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TRIBOLOGICAL PROPERTIES OF FLAX FIBER REINFORCED POLYMER COMPOSITES

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Abstract: The present work is an investigation of using 4% volume fraction of flax fiber as reinforcement in polymer matrix composites to predict the wear rate and coefficient of friction. The pin on disc wear tester were used to conduct the experiments at different applied loads (9.81 N- 49.03N) and sliding velocities (0.101 m/s- 0.523 m/s). Based on these results Fuzzy Clustering Algorithm method were developed the wear mechanism maps. Scanning Electron Microscope (SEM) was used to analyze the worn out specimens. The results found that the 4% of volume fraction (Vf) of Flax fibers polymer reinforced matrix composites shows that the normal force increasing in all sliding velocities the wear rate and coefficient of friction in increasing trend. The tribological properties of Flax Fiber Reinforced Polymer Composites influenced by the adhesion between matrix and the fibers. This can be achieved by the chemical modification of flax fiber which enhances adhesion between matrix and the fibers.

Keywords: Flax Fiber Reinforced Composites, Wear mechanism maps, Scanning electron microscope, wear, coefficient of Friction.

1. INTRODUCTION

The first generation of composites used in friction materials were asbestos fiber reinforced composites. It has been found that this material have a carcinogenic property and affected by Environment and human health. Therefore the natural fibers are used as reinforcements [1-2]. The scarcity and increase in petrochemical resources will almost immediately effect in a sturdy requirement for plastics based on renewable sources. The abundance in nature combined with the ease of its processing is an attractive feature, which makes it has an important substitute for synthetic fibers which are potentially toxic. Lignocellulose fibers such as jute, sisal, pineapple, banana, curaua etc., whose properties of the fibers, can generate rural jobs and potential as reinforcements in many polymers due to its low cost, low density, specific resistance, biological degradability, renewability, good mechanical, thermal and tribological properties and nontoxic. Besides that, they can easily modified by chemical treatments. However, the potential for natural fibers such as kenaf, jute, hemp, flax and sisal with expected growth rates of 15-20% every year and used for automotive components rapidly growing up to 45000 tons of natural fibers needed in international market. The use of natural fibers is to reinforce thermosets as an alternative to synthetic and glass fibers has been
continues to be the subject of research and development. The major components the plant based fibers consists of cellulose, hemicellulose and lignin. Since the strength and stiffness of fibers mainly depends on their cellulose content. Based on the cellulose content the properties of the fiber should be changed. [3-4]

Natural fiber generally contain large amount of the hydroxyl group, which makes them polar and hydrophilic in nature. The addition of hydrophilic natural fibers to hydrophobic plastics will result in a composite with poor mechanical properties due to non-uniform fiber dispersion in the matrix, and an inferior fiber-matrix inter phase leading to fiber swelling and voids in the fiber-matrix inter phase. Fiber surface treatments are generally used to solve these problems [5].

In the last two decades, the effect of natural fiber as reinforcement on the tribological properties of polymer composites have been studied. Flax, sisal, bamboo, hemp and banana fibers are probable replacement for synthetic fibers. Natural fibers have many advantages of biodegradable, low cost, environmental friendly and high strength to weight ratio[6-7]. In tribology applications Natural fiber reinforced materials are commonly used as frictional materials. Friction materials should have a high coefficient of friction, low wear rate at high speed and normal force. The frictional materials consists of binders, fibers, fillers, solid lubricants and friction modifiers. In tribological applications Fibers plays an important role. The superior property such as wear and thermal behavior of friction material composites, natural fibers were used as a reinforcement. It is inevitable to avoid the wear of the friction materials, but it should be minimized as far as possible while not compromising on the functional performance of the component.

The binder resin plays a crucial role in determining the friction characteristics of a material and is often blamed for in the friction material [8]. Frictional heat generated during the sliding process can easily raise the temperature at the interface beyond the glass transition temperature of the binder resin resulting in an abrupt change in the friction force during working. This occurs because of degradation of binder resin and other constituents over time and use [9].The influence of normal force and sliding speed on the wear behavior of the friction material were investigated. Furthermore the worn surfaces of the friction materials were studied in order to ascertain the wear mechanisms. Some studies have been carried out that the tribological behavior strongly dependent on many processing parameter such as operating parameters, characteristics of polymer material, physical and interfacial adhesion properties of fiber, additives and contact condition . There are few issues can be identified which are influences the wear and friction behavior such as operating parameters, reinforcing the natural fiber in polymers, chemical treatment of fiber, addition of friction modifiers and fillers etc.[10].

