preparation of the composite

The liquid metallurgy technique [15–17] was used to fabricate the composite specimens. This method is the most economical route to obtain composites with discontinuous fibres or particulates. In this process, the matrix alloy (Al 2219) was first superheated above its melting temperature to create a vortex in the melt using a stainless steel mechanical stirrer coated with aluminite (to prevent the migration of ferrous ions from the stirrer material to the aluminium alloy melt). At this stage, the preheated SiC particles were introduced into the slurry and the temperature of the composite slurry was increased until it was in a fully liquid state, and the stirring was continued for about five minutes at an average stirring speed of 300–350 rpm. Passing nitrogen subsequently degassed this melt. The melt was then superheated above the liquidus temperature (7 000 ºC) and finally poured into a permanent cast iron mould of 10 mm in diameter and 50 mm high.

2.3. Microscopy studies

The fabricated Al 2219/SiCp composites were subject to metallographic examination in order to establish their structural characteristics. The composite specimens

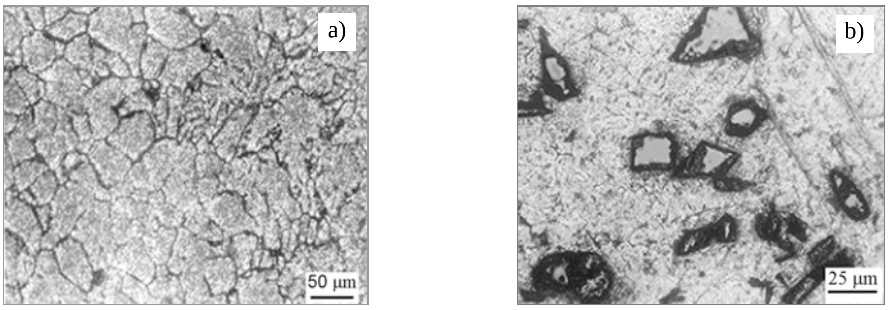

Fig. 1. Micrographs of: a) Al 2219, b) of Al 2219–10% SiCp

10 mm×20 mm in size were cut from the as-cast composite specimens for microstructural examinations. The specimens were carefully polished for metallographic examination. The samples were observed using a Carl Zeiss metallograph. Figures 1a, b show the optical micrographs of the Al 2219 alloy and its composite with a 10 wt. % of reinforcement. The figures show a uniform distribution of SiC particles in the aluminium matrix.

2.4. Wear testing of specimens

A pin-on-disc test apparatus was used to investigate the dry sliding wear characteristics of the aluminium alloy and Al-SiCp composites as per ASTM G99-95 standards. Wear specimen 10 mm in diameter and 40 mm high were cut from as-cast samples, machined, and then polished metalographically. Wear tests were conducted with loads ranging from 10 to 60 N and sliding speeds of 1.53 m/s, 3 m/s, 4.6 m/s, and 6.1 m/s for a sliding distance of 5000 m. All tests were conducted at room temperature. The initial weight of the specimens was measured using a single pan electronic weighing machine with an accuracy of 0.0001g. During the test, the pin was pressed against the counterpart rotating against an EN32 steel disc (hardness 65 HRc) by applying the load. All the specimens followed a single-track, 114mm in diameter, with a tangential force. A friction-detecting arm connected to a strain gauge held and loaded the pin specimen vertically into the rotating hardened steel disc. The frictional traction experienced by the pin during sliding was measured continuously by a PC-based data-logging system. After running through a fixed sliding distance, the specimens were removed, cleaned with acetone, dried, and weighed to determine the weight loss due to wear. The differences in weight measured before and after tests gives the wear of the composite specimen. The wears of the composite specimens were studied as a function of the volume percentage of reinforcement, sliding distance, applied load, and sliding velocity.

