Thermal and tribological characterizations of millscale-particles-reinforced ceramic matrix composites

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**ABSTRACT**

This paper evaluates some basic functional properties of iron-millscale-reinforced ceramic matrix composites (CMCs) as potential material for automobiles and aircraft brake pads’ application. The particulate CMCs were produced by the powder metallurgy method. Iron millscale particles’ addition varied from 3 to 18 wt.% in a matrix comprising a mixture of silica, magnesia and bentonite. After sintering, the composites were subjected to coefficient of friction (COF), wear, thermal and microstructural characterizations. Microstructure of the composites showed a uniform distribution of millscale particles in the ceramic matrix with a strong interfacial bonding between the particles. The composites demonstrated a comparatively high resistance to wear, appreciable COF (0.506–0.561) and a modest thermal conductivity (0.39–0.53 W/m K) coupled with high thermal stability. Contributions to these superlative performances were provided by the high level of friction induced on composites’ surfaces and strong interfacial bonding developed during sintering.

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1. Introduction

Wear has been the subject of intensive studies due to the continuous loss of materials resulting in most engineering components becoming dysfunctional. However, wear of materials is inevitable because two surfaces in contact and sliding relative to each other are bound to produce a range of physical and chemical processes that result in wear [1]. Hence, brake pads in similar operating environment are prone to high wear. The two major wear mechanisms associated with brake pads are abrasion and adhesion [2]. Sliding wear is determined by the contact pressure between the surfaces, sliding velocity and time of contact between the surfaces. Any variation in these parameters can alter the rate of wear coupled with changes in the wear mechanism with the tendencies to cause more friction generated heat. Ambient conditions such as temperature can also influence the rate of wear by inducing thermal or chemical process.

The processing of composite materials in relation to design and manufacturing technologies employed is part of intense area of advance materials’ development. This is predicated on the fact that composites are multifunctional materials having unprecedented physical and mechanical properties that can be tailored to meet the requirements of a particular application. Many composites exhibit excellent resistance to wear, high temperature, corrosion and oxidation. These unique characteristics provide engineers with design opportunities not possible with conventional monolithic materials [3]. Specifically, ceramic matrix composites (CMCs) combine reinforcing ceramic phases within a ceramic matrix to create materials with improved properties. The desirable characteristics of CMCs include high-temperature stability, high thermal shock resistance, high hardness, high wear and corrosion resistance, non-conductive properties and greater versatility in providing unique engineering solutions [4]. These properties can be induced in the composites through innovative materials processing. It is envisaged that the use of such composites as friction linings (brake pads) will boost their potential of performing optimally in high thermal and wear environments approximated by brake pads operating environment of automobiles and aircrafts.

This underscores the use of a combination of materials in developing a certain category of composites in order to effectively harness the property synergy which such materials may offer. Hence, the need for the development of such CMCs with potential for high wear and thermal resistance coupled with appreciable mechanical strength. This is possible through innovative processing of some materials that are compatible and are readily available. This forms the main focus of this study.

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2. Methods

2.1. Materials and equipment

The reinforcement material used in this study is iron millscale particles while the matrices are a proportionate blend comprising silica sand, magnesia and bentonite. Iron millscale particles were sourced from Universal Steels Lagos, Nigeria. Silica sand was obtained from the beach of the Lagos Atlantic Ocean. Magnesia and bentonite powders were obtained from a local vendor within the chemicals supplier trade group registered in Nigeria but were manufactured in China and Wyoming, USA, respectively. Pictures of these materials are presented in Figures 1 and 2 while their chemical composition is presented in Table 1. British Standard Sieves (BSS 150, 100, 85, 72 and 60), electronic digital weighing balance (Model No. UW1020H, SHIMADZU, Japan), mixer, steel ball mill (model A50 43, Mashine, France), 600 ml beakers, 30 mm × 20 mm × 20 mm metallic moulds, Ø 30 mm × 20 mm metallic moulds, hydraulic press (Model No. 38280, Capacity 100 T, Type P100 EH, Weber Hydraulik, Germany), muffle furnace model 5300A30/F6010-TS, oven model 2225-L of internal dimension 1570 mm × 1100 mm × 1290 mm, differential thermal analyser (DTA) model NETZSCH DTA 404 PC, wear tester and an ASPEX 3020 model variable pressure scanning electron microscope (SEM) equipped with Noran-Voyager energy dispersive X-ray spectrocope (EDS) capability were used for the production and characterization of the composites.

