September, 2006

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Tribo-surface characteristics of Al–B₄C and Al–SiC composites worn under different contact pressures

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Received 24 November 2004; received in revised form 9 January 2006; accepted 24 January 2006
Available online 28 February 2006

Abstract

Tribo-surface characteristics of two aluminium metal matrix composites (Al-MMC) of compositions Al–13 vol%B₄C and Al–13 vol%SiC sliding against a commercial phenolic brake pad have been investigated under dry conditions. The wear tests were carried out using a pin-on-disc type apparatus at a linear speed of 1.62 m s⁻¹ under contact pressures ranging from 0.75 to 3.00 MPa. The coefficient of friction was recorded on line. Wear rates were calculated from mass loss measurements. Scanning electron microscope equipped with energy dispersive X-ray spectroscopy was used to examine the tribo-surface. It is found that wear rate of both composites increases with increasing contact pressure which is accompanied by increased roughness of Al-MMC tribo-surface. The friction coefficient decreases slightly at high contact pressure. The wear rate and friction coefficient of Al–B₄C are lower than that of Al–SiC. A transfer layer consisting mostly of the constituents of the phenolic counterbody is observed on Al-MMC pins. The characteristics and role of the transfer layer, whose tribochemistry is dependent upon contact pressures, are discussed.

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Keywords: Tribology; Surface chemistry; Morphology; Composite; Scanning electron microscopy

1. Introduction

Incorporation of hard ceramic particles has been found to improve the wear resistance of aluminium to a great extent. Aluminium metal matrix composites (Al-MMC) reinforced by ceramic particles are therefore beginning to find commercial applications as wear resistant/friction materials in automobile, aircraft and other applications where the low density of Al-MMC is of great benefit. Considerable amount of research has been carried out on the tribology of Al-MMC. A majority of the work [1–9] involves Al-MMC sliding against a ferrous counter body. These studies revealed that during sliding, a transfer layer, also termed a mechanically mixed layer (MML), forms on the worn surface of Al-MMC. No such transfer layer or MML was found to form on unreinforced aluminium [2]. It was found by different workers that the transfer layer contains constituents of both Al-MMC and the ferrous counterbody. Vankatararaman and Sundararajan found that the thickness of the transfer layer increases as the normal load increases [2]. They suggested that the formation of the transfer layer controls the wear rate of Al-MMCs.

One of the important potential applications of Al-MMC is as automotive brake rotor materials. In such applications, the Al-MMC slides against phenolic based composite pad materials. A recent study [10] revealed that a transfer layer also forms on Al-MMC when it slides against a phenolic based break pad. Howell and Ball suggested [10] that the transfer layer that forms on Al-MMC while sliding against a phenolic based pad is mainly a graphite layer. Shorowordi et al. studied [11] the tribochemistry of the worn surface of Al-MMC sliding against phenolic pad. They found that the transfer layer contains all the constituents of both the Al-MMC and the phenolic pad. Shorowordi et al. also reported on the variation of the chemistry of the transfer layer as a function of sliding speed. This variation of the transfer layer chemistry was found to influence the wear and friction behaviour of Al-MMC.

The present paper reports on the effects of variation of contact pressure, another important wear parameter, on the tribochemistry and surface damage of worn Al–B₄C and
Al–SiC composites sliding against a commercial phenolic brake pad.

2. Experimental

Aluminium metal matrix composites of compositions Al–13 vol%B₄C and Al–13 vol%SiC were prepared by the stir-cast method followed by hot extrusion. The size of the ceramic particles, B₄C and SiC used as reinforcements was around 40 µm. The matrix material was pure aluminium (99.99%). MMC pins of 5 mm diameter and 12 mm length were machined out from the extruded bar of diameter 10 mm. The density of the extruded Al–B₄C and Al–SiC MMC was measured to be 2.64 and 2.71 g cm⁻³, respectively. The hardness of Al–B₄C and Al–SiC is 0.45 and 0.40 GPa. The end surface of the pin specimen was polished using a grit paper 1200, cleaned in distilled water and then dried in acetone.

