Explicit understanding of reinforcement effects on wear resistance of Metal Matrix Composites

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Abstract

The effect of reinforcement on wear mechanism of MMCs has been investigated in this paper by considering different parameters, such as, sliding distance (6 km), pressure (1.4 — 11 bar) and sliding speed (230 — 1480 rpm). The explicitness was introduced by comparing wear mechanism of an MMC and corresponding matrix material side by side under similar experimental conditions on a pin-on-disc wear machine. The pins were made of matrix material is 6061 aluminum alloy and, MMC which consists of 6061 aluminum alloy reinforced with 10 volume % Al_2O_3 particles (6–18 μm). The disc was made of steel. The major findings are: (1) MMC shows much higher wear resistance than the corresponding matrix material, (2) unlike matrix material the wear of MMC is very much linear and possible to predict easily under the conditions considered in this investigation, (3) the wear mechanism is similar for both materials other than the three body abrasion in case of MMC and (4) the reinforced particles resist the abrasion and restricts deformation of MMCs which cause high resistance to wear. These results reveal the roles of the reinforcement particles on the wear resistance of MMCs and provide a useful guide for a better control of their wear.

Key words: MMCs, particulates, aluminium, wear, pin on disc, alumina and long distance.

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INTRODUCTION

Aluminium alloys have been enormously used in aerospace and automobile industries due to superior properties, such as higher strength to weight ratio, excellent low-temperature performance, exceptional corrosion resistance, chemical inertness, etc. [1]. However, the poor high-temperature performance and wear resistance are the main weaknesses of aluminium alloys. To overcome these problems, aluminium alloys reinforced by ceramic particles, known as metal matrix composites (MMCs) have been developed [2-7]. Though the incorporation of the hard particles makes the processing of MMCs difficult [8, 9] the wear resistance of this material increases significantly [10]. This leads to the application of particle-reinforced metal-matrix composites (MMCs) in automobiles and aircrafts [11], and possibly in biomedical fields [12, 13]. The wear resistance of MMCs depends on the properties of reinforcements as well as the working condition and rubbing materials [14]. Zhang et al., [2, 3] showed that a transition from sliding wear to severe wear does occur with increasing loads. The wear rates of particular materials increase with sliding speed and then decrease because of either surface oxidation or the effects of work hardening. Jiang et al., [15] investigated the effects of load, sliding speed and longtime continuous friction on friction and wear properties of Al–5%Si–Al_2O_3 composites. They found that with the increase of load, wear loss and coefficient of friction increased. At higher sliding speed, the surface temperature of sample made the rate of the producing of oxidation layer increase, while wear loss and coefficient of friction decreased. With the increase of sliding distance, coefficient of friction increases because the adhesive in the initial stage, then formation and destruction of the oxide layer on the surface of the sample tended to a dynamic equilibrium, the surface state of the sample was relatively stable and so did the coefficient of friction. The experiment shows that the main wear mechanism of Al–5%Si–Al_2O_3 composites includes abrasive wear, adhesive wear and oxidation wear. Miranda et al., [16] assessed the contributions of metallic and ceramic reinforcements by producing aluminum–silicon hybrid composites reinforced with Ti and SiC particulates. Resistance and ductility properties (ultimate tensile strength and elongation to rupture) of AlSi-(Ti–SiC) hybrids; AlSi–SiC and AlSi–Ti composites were determined. The dry sliding behavior of AlSi, AlSi–Ti and AlSi-(Ti–SiC) composites against a Gray Cast Iron counterface was analyzed. The controlling wear mechanisms were investigated. Unreinforced AlSi specimens were tested (mechanical and wear tests) under the same conditions for comparison purposes. They found that the wear behavior of the AlSi–Ti/ Gray Cast Iron and also AlSi-(Ti–SiC)/ Gray Cast Iron tribopairs are improved when compared with the AlSi/ Gray Cast Iron system. AlSi-11.25%Ti-5%SiC hybrid composite exhibited the highest improvement in wear rate. MMCs generally demonstrate improved wear performance compare to the corresponding matrix material [17-19]. However, there are some reports where MMCs displayed wear resistance comparable to that of corresponding matrix materials under certain conditions [18, 20]. There are also inconsistent results on the effect of the different tribological parameters on the wear of MMCs [17, 20]. For example [21], decrease in the sliding wear resistance with the increase of particle volume fraction in a 2014 Al-SiC/steel [22] and Cu-Al_2O_3 composite [23] has been noted.

From the above discussion, it is clear that there have been huge investigations on the wear behavior of MMCs, but an explicit understanding on the contribution of the reinforcement on improved wear resistance of MMC is still missing. This research was conducted on a pin-on-disk wear testing unit to investigate the variables affected the wear of ceramic particle reinforced aluminium matrix composite. This paper gives a quantitative understanding on the improved wear resistance of MMCs due to addition of reinforcements for a wide range of parameters by comparing wear behavior of the alumina particle reinforced MMC and corresponding matrix material. The effects of sliding distance (6 km), load and speed will be investigated systematically by comparing wear properties of the MMC and corresponding 6061 aluminum matrix material. The role of ceramic reinforcements in improving wear resistance of MMC will be better understood by comparing these two materials.

EXPERIMENTAL PROCEDURES

The materials tested were 6061 A1 matrix alloy and its composites reinforced by 10 vol% angular shaped Al_2O_3 particles (particle size = 6–18 μm). Both of the materials were first direct chill (DC) cast and then hot-extruded. Samples of 50 mm long and 8 mm diameter were machined from a round bar of 30 cm long and 15 cm diameter. The selection of the rubbing pairs with metal-matrix composites is important as the different rubbing pairs may result in different wear behaviour. The steel components are widely used as wear counter faces in tribo-systems [21]. In addition, steels are most commonly used materials in daily life and it is likely that the MMC parts will be in contact/movement with steel parts during its practical application. Therefore, it is realistic to use steel disc as wear counter face in this investigation. A rotating hardened steel disc of 65 HRC hardness has been chosen in this investigation as the wear counter face. A Plint-Cameron pin-on-disc wear machine is used for dry sliding tests. During the sliding test the composite and matrix materials pin specimens were held against the rotating disc. The test was carried out up to the 6 km sliding distance. The surfaces of both the pins and disc were cleaned with acetone before wear test. A fixed track diameter of 80 mm was used in all tests. During wear test the steel disc was grounded after first 2 km sliding distance. Therefore the wear test was performed in two steps: first 2 km and, after 2 km with the disk grounded. One parameter was varied while keeping the others constant during testing to see the effect of individual parameters. The ranges of the three parameters are given in Table 1.

