Friction **4**(2): 144–152 (2016)
DOI 10.1007/s40544-016-0111-0

ISSN 2223-7690
CN 10-1237/TH

RESEARCH ARTICLE

Wear behavior of asbestos-free eco-friendly composites for automobile brake materials

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Received: 20 October 2015 / Revised: 31 December 2015 / Accepted: 02 May 2016

Abstract: The goal of this work is to study the wear behavior of materials that have the potential to be used as brake pad materials under different contact loads and speeds instead of asbestos. The three different brake pad materials studied are flax fiber reinforced phenolic composites (FFRC), basalt fiber reinforced phenolic composites (BFRC), and flax/basalt reinforced hybrid phenolic composites (HFRC). A wear mechanism map was developed by using the fuzzy c-means clustering algorithm method (FCM) to study the wear mechanism of composites. The results showed BFRC to be a better brake pad material than the other fiber reinforced composites studied, because the good thermal characteristics and bonding nature of basalt fiber increased the wear resistance of BFRC considerably.

Keywords: wear resistance; non-asbestos brake frictional materials; eco-friendly composites; wear mechanism maps; coefficient of friction; wear

1 Introduction

The first generation of composites used in modern brake friction materials relied on asbestos reinforced composites. Asbestos fiber reinforced polymeric composites are used in brake pads, brake linings and brake couplings; however, asbestos has been found to be hazardous to the environment and to human health [1]. Therefore, in recent years, non-asbestos reinforcements like Kevlar (aramid fiber), glass fiber, graphite, and natural fibers have been used as replacements for asbestos [2].

Conventional materials are being replaced by modern composite materials in many fields because of their many advantages such as light weight and easy processing. Reinforcing friction materials with natural and mineral fibers has provided significant enhancement in their mechanical and tribological properties. Although these fibers exhibit fairly good mechanical and friction properties, there are some serious drawbacks such as poor affinity with resin and susceptibility to friction-induced noise [3]. However, because of their excellent mechanical properties, low cost, and low environmental impact, these fibers have recently become increasingly attractive material candidates. In automotive applications, polymer matrix composites (PMC) are used as brake pads with cast iron or steel discs as counterparts [4]. It is impossible to avoid the wear of the brake pads, but wear should be minimized as far as possible without compromising on the functional performance of the component.

Even though the composite materials made with fibers such as asbestos, carbon, glass, and aramid fibers have good mechanical, thermal and tribological properties, they are expensive, non-biodegradable and hazardous to health. They are still used in many applications such as panels, packaging, kitchen utensils, furniture and the automotive industry.

Chemically treated flax fibers have been used in eco-friendly brake friction composites to replace aramid pulp in non-asbestos organic friction materials and

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to replace steel wool in semi-metallic friction composites [1]. Furthermore, basalt fiber is an inorganic fiber with an extremely good modulus, high strength, enhanced strain to failure, high-temperature resistance, excellent stability, good chemical resistance, and good processability [5]. Hence natural fibers, specifically flax and basalt fibers, have been suggested for use in friction materials because of their low cost, bio-friendliness, and renewable characteristics [6, 7].

From the studies of Yun et al. [8], it is observed that phenolic composites reinforced with 6% volume fraction of natural fiber are effective in improving the wear resistance of composites. Studies carried out by various researchers have found that there are four possible modes of failure during the operation of braking in automobiles: (i) chemical changes, (ii) thermal instability, (iii) wear mechanisms, and (iv) micro-cracks.

The goal of the present work is to investigate the wear behavior of three potential brake pad materials that are not in commercial use yet. They are flax fiber reinforced phenolic composites (FFRC), basalt fiber reinforced phenolic composites (BFRC), and flax/basalt reinforced hybrid phenolic composites (HFRC). Wear tests were carried out using a pin-on-disc wear tester. All the brake friction materials were tested against a cast iron disc. The influence of normal force and sliding speed on the wear behavior of the brake friction material was investigated. Furthermore the worn surfaces of the brake friction materials were analyzed using a JEOL scanning electron microscope (SEM).

2 Materials and methods

2.1 Raw materials

All the raw materials used in this study except the binder were selected based on their biodegradable and non-toxic properties, and their availability from natural sources.