| Compounds | Iron millscale | Silica | Magnesia | Bentonite |
|-----------|----------------|--------|----------|-----------|
| FeO       | 68.81          | 0.02   | –        | –         |
| Fe₂O₃     | 24.74          | 0.15   | 3.86     | 62.99     |
| Fe₃O₄     | 6.18           | –      | 23.25    | 0.18      |
| SiO₂      | 0.01           | 98.99  | 0.02     | 0.492     |
| MgO       | 0.02           | –      | 0.02     | 0.013     |
| CaO       | 0.22           | 0.02   | 2.67     | 0.04      |
| MnO       | 0.02           | –      | 0.03     | –         |
| Al₂O₃     | 0.18           | –      | –        | 0.52      |
| Na₂O      | 0.01           | –      | –        | 0.01      |
| K₂O       | 0.01           | –      | –        | 0.14      |
| TiO₂      | –              | –      | –        | 2.80      |
| L.O.I      | 0.001          | 0.492  | 0.013    | –         |

Note: L.O.I = Loss on Ignition.

2.2. Materials milling and blending

Iron millscale particles were milled using a steel ball mill (model A50 43, Mashine, France) and sieved using British Standard Sieves (BSS 150, 100, 85, 72 and 60, respectively) to particles size distribution of 106–250 µm. The matrix containing 212 µm silica sand, 53 µm magnesia and 15 µm bentonite was separately mixed with the iron millscale particles and clean water amounting to 12 wt.% of the total mixture was added. By manual mixing, a uniform distribution of reinforcement particles in the matrix blend was achieved and 80 g of the wet blended materials were fed into metallic moulds. The overall materials formulation is shown in Table 2.

2.3. Compaction

The Green samples were obtained by uniaxial cold pressing (0.33 MPa) using a hydraulic press (Model No. 38280, Capacity 100 T, Type P100 EH, Weber Hydraulik, Germany) to enhance the surface smoothness of the samples. Little lubricant was rubbed on the inner part of the moulds as a releasing agent for easy discharge of the samples from the moulds after compaction.

2.4. Drying and sintering

The samples were dried in open air for 3 days, followed by drying under a controlled humidity using an oven.
dryer at 110°C for 24 h to expel any moisture left in the composite and to avoid cracking during sintering. In order to facilitate the bonding of powder particles, the compacted samples were gradually heated to temperatures below the melting point of the materials but high enough to develop significant solid state diffusion. Sintering was carried out in a muffle furnace pre-set at heating rate of 10°C/min in the following sequence: (i) heating to 600°C and allowed to soak for 3 h, (ii) heating to 800°C and allowed to soak for 3 h, (iii) heating to 1000°C and allowed to soak for 3 h and (iv) finally heating to 1200°C and allowed to soak for 3 h. The samples were removed from the furnace and allowed to cool after which they were characterized. The picture of few of the produced ceramic composites is presented in Figure 3.

### 2.5. Microstructural test

The microstructure and the chemical compositions of the phases present in the test samples were examined using an ASPEX 3020 model variable pressure SEM equipped with Noran-Voyager EDS. The samples to be observed under the SEM were mounted on a conductive carbon imprint left by the adhesive tape prepared by placing the samples on the circular holder and coated for 5 min to enable it to conduct electricity. The samples were analysed at an accelerating voltage of 15 kV for the EDS.