Test type	Sliding distance (km)	Pressure (bar)	Sliding speed (rpm)
Sliding distance test	6	1.4	230 (57 m/min)
Effect of pressure test	3	2.2, 3.5, 5.0, 7.0, 9.0, 11.0	230 (57 m/min)
Effect of sliding speed test	3	1.4	310, 440, 600,760 1070, 1480

Table1 Details of the wear testing conditions

RESULTS AND DISCUSSIONS

During the wear test, there were occasional high pitch sounds coming from the contact region. It is most likely to have been caused by hard ceramic particles becoming exposed to the surface and being in direct contact with the steel disk. Unlike the softer matrix material phase, the ceramic doesn’t deform plastically because of high strength ionic bonding between its constituent atoms. This suggests why the sounds remained audible for several minutes and then ceased suddenly, probably when the ceramic particles fractured or detached from the MMC. A lot less noise was heard in case of matrix material. Soft rubbing sounds (similar to light furniture being pulled across a carpet) and little if any high pitch sounds were generated. Also no grooves or scratches were seen on the steel disk after the test in case of matrix material.

Effect of Sliding Distance

The experiment was conducted at a relatively low pressure (1.4 bar) and sliding speed (230 rpm) over 6 km on each specimen. At the beginning of the wear test a freshly machined MMC specimen was brought into contact with the steel disk. The specimen face had many groves and galleys which resulted from previous machining and thus a fraction of total surface area were under wear initially. This effect disappears with the sliding distance and the specimen face becomes completely flat against the disk. Fig.1 presents the wears of MMC and corresponding matrix material with sliding distance. It shows that the MMC has almost double wear resistant compare to that of matrix material for the given sliding conditions. A linear relationship between wear and sliding distance is found for MMC. This graph was used to estimate the wear coefficient by Archard wear equation. The results showed that the MMC behaved very much in accordance with the Archard wear equation in that the volume (or mass) of material removed is proportional to the sliding distance (Fig. 1). In addition to higher wear resistant of MMC, the wear behaviour of an ex-situ reinforced material is more predictable than the unreinforced base material for the current experimental conditions. The material removed over the several thousand meters could be predicted with very good confidence simply by observing Fig. 1. This would make the MMC a much more attractive material when designing components which move over each other because it would allow for appropriate estimates of the component service life.

The wear of matrix material was severe from the beginning of the test. A large amount of the matrix material starts to attach on the steel disk. The matrix material appeared more susceptible to adhesion and abrasive wear from small asperities on the steel disk. A linear wear/distance relationship and stable wear was displayed after the steel disk was grounded at 2 km. The increased wear rate during the first 2 km sliding of matrix material happens due to the transfer of small flakes of matrix material onto the disk. The transferred layer would speed up the abrasive wear mainly for two reasons; (i) self-matted materials sliding over each other tend to have a higher friction coefficient than when the materials are different and (ii) transferred material will tend to harden and act as a large asperity which will speed up abrasive wear. After 2 km, the disk was grounded to remove transferred matrix material as wear test was not possible because of the adhesion of matrix material on the steel disk. This proved to be effective since the graph shows a more linear and stable wear of the matrix material after 2 km.

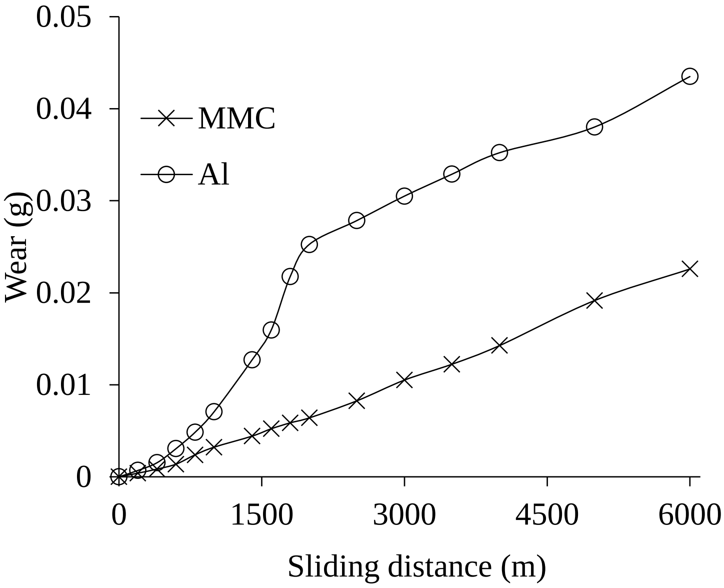
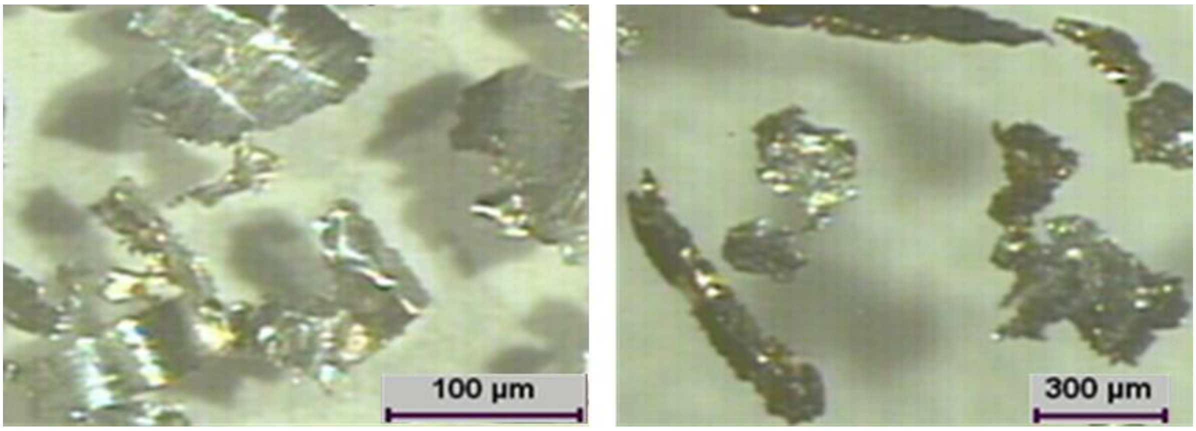


