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Research Article

Thrust Force and Delamination Analysis on Redmud-Filled Coconut Sheath Fiber Polyester Composite

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ABSTRACT

Developing customized drilling processes that minimize damage and improve overall performance in natural fiber composites relies on a thorough understanding of their drilling performance and potential damages. This study explores the variations in delamination and thrust force in a redmud-filled polyester composite reinforced with coconut sheath fibers. Employing a Taguchi factorial design, the experiment investigates the impact of drilling parameters, including drill diameter, spindle speed, and feed rate. The ANOVA analysis is employed to validate the experimental results. The findings indicate that increased feed rates and spindle speeds contribute to elevated thrust forces and delamination, influenced by the composite's inherent brittleness due to the addition of red mud. Among the drilling parameters, feed rate exerts the most significant influence on thrust force (ca. 30%), while the point angle has the greatest impact on delamination (ca. 60%). The analysis of drilled hole surfaces reveals matrix cracks, fiber extraction, and matrix smearing, underscoring the importance of optimizing drilling parameters, selecting appropriate tools, and implementing effective cooling methods to improve the overall surface finish and quality of drilled fiber composites. The research has the potential to aid in the development of strategies to minimize damages and enhance overall surface quality; ultimately, it contributes to advancing knowledge in materials science and engineering, with applications in the manufacturing and utilization of natural fiber composites across diverse industries.

1. Introduction

In polymeric composites, waste materials usage as fillers is a promising area of research that emphasizes environmental sustainability. This approach not only has the potential to improve composite performance, but it also contributes to the reduction of specific waste materials. Despite significant advances in developing composites from industrial waste,

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many of these materials have fallen short of meeting the requirements for practical applications. This limitation can be attributed to the tendency of research efforts to end at the characterization stage without a comprehensive understanding of the composites' behavior during machining operations, which is critical for their successful implementation. The drilling process is critical in many industrial applications, including construction, automotive, and aerospace where composite materials are widely utilized. Drilling operations on composite materials are difficult due to their heterogeneous and anisotropic nature. Damage from the drilling process, like delamination and thrust force generation, can compromise the surface quality of the composite and structural integrity.

Industrial waste products like red mud, fly ash, and copper slug have been successfully used in polymer composite materials production, resulting in improved properties. For example, Raghavendra et al. [1] successfully utilized fly ash in the jute/glass-based hybrid epoxy composites fabrication. The investigation's findings revealed that the hybrid composites mechanical properties improved after the addition of the fly ash filler. The 10% fly ash filler addition increased the hybrid composite strength by 10%, while the 5% fly ash addition increased the flexural strength by 5%. Bhardwaj et al. [2] had found similar results on the sugarcane-based epoxy composites. In a previous study, the authors used red mud, an industrial waste generated by the aluminum refining industries, to make polyester composites out of sisal, jute, and coconut fibers. The findings of the investigation clearly indicated a significant improvement in material strength. Notably, incorporating 30% red mud into a composite containing 20% sisal fibers resulted in a 9% hardness increase [3]. The 10% red mud addition to the coconut sheath fiber composite increased tensile strength by ca. 18% [4]. This result emphasizes the potential of using red mud as a filler material to effectively increase the composites mechanical properties, particularly when combined with natural fibers like jute fiber, coconut and sisal. These findings demonstrate the capability of enhancing red mud composite strength. However, in order to effectively apply red-mud-based composites in practical applications, a thorough understanding of their machining performance becomes imperative. Among the various machining processes employed in fiber composites, drilling is a primary method used for creating joints [5,6]. The drilling process encompasses multiple factors that can impact the drilling performance of composites. Therefore, it is crucial to comprehend the variation in drilling thrust force and delamination characteristics to optimize the drilling process and ensure the successful utilization of red-mud particle-reinforced coconut sheath fiber polyester composites. Through investigating the drilling parameters' influence on delamination and thrust force, valuable insights can be acquired, leading to enhancement in the overall performance and reliability of these composite materials [7–9]. Considering fiber composites drilling it is possible to find interesting results on different composite materials, including carbon natural fiber-reinforced composites, fiber-reinforced composites, and glass fiber-reinforced composites have been conducted [10–13]. Understanding the drilling performance of specific composites, such as those containing natural fibers, is more difficult due to their anisotropic nature [14–16]. Because of the anisotropic properties of natural fiber composites, extrapolating and comparing the findings from research on other types of composite materials becomes difficult. Furthermore, there has been no research on red-mud particle-reinforced coconut sheath fiber polyester composites. Thus, there exists a research gap in understanding the drilling behavior and performance of this specific composite material, necessitating additional research to fill this knowledge void.