3. Results

3.1. Wear characteristics

Figure 2 shows the variation of wear volume loss with sliding distance for both as-cast aluminium alloy 2219 and Al-SiCp composites with varying percentages of SiCp reinforcement. It can be seen that as the sliding distance increases, the wear of both the composites as well as the unreinforced alloy increases. The wear of the unreinforced alloy is more than that of the composites for all sliding distances. Further, as the percentage of reinforcement increases, the wear of the composite decreases. There is not much change in wear during the initial phase of the sliding distance for composites with different percentages. The incorporation of SiCp particles into the Al 2219 alloy improves the sliding wear resistance as compared to the unreinforced alloy.

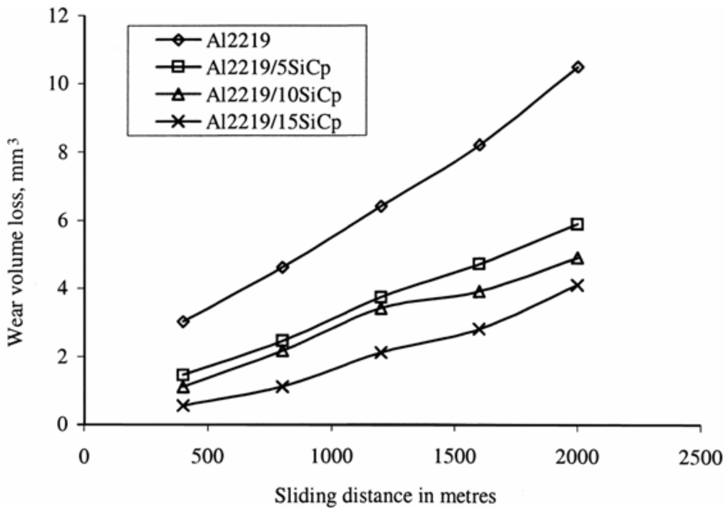

Fig. 2. Variation in volume loss with sliding distance for various composites and the alloy at a sliding speed of 1.53 m/s and load of 20 N

Figure 3 shows the variation in volume loss versus different percentages of SiCp reinforcement at different sliding distances at a constant sliding speed of 1.5 m/s and for a 40 N load for a fixed sliding distance of 5000 m. As the reinforcement content increases, the wear resistance of the composite increases. A drastic decrease in wear volume loss was observed for composites with 05 percent of SiCp. As the amount of reinforcement increases, the wear resistance increases for all sliding distances.

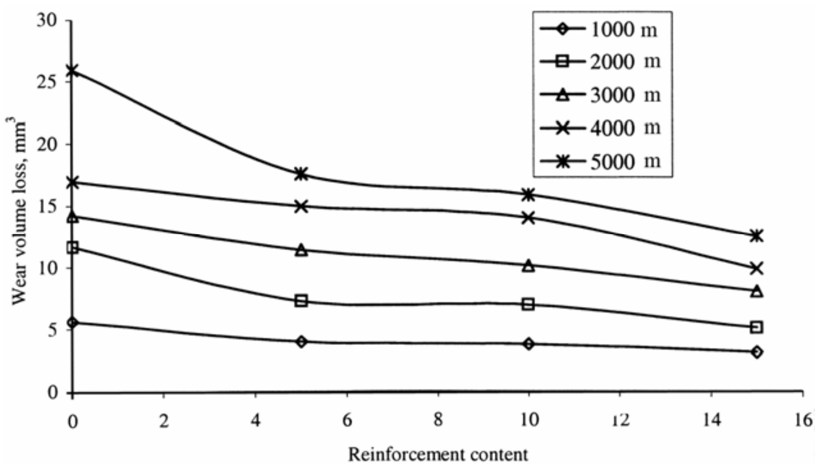

Fig. 3. Variation in volume loss vs. percentage of SiCp reinforcement at various sliding distances with a sliding speed of 1.5 m/s and 40 N load

Figure 4 shows the variation of the wear rate with sliding speed for the unreinforced alloy and for composites with different amounts of SiCp (5%, 10%, and 15%).