Fig. 1 Effect of sliding distance on wear of MMC and matrix material

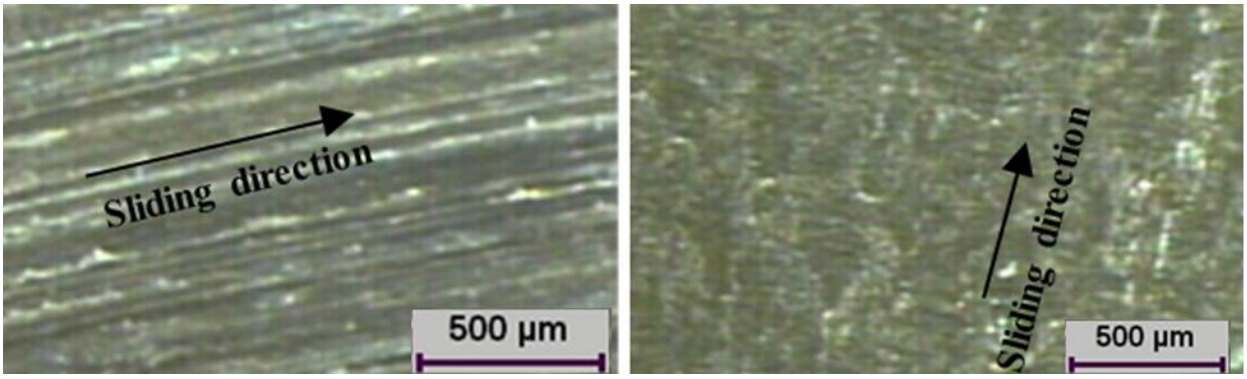
The photographs of wear debris (Fig. 2) and specimen surfaces (Fig. 3) show irregular shape and size of the debris as well as the smooth (with sliding marks) topography of both specimen surfaces after each test. These indicate that adhesion and abrasion are the primary wear mechanisms for both the MMC and matrix material [15]. The wear debris indicates that under these sliding conditions mostly adhesive and abrasive wear are happening. The debris from the MMC is dull and granular and has dimensions of around 100 µm which suggests that these are metal oxides that were dislodged from the surface. Debris from the matrix material is smaller and has a more lustrous finish than that of MMC (Fig. 2). This is probably because material was being removed at a rate which didn't allow an oxide film to form. As a result the softer and weaker matrix material was always exposed before any significant oxidation could occur.

The worn MMC surface contains discontinuous grooves while the matrix material surface is full of continuous grooves (Fig. 3). The worn surface of the MMC was relatively smooth and mostly dark with discontinuous grooves. Shinny and lustrous surface are noted around grooves. The dark regions are likely oxidation sites where a thin film of aluminium oxide must have started growing during the wear test. It is possible that ferrous oxide could also have started growing. The grooves present on the MMC specimen would have been caused by abrasive wear either from the detached alumina particles that are free in the two sliding surfaces or from grooves in the steel disk that would plough through the softer matrix material. The effect of the ceramic reinforcement is noticed by comparing the worn MMC surface (Fig. 3a) with that of matrix material surface over the same distance (Fig. 3b). On the MMC specimen the grooves appear scattered and dimpled almost as if there are some discontinuities in the line of ploughing. The grooves are evenly spaced and continuous from one end of the specimen face to the other in the matrix material. This suggests that the presence of reinforcement particles will limit the extent of abrasive wear that would otherwise happen in a monolithic metal. Abrasive wear requires one sliding surface to be predominantly harder than the other [5, 24]. When the steel disk slide along the MMC surface any asperities will plough through the matrix material but they will eventually encounter a ceramic particle. When this happens ploughing can no longer continue and the asperities will break off [6]. This doesn't happen on the matrix material surface as no reinforcements are present.



(a) Matrix material (b) MMC

Fig. 2 Wear debris of MMC and Matrix material



(a) Matrix material (b) MMC

Fig. 3 Worn surfaces of MMC and matrix material after 6 km sliding

Effect of Pressure

The effects of pressure on wear rate for MMC and matrix material are presented in Fig. 4. For MMC the wear rate is negligible until the pressure is 7 bar. The wear rate increases rapidly with further increase of pressure. This results larger wear debris and a rough MMC surface. A second transition from severe wear to sliding wear occurs with further increase of pressure (9 bar) though the rate of increase is lower than that at pressure 7 bar. This is most likely due to rapid oxidation of the surface material and work hardening. Fiction coefficients were lower in this experiment compared with the wear vs distance experiments where lower pressure was used. A possible reason for this is that the higher pressure increases surface temperature which causes more oxidation on the specimen surface. The evidence of surface oxidation was supported by progressively increase of hardness and darker regions in the surface with the increase of pressure. The presence of a metal oxide film had proved to be a valuable factor in improving the wear resistance of MMCs [8, 25, 26].

Fig. 4 also shows that the transition of sever wear for matrix material occurs at just above 2 bar which is much lower than that of MMC. The matrix material generally transfers to the steel disk and the asperities on the disk increases gradually. The adhesion of the matrix material to the disk was so severe that the disk was grinded after every test. The matrix material behaves differently because of less metallic oxide presence on the worn surfaces and formation of larger wear debris. The wear debris once again shows the presence of oxidation which explains the reduction in friction. MMC showed a wear roughly half of that of the matrix material in the wear vs sliding distance experiment at lower pressure. But when both materials have the same wear mechanism at a higher pressure the wear of MMC decreased to less than one tenth of that of the matrix material.

