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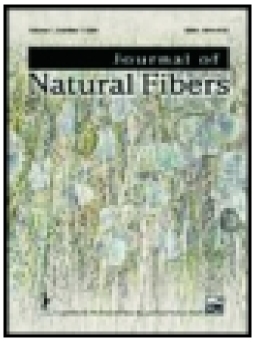

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ABSTRACT

In this work, the tribological performance of bidirectional jute/carbon fiber reinforced polyester composites was investigated using response surface methodology. The effects of three factors namely fiber weight fraction, load, and sliding velocity on the wear and friction values were examined. The composites were fabricated by using compression molding technique and the dry sliding test was conducted using pin-on-disk machine. The response surface methodology coupled with three factors – three-level Box-Behnken design was employed to examine the interactive effects of process variables on wear loss and coefficient of friction. Moreover, Analysis of Variance technique was used to inspect the statistical significance of the developed model. The outcomes revealed that the wear loss increased with the increase in sliding velocity and load and decreased with the increase in weight volume fraction due to diminishing contact between the polyester matrix and rotating disk. However, the coefficient of friction decreased with the increase in process variables. Furthermore, the morphology of worn-out samples was examined using scanning electron microscopy to understand wear mechanisms.

KEYWORDS

Natural/synthetic fibers; wear loss; coefficient of friction; RSM; ANOVA; wear mechanism

摘要

采用响应面法对黄麻/碳纤维双向增强聚酯复合材料的摩擦学性能进行了研究. 考察了纤维质量分数、载荷和滑动速度三个因素对摩擦磨损值的影响. 采用压缩成型工艺制备了复合材料，并在盘式针机上进行了干滑动试验. 采用响应面法结合三因素三水平Box-Behnken设计，研究了工艺变量对磨损损失和摩擦系数的交互影响. 采用方差分析技术对所建立的模型进行统计显著性检验. 结果表明，由于聚酯基体与转盘之间的接触减小，磨损量随滑动速度和载荷的增加而增大，随重量体积分数的增加而减小. 但随着工艺变量的增加，其系数逐渐减小. 此外，用扫描电子显微镜观察磨损样品的形貌，以了解磨损机理.

关键词

天然/合成纤维; 穿损失; 摩擦系数; 磨损机制

Introduction

The light weight structural members of automobiles, aerospace and other commercial fields are manufactured using fiber reinforced polymer composite materials due to their superior mechanical properties combined with high strength to weight ratio (Nagarjun, Kanchana, and Rajesh Kumar 2020). These polymer composites are usually developed by reinforcing the synthetic fibers like carbon, glass, aramid, and Kevlar in to the thermosetting and thermoplastic polymers which gives good overall performance (Nagaraja et al. 2020). However, in recent day the new legislations and growing environmental awareness boosted the use of natural fiber reinforced

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composites in various applications, because these natural fibers are biodegradable, light weight because of low density, available in abundance, nontoxic, and consuming less energy during processing (Almeida et al. 2013; Kumar, Hariharan, and Saravanakumar 2019; Rajeshkumar and Hariharan 2012; Ramakrishnan et al. 2019). Though, the natural fiber offers various advantages, it also has disadvantages like high moisture absorption, highly polar surfaces, inferior mechanical properties when compared to synthetic fibers and poor adhesion to polymeric matrices (Kavitha, Hariharan, and Rajeshkumar 2017; Agrebi et al. 2019; Rajeshkumar 2018; Rajeshkumar et al. 2020). Thus, the hybridization of natural and synthetic fibers appears promising.