The primary goal of this research is to show this knowledge gap by examining the drilling thrust force and delamination characteristics of red-mud particle-reinforced coconut sheath fiber polyester composites. The study's specific goals include quantifying drilling thrust force, analyzing delamination patterns, and determining the impact of drilling parameters such as spindle speed, feed rate, and drill diameter on these performance metrics. The findings of this study will provide important information about the redmud particle drilling properties of reinforced coconut sheath fiber polyester composites. The findings will aid researchers and engineers in optimizing drilling parameters, thereby improving the overall performance of these environmentally sustainable composite materials. Furthermore, the research findings will help to broaden the range of applications for red-mud particle-reinforced coconut sheath fiber polyester composites, facilitating their widespread adoption in a variety of industrial sectors.

2. Materials and Methods

In prior investigations, it was determined that the optimal mechanical performance was achieved by a composite comprising 20wt.% of red mud and 40wt.% of coconut sheath [4]. Hence, in the present study, composites with same composition was formulated and subjected to testing for its drilling capabilities.

The coconut sheath mat utilized in this study was sourced from agricultural fields in Madurai, India. The coconut sheath mat was treated using a 4% NaOH solution and a coupling agent, specifically 2% silane, which was procured from I.L.E.CO. in Madurai, India. The red mud, acquired from the National Aluminium Company Ltd in Damanjodi, India. For composite development, polyester resin was employed, along with the accelerator (cobalt naphthalate) and catalyst (methyl ethyl ketone peroxide), both provided by Vasavibala Resins Private Limited in Chennai, India. The compression moulding technique was employed to create composites with dimensions of 300×127×6 mm. The table 1. Shown the composition of redmud particles.

Table 1. Composition of Red mud

Composition	Wt.%
Al2O3	17
Fe2O3	52
SiO2	6
TiO2	5
Na2O	5
CaO	1.3

2.1. *Drilling Experiment*

For the drilling experiment, a JV 55 numerically controlled vertical drilling machine, provided by Laxmi Machine Works based in Amal Jyothi College of Engineering, Kerala, India, was utilized. The cutting feed rate is 10 m/min and the maximum spindle speed on this machine is 6000 rpm. The experimental variable and their range are specified in Table 2.

Table 2. Drilling parameters and their level used

Symbol	Process Variables	Level		
		I	II	III
A	Point angle (degree)	90	118	135
B	Spindle speed (rpm)	100	1500	2000
C	Feed rate (mm/min)	100	150	200

Using an L27 orthogonal array, the experiments were carried out which allowed for controlled changes in tool point angle, feed rate, and spindle speed. To drill high-speed steel (HSS) tool with an 8 mm diameter was used. During the drilling process the drill dynamometer 600A - IEICOS was used to measure the generated thrust force. This dynamometer is made up of a digital force indicator and sensor unit, with the amplifier for data collection linked to a computer system. In a dry environment, all drilling experiments were carried out, with no lubricants or cooling fluids used. The drilled composite is shown in Figure 1.

The drilled holes following the drilling experiment, were analyzed using an optical microscope (Kalasalingam Academy of Research and Education, Tamil Nadu, India), which was equipped with Motic Images Plus 2.0 ML image processing software digital control and an integrated Moticam 2500 camera. Delamination measurements were taken on the drilled hole exit side using the maximum delamination diameter method. To assess the extent of delamination, the delamination factor (Fd) was calculated below equation:

$$f_d = \frac{D_{max}}{D_o} \tag{1}$$


(a) Coconut fibre reinforced red-mud filled composite before drilling

(b) Coconut fibre reinforced red-mud filled composite after drilling

Fig. 1. Composite before and after drilling

In Equation (1), D_o denotes the nominal hole diameter and D_{max} represents the diameter at the maximum delamination area. The National Institutes of Health in Bethesda, MD, USA developed the open-source software Image-J, which was employed for accurate delamination measurements.