A commercial phenolic brake pad was used as the counterbody material. It is generally known that commercial pad materials, which are proprietary items, may contain phenolic resin, filler materials (BaSO₄/CaCO₃), fibers, phenolic particles and a small amount of metallic chips (e.g. brass), etc. [12,13]. The brake pad materials used in the present study was characterized by X-ray fluorescence spectroscopy (XRF), wet chemical analysis and optical microscopy [11]. XRF detected a number of elements, viz. O, Mg, Si, Al, S, Ca, Mn, Fe, Cu, Zn, Ba and C on the pad. Wet chemical analysis revealed that the pad material used in the present study contains 34% phenolic resin, 42% asbestos fiber, 3.7% copper, 2.1% zinc, 3.2% iron (along with other constituents). Discs of 65 mm diameter and 10 mm thickness were cut from the pad. One surface of the disc was polished using grit paper 1200, and cleaned by cotton.

A pin-on-disc type setup was used for the wear test in which Al-MMC pin pressed against a horizontal rotating disc made from the commercial phenolic pad. Tests were conducted for a total duration of 1 h in an ambient air of relative humidity 77 ± 5% and temperature 31 ± 2°C. Different contact pressures, viz. 0.75, 1.50, 2.25 and 3.00 MPa were used, while the linear speed was kept constant at value of 1.62 m s⁻¹. Wear rates (mm² m⁻¹) of the MMC pins were calculated from weight loss measurements. An average of at least six tests for each sliding condition was taken for wear rate measurements. Wear coefficient (k) was calculated using Archard equation, i.e. wear rate was multiplied by the hardness of the composite, and then divided by the normal load employed during the wear test (Eq. (1)).

\[
w = \frac{kF}{H}
\]

where \(w\) is the volume loss per unit sliding distance, \(k\) the wear coefficient, \(F\) the normal load, and \(H\) is the hardness.

The coefficient of friction was calculated from the friction force measured during the wear test. The steady state coefficient of friction reported here is the average calculated from at least three tests and is the mean value of \(\mu\) obtained from the last 1000 m of the \(\mu\) versus sliding distance curve. Investigations on the nature of worn surface of the MMC pins were done in a scanning electron microscope (SEM) (Philips XL30) equipped with an energy dispersive X-ray (EDS) analyser. SEM and EDS examinations of the samples were carried out on the worn surface without any cleaning. Chemical analyses were carried out extensively on the worn surface. For each experimental condition, analyses were done on at least two randomly selected samples. At least 10–12 analyses were carried out in the matrix region of the worn surface of these specimens. An average analysis result was calculated from all these results and was taken as representative of a particular wear test condition. A few selected samples were also examined after cleaning them in water and dried in acetone. Surface roughness \(R_s\) was measured across the sliding direction of the worn surface of MMCs.

3. Results

Fig. 1 shows the variation of wear rate of Al–B₄C and Al–SiC with contact pressures. The wear rates of both composites are found to increase as the contact pressure increases. The data in Fig. 1 seem to follow the Archard law. Within the range of contact pressure investigated, no pronounced transition from mild to severe wear is found to occur. The wear rate of Al–B₄C is seen to be lower than that of Al–SiC. The difference in the wear rate of the composites is seen to increase as the contact pressure increases.

Typical friction coefficient (\(\mu\)) versus sliding distance curves for Al–B₄C and Al–SiC under different contact pressures are presented in Fig. 2a and b, respectively. In general, \(\mu\) increases sharply at the beginning, reaching a peak at short sliding distances. It then decreases and attains a steady state value. This general behaviour is observed for both MMCs. The steady coefficient of friction (the mean values of \(\mu\) on last 1000 m sliding distance) are plotted in Fig. 3 as a function of load. It is seen that between the contact pressures of 0.75–2.25 MPa, the steady state \(\mu\) remains more or less constant for both the Al–B₄C and Al–SiC. However, at the highest load investigated, i.e., at 3.00 MPa, \(\mu\) decreases rather abruptly for both materials. Al–B₄C has lower \(\mu\) values as compared with the corresponding values of Al–SiC under all contact pressures.
The morphology of the worn surface of Al-MMCs shown in Fig. 4 at contact pressures of 0.75 and 3.00 MPa. Parallel sliding marks along the sliding direction are visible on the worn surface. It is clear from the SEM micrographs that contact pressure has a pronounced effect on the morphology. The sliding marks become wider as well as deeper as the contact pressure increases. Both Al–B₄C and Al–SiC show a similar trend. Surface roughness values (Table 1) measured across the sliding direction also corroborate this.