### 2.6. Flame resistance test

The initial weights of the samples before the test were determined using an electronic digital weighing balance (Model No. UW1020H, SHIMADZU, Japan) with sensitivity of ±0.001 mg. Each of the samples was placed on wire gauze positioned directly on the blue flame of a Bunsen burner for 30 min, after which the flame was removed, the samples were allowed to cool and their final weights measured.

### 2.7. Thermal conductivity test

The boiling method was used in determining the thermal conductivity of the samples. The thermal conductivity of the test samples was evaluated according to the expression in Equation (1) [5] after measuring the parameters.

\[
K = \frac{2.303MC\delta \log(\theta_1/\theta_2)}{A \times t},
\]

where \(K\) is the thermal conductivity of the sample in (W/m K), 2.303 is a constant, \(T_s\) is temperature of steam (°C), \(T_1\) is initial temperature of water in the beaker (°C), \(T_2\) is final temperature of water in the beaker (°C), \(t\) is time (s), \(A\) is area of the sample (length multiplied by breadth) in m², \(M\) is the mass of water in the beaker (kg), \(C\) is specific heat capacity of water in the beaker (J/kg °C), \(\delta\) is thickness of sample (m), \(\theta_1\) is \(T_s – T_1\) and \(\theta_2\) is \(T_s – T_2\).

### 2.8. Thermal stability test using a DTA

The test was carried out using a DTA model NETZSCH DTA 404 PC. It is fitted with a furnace facility of 10°C/min heating rate. The sample holder assembly consists of a thermocouple, each for the sample and inert reference sample, surrounded by a block to ensure an even heat distribution. The sample was kept in a small crucible designed with an indentation on the base to ensure a snug fit over the thermocouple bead. Five grams of the test sample in powdered form was put in the alumina crucible pan and heated with the reference sample to a temperature of 2100°C. The thermocouples were not placed in direct contact with the sample to avoid contamination and degradation. Changes in the sample due to the heat absorption were observed relative to the inert reference. The onset temperatures of destruction (\(T_{des}\)) of the samples, which depict that their thermal degradation temperature were recorded.

### 2.9. Coefficient of friction test

The coefficient of friction (COF) between the composites and a 60 cm smooth mild steel surface was determined by inclining the plane at 35°. Each sample was attached to a string and placed on the plane. The string was passed through a pulley which was connected to a mass hanger and loads ranging from 8 to 24 N were separately added to the hanger, which made the sample to slide along the surface of the

### Table 2. Materials’ formulation.

| Iron millscale (wt.%) | Silica (wt.% | Bentonite (wt.% | Magnesia (wt.% | Total (wt.% |
|----------------------|-----------|----------------|---------------|---------|
| 0                    | 30        | 30             | 40            | 100     |
| 3                    | 29.1      | 29.1           | 38.8          | 100     |
| 6                    | 28.2      | 28.2           | 37.6          | 100     |
| 9                    | 27.3      | 27.3           | 36.4          | 100     |
| 12                   | 26.4      | 26.4           | 35.2          | 100     |
| 15                   | 25.5      | 25.5           | 34            | 100     |
| 18                   | 24.6      | 24.6           | 32.8          | 100     |
steel plane. The COF is the ratio of frictional force (equivalent to mass at hanger to initiate sliding) to the normal reaction (weight of sample). Equation (2) [6] was used to determine the COF ($\mu$) between the samples and mild steel surfaces.

$$\mu = \frac{P - W \sin \theta}{W \cos \theta}, \quad (2)$$

where $P$ is the load on the hanger (N) and $W$ is the weight of the sample (N).