The hybrid composites used in applications like machine tools, bearing housings and, linkages etc., may have more chances for failure due to excessive frictional force. Therefore in-depth understanding of tribological properties of hybrid composites is absolutely necessary for having safer operating environment. In this context, Singh et al. (2019) investigated the wear behavior of bagasse – Kevlar fibers reinforced polymer composites at different fiber weight fraction, sliding velocity, sliding distance, and load. The experimental results revealed that, among these control factors the normal load influenced more on the tribological properties of the hybrid composites. Furthermore, the worn-out surfaces of the composites were analyzed using Scanning electron microscopy (SEM) to understand the wear mechanisms. Apart from these control factors, the tribological properties are also significantly influenced by the type of fiber and matrix, fiber length, fiber proportion, and fiber orientation (Omrani, Menezes, and Rohatgi 2016; Pei and Friedrich 2012; Shalwan and Yousif 2013). In another work, VinayKumar, Mohan, and Bongale (2019) determined the tribological properties of polyester hybrid composites developed using coir, banana, and glass fibers. The outcomes disclosed that, the fiber weight percentage significantly influenced the wear resistance of the composites followed by sliding speed and applied load. Some tribological studies have been conducted on the hybridization of natural/synthetic fibers such as sisal/glass (Ashok Kumar et al. 2010; Lima, Cardoso, and Lobo 2019), bamboo/glass (Biswas and Xess 2012; Latha et al. 2016), jute/glass (Dalbehera and Acharya 2015), and reported that the wear resistance has improved after the hybridization. In the same way, few studies reported the increasing trend of wear resistance of jute/carbon hybrid composites (Kumar et al. 2018; Rakshith, Bhat, and Sandeep 2019; Ravikumar, Giriraj, and Senthilkumar 2018a; RaviKumar, Giriraj, and Senthilkumar 2018b).

The response surface methodology (RSM) is a statistical technique used to understand and optimize any kind of complex systems. Moreover, this can also be used to assess the significance of numerous affecting factors even in the existence of complex interactions between the independent variables (Thirugnanasambandham, Sivakumar, and Maran 2015). To the best of author's knowledge there is no literature reporting the tribological performance of the bi-directional jute/carbon hybrid composites using RSM. Therefore, in the present work RSM coupled with Box-Behnken design (BBD) was used to optimize and investigate the impact of independent process variables such as sliding velocity, load, and fiber weight fraction on the wear loss, and coefficient of friction (CoF) of the fabricated hybrid composites. Finally, the worn-out surfaces were analyzed using SEM to predict the wear mechanisms.

Materials and methods

Materials

The jute (220 gsm) and carbon (400 gsm) fibers were procured from M/s Arrow Technical Textiles Pvt. Ltd., Mumbai, India. The unsaturated polyester resin, cobalt naphthalate (catalyst), and methyl ethyl ketone peroxide (accelerator) were procured from the M/s Covai Seenu and Company, Coimbatore, India. The jute and carbon fiber mats were shown in Figure 1.

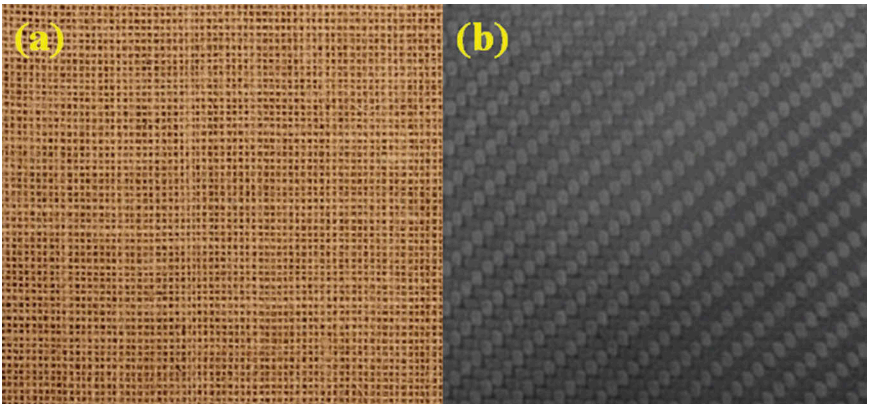

Figure 1. Jute and carbon fiber mats.