The present study investigates the wear behavior of Flax fiber reinforced phenolic resin composites. A pin on disc wear tester is used to conduct the wear tests. All the polymer matrix friction materials were tested against cast iron disc. The influence of normal force and sliding speed on the wear behavior of the polymer matrix friction material were investigated. The
tests are carried at different normal forces (9.81N -49.04N) and sliding velocities (.104 m/s -.523m/s) and the time duration for the test is maintained at 30 minutes per specimen. Furthermore the worn surfaces of the polymer matrix friction materials were studied in order to ascertain the wear mechanisms by the use of SEM.

2. EXPERIMENTAL PROCEDURE

2.1. Raw Materials

Materials used in this study are Flax fibers were chosen as a reinforcement based on their environmental and non-toxic properties from natural resources, except the binder. Phenolic resin is used as binder material which is a non-biodegradable substance.

2.2. Treatment of Flax Fibers

Flax fibers as received were treated by drying at 80°C for 30 min in a hot air oven. Cellulose is a hydrophilic characteristics in natural fibers. The aggressive absorption of moisture in cellulose is due to the attraction of hydrogen in water molecules to the groups of hydroxyl along the cellulose chain. Moisture reduces the adhesion between cellulosic reinforcements of natural fibers and hydrophobic polymer matrices such as phenolic resin, lead to a loss of stress transfer and thus leads to poor mechanical properties in composites. Sodium hydroxide can be used reduce the hydrophilicity of cellulosic fibers. They were then treated with 5% NaOH solution at room temperature for one hour. The treated fibers were washed with distilled water until PH value of 7 was attained and again dried in hot air oven for 5 hours at 80°C. Pretreatment of natural fibers improves the overall properties of the fiber due to the removal of impurities, waxes, hemicelluloses, and lignin from the surface thereby increasing the surface roughness. As a result, the surface is easily wettable by the resin, leading to good fiber impregnation and better fiber/matrix adhesion in the composite. After drying, the fibers were dipped in a solution of acetone/water (50/50 by volume) with 20 ml Trimethoxy methyl silane and stirred for proper mixing. Then the alkalized fibers were dipped in that solution for two hours. Then the fibers were washed by the acetone solution and dried in atmospheric air followed by hot oven drying at 80°C for five hours [11]. Hence it is possible to bring about compatibility by introducing a third kind of materials Silane coupling agents that forms a bridge of chemical bonds between the reinforcement and polymer matrix.

2.3. Preparation of Eco-friendly Friction Composites

In this present study 4% volume fraction of composite materials were developed by using flax fiber as reinforcement with phenolic resin as the binder in the matrix. The remaining ingredients shown in Table1 were used as fillers, additives, solid lubricants and friction modifiers. A mechanical stirrer was used for mixing and blending of composites for a period of 2 minutes. A cast iron die was used to pour the blended mixture at the size of 50 × 50 × 20 mm. The die was loaded with 10Mpa vertical load at 180°C in a diffusion bonding machine that provided an inert atmosphere to the mixture. The time taken for the compaction in diffusion bonding machine is 10 minutes for each composition.

The pressure was released several times to release the gases during the hot pressing process, that evolved from the cross
linking reaction (polycondensation) of the phenolic resin. Post heat treatment was done for the composites in a hot air oven for a period of 4 hours at 180°C temperature. Then the composites were cut to give the test samples with dimension of 10 × 10 mm square in cross section and a height of 20 mm[12]. There are two reasons for selecting the square cross section; First one is it was difficult to machine pin of circular cross section from the brake material and second one is the use of rectangular cross section results in less wear and less scatter in the friction surface[13].

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 ASTM G 99 test standard. The composite specimen in the form of pin was fixed on a holder. During the wear tests, the end surface of the specimen pins were pressed against a horizontal rotating cast iron. Different loads in the range of 9.81 N to 49.04 N were applied directly on the top of the pin and the sliding velocities were varied from 0.104 to 0.523 m/s for a period of 30min. The friction coefficient was calculated from the friction force measured during the wear test. The tests were carried out in ambient air with a relative humidity and temperature respectively. The worn surfaces of the composite specimen were analyzed in order to investigate the operating wear mechanisms by JEOL Scanning Electron Microscope [SEM]. The samples were coated with a thin layer of gold for the purpose of to increase the conductivity and also to avoid electro static charging during scanning examination of samples.