The enhanced wear resistance of MMC results from the hardness of the reinforced particles and the ability of such particles to resist deformation [6]. In addition to improve the resistance to adhesive wear, the ceramic reinforcements delayed the transition from mild to severe wear. The major differences between the wear mechanisms of MMC and matrix material were that the MMC had developed an oxide film and had only small irregular shaped debris. The reason for the oxide film to grow on the MMC was that the certain areas of the specimen were in contact with the disk at any time. The ceramic reinforcements not only slow the wear rate but also provide a solid base on which the metal oxide grows (Fig. 5). Matrix material wears away quickly until the oxide film is in contact with the disk as the matrix material is much softer than that of metallic oxides. At this point the hardened metal oxide does not provide enough support for the freshly exposed metal to start developing an oxide layer (Fig. 5). This film growth is not possible in matrix material as excessive material is added across the entire specimen surface. The removal of large fragments of matrix material was possible because of material being transferred over to the steel disk by adhesion. This transferred material work hardens through continuous cyclic loading and it forms very large asperities on the disk surface. Without reinforcement particles in the matrix material, the hardened asperities could easily plough through it and produce large debris. Such debris is more difficult to form in MMC because the reinforcement particles would prevent any asperities from penetrating through them. Thus, most of the surface area remains relatively intact and allow for metallic oxides to form wear debris of small size. It is evident that the oxidation occurs immediately adjacent to the areas where fresh MMC material is exposed. The specimen surfaces oxidized completely at higher pressures because of the elevated temperature and complete contact in the interface of disk and workpiece.

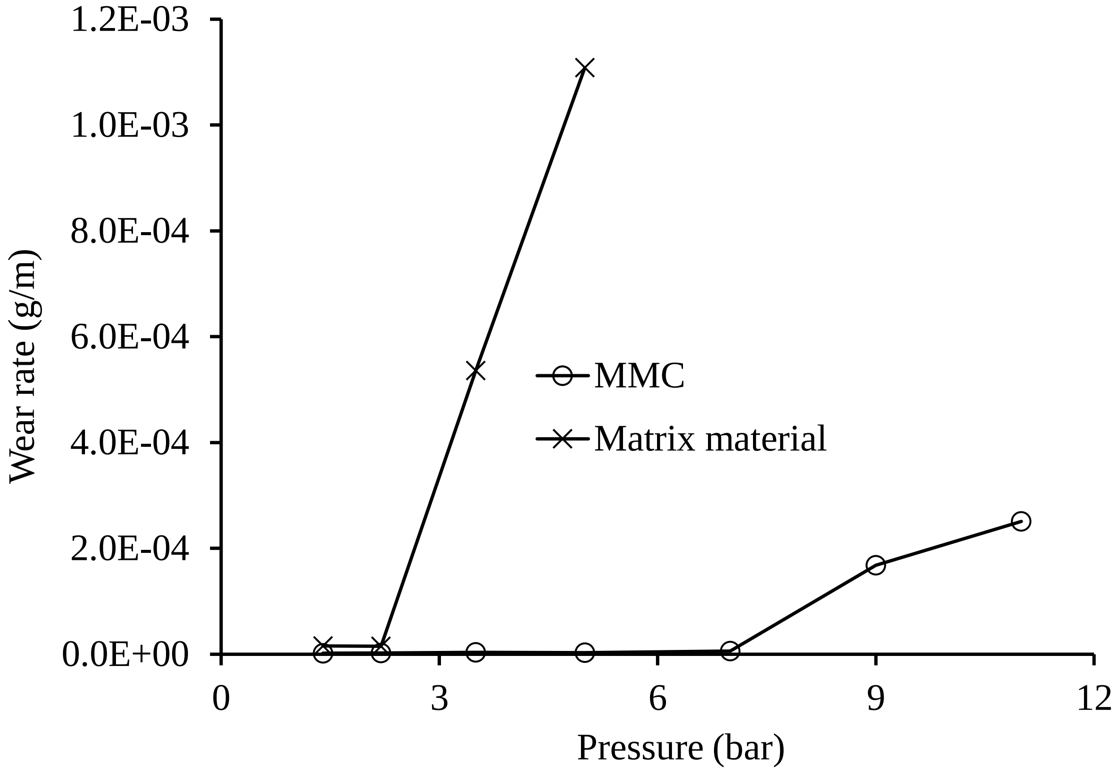


Fig. 4 Effects of pressure on wear rate for MMC and matrix material

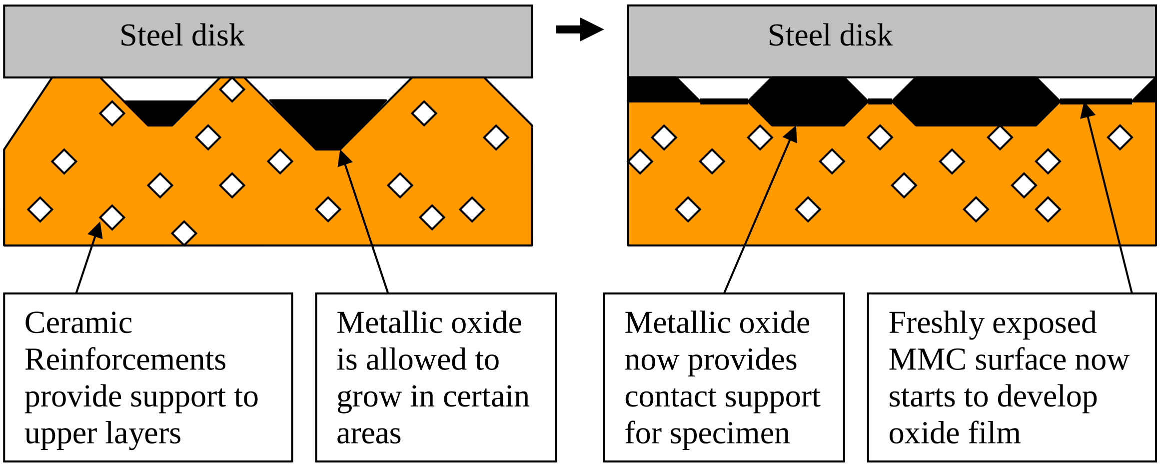
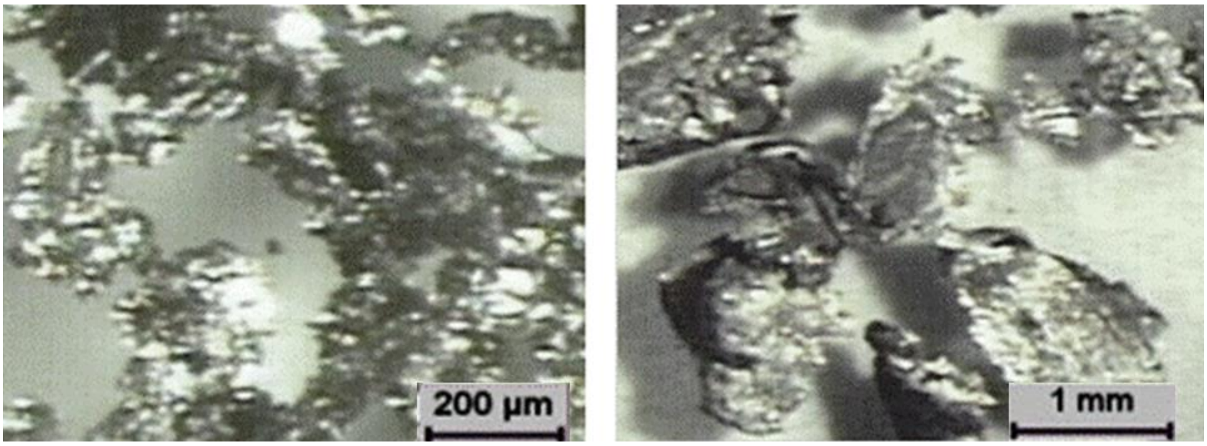