2.10. Wear test

The dry sliding abrasive wear test was conducted on the samples using a pin-on-disc wear tester at room temperature. Five normal loads (8, 12, 16, 20 and 24 N) were separately applied using dead weights at a constant sliding distance of 1257 m. The samples were weighed and recorded as $W_0$ before the test using an electronic digital weighing balance (Model No. UW1020H, SHIMADZU, Japan) with sensitivity of ±0.001 mg. A revolving disc upon which a Festool 496625 P36-grit sandpaper of 160 mm diameter surface has been mounted was used. The disc rotated with the help of a DC motor speed of 250 rpm and sliding occurred between the stationary sample and the rotating disc. As the disc rotated, the sand paper in direct contact with the sample also rotated at a speed relative to the disc and caused the sample to wear. After the pre-set time of 5 min, the machine was turned off. The sample was thoroughly cleaned and the final weight was measured and recorded as $W_1$. The weight loss of the sample was determined by finding the difference between the final and initial weights. Thus, the specific wear rate and other related wear parameters such as wear volume, and wear resistance were determined using Equations (3)–(7) [7,8]:

Wear volume,  

$$V (\text{cm}^3) = \frac{\Delta w}{\rho}, \quad (3)$$

$$\Delta w = w_1 - w_2, \quad (4)$$

where $\Delta w$ is the weight loss (g), $w_1$ is the weight of sample before wear (g), $w_2$ is the weight of sample after wear (g) and $\rho$ is the density of the sample.

Wear rate,  

$$\omega = \frac{\Delta w}{L}, \quad (5)$$

$$L = 2\pi NDt, \quad (6)$$

where $L$ is the sliding distance (m), $D$ is the diameter of the P36-grit sandpaper (abrasive) which is 16 cm, $N$ is the revolution per minute of the pin-on-disc which is 250 rpm, $t$ is the time taken to expose each of the samples to wear which is 5 min and $\pi = 3.142$.

Wear resistance,  

$$\Delta = \frac{2\pi NDt}{w_1 - w_2}. \quad (7)$$

The test results data generated were substituted into the relevant equations and each wear parameter was computed. The worn surfaces of some of the samples were also examined and analysed using the SEM.

3. Results and discussion

3.1. Microstructure

The SEM micrographs in Figures 4(a)–7(a) show that the samples are made up of different additives which confirm that they are heterogeneous with differences in the geometry of the particles which are globular and needle-like. The EDS spectrographs show a good combination of the elemental distribution, which also

![Figure 4](image-url)
shows the heterogeneous nature of the composites. The spectrograph shows the presence of O, Si, Al, Mg, Fe and Ca but the unreinforced (control) does not contain Fe (Figure 4(b)). There are also indistinguishable peaks in the spectrographs indicating the presence of other elements in very small amount. The white spots in the micrographs are particles of the magnesia (MgO) while the dark spots are FeO particles from the iron millscale. The ash coloured needle-like region is mullite (3Al₂O₃·2SiO₂) while the grey mixed with whitish spots are the spinel as shown in Figures 4(a)–7(a).

From the micrograph of the reinforced samples shown in Figures 5(a)–7(a), FeO particles are seen to be well distributed in the matrix without any form of agglomeration. The interfacial bonding between the reinforcement and the matrix is enhanced by the relatively close-spacing of the FeO particles. This also suggests a good vitrification of the reinforced composites during sintering.

3.2. Flame resistance of the ceramic composites

After 30 min of exposure to the Bunsen burner flame, none of the samples got burst into flame or charred. Virtually all have the same final weights as the initial weights except samples A, F and P which lost 0.001 g each shown in Table 3. This represents 0.002%, which indicates that 99.998% of the weight of samples A, F and P is retained while other samples have 100%
weight (no loss). This shows that the samples exhibit a high ability to absorb heat without disintegration indicating that they are highly refractory and thermally stable. This may be due to the very low thermal expansion of the ceramic materials and the strong interfacial bonding of the particles. The strong interfacial bonding of the particles effectively acted as barriers to decomposition of the samples during heating, thereby enhancing the thermal stability of the composites [9]. In earlier studies [10,11], 3.55 g sample of asbestos-based commercial automobile brake pad (sample Q) was left for 10 min on the Bunsen burner flame after which the flame was removed. It was observed that the brake pad did not burst into flame but charred and when weighed, it was 3.15 g, which indicates a mass loss of 11.3% (ash/volatile materials). Comparing this with the result of this study, the ceramic composites are more thermally stable than existing asbestos-based commercial brake pad.