3. RESULTS AND DISCUSSION

3.1. Development of Wear Mechanism Map by Fuzzy Clustering Method

Fuzzy Clustering Method Algorithm has been used in numerous engineering and scientific applications. In view of that, the initially developed FCM makes use of the squared-norm to determine the similarity between prototypes and data points and it performed well only in the case of clustering spherical clusters. During the survey, it also found some points that can be further improvement in the future using advanced clustering technique to achieve accuracy and reduce the time taken for data and information retrieval from large dataset. Wear rate maps can be constructed by Fuzzy Clustering Method Algorithm.

Wear rate map is the graphical representation to study the effect of sliding velocity and normal force on wear rate. The wear rates are drawn as contours. Hence, from the wear rate map it is easy to construct a wear mode map which is otherwise called a wear regime map or wear transition map or wear mechanism map. From an engineering point of view, a mild wear regime might well be considered acceptable whereas the transition to severe and ultra severe wear conditions often represents a change to commercially unacceptable values. It is always a great challenge to determine the boundaries in the wear mechanism and hence it is decided to use Fuzzy C means Algorithm for classification of wear mechanisms. The fuzzy clustering and data analysis toolbox is a collection of mat lab functions.

In this work, the centroids of each wear regime were found out by fuzzy clustering method. Therefore the boundaries between the
wear regimes were drawn by removing the intermediate contours of the wear rate map [14].

3.2 Friction and Wear characteristics of FFRC

Figures 1a and 1b shows the effect of sliding velocity and normal force on the wear rate and coefficient of friction of FFRC.

![Figure 1a: Effect of normal force and sliding velocity on wear rate of FFRC](image1a)

![Figure 1b: Effect of normal force and sliding velocity on COF of FFRC](image1b)

At all sliding velocities the wear rates and coefficient of friction are found to increase with increasing the applied load.

This is due to the softening process and subsequent film generation and removal process during sliding. From Figure 2, it can be seen that transition of wear mechanism changes with increasing normal force. The mild wear regime has the maximum wear rate of 3.6 microns and maximum coefficient of friction of 0.04, which is well supported by the micrographs of worn out specimens shown in Figure 2a. The dominant wear mechanism in the regime is Ironing mechanism where a strong bond between the fiber and the matrix made the separation of material from the pin more difficult and hence contributed to higher wear resistance and also there is no sufficient load to deform the specimen which would increase the wear rate [15]. The detached wear debris from the composites might have embedded in the contacting asperities that improved the wear resistance of FFRC. In the case of sliding process, it is known that the organic ingredients, fibrous materials and solid lubricants play a roles in creating the transfer layer at the friction surface and this transfer layer becomes momentous and more effective at high pressure in mild wear regime of FFRC [16].

When the load was increased beyond 25N, the wear regime shifted from mild wear to severe wear which has the maximum wear rate of 9.5 microns and a maximum coefficient of friction of 0.09. In this regime, there was a considerable increase in coefficient of friction and wear rate which may be due to elastic deformation of surface asperities due to increasing contact temperature. The micrographs of worn out specimens shown in Figure 2b reveals the presence of matrix fracture and ploughing mechanisms [17].

SEM micrographs of worn out specimens in the ultra severe regime shown in Figure 2c confirms the presence of fiber matrix debonding and fiber fracture mechanisms.
As the temperature in the contacting surfaces are not uniform thermal gradients and developed which generates thermal stresses in the specimen which leads to weakening of fiber matrix bonding at interface. Fibers become loose and shear easily due to repeated axial thrust during sliding [18]. The damage of fibers by fiber fracture mechanism. This fiber debris is transferred on to the counter face along with thin polymer film which surrounds the fiber particles [19].

The results also suggest that the wear rate is highly determined by the type or constituents of the friction material. On micro scale, the friction and wear characteristics of friction material depend on the formation, growth, disintegration of contact plateaus, shape adaption and thermal induced deformation [20]. The mechanism of the friction film formation in multiphase materials is very complicated and strongly influenced on the thermal history of sliding interface.