Fig.5 Diagram of likely process for oxide film growth

The wear resistance of MMCs is related to the bond between Al_2O_3 particles and the 6061 A1 matrix alloy [27]. Microhardness on the reinforcement particles and inter-particle distance are good indicators of the strength of the interface between particles and the matrix. Interfacial characteristics in particulate reinforced metal matrix composites can reasonably be evaluated by correlating inter-particle distance with microhardness on particles, wear and coefficient of friction [28]. Though the oxide films provide improved wear resistance, their effect can also be reduced if there is not enough support provided by the underlying material. This can happen due to localized weakening of the underlying material or from an asperity junction causing an extremely high normal stress concentration in that area which could have resulted in premature severe wear. It is important to remember that manufacturing techniques can never guarantee reinforcement particles will be perfectly distributed throughout an MMC block. If a certain area has fewer particles per unit volume then that area will be less capable of supporting wear and shear stresses like the rest of the material will. It is important to consider localized severe wear when designing brake systems. Even though certain pressure may appear harmless to an MMC during wear testing, they can still cause significant material loss in some areas if specified break loads area exceeded. There is also the emphasis on making MMC manufacturing techniques as consistent as possible and to ensure the reinforcements are evenly distributed to avoid certain areas being weakened.

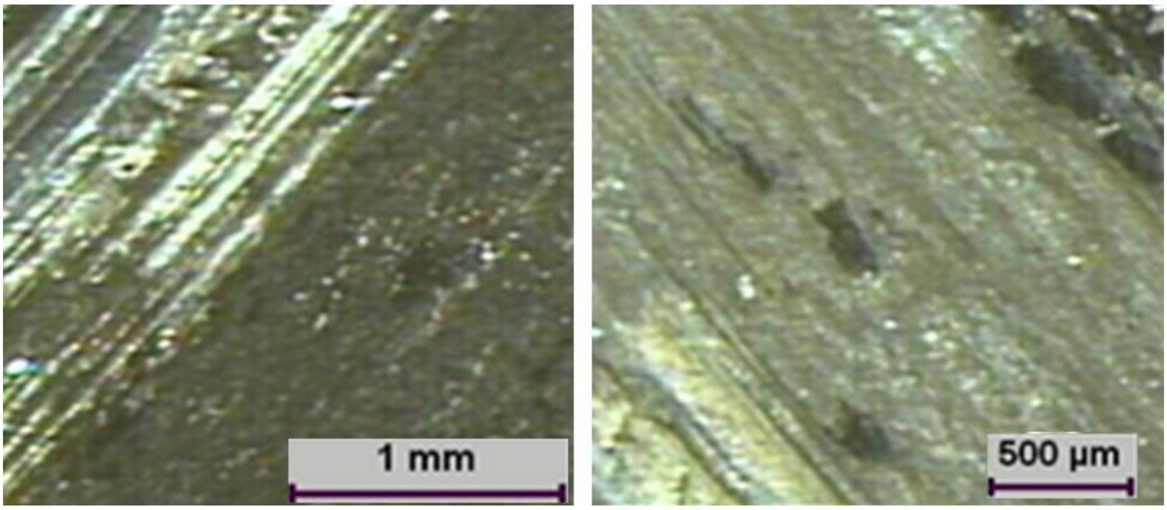
The size of the wear debris depends on the pressure. At higher pressure these are irregular in shape, bigger in size and, have a more lustrous and shiny appearance than the wear debris at lower pressure for MMC (Fig. 6). This suggests that the more MMC material fails beneath the contact interface at higher pressure which results in formation of larger debris. This left a fresh surface underneath which would also get worn away. It is also supported by the appearance of the worn surfaces. The worn surfaces appear to have progressively more oxidation as pressure increases which are indicated by the dark regions (Fig. 7). This is due to the increased temperature which came from the high friction forces generated. Many grooves are noted among the darker oxidized regions. Patches of dark yet lustrous films which probably caused by localized melting of matrix material that stretched across the face during sliding were noted in the sliding direction.

The debris from the matrix material appear to have been formed by adhesive wear. The fragments are dark or grey in color and have an irregular shape. When the transition load has been reached the wear debris increase in size (dimensions exceeding 3 mm). Those have a very shinny surface finish, and are shaped like thin plates. Although an increase in wear debris size was observed for the MMC (Fig. 6), a fine granular texture similar to that of freshly exposed MMC specimen face during severe wear was noted. This was not found in the matrix material where debris has a much smoother texture (Fig. 8), and the plates appear to have lengthwise layering rather than grains running along their surface during severe wear. In contrast to the MMC specimen surfaces, the matrix material has a more lustrous appearance. The MMC specimen has dark regions (Fig. 7) that are randomly scattered across the surface, while the matrix material has grooves that are spaced much more consistently throughout the surface. In the matrix material, the same texture (lustrous and metallic) appears throughout the entire worn interface with no significant variation (Fig 9). But presence of bars (irregular lumps) was noted all over the surface (Fig 9). A high ductility of the matrix material may have contributed these lumps.