2.2 Treatment of flax and basalt fibers

The as-received flax and basalt fibers were shortened to 8 mm length [9] and dried at 80 °C for 30 min in a hot air oven. The dry fibers were then treated with 5% NaOH solution at room temperature for 1 h. The treated fibers were washed with distilled water until a pH value of 7 was attained and again dried in a hot air oven for 5 h at 80 °C. After drying, the fibers were soaked in a solution of acetone/water (50/50 by volume) with 20 mL of trimethoxy methyl silane for 2 h and stirred for proper mixing. Then the alkalized fibers were washed in the acetone solution and dried in atmospheric air followed by hot oven drying at 80 °C for 5 h [10].

2.3 Preparation of eco-friendly friction materials

Three different types of composite materials were developed by using flax, basalt and their hybrids as reinforcements with phenolic resin as a binder matrix. The remaining ingredients shown in Table 1 were used as fillers, additives, solid lubricants and friction modifiers [8]. All the ingredients were mixed and

Table 1 Volume fraction of brake materials.

Functions	Ingredients	Volume fraction of flax fiber reinforced composites (FFRC)	Volume fraction of basalt fiber reinforced composites (BFRC)	Volume fraction of hybrid fiber composites reinforced (HFRC)
Binder	Phenolic resin	25	25	25
Fillers	Baryte	15	15	15
	Vermiculate	5	5	5
Friction modifiers	Graphite	12	12	12
	Coke	18	18	18
	Molybdenum disulfide	1	1	1
	Magnesium oxide	5	5	5
	Potassium titanate	6	6	6
	Aluminium oxide	5	5	5
	Zirconium silicate	2	2	2
Reinforcement	Flax	6		3
	Basalt		6	3

blended in a mechanical stirrer for 2 min. Then the blended mixture was poured into a 50 mm × 20 mm cast iron die, and the die was loaded with a vertical load of 10 MPa at 180 °C in a diffusion bonding machine that provided an inert atmosphere around the mixture. The time for the compaction in the diffusion bonding machine was 10 min for each composition.

During the hot-pressing process, pressure was released several times to release the gases that evolved from the cross linking reaction (polycondensation) of the phenolic resin. Post-heat treatment of the composites was performed in a hot air oven for a period of 4 h at 180 °C [11]. Then the composites were cut into 10 mm × 10 mm square samples with a height of 20 mm [12]. There are two reasons for selecting the square cross section: (1) it was difficult to machine a pin with a circular cross section from the fiber reinforced composites, and (2) the use of a rectangular cross section results in less wear and less scatter in the friction surface [13, 14].

2.4 Wear tests

A pin-on-disc type apparatus was used to investigate the dry sliding frictional and wear behavior of the composite material according to the ASTM G 99 test standard. The specimen pin was mounted onto the arm of a tribometer. During the wear tests, the end surfaces of the specimen pins were pressed against a 55-mm diameter by 10-mm thick horizontal rotating cast iron disc. The sample was made to rotate on the wear disc. Different loads in the range of 9.81 to 49.04 N were applied directly to the top of the pin, and the sliding velocities were varied from 0.104 to 0.523 m/s for a period of 30 min. The friction coefficient was calculated from the friction force measured during the wear test, and the wears are calculated in microns (μm) as displayed by the tester. The worn surfaces of the composite specimen were analyzed by SEM to investigate the operating wear mechanisms.

3 Results and discussion

3.1 Development of the wear mechanism map by a fuzzy clustering method

A wear map is a graphical representation used to study the effect of sliding velocity and normal force on wear values. A wear map is drawn in the form of contours. The contour lines represent the change of wear mode from mild wear to severe wear or from severe wear to ultra-severe wear. Wear maps were developed from simple MATLAB programs by plotting the sliding velocity on the *X*-axis, the normal force on the *Y*-axis, and the resultant wear on the *Z*-axis.

From the wear map, it is easy to construct a wear mode map, which is sometimes called a wear regime map, a wear transition map, or a wear mechanism map. The search for boundaries of regions of predominant wear and their transitions is one of the important problems in constructing the wear mechanism map where the competing processes may change the wear values [15]. There are boundaries between mild wear, severe wear, and ultra-severe wear in the mechanics of sliding wear.