2.2. *Taguchi Experimental Design*

The experiment was designed and the results were analyzed using the MINITAB 19 software tool. To analyze and design the output response and the significance of the control variables the Taguchi Experimental Design was used in the current experimental study. The primary goal of using the Taguchi method is to produce high-quality outputs at a low cost and save time. This is accomplished by employing Taguchi's orthogonal array. The total number of required experimental runs by using the Taguchi factorial experimental design can be reduced significantly.

In our particular experiment, the total number of runs from 243 to 27 was reduced, resulting in a more advantageous setup for the experimental work. Standard Taguchi L27 (3^{13}) orthogonal array was used for this investigation. Table 1 shows the corresponding levels for the feed rate (C), spindle speed (B), and control variables point angle (A). Table 2 shows the experimental results obtained after the machining process.

To evaluate the quality characteristics of a control variable the signal-to-noise (S/N) ratio is used, where the signal represents the noise and the desired output refers to variations in the output caused by undesirable factors. The output response is analyzed in three categories in Taguchi experimental analysis: "smaller is the best" "larger is the best" and "nominal is the best". The mean response of the experimental data is assessed using Taguchi analysis by converting the output data into a signal-to-noise ratio (S/N). The S/N ratio of the output response was determined in the current experiment based on the "smaller is better" condition, as the thrust force and delamination should be minimized. As shown in Equation 2, "smaller is better" is better for the S/N ratio, and the condition is expressed as a loss function of the logarithmic transformation.

$$\frac{S}{N} = -10\ Log\ \frac{1}{n}\sum y^2 \qquad (2)$$

In Equation (2), 'y' represents the observed data, and 'n' represents the number of observations. A main effect plot can be generated by using the S/N ratio, allowing for the identification of the optimum state to achieve performance improvement in terms of delamination factor and thrust force.

In addition, an ANOVA test was performed to determine each parameter to the output response percentage contribution. This aids in determining the relative importance of the control variables in influencing the desired outcomes.

3. Results and Discussion

In Table 2 the experimental results are tabulated. Figures 2 and 3 show the effect of the point angle, and feed rate on the thrust force, spindle speed, and delamination factor, respectively. The delta values provided in Tables 3 and 4 serve as indicators of the corresponding control factors' significance on the output response, with higher delta values indicating a parameter significance higher level. The table analysis clearly shows that, when compared to other parameters, the feed rate influences the thrust force, whereas the point angle influences the delamination factor.

Table 1. Drilling experiment results

Ex.No	Point angle (º)	Spindle speed (rpm)	Feed rate (mm/min)	Thrust Force (N)	SN ratio for thrust force	Delamination factor	SN ratio for delamination factor
1	90	1000	100	68.67	-36.74	1.02	-0.14
2	90	1000	150	78.48	-37.90	1.03	-0.21
3	90	1000	200	98.10	-39.83	1.03	-0.26
4	90	1500	100	78.48	-37.90	1.02	-0.18
5	90	1500	150	98.10	-39.83	1.03	-0.27
6	90	1500	200	127.53	-42.11	1.05	-0.42
7	90	2000	100	78.48	-37.90	1.03	-0.29
8	90	2000	150	107.91	-40.66	1.05	-0.45
9	90	2000	200	147.15	-43.36	1.07	-0.57
10	118	1000	100	58.86	-35.40	1.03	-0.23
11	118	1000	150	68.67	-36.74	1.04	-0.35
12	118	1000	200	88.29	-38.92	1.06	-0.51
13	118	1500	100	68.67	-36.74	1.05	-0.40
14	118	1500	150	107.91	-40.66	1.06	-0.53
15	118	1500	200	117.72	-41.42	1.08	-0.64
16	118	2000	100	88.29	-38.92	1.08	-0.65
17	118	2000	150	137.34	-42.76	1.09	-0.74
18	118	2000	200	166.77	-44.44	1.12	-0.96
19	135	1000	100	78.48	-37.90	1.06	-0.45
20	135	1000	150	107.91	-40.66	1.11	-0.87
21	135	1000	200	127.53	-42.11	1.13	-1.05
22	135	1500	100	107.91	-40.66	1.07	-0.62
23	135	1500	150	156.96	-43.92	1.12	-0.99
24	135	1500	200	186.39	-45.41	1.14	-1.14
25	135	2000	100	127.53	-42.11	1.14	-1.10

26	135	2000	150	186.39	-45.41	1.17	-1.36
27	135	2000	200	196.20	-45.85	1.20	-1.57