(a) 2.2 bar (b) 9.0 bar

Fig. 6 Wear debris from MMC specimen at different pressure



(a) 3.5 bar (b) 5 bar

Fig. 7 Worn MMC surface at different pressure

Effect of Sliding Speed

Fig. 10 shows the effect of sliding speed on wear of MMC and corresponding matrix material. The first four wear results (up to 440 rpm) for the MMC show that the wear rate increases steadily with sliding speed which is expected as more distance is covered per unit time at higher speeds. At 760 rpm the wear rate dropped slightly, and at 1480 rpm the wear rate increased dramatically by 30 fold. This was due to severe wear and was evident by the large wear fragments and rough MMC surface at higher speed. One of the possible causes for the reduced wear rate at the start could have been because of surface oxidation which might have increased the local hardness and strength at the interface. But the drop of wear rate after 600 rpm is unexpected and so there must be another factor which causes the MMC to have increased wear resistance. It seems that the effects of oxidation increases after 600 rpm. During wear process, two opposing processes, such as, softening and hardening take place simultaneously [30]. Softening of the surface material occurs with the increase of temperature and the increase of strength and hardness occur with the formation of metal oxides. The oxidation is a continuous process at all rotational speeds but it only becomes significant at speeds in 600 to760 rpm. At this point the metal oxide film thickness would possibly grow at a faster rate than the rate of material removal meaning only the strengthened and hardened metal oxide would be present at the interface and it would 'mask' the softer matrix material underneath.

The friction coefficients in the sliding distance and pressure test showed no overall relationship between the controlled variables and the friction behavior. In this experiment, the results show a steep decline in measured friction coefficient with sliding speed in the early part of the test (230 – 600 rpm). After this speed the friction coefficient appears to around a minimum value of 0.2. This reduction in friction is further evidence of the effects of oxidation on the wear process. Oxidation reduces the maximum shear stress of the surface and hence plastic flow and junction growth can't occur as readily as in solid metal alloys.

Another likely reason for the reduced friction coefficient at larger rotational speeds could be the large amount of heat energy generation, which would soften the underlying metal. If this happens, the upper oxide film weakly bonded to the un-oxidized bulk material at higher temperatures. This can happen because even though the metal oxide interface is strong and has a higher melting temperature than the pure metal, the oxide film still needs to be supported in shear stress by the underlying materials. If the underlying portion of the specimen becomes weaker due to increased temperatures, it can no longer support the oxide film in shear stress. With the likelihood of a sliding interface, the asperities on the specimen surface no longer behave as idealized asperities. The theory of friction by adhesion predicts that the friction force will be the product of the true contact area and the shear strength of the asperities. The shear strength of the material does not drop at high temperature since metal oxides have much higher melting temperatures and higher strength at high temperature. This means that the friction coefficient predicted by the adhesion theory would be lower at higher temperatures. While the upper portion of the interface would slide more readily due weak underlying material, junction growth would still be retarded since the immediate interface material would be the metal oxide which will not deform plastically. This reduction in friction coefficient with rotational speed needs to be considered when designing break systems for machinery which operates at very high rotational speeds.

Once again there are difficulties in conducting this test in matrix material as severe wear occurs very early (<200 m of sliding) which results the transfer of matrix material to the steel disk. To ensure the conditions are consistent the steel disk were ground in order to remove this transferred layer for each test. There is no obvious relationship between wear rate and sliding speed that was obtained for this particular experiment. This was because the matrix material is much softer than steel and was easily deformed during sliding. The transferred layers harden and result in more adhesive wear. This not only increases the wear rate but it also causes continuous growth of the transfer layer. The same trend was noted for all the tests where matrix material layer was formed on the steel disk at the area of contact. Much less oxidations occur in the wear debris or specimen surface at higher speed. The friction coefficient of matrix material followed the trend similar to that of MMC which shows a gradual decrease friction coefficient with the increase of rotational speed. If less metal oxide is present on the surface and increased rotational speeds results in lower friction coefficients then these suggest lower material shear strength due to higher temperatures. There is also the possibility of localized melting of the specimen at the asperity contacts where flash temperatures can reach as high as 1000ºC which is well over the melting temperature (580ºC to 660ºC) of 6061 aluminium alloy.