The wear rate of both unreinforced alloy and the composites decreases as the sliding speed increases up to 3 m/s. At a speed of 4.6 m/s, only the wear trend of the unreinforced alloy changes from mild to severe, while the composites continue to show the same trend. At a speed of 6.1 m/s, the composite wear rate curve pattern changes to severe wear. The unreinforced alloy shows seizes at 6.1 m/s, whereas as the composite does not. Further, the wear rate of the composite decreases as the amount of reinforcement. Heavy noise and vibration were observed during the process and transfer of the pin material to the disc was also observed.

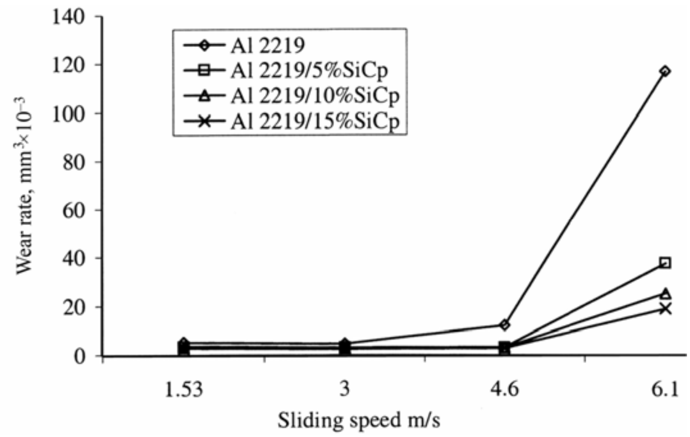

Fig. 4. Variation in wear rate with sliding speed for both composites and the alloy at a fixed load of 40 N and fixed sliding distance of 5000 m

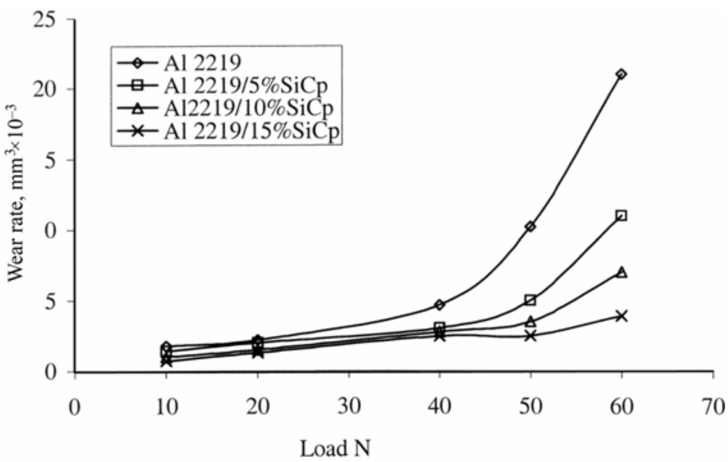

Fig. 5. Variation in wear rate with the applied load for various composites and the alloy for a fixed distance of 5000 m

Figure 5 presents the dependence of wear rate on the applied load for a fixed sliding speed of 3 m/s. Mild wear was observed for a small applied load, but as the load was further increased up to 20 N, the wear rate of the unreinforced alloy and composite increased. At the load of 20 N, the wear pattern changes for the unreinforced alloy, while the composite follows the same trend up to 50 N (the unreinforced alloy seizes at this load). At a 60 N load, the SiCp reinforced composites show a change in the wear rate pattern to severe wear. The percentage of wear rate also decreases with further increasing the reinforcement content. From the above graphs, the positive effect of the reinforcing silicon carbide particles in reducing the wear rate of materials can be seen. A similar trend was also observed independently for different wear distances as a function of load and speed.