When carefully examined at a higher magnification, the worn surface showed three main features: (i) polished ceramic reinforcing particles, (ii) matrix region around the ceramic particles, and (iii) bright debris particles scattered on the surface. The bright particles were particularly visible on the worn surface examined without a gold coating (Fig. 4a and b). This means that the bright particles appear bright due to charging effect and are poorly conductive.
Table 2
Average chemical composition (major elements) of matrix region of the worn surface of Al–B₄C and Al–SiC MMC under the different contact pressures

<table>
<thead>
<tr>
<th>Elements</th>
<th>Al–B₄C</th>
<th>Al–SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.75 (S.D.)</td>
<td>1.50 (S.D.)</td>
</tr>
<tr>
<td>Al</td>
<td>37.56 (5.38)</td>
<td>31.48 (6.77)</td>
</tr>
<tr>
<td>Mg</td>
<td>5.62 (1.81)</td>
<td>9.82 (2.95)</td>
</tr>
<tr>
<td>Si</td>
<td>6.24 (2.52)</td>
<td>8.16 (2.43)</td>
</tr>
<tr>
<td>C</td>
<td>13.27 (2.56)</td>
<td>11.03 (2.07)</td>
</tr>
<tr>
<td>O</td>
<td>32.35 (5.84)</td>
<td>32.80 (5.47)</td>
</tr>
</tbody>
</table>

EDS analysis showed that the polished surface of the reinforcing ceramic particles contain the constituents of the ceramic particles only. No other element was detected by EDS on the ceramic particles. The matrix region, however, was found to contain a number of elements, viz. Mg, Si, C, O, Fe, Ca, etc., in addition to aluminium. It may be noted that the phenolic based counter body is a composite material containing a large number of constituents, viz. phenolic matrix; phenolic particles; asbestos fiber reinforcement; fillers, such as BaSO₄, CaCO₃; metallic chips, e.g. brass, steel, etc. [11]. The phenolic matrix and phenolic particles of the counterbody contain C; asbestos fiber contains Mg, Si, O, etc.; barium sulphate contains Ba, S, O; calcium carbonate contains Ca, C, O; brass chips contains Cu, Zn; steel chips contain Fe, etc. Thus the elements, other than aluminium, that have been found in the matrix region of the worn surface belong to the phenolic based counterbody. Some oxygen is also likely to originate from the oxidation of aluminium of the MMC. Therefore a transfer of material from the phenolic based counterbody to the Al-MMC has occurred during sliding. Considering the depth resolution of EDS (of the order of a few μm) and the widespread occurrence of the pad constituents (during 10–12 random spot analysis on at least two samples, no single point was found where substantial pad materials was not present), it is thought that the continuous transfer layer of a few micrometers in thickness covers the top surface of the MMC. The presence of such a transfer layer has been previously identified on MMC sliding against both ferrous materials [2] and phenolic based friction materials [10,11].

The average compositions of the transfer layer occurring at the matrix region of the worn surfaces of Al–B₄C and Al–SiC were determined by EDS and are given in Table 2 as a function of contact pressure. The composition shown in Table 2 is an average of at least 10–12 chemical analysis done at randomly selected positions in the matrix region. Table 2 shows that the transfer material in the matrix region of worn MMC contains a large amount of the constituents of the phenolic counterbody. It is observed, in spite of the scatter in the data, that for both MMCs the amount of aluminium in the transfer layer decreases as the contact pressure increases. This implies that the overall amount of the pad constituents in the transfer layer increases with contact pressure. Individual elements like Mg, Si, etc. generally show an increase with contact pressure. C generally shows a decrease with contact pressure followed by an increase at 3.0 MPa. O shows some scatter in the data. Analysis of the bright debris particles scattered on the worn surface of the MMC reveals that they contain mainly the pad material and have an aluminium content of only a few percent (<5.0% Al).