3.3. Thermal conductivity

There is a progressive increase in the thermal conductivity of all the composites with increasing wt.% iron millscale particles’ addition from 3 to 18 wt.% (Figure 8). The thermal conductivity of the unreinforced (0 wt.%) composite is 0.39 W/m K being the lowest among the composites, while the 106 µm iron-millscale-particles reinforced composite at 18 wt.% exhibits the highest thermal conductivity of 0.53 W/m K.

The increase observed in thermal conductivity of the composites may be due to the strong interfacial bonding of the particles of FeO and the matrix thereby enhancing heat transfer. The increase in thermal conductivity may also be attributed to the presence of iron (Fe), which is a good conductor of heat. When brake associates have improved thermal conductivity, they tend to improve the braking efficiency [10]. Generally, the standard thermal conductivity of friction materials (brake pads) ranges from

| Sample | Details | Initial weight (g) | Final weight (g) | Weight loss (g) | Weight loss (%) | Weight retained (%) |
|--------|---------|--------------------|------------------|----------------|-----------------|---------------------|
| A      | Unreinforced CMC (Control) | 38.837             | 38.836           | 0.001          | 0.002           | 99.998              |
| B      | 12 wt.% of 106 µm CMC | 42.796             | 42.796           | –              | –               | 100                 |
| C      | 12 wt.% of 150 µm CMC | 42.816             | 42.816           | –              | –               | 100                 |
| D      | 12 wt.% of 180 µm CMC | 42.863             | 42.863           | –              | –               | 100                 |
| E      | 12 wt.% of 212 µm CMC | 42.874             | 42.874           | –              | –               | 100                 |
| F      | 12 wt.% of 250 µm CMC | 42.882             | 42.881           | 0.001          | 0.002           | 99.998              |
| G      | 15 wt.% of 106 µm CMC | 55.219             | 55.219           | –              | –               | 100                 |
| H      | 15 wt.% of 150 µm CMC | 52.857             | 52.857           | –              | –               | 100                 |
| I      | 15 wt.% of 180 µm CMC | 49.426             | 49.426           | –              | –               | 100                 |
| J      | 15 wt.% of 212 µm CMC | 46.528             | 46.528           | –              | –               | 100                 |
| K      | 15 wt.% of 250 µm CMC | 43.887             | 43.887           | –              | –               | 100                 |
| L      | 18 wt.% of 106 µm CMC | 44.981             | 44.981           | –              | –               | 100                 |
| M      | 18 wt.% of 150 µm CMC | 44.996             | 44.996           | –              | –               | 100                 |
| N      | 18 wt.% of 180 µm CMC | 45.016             | 45.016           | –              | –               | 100                 |
| O      | 18 wt.% of 212 µm CMC | 45.025             | 45.025           | –              | –               | 100                 |
| P      | 18 wt.% of 250 µm CMC | 45.032             | 45.031           | 0.001          | 0.002           | 99.998              |
| Q      | Chip of commercial automobile brake pad (asbestos-based) | 3.55                | 3.15             | 0.4            | 11.3            | 88.7                |

*Figure 7.* (a) SEM (b) EDS of the 12 wt.% 180 µm millscale reinforced ceramic composite.
0.47 to 0.804 W/m K [10]. The thermal conductivity values of the developed composites are within the range of the standard values.