Preparation of composite samples

The composite panels were fabricated using compression molding technique. At first, the mold release agent (silicone) was sprayed on the mold for easy removal of the composite plate after curing. Then the jute and carbon fiber mats (at different weight fractions 10, 20, and 30%) were aligned bi-directionally (five layers) in the mold of size 150 mm × 150 mm × 10 mm and subsequently the prepared matrix system was poured into the mold (Rajini et al. 2019; Vigneshwaran and Rajeshkumar 2018). After that the mold was closed and compacted using hydraulic press for 12 h at 2 ton and room temperature to obtain the uniform thickness panel. The post curing process was carried out at 80°C for 120 min in an oven with air circulation. Then the cured composite panel was cut to the dimension of 25 mm × 10 mm × 10 mm in accordance with the ASTM standard and the dry sliding wear tests were performed on 10 mm × 10 mm apparent contact area (Chin and Yousif 2009). The formulation of hybrid composites was presented in the Table 1 and the fabricated composites were shown in Figure 2.

Experimental design

In this present work, RSM coupled with three factors-three level BBD was employed to examine the interactive effects of process variables on wear loss, and CoF of fabricated composite samples. The sliding velocity (A), load (B), and weight fraction of reinforcement (C) were selected as independent variables, whereas wear loss, and CoF was selected as response. The process variables and their ranges were shown in Table 2.

The analysis of variance (ANOVA) tool was used for each response model with a confidence level of 95%. Moreover, the obtained BBD results were fitted into the second order polynomial response surface empirical model as follows (Ragunath, Velmurugan, and Kannan 2017; Thirugnanasambandham, Sivakumar, and Maran 2015):

Table 1. Formulation of jute/carbon bidirectional hybrid composites.

Composites designation	Polymer content (wt%)	Reinforcement (jute + carbon) content (wt%)
JC1	90	(2.5 + 7.5) = 10
JC2	80	(5 + 15) = 20
JC3	70	(7.5 + 22.5) = 30

where, J, jute fiber; C, carbon fiber

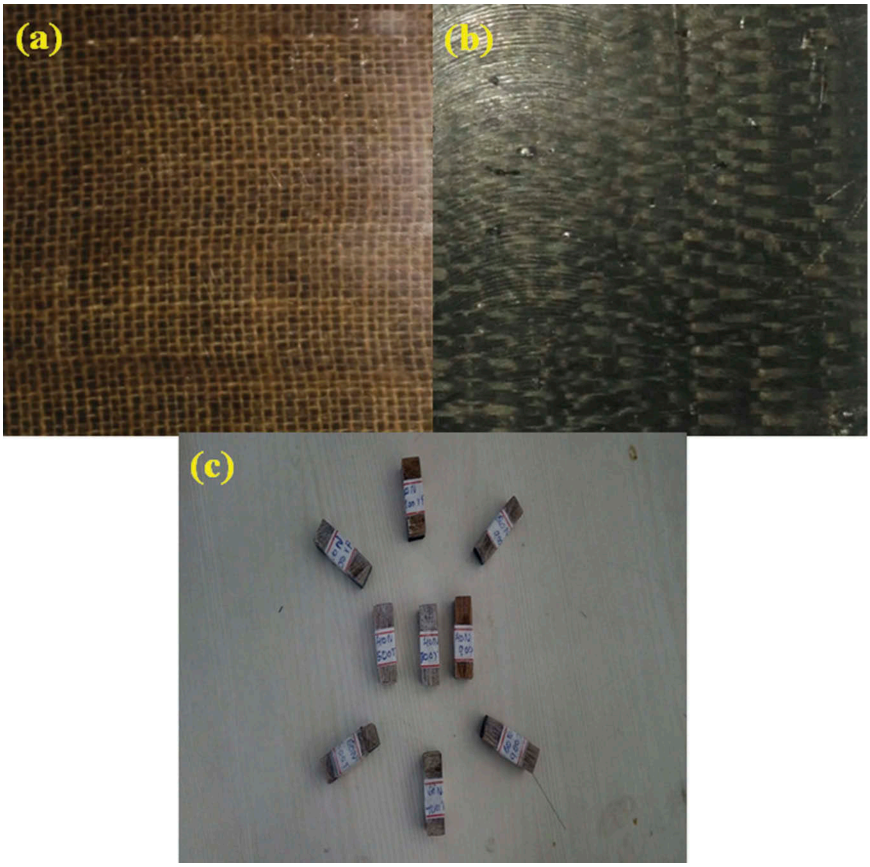

Figure 2. Fabricated composite samples: (a) jute fiber at top, (b) carbon fiber at bottom, and (c) samples for tribological test.