4. CONCLUSION

In this work, flax fibers were used to enhance the tribological properties of the phenolic resin polymer matrix composites. The following conclusions can be drawn:

- Flax Fibre Re-Inforced Composite is found to be better wear resistant friction material.
- In mild wear regime Flax Fibre Re-Inforced Composites have a wear rate of 3.6 microns and the coefficient of friction of 0.04 and in severe wear regime the wear rate of 9.5 microns and the coefficient of friction of 0.09.
• The wear mechanism map for Flax Fibre Re-Inforced Composite confirms that the mild wear regime is dominated by ironing mechanism.
• The severe wear regime is dominated by matrix fracture and ploughing while the ultra severe wear regime is dominated by fiber matrix debonding and fiber fracture.

REFERENCES

Morphological Analysis of Wear Behavior of Flax Fiber Reinforced Composites

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This paper aims to investigate the dry sliding wear behavior of Flax Fiber Reinforced Composites (FFRC) using pin on disc wear tester. Two different volume fraction of polymer matrix composites were fabricated using compression moulding process in a vacuum condition. The objective of the present study is to importance on the analysis of the influence of some predominant process parameters such as normal force, sliding velocity and volume fraction of reinforcement on minimum wear rate and co-efficient of friction. The worn-out specimens of microstructural characterizations were analyzed by Scanning Electron Microscope and Fuzzy Clustering Algorithm was used to develop the wear mechanism map. The study was concluded that FFRC2 reinforced with 4% volume fraction \((V_f)\) of fiber is found to be a better wear resistant material than FFRC1 reinforced with 2% \(V_f\) of fibers. The main wear mechanisms showed in all illustrations were ironing, ploughing, matrix fracture, fiber matrix debonding and fiber fracture.

**Keywords:** Flax Fiber Reinforced Composites, Wear Mechanism Map, Scanning Electron Microscope, Fuzzy Clustering Algorithm, Wear Rate.

1. INTRODUCTION

Natural fiber reinforced materials are commonly used as frictional materials in tribology applications. Friction materials should have a high coefficient of friction, low wear rate at high speed and normal force. However to meet those requirements, the frictional materials consists of binders, fibers, fillers, solid lubricants and friction modifiers. Fibers plays an important role in a tribological applications. Natural fibers were used as a reinforcement in composites for the superior property such as wear and thermal behavior.¹

In the last two decades, the effect of natural fiber as reinforcement on the tribological properties of polymer composites have been studied. Flax, sisal, bamboo, hemp and banana fibers are potential replacement for synthetic fibers. Natural fibers have many advantages of biodegradable, low cost, environmental friendly and high strength to weight ratio.² The lesser weight (20–30 wt%) and higher volume of natural fibers compared to synthetic fibers to improve the mechanical and tribological properties specifically in automobile applications. This is due to their superior’s advantages over synthetic fibers in term of relatively low cost, low weight, less damage and good relative mechanical, thermal and tribological properties. Tribological performance of polymeric composites based on natural fibers used most of the industrial and manufacturing parts are exposed to tribological loadings such as adhesive, abrasives etc. therefore, tribological performance of materials becomes an essential element to be considered in design of any mechanical parts. However less work is found on the effects of natural fibers in literature review of polymeric composites. Some studies have been carried out that the tribological behavior strongly dependent on many processing parameter such as operating parameters, characteristics of polymer material, physical and interfacial adhesion properties of fiber, additives and contact condition. There are few issues can be identified which are influences the wear and friction behavior such as operating parameters, reinforcing the natural fiber in polymers, chemical treatment of fiber, addition of friction modifiers and fillers etc.³

The present study investigates the wear behavior of Flax fiber reinforced phenolic resin composites. The tests are carried at different normal loads (9.81N-49.04) and sliding velocities (.104 m/s–.523 m/s) and the time duration for the test is maintained at 30 minutes per specimen.

2. EXPERIMENTAL DETAILS

2.1. Raw Materials

All the raw materials used in this study were chosen based on their environmental and non-toxic properties from natural resources, except the binder. Phenolic resin
is used as binder material which is a non-biodegradable substance.