From an engineering point of view, a mild wear regime might well be considered acceptable whereas the severe and ultra-severe wear conditions are considered unacceptable. Classification of boundaries between different wear modes was done by using the fuzzy clustering method [16]. The fuzzy c-means clustering algorithm uses the minimization of the fuzzy c-means functional. The three input parameters used are: param:c, as the number of clusters or initializing partition matrix; param:s, as the fuzziness weighting exponent; and param:e, as the maximum termination tolerance. The latter two parameters assume default values if the user does not specify them. The standard Euclidean distance norm was calculated by a function where the norm-inducing matrix is an $n \times n$ identity matrix. The result of the partition is collected in structure arrays. At each iteration step, the partition matrix cluster centers, the squares of the distances, the number of iterations, and the values of the c-means functional can be obtained.

In this work, the centroids of each wear regime were discovered by the fuzzy clustering method, and the boundaries between the wear regimes were drawn by removing the intermediate contours of the wear map [17].

3.2 Friction and wear characteristics of FFRC

Figure 1(a) shows the wear behavior of FFRC with respect to normal force and sliding velocity. The wear values increase with an increase in normal force when the sliding velocity is between 0.1 m/s and 0.5 m/s. Similarly, the coefficient of friction (COF) shown in Fig. 1(b) increases with an increase in normal force, because the edges at the contacting asperities restrict the smooth sliding between sliding pairs. Figure 2 shows the wear mechanism map of FFRC. The mild wear regime of FFRC has a maximum wear of 3.5 μm and a maximum COF of 0.04, which is well-supported by the micrographs of worn-out specimens shown in Fig. 2(a). The dominant wear mechanism in this regime is the ironing mechanism and there is not sufficient load to deform the specimen that would

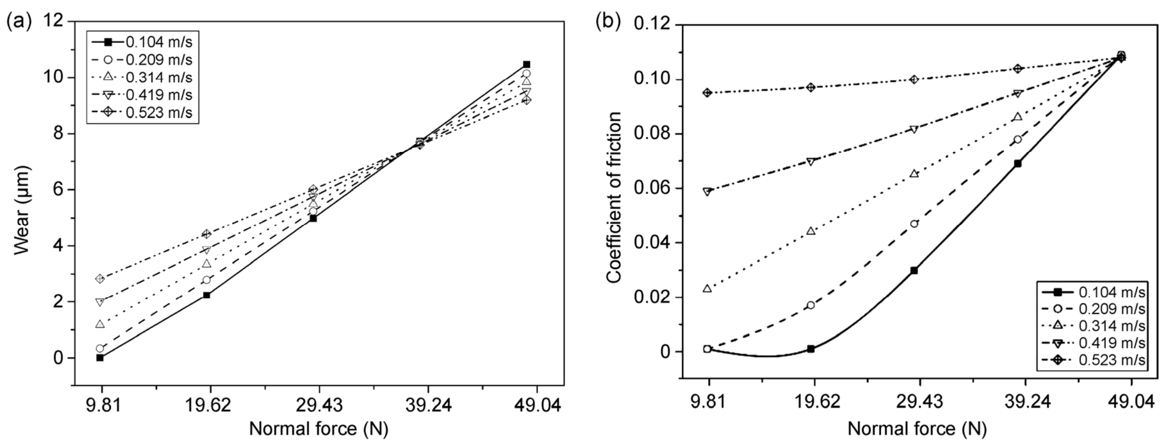

Fig. 1 (a) Effect of normal force and sliding velocity on wear of FFRC; (b) effect of normal force and sliding velocity on the coefficient of friction (COF) of FFRC.

