Investigations on Tribological Performance of Sisal Fiber Reinforced Polypropylene Composites

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ABSTRACT

There has been an increase in global interest in the development of natural fiber-reinforced composites. Natural fibers extracted from plants are receiving more attention from researchers, scientists, and academics due to their use in polymer composites and their environmentally friendly nature and sustainability. Recently, sisal fiber-reinforced polymer composites have been used in a variety of engineering applications like aerospace, automotive, marine, and other mechanical components, where tribological properties are of prime consideration. In this endeavor, experiments have been conducted to determine the tribological behavior of sisal fiber-reinforced polypropylene composite. Pin-on-disc wear tests have been conducted on specimens at various combinations of sliding velocities (1-3 m/s), sliding distances (1000-3000 m), and applying normal loads (10-30N). Using Response Surface Method (RSM), a mathematical model has been developed to predict the friction and wear loss behavior of the sisal fiber-reinforced polypropylene (PP) composites. To ensure the validity of the developed model, the Analysis of variance (ANOVA) technique has been applied. Important process parameters and material variables that exert significant influence on sliding wear loss have been determined with the help of systematic experimentation. Scanning Electron Microscope (SEM) has been used to probe morphological observation of the worn surface. Results revealed that the highest volumetric wear loss has been recorded at the highest values of applied load and this has been supported by the morphological study demonstrated by the scratches, as well as wider and deeper plowing marks on the worn surfaces.

Keywords: Polymer matrix composites, Sisal fiber, Polypropylene, Friction, Wear loss, RSM, SEM.

1. INTRODUCTION

Ethiopian farmers are under the constant threat of drought conditions when crop harvests are slim or non-existent. Identifying local resources should be done to combat this, through dry farms and introducing alternative income sources. Sisal plant, locally called *'Ekka'* is one such a non-seasonal natural resource which easily grows in various parts of Tigray; where it's potential to make profit as natural fiber seemed to show promise as just such a resource that could be used to replace synthetic materials (Teklu et al., 2017, 2019).

Recently, natural fiber reinforced polymer matrix composites are being used as a sustainable alternative to wood and synthetic fiber reinforced composites in many engineering applications, such as, in automotive and packaging industry (Yallew et al., 2016a, 2016b). The last two decades have witnessed considerable progress in the use of bio-composites. This has been propelled by the global concern for environment, use of non-renewable resources and the subsequent hunt for eco-friendly materials. In particular, the concern has led to new and strict environmental policies forcing the automotive, packaging and construction industries look out to substitute reinforcements for traditional composite materials having a polymer matrix (Yallew et al., 2018, 2020; Sanjay and Yogesha, 2017; Manimaran et al., 2018).

Over the last decade, there has been a steady rise in technological applications of plastics and their composites for tribological applications which include, gears, bearings, coatings, tires, shoe soles, human hip and knee joints, non-stick pans, automobile brake pads, and floorings (Yallew et al., 2014, 2015; Sanjay et al., 2016, 2018). The use of natural fibers as reinforcement has been found to result in a better tribological effect in terms of the friction and wear characteristics. These improved tribological characteristics along with better mechanical properties favor the composites as the right candidates for engineering applications involving sliding contact. The use of sisal fiber reinforced polypropylene for tribological applications require adequate knowledge of their tribological properties, which are different from much better understood tribological properties of metals and ceramics (Yallew et al., 2014, 2015; Sanjay et al., 2016, 2018; Shalwan and Yousif, 2013).

This has kindled the curiosity of researchers to explore the possibility of using natural fibres in still more applications, under various loading conditions. In the main, the parts used as industrial and manufacturing parts are susceptible during adhesive and abrasive tribological loadings. This fact has underscored the importance of taking account of the tribological performance of materials in the design of the mechanical parts. However, we see in the literature, an apparent dearth of studies on the effects of dry sliding parameters on the tribo-performance of polymeric composites (Yallew et al., 2014, 2015; Sanjay et al., 2016, 2018; Shalwan and Yousif, 2013; Molazemhosseini et al., 2013; Briscoe and Sinha, 2008; Basavarajappa et al., 2007; El-Tayeb et al., 2009, 2010).