Careful examination of the worn surface revealed that higher contact pressure causes an extensive surface damage in both composites. Fig. 5 shows a damaged area on Al–B₄C sample tested at 2.25 MPa. Extensive delamination of compacted surface layer in the form of flakes is obvious. The flake marked “A” is just about to be removed. Microanalysis revealed that this flaky area contains about 15.63% Al, the rest being mainly the constituents of the counterbody. The area where the flake has already been removed (marked “B”) shows a higher percentage of aluminium (48.70%). The area marked “C” appears to be a heap of loose debris. It contains only about 3.34% Al. This debris is the transfer material from the pad that has not yet mixed...

Fig. 6. SEM image showing extensive surface damage on worn Al–SiC MMC tested at 1.62 m s$^{-1}$ under 3.00 MPa [Au coated].

Fig. 7. Particle pullout on the worn surface of Al–SiC tested at 1.62 m s$^{-1}$ under the contact pressure 2.25 MPa [Au coated].

well with the aluminium MMC. Similar features were obtained at 3.00 MPa.

Fig. 6 shows the morphology of a damaged area on Al–SiC obtained at 3.0 MPa. The general features of the damage are similar to that on Al–B$_4$C. It is observed in Fig. 6 that a large flaky piece (“A”) is about to be dislodged from the surface. The flake has compact appearance and contains both aluminium and constituents of the pad. Uncompacted powdery debris (marked “B”) is seen to contain only a small amount of Al and is basically the transfer material from the pad. In addition to the above damage features at higher load, Al–SiC also exhibited cracks at the SiC particle/Al matrix interface and particle pull out. Fig. 7 shows a pit where SiC particle pull out has occurred. The pit has been filled up with debris mainly from the pad. The occurrence of such pull out was found to increase as the contact pressure increased. In the case of Al–B$_4$C, however, no particle pull out event was found after an extensive search of the worn surface. The particle pull out in Al–SiC might be linked to the existence of a brittle phase at the SiC–Al interface detected in an earlier study [14]. Decohesion between SiC and matrix Al during wear has also been observed by others [4]. No such weak interface was detected between the B$_4$C particles and the Al matrix [14].

4. Discussions

4.1. Friction coefficient

The variation of friction coefficient of the MMC with applied normal load was reported by other researchers. It was found by Venkataraman and Sundararajan [2] that steady state $\mu$ of Al–10 vol%SiC increases from about 0.25 to 0.7 as the load increased from 30 to 250 N. Modi et al. [15] found $\mu$ values in the range of 0.2–0.48 for Al-MMC (LM11–10%SiC) sliding against EN25 steel (32HRC). How and Baker [3] observed that $\mu$ of Al–A$_2$O$_3$ composite sliding against steel decreased from 0.85 to 0.45 as the contact pressure increased from a low value to about 1.8 MPa. Venkataraman and Sundararajan [16] earlier observed that Al–10 vol%SiC versus alloy steel pair exhibited a $\mu$ value of almost 0.7, which was independent of contact pressure (1.8 and 4.3 MPa). In the present case, where Al-MMC slid against a phenolic pad, steady state $\mu$ is also found to be independent of the contact pressure upto 2.25 MPa. The steady state coefficient of friction decreases from 0.39 to 0.35 for Al–B$_4$C and from 0.42 to 0.38 for Al–SiC as the contact pressure increases from 2.25 to 3.00 MPa. The range of friction coefficients obtained in the present investigation is found to lie well within the recommended range for automobile brake application [17]. A decreasing trend of $\mu$ with applied load was observed by Straffellini et al. [18] for Al-MMC sliding against semi-metallic friction materials. The present study also revealed that Al–B$_4$C tends to have a slightly lower $\mu$ values than Al–SiC. Researchers [19,20] suggested that the formation of boron oxide on the B$_4$C surface during sliding resulted in a decrease in coefficient of friction. The existence of oxidized state of boron on the worn surface of Al–B$_4$C composite was revealed by XPS in an earlier study [21]. In the present case, it is therefore believed that the formation of boron oxide on Al–B$_4$C composite during sliding slightly reduces the $\mu$ as compared to Al–SiC under various contact pressures employed.