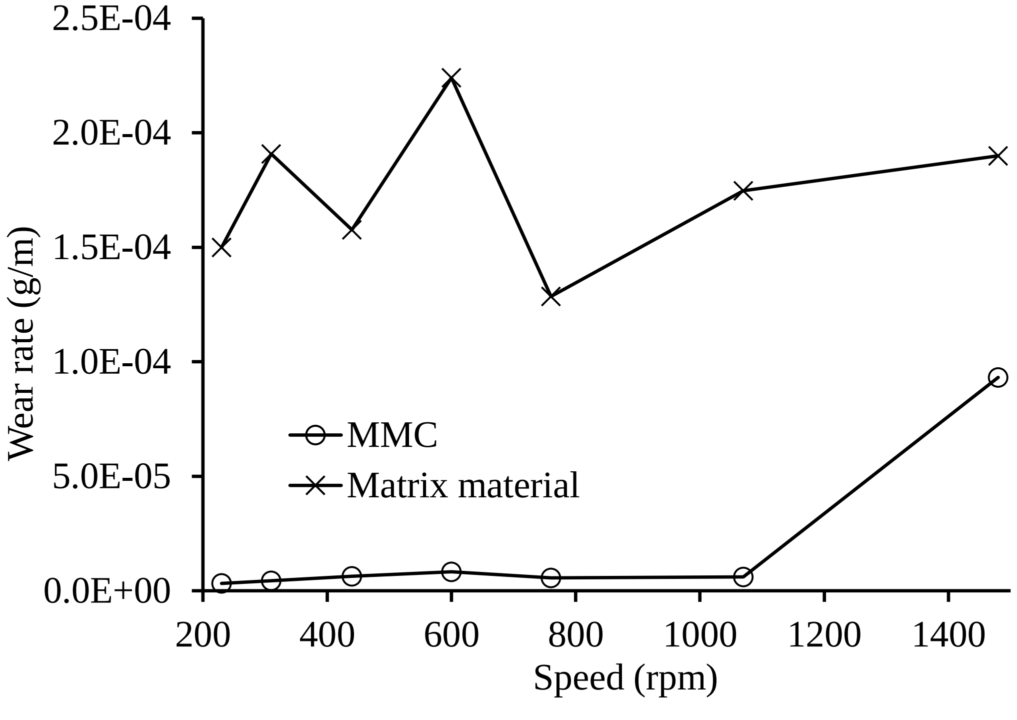
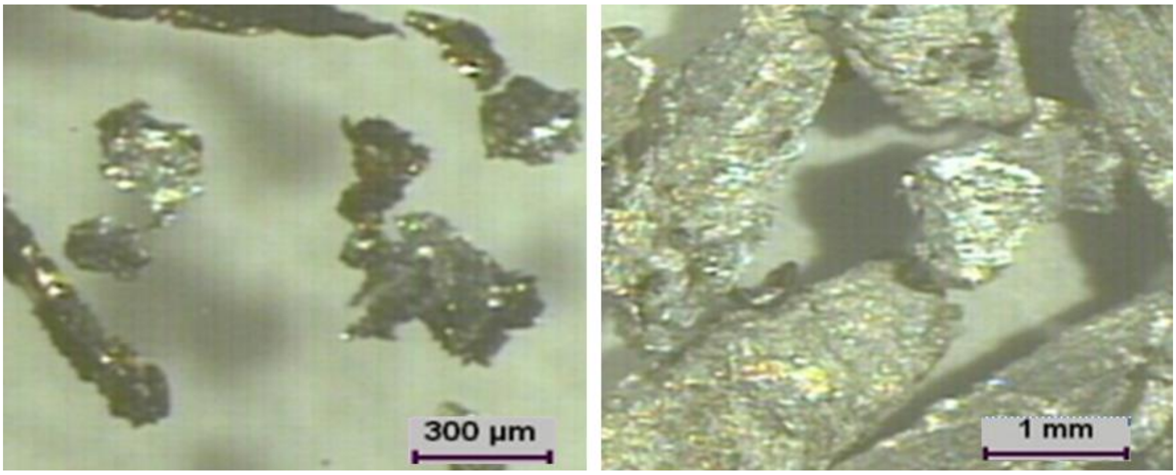


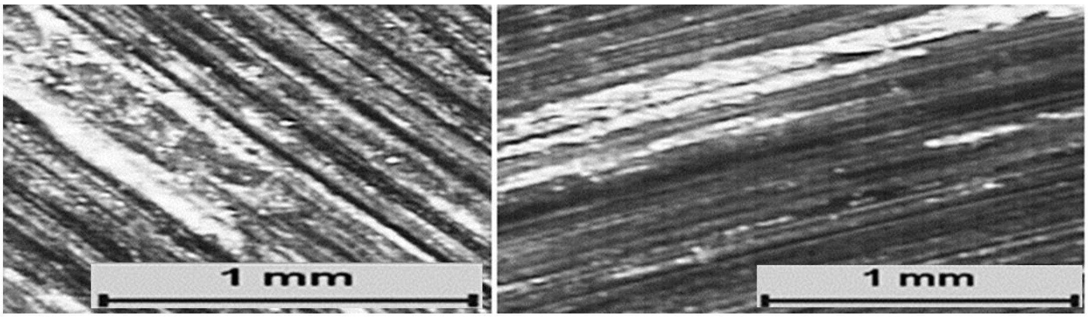
Fig. 10 Effect of sliding speed on wear rate of MMC and matrix material

Fig. 12 shows that the removed material for MMC is very irregular in shape and has a dark texture. The size of the detached debris increases with the increase of sliding speed. This suggests that adhesion between the asperities causes the material to deform and eventually separate from the surface with continuous sliding. Oxidation could have already occurred on the surface and so the asperities would have failed by brittle fracture. Another likely cause for the dark texture is that metallic debris would have been dislodged and then would oxidize outside the interface since it is still at a high temperature. At 1480 rpm debris have dimensions in excess of 3 mm and have a shiny yet granular texture similar to the debris found in other experiments. These fragments are clearly the result of severe wear. The worn surface at 440 rpm appears scattered regions where oxidation would have occurred and only localized grooves where hard asperities would have ploughed through the softer material. As sliding speed increases more of the specimen surface area is oxidized (as indicated by the dark regions), the grooves become more continuous and plastic deformation starts to occur on the specimen. With the increase of sliding speed, the temperature, which facilitates the oxidation rate, increases. Evidence of this progression becomes stronger with more grooves that appear dark or grey as the sliding speed increases. Fig. 13 shows the MMC surface after severe wear. There is a much rougher topography than the other specimens and the surface appears lustrous and a fresh layer of material was exposed (Fig. 13b).