Table 2. Process variables and their ranges.

Factors	Level I	Level II	Level III
Sliding velocity (m/s)—(A)	2.62	3.66	4.70
Load (N)—(B)	20	40	60
Fiber weight fraction (%)—(C)	10	20	30

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i=1\&j=1}^{k} \beta_{ij} X_i X_j + e_i \tag{1}$$

where, Y represents the response, β_o is the model intercepts coefficient, β_j, β_{jj}, and β_{ij} represents interaction coefficients of linear, quadratic, and the second-order terms, respectively, X_i and X_j are interaction independent variables, k represents number of independent variables (in this study $k = 3$) and e_i is the error. The interactive effect of process variables on the wear loss and CoF were studied using three-dimensional (3D) response surface plots. The statistical analysis was done using Design-Expert 8.0.7.1 (State-Ease Inc., Minneapolis, MN, USA) package (Thirugnanasambandham, Sivakumar, and Maran 2015).

Tribological test

The tribological testing was conducted as per ASTM G 99 standard using Pin-on-Disk machine (DUCOM: TR-20LE-CHM-400) under dry sliding condition for a constant sliding distance of 1800 mm. The test specimens of cross section of 10 mm × 10 mm were made to slide against EN 31 steel disk having a hardness of 180 BHN. Table 2 shows the test parameters used for wear testing at three different levels. The electronic weighing machine with a least count of 0.001 g was used to measure the weight of the specimen before and after the wear tests.

Morphological analysis

SEM is used to evaluate the worn surface morphology and analyze the wear mechanism of the composites (Rajeshkumar 2020a). In this investigation the SEM analysis of the worn out composite samples were performed using an EVO 18–CARL ZEISS typed SEM at 20 kV accelerating voltage. Before the scanning, the samples were gold coated to make it conductive and also to avoid electrostatic charge ((Rajeshkumar 2020b).

Table 3. Experimental test results of jute/carbon hybrid composites.

S. no.	(A) Sliding velocity (m/s)	(B) Load (N)	(C) Weight fraction (%)	Wear (microns)	CoF
1	2.62	40	30	178.43	0.43
2	3.66	40	20	253.86	0.46
3	4.7	40	30	282.43	0.45
4	3.66	20	10	239.71	0.59
5	3.66	60	30	270.34	0.36
6	3.66	40	20	245.86	0.42
7	3.66	40	20	258.86	0.52
8	3.66	40	20	249.86	0.46
9	2.62	40	10	224.97	0.55
10	3.66	40	20	236.86	0.57
11	2.62	60	20	216.05	0.41
12	4.7	20	20	231.44	0.62
13	3.66	60	10	278.52	0.43
14	4.7	40	10	294.97	0.49
15	4.7	60	20	312.94	0.37
16	2.62	20	20	169.14	0.61
17	3.66	20	30	189.71	0.59

Table 4. ANOVA result for wear loss of hybrid composites.

Source	Sum of squares	*df*	Mean square	*F* value	*p* value Prob> *F*	Remarks
Model	26.70	9	2.97	65.85	<0.0001	Significant
A-Sliding velocity	14.64	1	14.64	324.97	<0.0001	
B-Load	8.09	1	8.09	179.56	<0.0001	
C-Fiber weight fraction	1.97	1	1.97	43.64	0.0003	
AB	0.15	1	0.15	3.41	0.1074	
AC	0.40	1	0.40	8.98	0.0200	
BC	0.53	1	0.53	11.86	0.0108	
A^2	0.43	1	0.43	9.58	0.0174	
B^2	0.40	1	0.40	8.85	0.0207	
C^2	0.065	1	0.065	1.45	0.2672	
Residual	0.32	7	0.045			
Lack of fit	0.034	3	0.011	0.16	0.9180	Not significant
Pure error	0.28	4	0.070			
Corresponding total	27.02	16				

Results and discussions

Statistical analysis

RSM was used to optimize the input parameters such as sliding velocity, load and sliding speed because it consumes less time, space and raw materials when compared to traditional single parameter optimization technique (Subashini et al. 2020). The results of this design were presented in Table 3.