4.2. Wear rate and wear coefficient

Effects of load or contact pressure on the wear rate of MMC have been reported by different researchers [1–3,6,15]. All these studies revealed that the wear rate of MMC increases as the applied load increases. However, Straffellini et al. [18] found that the wear rate increases with contact load for Al–10 vol%SiC, whereas it decreases with load for Al–20 vol%SiC. A couple of studies [1,2,15] further revealed that there exists a transition load above which the wear rate increases much more rapidly, even leading to seizure [15]. Kwok and Lim [1] observed that the transition load occurs at 2.55 MPa for a sliding velocity of 3 m s$^{-1}$. Venkataraman and Sundararajan [2] reported that for Al–10%SiC composites, the transition occurs at 4.24 MPa at a sliding speed of 1 m s$^{-1}$. Data obtained by Modi et al. revealed that for MMC containing 10% SiC, transition occurs between 1.5 and 2.5 MPa and complete seizure occurs at 3 MPa (see
Table 3
Literature data on the occurrence of the transition in wear rate or seizure

<table>
<thead>
<tr>
<th>Reference</th>
<th>Transition contact pressure, ( P ) (MPa)</th>
<th>Sliding speed, ( V ) (m s(^{-1}))</th>
<th>PV factor (MPa m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwok and Lim [1]</td>
<td>2.55</td>
<td>3</td>
<td>7.65</td>
</tr>
<tr>
<td>Modi et al. [15]</td>
<td>1.5–2.5</td>
<td>2.68</td>
<td>4.02–6.7</td>
</tr>
<tr>
<td>Seizure: 3</td>
<td>2.68</td>
<td>8.04</td>
<td></td>
</tr>
<tr>
<td>Present work</td>
<td>0.75–3.00</td>
<td>1.62</td>
<td>1.22–4.86</td>
</tr>
</tbody>
</table>

Table 4
Wear rate data from literatures are compared with the data of the present work

<table>
<thead>
<tr>
<th>Reference</th>
<th>Materials</th>
<th>Wear rate (mm(^3) m(^{-1}))</th>
<th>Test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwok and Lim [1]</td>
<td>Pin: Al–4.5Cu–13 vol%SiCp Counterbody: Tool steel (63 HRC)</td>
<td>(2.99 \times 10^{-3})</td>
<td>Speed: 1.00 m s(^{-1}) MPa: 3.00</td>
</tr>
<tr>
<td>Venkataraman and Sundararajan [2]</td>
<td>Pin: Al–10 vol%SiCp Counterbody: Medium carbon steel (532HV)</td>
<td>(12.87 \times 10^{-3})</td>
<td>Speed: 1.00 m s(^{-1}) MPa: 2.82</td>
</tr>
<tr>
<td>Straffelini [4]</td>
<td>Pin: Al–30 vol%SiCp Counterbody: AISI M2 steel (65RC)</td>
<td>(3.40 \times 10^{-3})</td>
<td>Speed: 0.63 m s(^{-1}) MPa: 0.50</td>
</tr>
<tr>
<td>Modi et al. [15]</td>
<td>Pin: LM11–10 vol%SiCp Counterbody: EN25 steel (32HRC)</td>
<td>(8.00 \times 10^{-3})</td>
<td>Speed: 2.68 m s(^{-1}) MPa: 2.50</td>
</tr>
<tr>
<td>Present study</td>
<td>Pin: Al–13 vol%SiCp Pin: Al–13 vol%B(_4)C Counterbody: Phenolic brake pad</td>
<td>(5.78 \times 10^{-4}) (4.23 \times 10^{-4})</td>
<td>Speed: 1.62 m s(^{-1}) MPa: 3.00</td>
</tr>
</tbody>
</table>