3.4. Thermal stability of the composites from the DTA

The temperatures of destruction ($T_{\text{des}}$) of the millscale-particles-reinforced CMCs are presented (Figure 9). The maximum thermal decomposition of the samples took place in the temperature region 1648–1727°C. All composites exhibit very high resistance to thermal decomposition but the 106 µm millscale-reinforced composite (sample B) has maximum thermal decomposition at 1727°C. This implies that the samples exhibit high ability to absorb heat before disintegration, indicating that they are thermally stable. This is due to the high refractoriness of the ceramic materials and the strong interfacial bonding of the particles. The strong interfacial bonding of the particles effectively acted as barriers to decomposition of the samples during heating, thereby enhancing the thermal stability of the composites [9]. Also, the thermal compatibility between the millscale particles and the ceramic matrix prevented internal stress during heating, cooling and thermal mismatch strain in the composites [12]. These ceramic composites exhibit higher decomposition temperatures than conventional asbestos brake pads and many agro-wastes-based brake pads. This is an indication that the ceramic composites developed in this study are more thermally stable. This supports the fact that ceramic materials exhibit high-temperature resistance and thermal stability [4]. Materials for use as brake pads must be capable of absorbing heat to prevent distortion or cracking from thermal expansion until the heat is dissipated [2,13].

3.5. COF of the ceramic composites

COF is a dimensionless property indicating the friction quality of one material sliding over another. The COF of the composites decreases with increasing applied load as shown in Figure 10. This may be due to insufficient amount of tribo-layer formation between the sliding interfaces. Similar observation was reported in [14,15]. However, the COF increases with a decrease in millscale particles’ size reinforcement. The range of the COF values of the composites is from 0.506 to 0.561, which indicates a rather severe friction on the surface of the composites. The 106 µm millscale-particles-reinforced composite exhibits higher friction coefficient than the other composites. Increase in friction coefficient does not translate to higher wear rate. The trend shows that the friction coefficient and wear performance do not go together because when the friction behaviour is good, wear performance is poor and vice versa [14]. Hence, an opposite trend exists between the friction coefficient and wear rate since friction coefficient decreases as applied normal load increases but wear rate increases with increasing load (Figure 12).

The values of the COF of the composites is within industrial standard (0.3–0.6) recommended for automobiles brake pads [10,16]. Braking materials (brake pads) must ensure a sufficiently high COF and must not decompose or break down in such a way that the
friction coefficient with the brake disc is not compromised at high temperatures [14,17].

3.6. Mass loss due to wear

The wear behaviour of the composites under applied loads of 8, 12, 16, 20 and 24 N at constant sliding distance of 1257 m is shown in Figure 11(a,b). In all the composites, the mass loss due to wear increases with increasing applied load. It is quite natural for wear to increase with applied load. This may be due to plastic deformation of materials in the friction surface as a result of increase in the shear force between asperities and the ploughing force of asperities [15]. In each of the reinforced composites, the highly reinforced samples (15 and 18 wt.%) exhibit the lowest mass loss. This indicates the effect of concentration of mill-scale reinforcement in reducing mass loss. Generally, all the CMCs exhibit minimal mass loss due to the strong interfacial bonding of the particles during the high-temperature sintering process.

3.7. Wear rate and wear resistance

In all the composites, the wear rate increases as shown in Figure 12(a,b) with increasing applied load, while the wear resistance decreases as shown in Figure 13(a, b). This may be due to plastic deformation of materials in the friction surface as a result of increase in the shear force between asperities and the ploughing force of asperities [15]. The highly reinforced samples (15 and 18 wt.%) exhibit the lowest wear rate and

Figure 10. COF of the CMCs at a varying normal load.

Figure 11. (a) Effect of load on mass loss of the 106 µm millscale-particles-reinforced CMCs. (b) Effect of load on mass loss of the 150 µm millscale-particles-reinforced CMCs.
Figure 12. (a) Effect of load on wear rate of the 106 µm iron-millscale-particles-reinforced ceramic composites. (b) Effect of load on wear rate of the 150 µm iron-millscale-particles-reinforced ceramic composites.

Figure 13. (a) Effect of load on wear resistance of the 106 µm iron-millscale-particles-reinforced ceramic composites. (b) Effect of load on wear resistance of the 150 µm iron-millscale-particles-reinforced ceramic composites.
highest wear resistance. This indicates the effect of concentration of millscale reinforcement in reducing wear.