3.2. Examination of wear test specimens

Scanning Electron Microscope (SEM) studies of the worn specimens were carried out using a JEOL model SEM. SEM Micrographs are shown in Fig. 6 of the worn

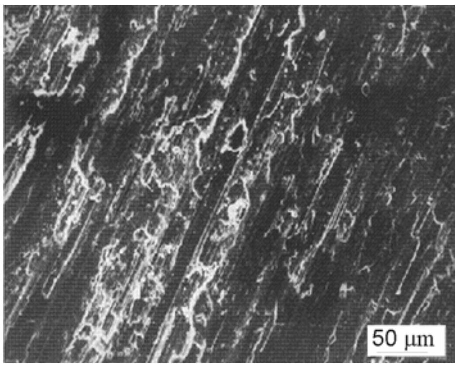

Fig. 6. The wear surface of the Al 2219/5% SiCp composite at a speed of 3 m/s and load of 20 N, after running for a distance of 5000 m

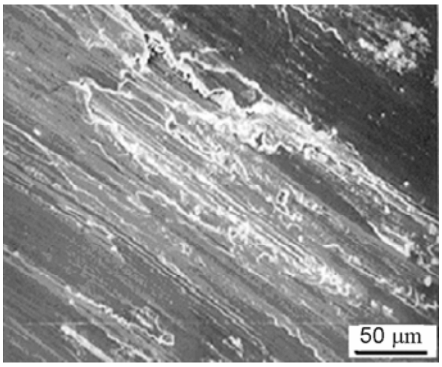

Fig. 7. SEM images of Athe l 2219/10% SiCp composite at a speed 3 m/s and a load of 40 N, after running for a distance of 5000 m

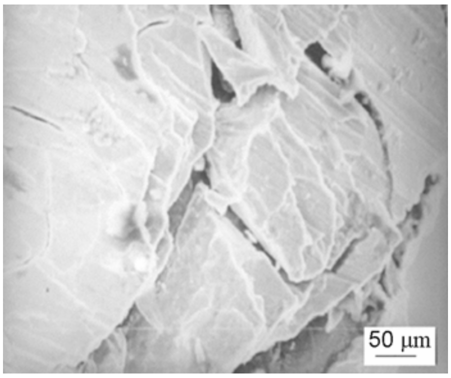

Fig. 8. SEM images of the worn surface of the composite containing 15% SiCp reinforcement after sliding 5000 m under the 40 N load and at a sliding speed of 3 m/s

surfaces of aluminium alloy 2219, for a load of 20 N, speed of 3 m/s, and distance of 5000 m. Figures. 7 and 8 show the wear track morphology of the specimens tested at a load of 40 N, sliding speed of 3 m/s, and a sliding distance of 5000 m, for 10% and 15% of SiCp reinforcement, respectively. The micrograph shows the interaction of SiCp particles with the surface of hard disc, such that the initial formation of the lubricant layer can be observed and the SiCp particles are projecting outside. The cracking of particles is also seen to initiate at a particular location. A large deformation and cracking of the surface can be observed in the specimen containing 15% reinforced composite, in which voids and particle clustering occurred. The same explanation holds even for the other composites, however, and with other sliding distances and loads. A large amount of plastic deformation was observed on the surface of the unreinforced alloy. In the case of composites containing 5% SiCp, 10% SiCp, and 15% SiCp, the worn out surfaces are not smooth. Grooves were formed by the reinforcing particles. On these surfaces, areas showing a fractured appearance can be observed.

It can be seen that a layer of material was removed as debris from the surface and that this debris is in the form of thin sheets. It has been reported that tearing (fracture) has influence on the formation of wear debris [18]. The specimen (Fig. 7) shows continuous wear grooves and cracking of flakes along the wear track. In some places, the diversion of wear grooves is also observed. When delamination wear occurs, the subsurface cracks, which may exist previously or become nucleated due to stress, propagate during the course of wear. When such subsurface cracks join with the wear surface, delamination becomes the dominant wear mechanism [19].