In comparison, no transition load was observed in the present case where the contact pressure is varied between 0.75 and 3.0 MPa. The PV (product of contact pressure and sliding speed) factor is often considered as representing the severity of the wear condition in the dry state. The values of the PV factor at which transition occurs in the above studies are compared with the PV factor employed in the present work in Table 3. The table reveals that the transition load varies in a wide range: 4.02–7.65 MPa m s\(^{-1}\). The higher side of the PV factor range used in the present study overlaps with the lower side of the transition range found in the literature.

The wear rates of the Al-MMCs obtained at 3.0 MPa in the present study are compared with some literature results in Table 4. Although the experimental conditions of different authors are not exactly the same as that in the present work, it can be seen that the wear rates of the MMCs obtained in this work are much lower. This is suggested to be due to the phenolic counterbody used in this study which has a lower composite hardness, as compared with ferrous counterbody used by researchers quoted in Table 4. Clearly, phenolic pad is less “harsh” a material as a counterbody as compared with ferrous materials. The existence of a transfer layer on Al-MMC containing a large amount of pad constituents is also expected to contribute to better wear protection of the MMCs.

As has been found, wear rate of both Al–B\(_4\)C and Al–SiC increases with contact pressure. With the increase of load, the transfer layer becomes heavily damaged leading to delamination. This has been responsible for increased wear rate. It may be noted here that increased wear rate with the increase of contact pressure is also accompanied by an increase in the percentage of constituents of counterbody in the transfer layer (Table 2). Such an increase in the percentage of pad constituents in the transfer layer does not seem to increase the load bearing capacity of the latter. The higher wear rate experienced by Al–SiC is suggested to be contributed by the particle pullout. This damage mode is seen to be absent in Al–B\(_4\)C under the present experimental conditions. Besides, the higher hardness of B\(_4\)C particle as compared with that of SiC particle is also expected to contribute to the lower wear rate of Al–B\(_4\)C.

The wear rate data obtained in the present work are plotted as wear coefficient in Fig. 8. It is observed that the wear coefficient of both materials tends to decrease as contact pressure increases. But it increases again at 3.0 MPa. Wear coefficient is interpreted as the probability of formation of wear debris in a tribological system. The change in the wear coefficient signals a change in the wear mechanism. Fig. 8. Showing the wear coefficient of Al–B\(_4\)C and Al–SiC tested at the sliding speed of 1.62 m s\(^{-1}\) under different contact pressures.
material properties such as hardness, flow stress, etc. Hardening effect in the transfer layer on MMC has been observed [22]. The initial decrease in the wear coefficient is thought to be linked to a hardening effect caused by the better consolidation/compaction of the transfer layer as the load increases [23].

It is suggested that with increasing contact pressure beyond 2.25 MPa, the counter body wears out at a higher rate making more debris from the counter body available for mixing in the transfer layer on MMC. The greater amount of carbon in the mechanically mixed transfer layer is suggested to impede its consolidation/sintering, resulting in lower flow stress. This leads to the increase in the wear rate of the transfer layer which eventually increases the wear coefficient of the Al-MMC. It has been suggested in earlier studies [10] that the carbon in the transfer layer of Al-MMC is in the form of graphite. The increase in the carbon content of the transfer layer at 3.0 MPa should also result in a decrease in the coefficient of friction. This has indeed been found in the present study, i.e., the increase in carbon content in the transfer layer is accompanied by a decrease in friction coefficient at 3.00 MPa.