The 106 µm millscale reinforced composite exhibits the lowest wear rate of $1.99 \times 10^{-6}$ g/m at maximum load of 24 N. It is an indication of the positive effect of small particles size of iron millscale reinforcement in reducing wear much better than bigger (150 µm) particles size.

The wear rate of conventional brake pad is $3.8 \times 10^{-6}$ g/m [18]. The wear rate of all the composites

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**Figure 14.** Micrographs of worn surfaces of the composites under load of 24 N (a) unreinforced, (b) 18 wt.% 106 µm iron-millscale-particles-reinforced, (c) 15 wt.% 150 µm iron-millscale-particles-reinforced, (d) 15 wt.% 180 µm iron millscale-particles-reinforced, (e) 12 wt.% 212 µm iron-millscale-particles-reinforced and (f) 15 wt.% 250 µm iron-millscale-particles-reinforced ceramic composites.
developed in this study is much lower than that of the conventional brake pad. Thus, low rate of wear means that the composites have increased wear resistance. The decrease in wear rate of the composites is attributed to the diffusion of iron millscale particles and their deep penetration into the ceramic matrix. These result in a strong interfacial bonding between the ceramic matrix and millscale particles, thereby forming a coherent phase with high wear resistance. The strong interfacial bonding significantly reduces the possibility of particles pull out.

3.8. Morphology of the worn surfaces of the ceramic composites

The SEM micrographs in Figure 14(a–f) show the microstructure of the worn surfaces of the composites after wear tests at maximum applied load of 24 N. The surfaces of the iron-millscale-reinforced ceramic composites show a typical abrasive wear mode in which debris, scratches, shallow and deep grooves are formed along the wear direction. It is observed that the worn surface of the unreinforced composite (Figure 14(a)) has more groove defects than the reinforced shown in Figure 14(b–f). The highly reinforced (15 and 18 wt.%) composites have less scratches and grooves than the lightly reinforced composites. This behaviour compared well with the fact that abrasive wear in contacting surfaces results in scratching, furrows, work hardening or grooves [19,20].

The worn surfaces appeared to be rough on the microscopic scale. During the wear process, wear debris are generated and they are mainly fine powders that are either released into the environment or trapped between the contact areas. Occasionally, some of the wear debris may also be trapped in any available porous or void area of the samples. The wear debris accumulate and pile up against the contact areas. This phenomenon results in the contact areas increasing in size to form a friction layer and patches due to the compaction of wear debris trapped between the sliding surface, as observed in most of the micrographs. The debris in the micrographs may have aggravated the rate of wear of the samples. Similar observations have also been reported in [2,21].

The micrographs of the worn samples reveal that abrasion, adhesion and groove formation are the wear types that were in operation during the wear process. Abrasion is always characterized by the presence of shallow grooves of ploughed marks on the friction layers. This wear mechanism is observed in all the micrographs and a similar observation has been reported in [22]. This phenomenon could be due to the hard particles of the ceramic materials which exist during the wear process that ploughed into the worn surface. Adhesion also occurs as the contact areas grow to form patches due to the compaction of wear debris trapped between the sliding surfaces.

4. Conclusion

The thermal, friction and wear properties of millscale reinforced CMCs were evaluated to determine their suitability as automobiles and aircrafts brake pads. From the results obtained, it is clear that the composites exhibited a relatively high COF (0.506–0.561), a modest thermal conductivity of 0.39–0.53 W/m K and high resistance to thermal decomposition (1648–1723°C). The composites also exhibited low wear rate (1.99 × 10⁻⁶ g/m). The most desirable characteristics are demonstrated by the highly reinforced samples containing 15 and 18 wt.% millscale. These results compared well with standard automobiles and aircrafts brake pad properties’ specifications, thereby indicating that the composites have high potential for application as automobiles and aircraft brake pads.

Disclosure statement

No potential conflict of interest was reported by the authors.

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