Using sisal fiber as reinforcement has been found to result in composites with good tribological (friction and wear) characteristics. Due to their wear-resistance and good specific strength and modulus, they stand as the right candidates for engineering projects involving sliding contact (Shalwan and Yousif, 2013; Molazemhosseini et al., 2013; Briscoe and Sinha, 2008; Basavarajappa et al., 2007; El-Tayeb et al., 2009, 2010). Considering the foregoing

discussion, an attempt has been made in this investigation to study the effect of applied load, sliding speed and sliding distance on dry sliding wear behavior sisal fiber reinforced polypropylene composite under various testing conditions. RSM was adopted to obtain an empirical model of volumetric wear loss (response) as a function of sliding velocity, sliding distance, and applied load. An SEM analysis of worn surfaces has also been used to support the outcome discussion.

2. EXPERIMENTAL DETAILS

2.1. Specimen Fabrication

The following procedure was used in the preparation of the Polymer Matrix Composite (PMC) laminates. Initially Polypropylene sheets of size 150 mm x 80 mm x1mm were prepared by melting and compressing pre-weighed polypropylene on a compression moulding set up consisting of a mould set with heating arrangement. Then, the sisal fabric and the polymer sheets were stacked in the mould with the sisal fiber kept between the two polymer sheets. To prevent polymer sheets from sticking to the mould plates, 2 mm thick Teflon sheets were used on the top and bottom of the mould plates. The materials were then hot-pressed for 8 minutes in a 165^0C temperature and pressure of 4MPa. At this temperature, PP melts and impregnates with sisal fiber, and compaction occurs. Later, pressure was increased by 2MPa for 2 minutes before the composite was left to cool down. Finally, the composite laminates were removed from the mould at a temperature of 80^0C (Yallew et al., 2014, 2015). The schematic of the composite fabrication process is shown in figure 1.
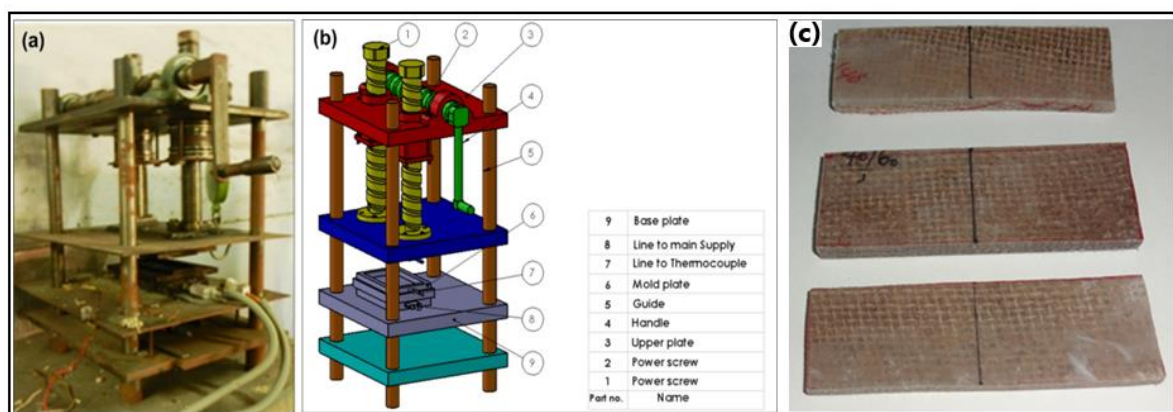

Figure 1. In-house Developed Compression Moulding Setup (a) Actual Image and (b) Detailed Schematics c) Composite Laminates (The PMC fabrication process, Yallew et al., 2014 and 2015).