Interactive effects of process variables on wear loss

The ANOVA of wear testing results of composite samples was shown in Table 4. It could be observed that the *F*-ratio for the model was 65.85 at 99% confidence interval. Furthermore it was noted that the V_S was the most significant factor affecting the wear loss of the samples followed by F and F_{WF}. The other interactions were found to be significant at 95% confidence interval (CI). The regression equation for wear loss of the fabricated composites as a function of independent process variables is as follow:

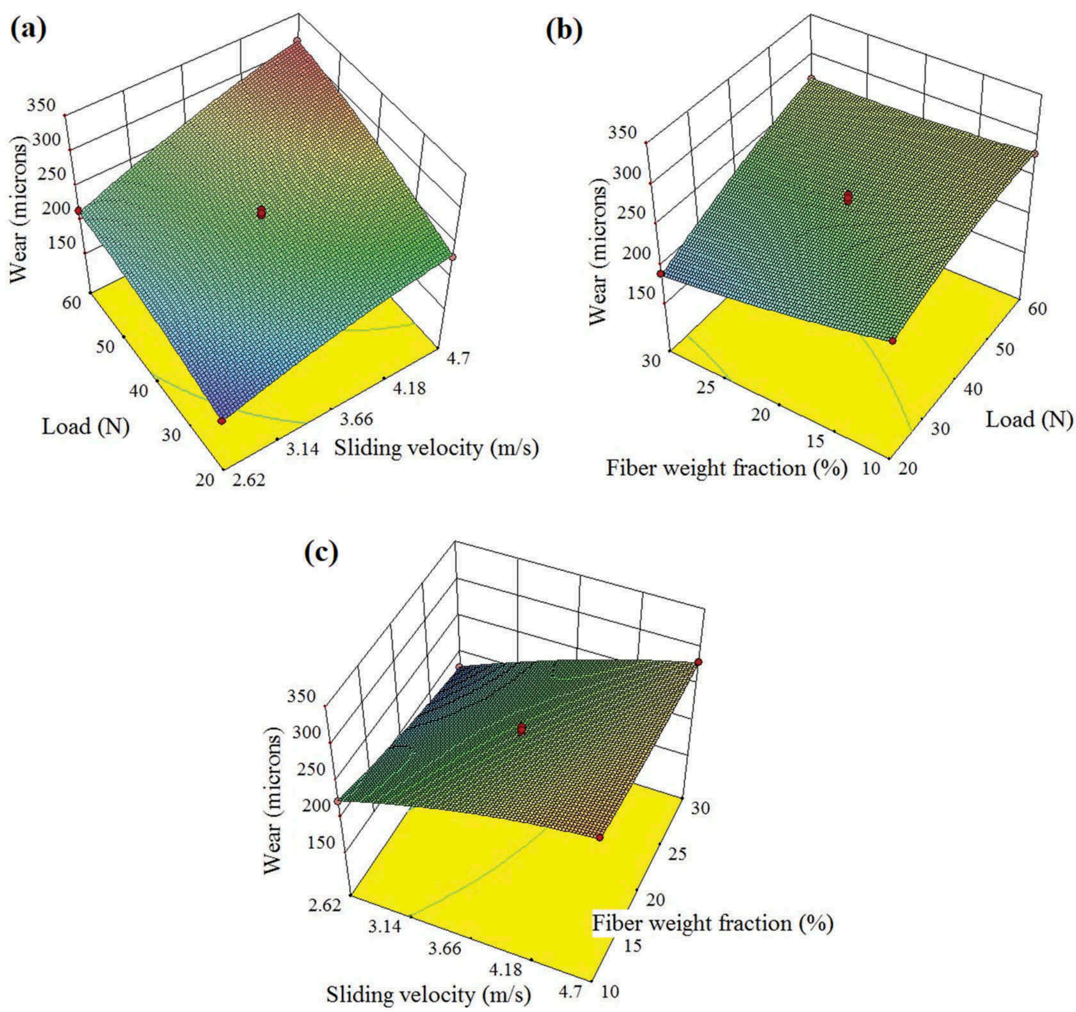

Figure 3. Interactive effects of process variables on wear loss.

$$\text{Wear loss} = 10.38016 + 2.47981A - 0.28449B - 0.28449C + 0.0094195AB + 0.030582AC + 0.00182768BC - 0.29609A^2 - 0.000769436B^2 + 0.000124683C^2 \quad (2)$$

The effect of variables, responses, and variable interactions could be predicted by using this regression equation (Ragunath, Velmurugan, and Kannan 2017).