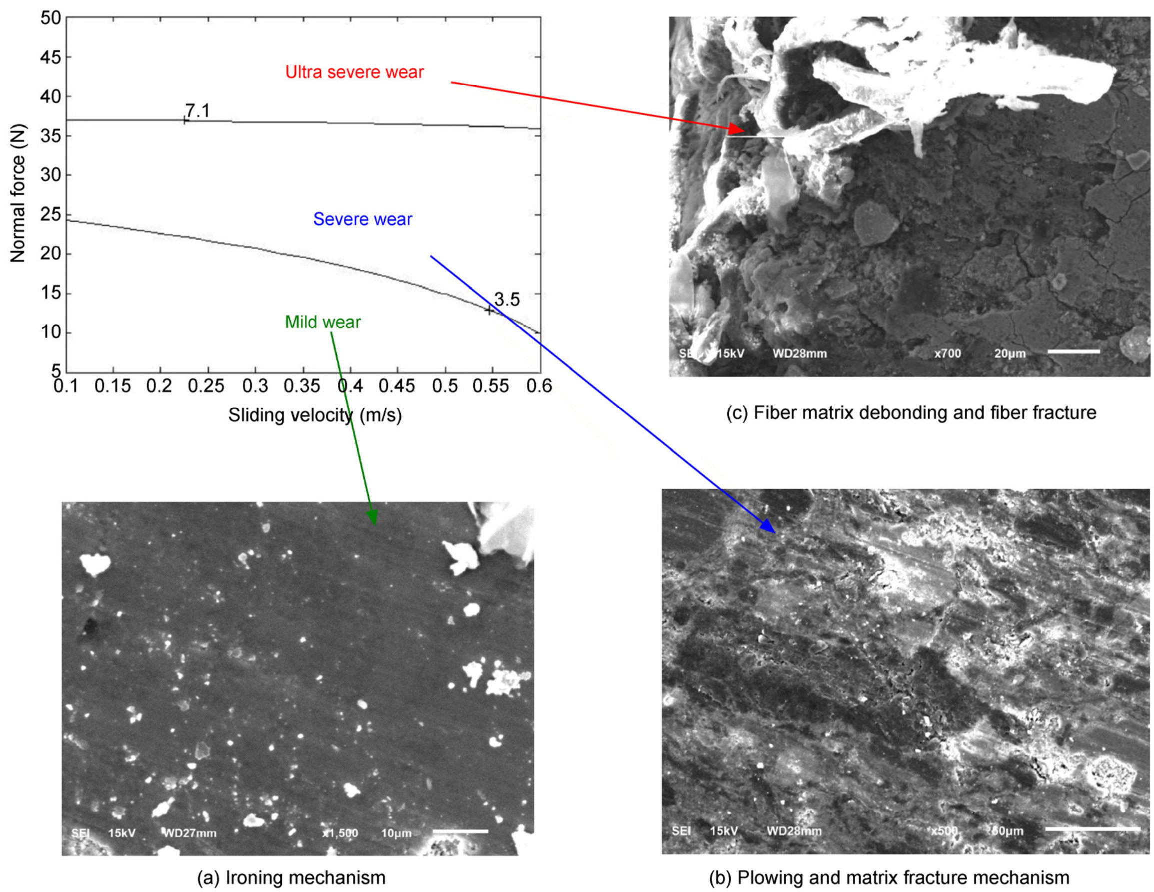

Fig. 2 Wear mechanism map for FFRC composites.

increase the wear. A strong bond between the fiber and the matrix made the separation of material from the pin more difficult and contributes to the higher wear resistance [18].

When the load was increased beyond 25 N, the wear regime shifted from mild wear to severe wear which has a maximum wear of 7 μm and a maximum COF of 0.087. In this regime, there was a considerable increase in COF and wear that may be due to elastic deformation of surface asperities as a result of increasing contact temperature. The micrographs of worn-out specimens shown in Fig. 2(b) reveal the presence of matrix fracture and plowing mechanisms. Due to repetitive application of loads, the matrix material starts to crack first, followed by matrix fracture. Once the fractured surface is exposed to increased load conditions, plowing of matrix material takes place. The above statement agrees well with the studies of Zhang et al. [19]. Matrix fracture is a mechanism where stresses appear in the matrix material as a result of the applied load, which can lead to the formation of large cracks. This mechanism was predominant in the severe wear regime with higher loads and a low sliding velocity. A plowing mechanism accounts for a small proportion of the displaced material that was detached from the surface. The matrix damage, where deep longitudinal cracks observed on the surface can modify the surface topography; this is due to the repeated plowing causing surface fatigue [20].