2.2. Dry Sliding Test of the Specimen

The sliding wear and friction behaviour of the sisal fiber reinforced polypropylene composites was investigated using the pin-on-disc tester, a computerized rotating disc friction and wear tribometer (TR201LE-M8: Ducum India). Schematic for the pin-on-disc tester is depicted in figure 2. Sliding test was carried out in accordance with ASTM G-99-55 standard procedure. Representative composite specimens with 40% fibre weight and a size of $10x05x05mm^3$ were cut from the fabricated composite laminates. Initially, to reduce running-in period and maintain initial roughness, disc surfaces and the prepared wear specimens were rubbed with dry SiC abrasive papers of 1500- and 2000-grit respectively. Then, the sliding specimens and disc counter face, having been cleaned with acetone and dried up, were made ready for testing. Readings were taken through a system of data acquisition controlled by microprocessor (Yallew et al., 2014, 2015). Each of the tests was carried out thrice and the mean values are reported with the view to ensure reliability of test results. The volumetric wear losses were calculated from the difference in weight of the specimen measured before and after the test to the nearest of 0.1 mg using analytical density value. The physical and mechanical properties of the fabricated composite laminates are described in table1.
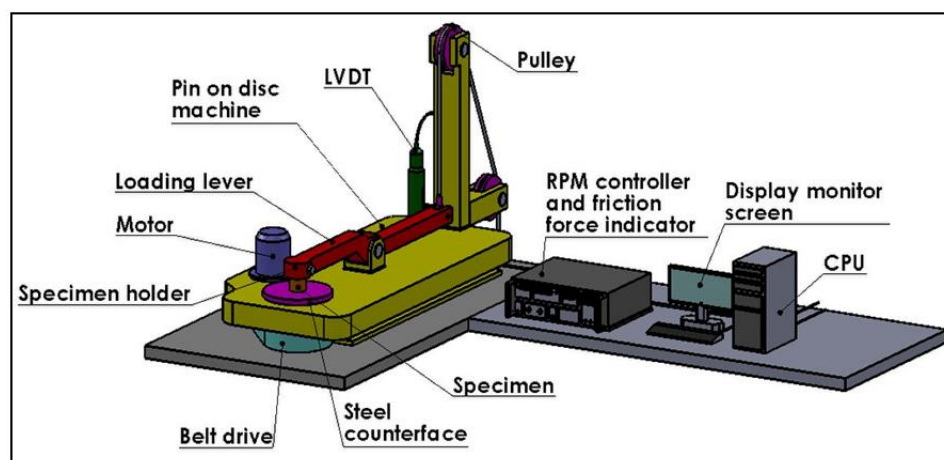

Figure 2. Schematics of wear pin-on-disc set up (Yallew et al., 2014 and 2015).

2.3. Morphology of Worn Specimen

Morphological observation of specimens was done at room temperature using model XL 30, Philips Scanning Electron Microscope (SEM). The specimen was coated with a very thin film of gold using Sputter Coater to enhance conductivity before micrographs were taken as depicted in figure 3 (Yallew et al., 2014, 2015).

Figure 3. Morphological specimen preparation.

Table 1. Physical and mechanical properties of the fabricated composite laminates.

S. No	Properties of fabricated composite	Unit	Amount
1	Theoretical density	(g/cm^3)	1.03
2	Actual (Experimental) density	(g/cm^3)	1.02
3	Void volume fraction	%	1.9
4	Sisal fiber weight	%	40
5	Tensile strength	MPa	28
6	Tensile modulus	MPa	408
7	Flexural strength	MPa	68
8	Flexural modulus	GPa	7.7

2.4. Mathematical Approach

Mathematical modeling using the Design of Experiments (DOEs) has been implemented to reduce the amount of testing activity and maximize quality of results. The present design involves three levels of interactions for each factor: for sliding speed (1, 2, and 3m/s), for sliding distance (1000, 2000 and 3000m) and for applied load (10, 20, and 30N).