The 3D response surface plot representing the interactive effects of process variables on wear loss was depicted in Figure 3. It was observed that the wear loss increased with the increase in sliding velocity and load (Figure 3a). This could be due to the fact that at higher load and sliding velocity, the pulverized reinforcement was easily peeled out from the sample which results in worn-out of sample (Rajini et al. 2019). On the other hand, a decreasing trend of wear loss was noted with respect to the increase in fiber weight fraction (Figure 3b,c). This could be explained by taking into the account that the incorporation of jute and carbon fiber into the matrix reduced the direct contact between the polyester matrix and rotating disk led to lower wear of the hybrid composites (Kumar et al. 2019).

Interactive effects of process variables on CoF

Table 5 shows the ANOVA results of CoF of hybrid composites. It could be observed that the *F*-ratio for the model was 9.96 and was significant at 95% CI. The process variables namely sliding velocity (A), load (B), and fiber weight fraction (C) were found to be significant model terms at 95% CI. Moreover, it was noted that the load was the most significant factor affecting CoF (*F* value for load = 60.54 N) and 'Lack of fit' of model was "not significant" with *F* value of 0.932 which shows that the model fits the experimental results adequately. The regression equation for CoF of the hybrid composites as a function of independent process variables is as follow:

$$\text{CoF} = 0.90926 - 0.022441A - 0.00207607B - 0.00226778C - 0.000461683AB + 0.00136289AC - 0.0000696798BC + 0.00100759A^2 + 0.0000175926B^2 - 0.0000517054C^2 \quad (3)$$

Figure 4 show the 3D response surface plot representing the interactive effects of process variables on CoF of the hybrid composites. It was observed that the CoF decreased with the increase in load (Figure 4a). This was expected in the case of fiber reinforced polymer matrix composites because under dry sliding condition the temperature at the contact region of samples and rotating disk get increased which results in the development of thermal stresses in the samples. At higher temperature the bonding between the reinforcement and matrix get weakened which result in decrement of CoF (Chauhan, Kumar, and Singh 2010; Rajeshkumar 2020a). Moreover, higher CoF at lower load was due to the mechanical interlocking of

Table 5. ANOVA result for CoF of hybrid composites.

Source	Sum of squares	*df*	Mean square	*F* value	*p* value Prob> *F*	Remarks
Model	0.051	9	5.700E-003	5.20	0.0204	Significant
A-Sliding velocity	3.407E-004	1	3.407E-004	0.31	0.5945	
B-Load	0.045	1	0.045	41.11	0.0004	
C-Fiber weight fraction	3.647E-003	1	3.647E-003	3.33	0.1109	
AB	3.689E-004	1	3.689E-004	0.34	0.5800	
AC	8.036E-004	1	8.036E-004	0.73	0.4202	
BC	7.768E-004	1	7.768E-004	0.71	0.4276	
A^2	5.001E-006	1	5.001E-006	4.563E-003	0.9480	
B^2	2.085E-004	1	2.085E-004	0.19	0.6758	
C^2	1.126E-004	1	1.126E-004	0.10	0.7579	
Residual	7.671E-003	7	1.096E-003			
Lack of fit	6.334E-004	3	2.111E-004	0.12	0.9436	Not significant
Pure error	7.038E-003	4	1.759E-003			
Corresponding total	0.059	16				