When the loading was increased beyond 36 N, a transition of the wear regime from severe wear to ultra-severe wear took place. The wear values in this regime are more than 7 μm and the corresponding COF is more than 0.09. The SEM micrograph of worn-out specimens in the ultra-severe regime shown in Fig. 2(c) confirms the presence of fiber matrix debonding and fiber fracture mechanisms. As the temperature in the contacting surfaces is not uniform, the thermal gradients have generated thermal stresses in the specimen, which lead to weakening of fiber matrix bonding at the interface. Fibers become loose and shear easily due to repeated axial thrust during sliding [21–23]. When the debonded fibers are exposed to severe load conditions, fractures can be seen in the fibers.

3.3 Friction and wear characteristics of BFRC

Figure 3(a) shows the wear dependence on normal force and sliding velocity. The wear values initially increase with normal force, but when the normal force exceeds 29.43 N, the wear values begin to decrease. This may be due to wear debris entrapped in the contracting asperities that are welded to the specimen pin. On the other hand, the COF values shown in Fig. 3(b) follow an increasing trend when the normal force is increased.

Also, the good thermal characteristics and bonding nature of basalt fibers make BFRC a material with good wear resistance. From the wear mechanism map shown in Fig. 4(a), it can be observed that the transition of wear regimes is directly proportional to the normal force applied [24, 25]. In this regime, a maximum wear of 1.64 μm and a maximum COF of

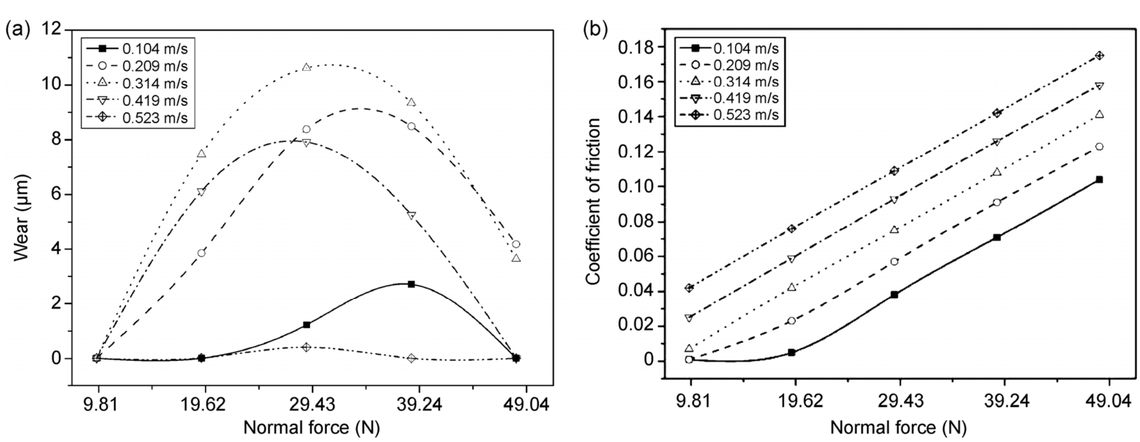

Fig. 3 (a) Effect of normal force and sliding velocity on wear of BFRC; (b) effect of normal force and sliding velocity on COF of BFRC.