2.2. Treatment of Flax Fibers
Flax fibers as received were treated by drying at 80 °C for 30 min in a hot air oven. They were then treated with 5% NaOH solution at room temperature for one hour. The treated fibers were washed with distilled water until PH value of 7 was attained and again dried in hot air oven for 5 hours at 80 °C. After drying, the fibers were dipped in a solution of acetone/water (50/50 by volume) with 20 ml Trimethoxy methyl silane and stirred for proper mixing. Then the alkaliized fibers were dipped in that solution for two hours. Then the fibers were washed by the acetone solution and dried in atmospheric air followed by hot oven drying at 80 °C for five hours.4

2.3. Preparation of Eco-Friendly Friction Composites
Two different volume fraction of composite materials were developed by using flax fiber as reinforcement with phenolic resin as the binder in the matrix. The remaining ingredients shown in Table I were used as fillers, additives, solid lubricants and friction modifiers. A mechanical stirrer was used for mixing and blending of composites for a period of 2 minutes. A cast iron die was used to pour the blended mixture at the size of 50×50×20 mm. The die was loaded with 10 Mpa vertical load at 180 °C in a diffusion bonding machine that provided an inert atmosphere to the mixture. The time taken for the compaction in diffusion bonding machine is 10 minutes for each composition.

The pressure was released several times to release the gases during the hot pressing process, that evolved from the cross linking reaction (polycondensation) of the phenolic resin. Post heat treatment was done for the composites in a hot air oven for a period of 4 hours at 180 °C temperature.5 Then the composites were cut to give the test samples with dimension of 10×10 mm square in cross section and a height of 20 mm.6 There are two reasons for selecting the square cross section; First one is it was difficult to machine pin of circular cross section from the brake material and second one is the use of rectangular cross section results in less wear and less scatter in the friction surface.7

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 ASTM G 99 test standard. The composite specimen in the form of pin was fixed on a holder. During the wear tests, the end surface of the specimen pins were pressed against a horizontal rotating cast iron. Different loads in the range of 9.81 N to 49.04 N were applied directly on 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. The tests were carried out in ambient air with a relative humidity and temperature respectively. The worn surfaces of the composite specimen were analyzed in order to investigate the operating wear mechanisms by a JEOL Scanning Electron Microscope (SEM).

3. RESULTS AND DISCUSSION
3.1. Development of Wear Mechanism Map by Fuzzy Clustering Method
Fuzzy Clustering Method Algorithm has been used in numerous engineering and scientific applications. In view of that, the initially developed FCM makes use of the squared-norm to determine the similarity between prototypes and data points and it performed well only in the case of clustering spherical clusters. During the survey, it also found some points that can be further improvement in the future using advanced clustering technique to achieve accuracy and reduce the time taken for data and information retrieval from large dataset. Wear rate maps can be constructed by Fuzzy Clustering Method Algorithm.

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In this work, the centroids of each wear regime were found out by fuzzy clustering method. Therefore the boundaries between the wear regimes were drawn by removing the intermediate contours of the wear rate map.8

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Volume fraction in FFRC1</th>
<th>Volume fraction in FFRC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenolic resin</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Baryte</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Vermiculate</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Graphite</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Coke</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Molybdenumdisulfide</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Potassium titanate</td>
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<td>7</td>
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<tr>
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<tr>
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<td>2</td>
</tr>
<tr>
<td>Flax</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
3.2. Friction and Wear Characteristics of FFRC1

Figures 1(a, b) shows the effect of sliding velocity and normal force on the wear rate and coefficient of friction of FFRC1 respectively. At all sliding velocities the wear rates and coefficient of friction are found to increase with increasing the applied load except for the sliding velocity of 0.523 m/s the wear rate remains constant up to 39.24 N, after that the wear rate follows the increasing trend. This can be due to the poor wear performance of less volume fraction of fiber reinforcement. This is due to the softening process and subsequent film generation and removal process during sliding. From Figure 2, it can be seen that transition of wear mechanism changes with increasing normal force. The mild wear regime has the maximum wear rate of 5.4 microns and maximum coefficient of friction of 0.05, which is well supported by the micrographs of worn out specimens shown in Figure 2(c). The dominant wear mechanism in the regime is Ironing mechanism where a strong bond between the fiber and the matrix made the separation of material from the pin more difficult and hence contributed to higher wear resistance and also there is no sufficient load to deform the specimen which would increase the wear rate. 