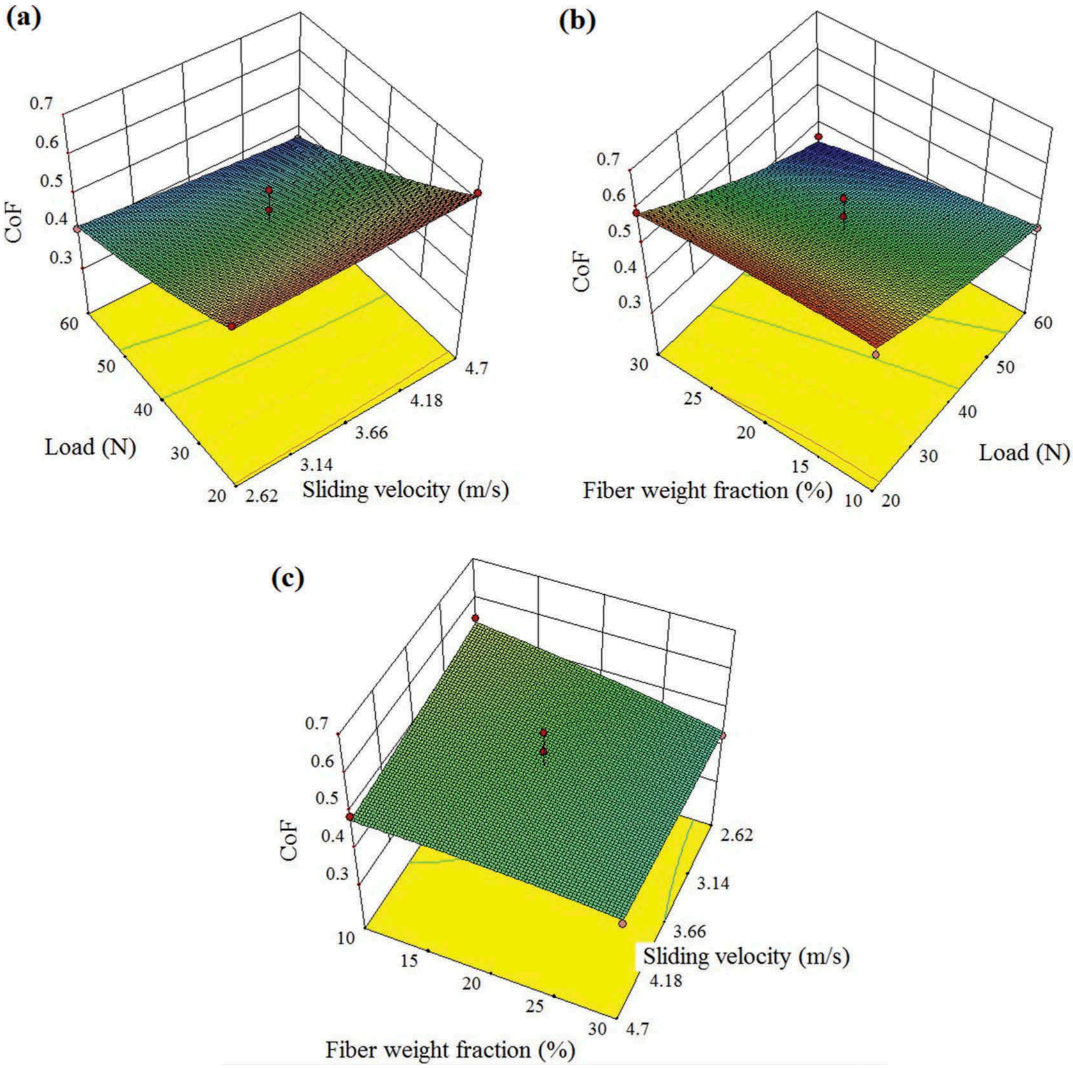

Figure 4. Interactive effects of process variables on CoF.

asperities at the interfacial region between the hybrid composites and the rotating disk (Bajpai, Singh, and Madaan 2013). From Figure 4b,c it was noted that the CoF decreased with the increase in fiber weight fraction. The presence of jute and glass fibers on the composite surface smoothen the film transfer on the disk surface which reduced the interlocking phenomenon between the asperities and glazing of sliding surface of the composite samples led to lower CoF (Idicula et al. 2006).