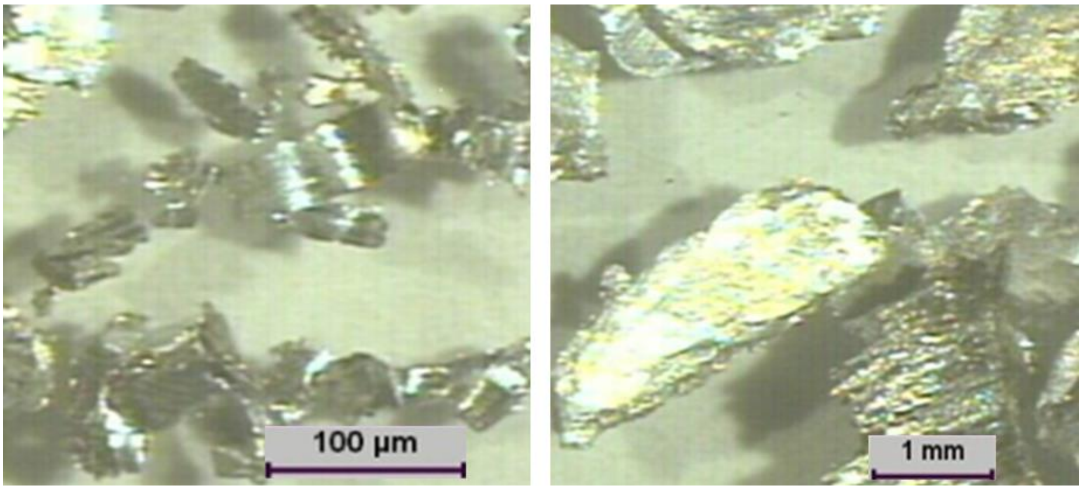
(a) 440 rpm (b) 1480 rpm

Fig. 12 Wear debris of MMC at different speeds



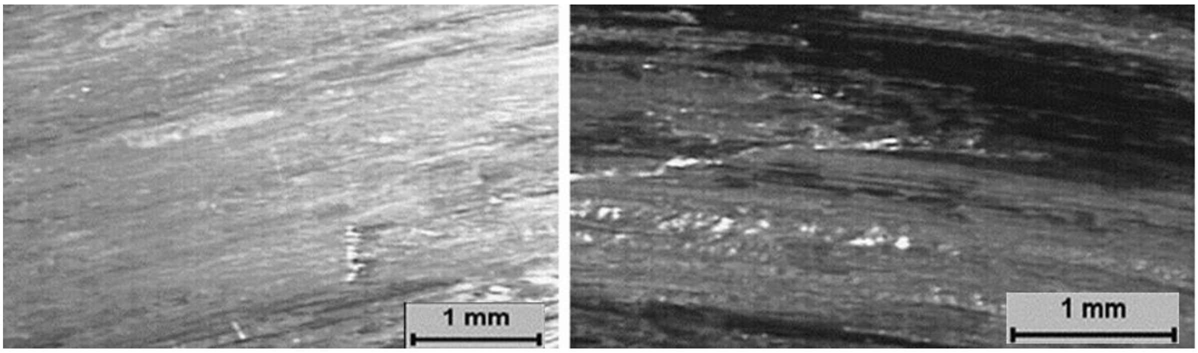
(a) 600 rpm (b) 1070 rpm

Fig. 13 Worn MMC surface at different speeds



(a) 440 rpm (b) 760 rpm

Fig. 14 Wear debris from matrix material at different speeds



(a) 310 rpm (b) 760 rpm

Fig. 15 Worn matrix material surface at different speeds

At lower sliding speed (Fig. 15a) minor grooves on matrix material are discontinuous when running from one end of the specimen to another. At higher sliding speed (Fig. 15b) the grooves are continuous throughout the entire specimen surface and there is little or no grazing visible. This demonstrates that the increased temperature at higher speed soften the surface material and allow for complete abrasive wear to occur. Even though ceramic reinforcements are harder than steel and are always present throughout the bulk specimen, they appear to have no effect of stopping the grooves at high sliding speeds. A possible reason for this is that the matrix material becomes softer and fails to hold the reinforcements during sliding. Thus significantly less energy is needed to separate the ceramics from the matrix. Surface of the matrix material deforms plastically and stretches across the specimen until it hangs over the edge. This is evidenced by very thin plates and fibers which protrude over the circular edge in the direction of sliding. This phenomenon was not taken into account in the Archard wear equation. The model of adhesive wear predicted that both plastically and elastically deformed regions would be in true contact and only plastically deformed regions resulted in wear. The theory predicts that plastically deformed asperities will not change position, which simply stays in their location until they detach from the specimen. Clearly this is not the case as plastically deformed surface material does flow when temperatures are high enough. The worn surface shows a distinct layer which has formed on top of the underlying matrix material. The layer has a darker colour and is not as lustrous as matrix alloy.

Both materials showed some noticeable trends as sliding speed increased, those are, (i) gradual reduction in friction coefficient with increasing sliding speed, (ii) darker surface appearance with increasing sliding speed and (iii) more material protruding from the specimen edge in the form of thin plates. Both materials had similar friction coefficient towards the latter stages of the experiment when high rotational speeds were used. The appearance of darker worn surfaces and increased hardness both show the presence of oxidation. This of course resulted from the increased temperature.

Overall Wear Resistance of the MMC

The results in the forgoing sections clearly show that MMC has enhanced wear properties over the unreinforced matrix material. On several occasions the calculated MMC wear was up to an entire order of magnitude smaller than that of matrix material. In addition to having better wear resistance on all tests throughout the paper, the MMC also displayed much more predictable wear behavior than the matrix material. The matrix material is susceptible to gross abrasive wear during the early stages of the experiment. The overall wear resistance of the MMC under all control conditions can be attributed to the ceramic particles which have the ability to restrict deformation and to prevent hard asperities from causing abrasive wear [6, 18]. MMCs that have been tested have shown to support the formation of metallic oxide films on their surfaces. This can be a valuable feature of the MMC if it is used in brake pads for vehicles. Since oxygen will always be available in these conditions the brake pads will lose less mass of material because of continuous re-oxidation of worn surfaces.

CONCLUSIONS

The only difference between the two materials was that the MMC contained a 10% volume fraction of alumina reinforcements, so any difference in the nature of wear would have shed some light on the role played by the reinforced ceramic particles in enhancing the wear resistance. From the above analysis the following conclusions are drawn for MMCs consist of 6061 aluminum alloy reinforced with 10 volume % Al_2O_3 particles of size range 6–18 μm.

(a) Ceramic reinforcements improve the wear resistance of a monolithic metal in all changing variables of distance, load and sliding speed considered in this study.
(b) Ceramic reinforcements delay the transition load of a material from sliding wear to severe wear. Those also limit the effect of abrasive wear when sliding against a steel counter face.
(c) The ceramic reinforcements enhance wear resistance by the following means:
    i. Resistance to deformation and thus stopping plastic deformation from happening in the immediate vicinity of the particle.
    ii. Preventing large wear fragments from becoming detached by gross seizure and abrasive wear.
    iii. By providing a supported base on which a metallic oxide film can develop on the material surface, this film will harden and strengthen the interfacing material.
(d) Both materials have almost similar kind of wear mechanisms except the three body abrasion and higher oxidation in case of MMC.
(e) The size of the debris was bigger for matrix material than that of MMC. For both materials the size of the debris increases with the increase of pressure and sliding speed.

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