4. Discussion

The graphs from the wear tests show that the wear rate of the metal matrix reinforced with SiC particles reduces with increasing reinforcement content for dry sliding wear tests, and this has been confirmed by other researchers [20, 21]. The examination of the worn surfaces shows areas from where material has been removed. As the load increases, the morphology of the worn surfaces gradually changes from fine scratches to distinct grooves, and damaged spots in the form of craters can be seen [22]. The asperities of both the pin and counterface are in contact with each other and are subject to relative motion under the influence of applied load. Initially, both the surfaces are associated with a large number of sharp asperities, and contact between the two surfaces takes place primarily at these points. In the present case, the asperities of the pin also have a large number of reinforcements in the form of asperities. Under the influence of applied load and speed, when the asperities on each surface come in contact, they are either plastically deformed or remain in elastic contact. As the asperities have very sharp shapes, the effective stress on these sharp points may be more than the elastic stress, and then all these sharp asperities are plastically deformed at their contact points except for the partially projected points of the SiCp reinforcement. The other plastically deformed surface may fill the valley of the material both on pin and counterface during the course of action. Thus, there is a possibility of fracturing a few asperities on both surfaces, leading to very fine debris particles. At lower loads, the projected SiC particles in the composites will be in contact with the counterface during the course of wear. The asperities of the sliding pin surface come into contact with the steel disc surface, and are work hardened under the applied load and speed due to cold working on the surface of the pin [23]. The SiC particles are very strong in compression than in tension. Therefore, instead of the surfaces of particles cracking, they will be pushed back into the soft Al 2219 alloy. The initial run in period in all cases, the wear rate is more due to the fact that a few highly projected broken SiC particles on the pin will act as debris and plough the surface, particularly in the Al 2219-SiCp composite specimen, leaving projecting SiC in the composite.

The stress on the surface of the Al 2219 alloy is almost uniform and contact between the pin and counterface results in a larger contact area and hence larger stress and wear. The wear rate is largest in the initial period, and as the speed increases for a constant load of 40 N, the wear rate slowly decreases in the case of composites and stays almost constant in the case of unreinforced Al 2219. At speeds above 3 m/s, the wear rate starts to increase in unreinforced specimens. It is evident from the study that a combination of abrasive and delamination wear is in operation. At speeds above 6.1 m/s, only severe delamination wear is in operation, leading to the seizure of the material [24].

In SiCp reinforced composites, the wear rate approaches a minimum as the speed increases up to 4.6 m/s, beyond which abrasive wear begins to operate, and the wear pattern changes to severe at speeds above 6.1 m/s. The wear rate at the beginning is larger, because the asperities of SiC particles are not projected and the entire surface is under the same amount of stress, so that the asperities deform easily and the fractured particles and un fractured SiC particles plough the surface of the counterface and pin. When the speed increases, the ploughed surface of the counterface (i.e. steel) reacts and forms Fe_3O_4, which causes SiC particles to crush and form very minute particles [14, 25]. Fe_3O_4, Fe, and minute particles of SiC form a layer between the work hardened pin and the counterface and reduce the wear rate up to a speed of 4.6 m/s. When the speed increases to 6.1 m/s, the surface film breaks for the same combination of speed and sliding distance, and the sub surface, which had work hardened, will be under severe stress. The microscopic projections or asperities at the sliding surface form a combination of abrasive and adhesive wear [26]. The sliding forces fractures bonds, tearing metal from the pin surface and minute projections of the Al 2219 on the counterface. This further leads to the seizure of the wear surface. Thus, due to plastic deformation and fracturing, the surface becomes smoother with increasing in sliding distance.

5. Conclusions

SiC particles can be used as reinforcement material to improve the properties of the Al 2219 alloy. The microstructure of the SiCp-reinforced composite showed a reasonably uniform distribution of particles and good interfacial bonding of dispersed particles with the matrix alloy. The DRMMCs reinforced with SiCp exhibit better dry sliding wear resistance than the unreinforced Al 2219 alloy. In the present investigation, the 15% SiCp-reinforced composite exhibited better wear resistance than the other combinations of Al 2219 and SiCp. Wear rate decreases as the sliding speed increases up to 4.6 m/s for a load of 40 N, after which the wear rate also increases as the speed increases. This may be due to the work hardening of the surface, the formation of iron oxide, and crushing of the SiC particles.

The wear rate of both reinforced and unreinforced specimens increases as the load increases. The unreinforced alloy specimen seized much earlier than the composites. A combination of adhesion and delamination wear was in operation.

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Received 27 June 2005
Revised 21 November 2005