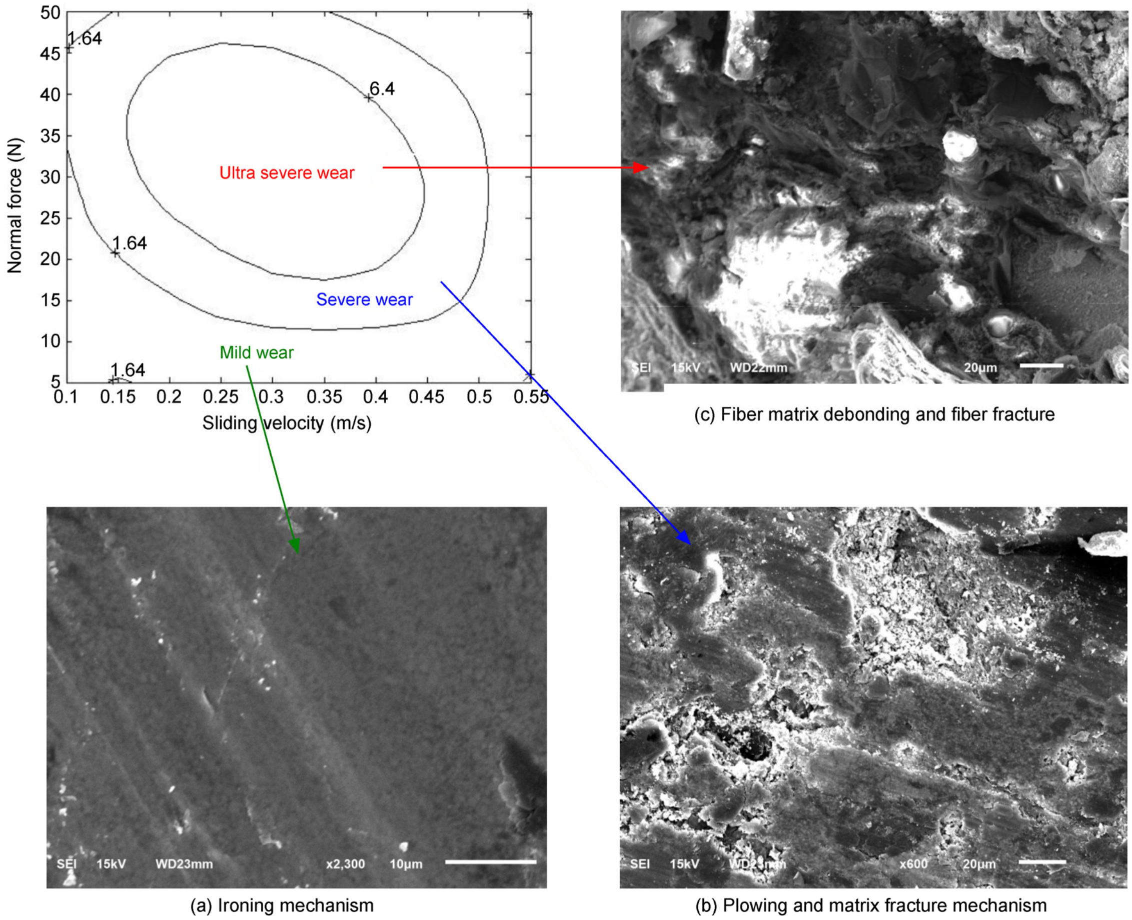

Fig. 4 Wear mechanism map for BFRC composites.

0.05 were obtained. From the micrographs of worn-out specimens taken in the mild wear regime, the dominance of the ironing mechanism can be clearly seen where the bulk of the material recovers elastically, as evidenced by a localized decrease in roughness [26]. Similar to wear behavior of FFRC, the severe wear regime was dominated by plowing and by the matrix fracture mechanism shown in Fig. 4(b). For the severe wear regime, the wear values range from 1.64 μm to 6.38 μm, whereas the COF ranges from 0.05 to 0.11.

The ultra-severe wear regime shown in Fig. 4(c) displays the dominance of fiber-matrix debonding, and the magnitude of fiber fracture is greatly reduced for the BFRC. The corresponding values of wear and COF exceed 6.38 μm and 0.11 respectively. In comparison with FFRC, the wear resistance of BFRC has greatly increased; that is, the maximum wear of BFRC in mild wear is 1.64 μm whereas the maximum wear of FFRC in the mild wear regime is 3.5 μm.

The results also suggest that the wear is highly determined by the type or ingredients of the friction material. On a microscale, the friction and wear characteristics of friction material depend on the formation, growth, and disintegration of contact plateaus; shape adaption; and thermally induced deformation [27]. The mechanism of the friction film formation in multiphase materials is very complicated and strongly depends on the thermal history of the sliding interface. In the case of normal braking applications, it is known that the organic constituents, fibrous materials and solid lubricants all play a role in establishing the transfer layer at the friction surface and this transfer layer becomes significant and more effective at high pressure in the mild wear regime of BFRC [28, 29].