A full factorial design (3^3=27) is used with three design factors of each of the three levels to describe wear-loss response and estimate the parameters. The coded levels of the independent variables are depicted in table 2. The three experiments include three independent variables with three levels coded according to the transforming Equation [1] for each of the independent variable.

$$x_1 = \frac{\text{Sliding speed} - 2}{1}; \quad x_2 = \frac{\text{Sliding distance} - 1000}{1000}; \quad x_3 = \frac{\text{Applied load} - 20}{10} \quad (1)$$

Table 3 presents a list of the results of ANOVA for wear loss. Analysis of variance (ANOVA) was carried out to examine the adequacy of the model as well as to determine the significant parameters and the validity of the equations for the two-factor interaction (2FI) model in Equation 4. It can be observed that the P-value is less than 0.05, which indicates the

model's significance at 95% confidence level, denoting the significant effect; the terms in the model have on the response. The significant model terms are the main effects of sliding speed, sliding distance, and applied load, as well as the two-level interactions of sliding speed with applied load and of sliding distance with applied load.

Table 2. Factorial design matrix and response.

	Input			Response
	Sliding speed (m/s)	*Sliding distance (m)*	*Applied load (N)*	*Volumetric wear loss (mm³)*
S. No	x_1	x_2	x_3	y
1	-1	0	-1	-1.00
2	-1	0	0	-0.61
3	-1	0	1	0.31
4	0	0	-1	-0.60
5	0	0	0	0.46
6	0	0	1	-0.95
7	1	0	-1	0.76
8	1	0	0	-0.58
9	1	0	1	-0.91
10	-1	1	-1	0.85
11	-1	1	0	-0.45
12	-1	1	1	-0.90
13	0	1	-1	-0.43
14	0	1	0	1.38
15	0	1	1	-0.89
16	1	1	-1	1.58
17	1	1	0	-0.32
18	1	1	1	-0.83
19	-1	2	-1	-0.64
20	-1	2	0	1.83
21	-1	2	1	-0.30
22	0	2	-1	-0.30
23	0	2	0	-0.63
24	0	2	1	1.98
25	1	2	-1	-0.29
26	1	2	0	-0.61
27	1	2	1	2.07

Table 3. ANOVA for volumetric wear model.

Source	Sum of squares	Df	Mean square	F-value	p-value	Model
Wear volume (mm^3)						
Model	25.54	18	1.42	242.88	< 0.0001	Significant
A-Sliding speed	0.18	2	0.088	15.13	0.0019	
B-Sliding distance	2.15	2	1.07	184.01	< 0.0001	
C-Applied load	21.68	2	10.84	1855.83	< 0.0001	
AB	0.038	4	9.415E-003	1.61	0.2619	
AC	0.17	4	0.043	7.29	0.0089	
BC	1.32	4	0.33	56.57	< 0.0001	
Residual	0.047	8	5.842E-003			
Cor Total	25.59	26				
Std. Dev.	0.076				R-Squared	0.9982
Mean	-2.651E-007				Adj R-Squared	0.9941
C.V. %	2.883E+007				Pred R-Squared	0.9792
PRESS	0.53				Adeq Precision	48.473

Note: ANOVA: Analysis of variance; df: degree of freedom; SD: Standard deviation; CV: coefficient of variation.

2.5. Response Surface Methodology (RSM)

In the present work, to represent the relationship between volumetric wear loss and tribo-test independent variables, a polynomial model of 2FI order type is used. The input variables are sliding speed(x_1), applied load (x_2) and sliding distance (x_3)while the output is the volumetric wear loss (y). A response surface model is usually expressed as:

$$y = f(x_1, x_2, x_3) + \varepsilon \quad (2)$$

Where, ε is a random error. The 2FI order can be represented by the model equation (3)

$$y = \beta_0 + \sum_{i-1}^{k} \beta_i x_i + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \; for \; i < j \qquad (3)$$

The β parameters of the polynomial are the unknown as regression coefficients to be estimated by method of least squares. k is the number of input factors. To allow reasonable approximations two-factor interaction (2FI) is chosen so that the two-factor interaction (2FI) can be analyzed.