Morphological analysis

The worn-out surfaces of the wear tested samples were analyzed using SEM, as shown in Figure 5a–c. The analysis was performed for particular process parameters such as sliding velocities of 2.62, 3.66, and 4.7 m/s and 60 N load. An increase in wear rate and uneven surfaces were observed from the SEM images with respect to increase in sliding velocity due to damage of sample layers. In particular, the increase in wear rate at higher sliding velocities was due to damage and detachment of jute fibers. It can be further explained by taking into account that at higher load and sliding velocity the interface temperature get

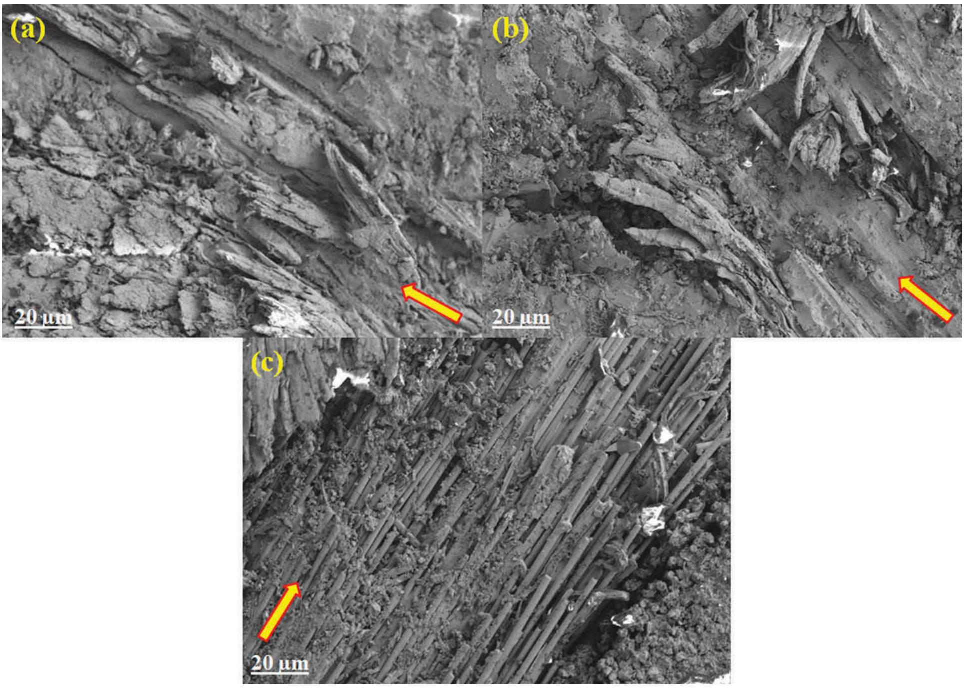

Figure 5. Worn-out topography of hybrid composites at (a) sliding velocity of 2.62 m/s and 60 N load, (b) sliding velocity of 3.66 m/s and 60 N load, and (c) sliding velocity of 4.7 m/s and 60 N load.

increased which results in increased wear rate (Nirmal et al. 2010). However, the presence of carbon fibers in the composites helps to maintain lower wear rate by reducing the thermo-mechanical effect caused during dry sliding test.

Conclusions

The experimental study on tribological performance of hybrid composites were effectively carried out through RSM coupled BBD and ANOVA tools. Based on the obtained results the following conclusions were arrived.

- The wear loss of the hybrid composites increased with the increase in sliding velocity and load due to pulverization of samples at the contact region.
- The decrement of wear loss with respect to increase in fiber volume fraction was attributed to reduction in direct contact between the polyester matrix and rotating disk.
- The CoF of hybrid composites decreased with the increase in sliding velocity and load due to the development of thermal stresses in the samples.
- The CoF also decreased with the increase in fiber weight fraction, because the presence of fibers supports the matrix during sliding.
- The morphological study indicated that the wear rate was more at higher sliding velocity and load due to high temperature at the contact region. However, this temperature has less effect on carbon fibers which helps to prevent the composites from higher wear rate.
- Finally, the composites reinforced with 30% of fibers have less wear rate at all operating conditions and are suitable for fabricating polyester based friction composites.

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