When the load was increased beyond 25 N, the wear regime shifted from mild wear to severe wear which has the maximum wear rate of 14.5 microns and a maximum coefficient of friction of 0.13. In this regime, there was a considerable increase in coefficient of friction and wear rate which may be due to elastic deformation of surface asperities due to increasing contact temperature. The micrographs of worn out specimens shown in Figure 2(d) reveals the presence of matrix fracture and ploughing mechanisms. The matrix fracture is a mechanism, where due to the applied load and stresses appear in the matrix material, which can lead to large cracks forming. In order to clearly separate this mechanism from the fiber-matrix debonding, these cracks were only taken as a result of the applied stresses, as long as there was no direct relation with fibers. The mechanism was predominant in the severe wear regime with higher loads and a low sliding velocity. A ploughing mechanism is a small proportion of the displaced material that was detached from the surface. It is a matrix damage, where deep longitudinal cracks observed on the surface can modify the surface topography, this is due to the repeated ploughing mechanism that causes surface fatigue. When the loading conditions were increased beyond 36 N, and transition of wear regime from severe wear to ultra-severe wear took place. The wear rates have exceeded 14.5 microns in the ultra severe wear regime and the corresponding coefficient of friction is more than 0.13.

SEM micrographs of worn out specimens in the ultra severe regime shown in Figure 2(b) confirms the presence of fiber matrix debonding and fiber fracture mechanisms. As the temperature in the contacting surfaces are not uniform thermal gradients and developed which generates thermal stresses in the specimen which leads to weakening of fiber matrix bonding at interface. Fibers become loose and shear easily due to repeated axial thrust during sliding. The damage of fibers by fiber fracture mechanism. This fiber debris is transferred on to the counter face along with thin polymer film which surrounds the fiber particles.

3.3. Friction and Wear Characteristics of FFRC2

Figures 3(a, b) represents the effect of sliding velocity and normal force on the coefficient of friction and wear rate of FFRC2 respectively. In these composites at all sliding velocities, the coefficient of friction observed are increasing with increase in normal force and the wear rates are increasing up to normal force of 30 N and then decreasing with increase in normal force. The detached wear debris from the composites might have embedded in the contacting asperities that improved the wear resistance of FFRC2. From the wear mechanism map shown in Figure 4(c) it can be observed that the mild wear regime exists at low normal forces for all sliding velocities. In this regime a maximum wear rate of 3.6 microns and a maximum coefficient of friction of 0.04 were obtained respectively.

Fig. 1. Effect of normal force and sliding velocity on (a) wear rate and (b) COF of FFRC1.
Fig. 2. (a) Wear mechanism map for FFRC1 composites: (b) fiber matrix debonding and fiber fracture; (c) ironing mechanism; (d) ploughing and matrix fracture mechanism.

From the micrographs of worn out specimen taken at mild wear regime, it is clearly seen the governance of Ironing mechanism where the bulk of materials recovers elastically which is evidenced by a controlled decrease in roughness. Figure 4(d) shows the severe wear regime where the wear rate values ranges from 3.6 microns to 9.5 microns and the coefficient of friction values ranges from 0.04 to 0.09. The ultra severe wear regime shown in Figure 4(b) displays the dominance of fiber-matrix debonding and the quantum of fiber fracture is greatly reduced. The corresponding values of wear rate and coefficient of friction have exceeded 9.5 microns and 0.09.
respectively. In comparison with FFRC1, the wear rates of FFRC2 were greatly reduced, that is the maximum wear rate of FFRC1 in mild wear is 5.4 microns whereas the maximum wear rate of FFRC2 in mild wear regime is 3.6 microns. The results also suggest that the wear rate is highly determined by the type or constituents of the friction material. On micro scale, the friction and wear characteristics of friction material depend on the formation, growth, disintegration of contact plateaus, shape adaption and thermal induced deformation. The mechanism of the friction film formation in multiphase materials is very complicated and strongly influenced on the thermal history of sliding interface. In the case of normal breaking applications, it is known that the organic ingredients, fibrous materials and solid lubricants play a roles in creating the transfer layer at the friction surface and this transfer layer becomes momentous and more effective at high pressure in mild wear regime of FFRC2.

4. CONCLUSIONS

In this work, flax fibers were used to enhance the tribological properties of the phenolic resin polymer matrix composites. The following conclusions can be drawn:

- FFRC2 is found to be better wear resistant material than FFRC1.
- In mild wear regime FFRC2 have a wear rate of 3.6 microns and the coefficient of friction of 0.04 whereas FFRC 1 has a wear rate of 5.4 microns and coefficient of friction of 0.05.
- The wear mechanism map for FFRC1 and FFRC2 confirms that the mild wear regime is dominated by ironing mechanism.
- The severe wear regime is dominated by matrix fracture and ploughing while the ultra severe wear regime is dominated by fiber matrix debonding and fiber fracture.

References and Notes

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