2.6. Volumetric Wear Loss Model

A total of 27 experiments were conducted using the full factorial design, and regression coefficients were analyzed. If volumetric wear loss is represented by y, the 2FI regression equation for these experiments could be written as Equation 4.

$$y = -0.054 + 0.10x_1 + 0.44x_2 + 1.02x_3 - 0.033x_1x_2 + 0.070x_1x_3 + 0.27x_2x_3 \quad (4)$$

3. RESULTS AND DISCUSSION

3.1. Effect of the Main Parameters

Comparisons of the effect of the main input parameters (sliding speed, applied load, and sliding distance) on the response (volumetric wear volume) are depicted in figures 4, 5 and 6. The effect of the parameter interactions (applied load/sliding speed, sliding distance /sliding speed, and applied load/sliding distance) in the form of response surfaces are shown in figures 7, 8 and 9. The results of the interactions recorded in the figures were calculated using Equation 4.
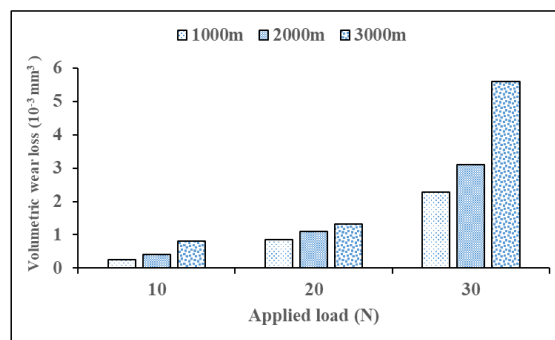
Figure 4. Variation of volumetric wear loss with applied load at various sliding distances.
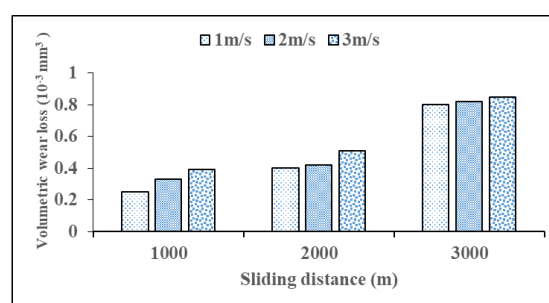

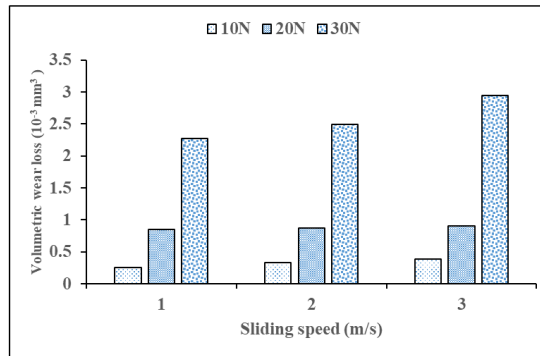Figure 5. Variation of volumetric wear loss with sliding distance at various sliding speed.

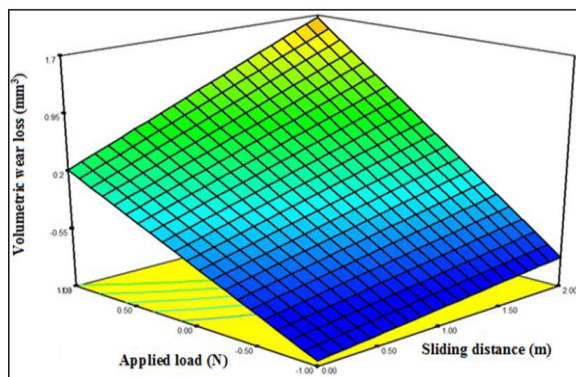Figure 6. Variation of volumetric wear loss with sliding speed at various applied loads.