3.4 Friction and wear characteristics of HFRC

Figure 5(a) shows the influence of sliding velocity and normal force on the wear values of HFRC. Wear decreases with normal force up to 29.43 N. Beyond this, wear increases with increasing normal force.

Figure 5(b) shows the dependence of the COF on sliding velocity and normal force. The COF decreases with an increase in normal force, when the sliding velocity is maintained at 0.1 m/s. When the sliding velocity is increased beyond 0.2 m/s, the COF increases with increases in normal force. The entrapped wear debris in the contacting asperities of the pin and the disc might have helped increase the COF.

The wear mechanism map of HFRC shown in Fig. 6 reveals that the mild wear regime has a maximum wear of 6.38 μm and a corresponding COF of 0.05. Figure 6(a) shows the dominance of ironing in the mild wear regime [30]. The severe wear regime of HFRC composites shows wear ranging from 6.38 to 12.4 μm, and the COF varies from 0.05 to 0.13. SEM images of worn-out specimens in the severe wear

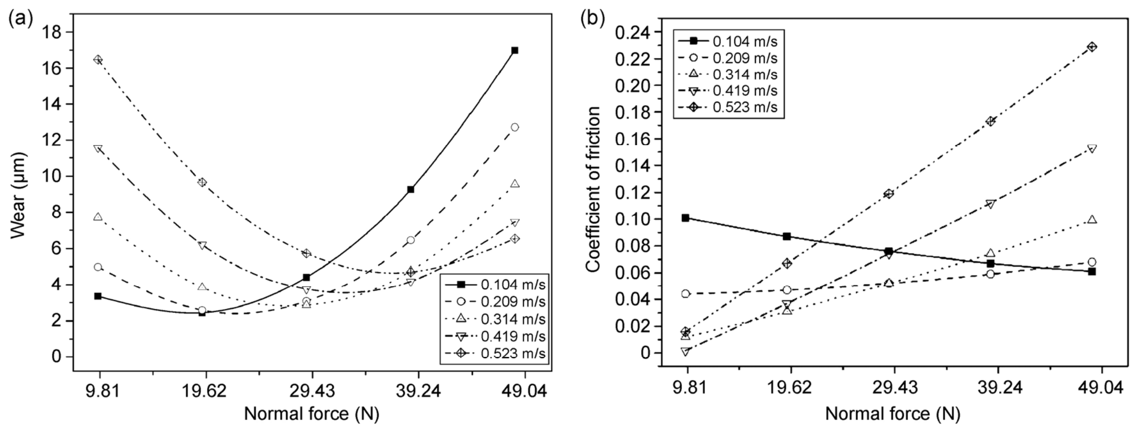

Fig. 5 (a) Effect of normal force and sliding velocity on wear of HFRC; (b) effect of normal force and sliding velocity on COF of HFRC.