4.3. Surface chemistry of MMC

It has been observed that the chemistry of the transfer layer is dependent upon the contact pressure. The percentage of Al decreases and hence the overall percentage of pad constituents in the transfer layer increases with contact pressure (Table 2). The measured values of carbon content in the transfer layer on Al-MMC is shown in Fig. 9 as a function of contact pressure. It may be recalled that C in the transfer layer on Al-MMC mainly comes from phenolic resin of the counterbody. Since the pad has a fixed compositional make up, if the pad is transferred to the MMC without any decomposition then the ratio of a pair of elements on the transfer layer should be the same as that in the pad. As both Mg and C are coming from the pad, where Mg:C ratio is known, a theoretical carbon percent in the transfer layer can be calculated based on the amount of Mg in the transfer layer. The choice of Mg as reference is a logical one since it is coming from asbestos which has a high thermal resistance. Mg content is not expected to be altered as no decomposition of asbestos under the experimental conditions is likely to take place [11]. The calculated carbon percent is also shown in Fig. 9. In spite of the fluctuation of the data, it can be seen that the actual carbon percent in the transfer layer is generally smaller than the corresponding theoretically predicted value. The lower carbon content in the transfer layer can be due to (i) thermal degradation of organic phenolic material caused frictional heating [24,25], and (ii) preferential removal of phenolic material from the tribo-surface as contact pressure increases. Although thermal degradation of phenolic material has been reported [24,25], no evidence of preferential removal of the same has been found in the literature. Further study is necessary in this connection.

4.4. Wear mechanism

Based on the research done by others and the results obtained in this study, a phenomenological description of the wear process of Al-MMC sliding against a phenolic pad can be suggested. Both the Al-MMC and phenolic composites are heterogeneous and contain hard as well as softer constituents. During the initial running-in, the softer constituents in both bodies wear out preferentially as compared to the harder constituents. Thus the harder constituents become the “high lands” and softer constituents become “low lands” [26]. The high lands of one body then touch the second body and vice versa to support the applied load. As the wear process progresses, interaction between the two bodies produces a third body which consists of fragments of both the first and the second bodies. Under the geometrical constraints at the wearing surface, the third body gets fragmented, milled, comminuted and mixed. Milling/comminution of the third body can occur to such an extent that nanometer sized particles are generated in the mixture [27]. During the above events trbooxidation also takes place [27]. The third body gets embedded in the soft aluminum matrix and forms a transfer layer on it. The initial rise in the $\mu$ versus sliding distance curve (Fig. 2) corresponds with the running-in. Once a stable transfer layer forms, $\mu$ drops down to a steady state value. The worn surface morphology of the MMC found in the present study mainly consists of parallel ploughing marks. As the contact pressure is increased, both wear rate and surface roughness increase. Bhushan [28] suggested that under abrasive wear conditions, there exists a correlation between wear rate and surface roughness. The ploughing marks on the worn surface and the positive correlation between wear rate and surface roughness suggest that abrasive wear mainly operates under the present experimental conditions.
5. Conclusions

Tribo-surface characteristics of Al–13 vol% B₄C and Al–13 vol% SiC MMCs worn against a commercial phenolic brake pad under different contact pressures in the range of 0.75–3.00 MPa have been investigated at a constant sliding speed 1.62 m s⁻¹. It is observed that wear rate and surface roughness of both MMCs increase with the increase of contact pressures. However, the coefficient of friction shows a decrease at high contact pressure. The calculated wear coefficient exhibits a general tendency to decrease between the contact pressures of 0.75–2.25 MPa. The wear coefficient however increases at 3.00 MPa. The wear rate and friction coefficient of Al–B₄C are found to be lower than those of Al–SiC. A transfer layer consisting mostly of the constituents of material from the phenolic based counterbody is found to form on Al-MMC. The amount of pad constituents in the transfer materials increases as the contact pressure increases. The surface chemistry of the transfer layer particularly the carbon percentage, is suggested to influence the both wear coefficient and the friction coefficient.

Acknowledgements

The authors acknowledge with thanks the financial support provided by the Belgian Agency for Development Cooperation (ABOS) and the Government of Bangladesh under a joint R&D collaboration project.

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