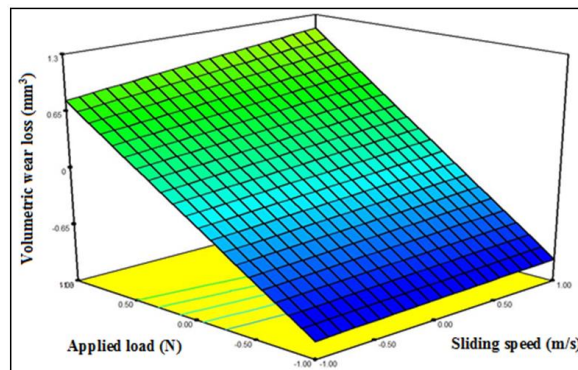Figure 7. Combined effect of applied load and sliding distance on volumetric wear loss.

Figure 8. Combined effect of applied load and sliding speed on the volumetric wear behavior.
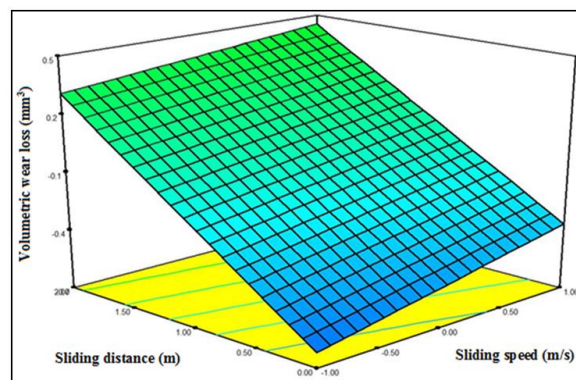

Figure 9. Combined effect of sliding distance and sliding speed on the volumetric wear loss behavior.

Sliding wear characteristics are generally known to be strongly dependent on applied load, sliding speed, sliding distance, temperature, contact geometry, surface roughness, ambient atmosphere, and material surface composition. As shown in figures 4 and 5, under dry sliding, an upsurge in volumetric wear loss was observed with increasing applied load and sliding distance, while no dependence on sliding speed was observed as shown in figure 6. The want of the sliding speed effect on the sliding wear behavior may be related to the reduced flow stress sensitivity of the composite material to applied strain rate (Shalwan and Yousif, 2013; Molazemhosseini et al., 2013; Briscoe and Sinha, 2008; Basavarajappa et al., 2007; El-Tayeb et al., 2009, 2010).

3.2. Effect of the Interaction Parameters

The combined effect of sliding speed and applied load on the fabricated composite's volumetric wear loss under dry sliding is presented in figure 8. The specimen's volumetric wear loss rises with increase in applied load; no or slight effect is observed with the sliding speed, especially at higher levels where the combined effect of both factors is considerably larger. Clearly, the volumetric wear loss changes slightly as applied load increases with the sliding speed. Also, the volumetric wear loss shows a 'minimum slope' line with sliding speed and a linear one with applied load. An important role is still played by the combination of applied load and sliding speed in influencing the volumetric wear loss. The peak value of volumetric wear loss follows the highest values of applied load and sliding speed. On the contrary, sliding distance shows a linear correlation with both applied load and sliding speed.

Figure 7 shows the combined effect of sliding distance and applied load as well as the significant effect of increasing the load. As could be observed, the uppermost volumetric wear loss is predicted to occur at the highest applied load and sliding distance. Applied load is more influential than sliding distance while sliding speed doesn't have significant effect on volumetric wear loss. So, volumetric wear loss upsurges with a rise in sliding distance for high load region while for long sliding distance; it upturns with a rise in load. Perhaps, the heat accumulated at the sliding interface is softening the composite material, making it weaker and exposed to wear.

Figure 9 presents a record of the effect of sliding speed and sliding distance on the predicted volumetric wear loss. The surfaces plot clearly shows a considerable linear increase of the volumetric wear loss with sliding speed and sliding distance. However, compared to the sliding distance, the influence of applied load on the dry sliding wear behavior of the developed composite grows significantly.

Overall, the developed composite's volumetric wear loss increases with increase in applied load and sliding distance and the surge is more pronounced at higher levels of the variables. Increase in applied load and sliding distance is known to result in a rise in interface temperature. Just like, increase in interface temperature, application of load increases the real contact area. On the other hand, a change in mechanical properties of sliding surfaces may occur due to thermal softening, increasing wear loss. Also, an upturn in surface temperature increases oxidation-triggered contamination of the sliding surface. Thus, a relatively higher wear is produced by the combined effect of any two factors of applied load and sliding distance at their highest levels.