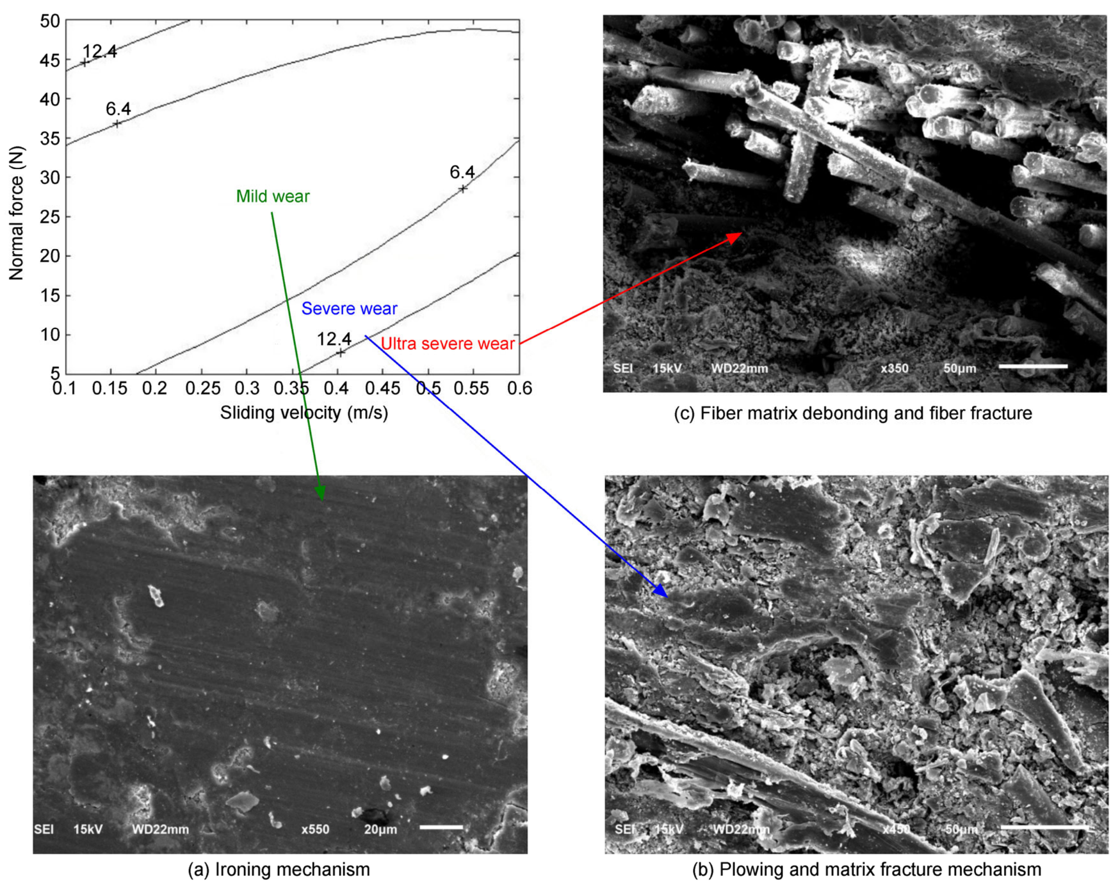

Fig. 6 Wear mechanism map for HFRC composites.

regime shown in Fig. 6(b), demonstrate the dominance of matrix fracture and plowing mechanisms. In the ultra-severe regime, the presence of fiber-matrix debonding and fiber fractures is noticed, and the wear values are above 12.4 μm as shown in Fig. 6(c).

In this study, it was found that the BFRC has a maximum wear of 1.6 μm in the mild wear regime while the FFRC and HFRC have maximum wear of 3.5 and 6.4 μm respectively. The maximum wear in the severe wear regimes of BFRC, FFRC and HFRC are 6.4, 7.1, and 12.4 μm, respectively. As the bonding nature of basalt fibers is large compared to flax fibers, BFRC is found to have better wear resistance than FFRC and HFRC. Also, the residual moisture content in the flax fibers might be the reason behind its poor behavior. The COF increases with increases in normal force for FFRC, BFRC, and HFRC; however, the wear values follow a different trend for each composite.

4 Conclusions

In this study, three combinations of asbestos-free eco-friendly composites including FFRC, BFRC, and HFRC were prepared and subjected to wear studies. The following conclusions were drawn:

(1) Of the three composites used in this study, BFRC was found to be a suitable candidate for brake pad applications. When the normal force is increased, the wear is increased for FFRC and HFRC whereas the wear is decreased in the case of BFRC because the strong basalt fibers showed a remarkable resistance to wear at higher sliding conditions.

(2) Ironing is the dominant mechanism in the mild wear regimes as per the wear mechanism maps that were prepared for all the composites used in this study. Plowing and matrix fractures are dominant in the severe wear regimes, but the ultra-severe regimes were dominated by fiber matrix debonding and fiber fractures.

(3) The maximum wear in the mild wear regime of BFRC is 1.6 μm, compared to 3.5 μm for FFRC and 6.4 μm for HFRC.

(4) The improved wear resistance of BFRC is attributed to its good thermal characteristics and to the bonding nature of basalt fibers. Also, the wear debris of basalt fibers acts as a protective barrier for the BFRC composites that greatly increased the wear resistance of the composites.

(5) The ultra-severe wear regime of BFRC displayed a low fiber fracture mechanism compared to the ultra-severe wear regimes of FFRC and BFRC.

(6) The wear mechanism map developed using the fuzzy clustering method proved to be an effective tool in the study of wear behavior of materials.

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