A surge in sliding distance results in a rise in the sliding test duration. As a result, more heat is generated and accumulated at the sliding interface, causes material softening attributable to plastic instability, which produces higher volumetric wear loss. The microscopic observation of the worn surfaces supports this point (Shalwan and Yousif, 2013; Molazemhosseini et al., 2013; Briscoe and Sinha, 2008; Basavarajappa et al., 2007; El-Tayeb et al., 2009, 2010).

3.3. SEM Observations of Worn Surfaces

The microscopic observation of worn specimens of sisal fiber reinforced polypropylene composite (due to the effects of sliding parameters- sliding speed, applied load and sliding distance) is shown in figure 10.
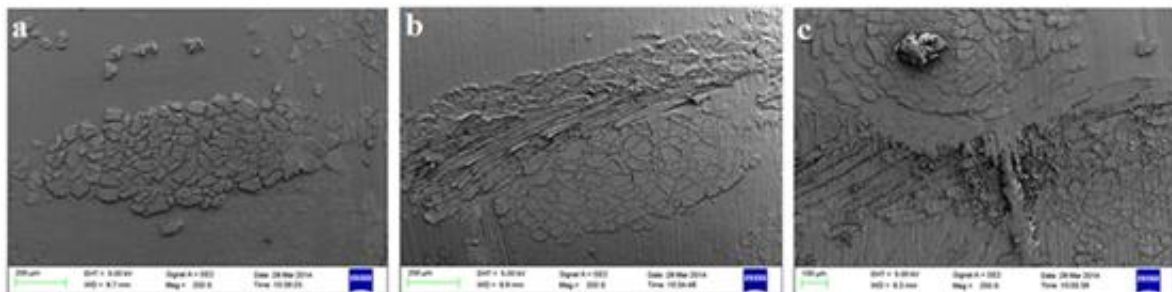

Figure 10. Micrograph of worn sisal fiber /PP composite specimen at a) 10N and 3m/s; b) 20N and 2m/s; c) 30N and 1m/s.

At higher applied load of 30N, the worn micrographs depict images with damage features very different from those observed in results of tests at a lower applied load (Fig 10 a and b). The surface of the composite shows resinous regions that appear to be softened and deformed, particularly, at extended sliding distances, in the condition where there is better adherence of fiber and matrix there is less debonding (Yallew et al., 2014 and 2015). A possible conclusion to follow is that the effect of applied load on wear behavior is higher than that of the other parameters. As discussed in previous section; the influence of increase in applied load was generally higher than the influence of sliding distance and sliding speed.

4. CONCLUSIONS

In the current study, sisal fiber reinforced polypropylene composites has been fabricated. The effect of the dry sliding parameters on the tribo-performance of the fabricated specimens has been investigated. SEM study has been conducted to substantiate the outcomes. From this extensive investigation the following conclusions can be drown.

1. The relationship between the volumetric wear loss and the sliding variables (sliding speed, sliding distance and applied load) has developed successfully using RSM. The model results are in agreement with the experimental values within the range of tested parameters.

2. In general, the highest volumetric wear loss has been recorded at the highest values of applied load and sliding distance. But compared with sliding distance, applied load is more influential, while the effect of sliding speed on the volumetric wear loss is not that significant.

3. Some of the causes leading to an increase in volumetric wear loss include the mechanical behavior of sliding surfaces, increase in surface temperature resulting from high contamination, and heat generation following extended test duration.

4. The experimental results are supported by the morphological study of the woven sisal fabric reinforced polypropylene composites, as demonstrated by the scratches, as well as wider and deeper ploughing marks (high wear loss) observed on the worn surfaces at higher applied load values.

5. ACKNOWLEDGEMENTS

6. CONFILICT OF INTERESTS

There are no conflicts of interests.

7. REFERENCE

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