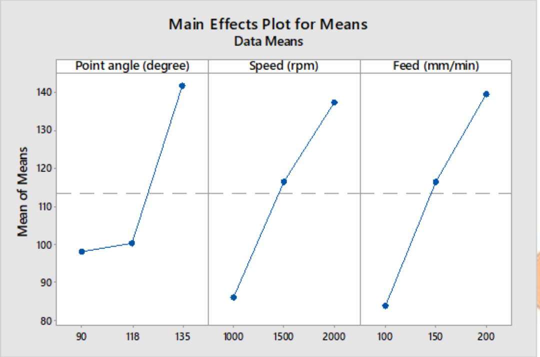

Fig. 2. Mean effect plot for thrust force

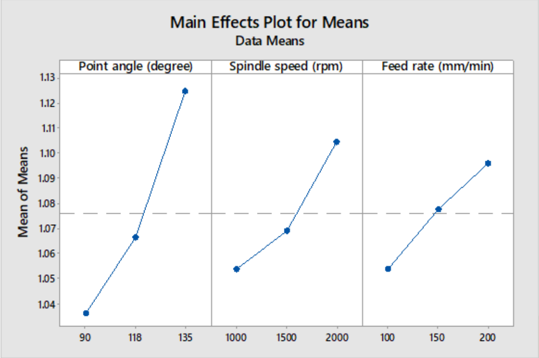

Fig. 3. Mean effect plot for delamination

Tables 5 and 6 display the ANOVA thrust force and delamination factor analysis results respectively. The current experimental data was subjected to an ANOVA experiment in order to statistical significance determination of the drilling parameters. The R^2 value must be equal to or greater than 90% and can be used with the experimental data to determine the fitness of the predicted model. The R^2 values in this analysis were 99.10% and 99.66%, indicating that the examined model fits the experimental data well. The p-value denotes the drilling variables' significance in determining thrust force and delamination factor (the lower the p-value, the greater the significance). According to the p-value, all three variables were significant in influencing lamination factor and thrust force, but the contribution percentage varied. According to the ANOVA results presented in Tables 5 and 6, feed rate contributed the most (ca. 30%) to determining thrust force, while point angle contributed the most (ca. 60%) to determining delamination.

Table 3. Delta values of thrust force

Level	Point angle	Spindle speed	Feed rate
1	-39.58	-38.46	-38.25
2	-39.55	-40.96	-40.95
3	-42.67	-42.38	-42.61
Delta	3.12	3.91	4.36
Rank	3	2	1

Table 4. Delta values of delamination factor

Level	Point angle	Spindle speed	Feed rate
1	-0.3099	-0.4508	-0.4511
2	-0.5563	-0.5762	-0.6422
3	-1.0161	-0.8552	-0.7889
Delta	0.7062	0.4044	0.3378
Rank	1	2	3

Table 5. ANOVA result of thrust force

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A	2	10864	26.96%	10864	5431.99	119.53	0.000
B	2	11954.7	29.67%	11954.7	5977.33	131.53	0.000
C	2	14050.5	34.87%	14050.5	7025.24	154.59	0.000
AB	4	1368.7	3.40%	1368.7	342.17	7.53	0.008
AC	4	556	1.38%	556	139.01	3.06	0.084
BC	4	1133.4	2.81%	1133.4	283.36	6.24	0.014
Error	8	363.6	0.90%	363.6	45.44		
Total	26	40290.8	100.00%				

R^2 = 99.10% **R^2Adj = 97.07%**

Table 6. ANOVA result of delamination factor

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A	2	0.036415	60.18%	0.036	0.018207	706.06	0.000
B	2	0.012209	20.18%	0.012	0.006105	236.74	0.000
C	2	0.008105	13.40%	0.008	0.004053	157.16	0.000
AB	4	0.001773	2.93%	0.0018	0.000443	17.19	0.001
AC	4	0.001741	2.88%	0.0017	0.000435	16.88	0.001

BC	4	0.00006	0.10%	0.0001	0.000015	0.58	0.687
Error	8	0.000206	0.34%	0.0002	0.000026		
Total	26	0.06051	100.00%				

R^2 = 99.66% **R^2Adj = 98.89%**

3.1. *Thrust Force Analysis*

The variation of thrust force with respect to changes in the drilling parameters is illustrated in Figure 4. Initially, during the initiating stage of drilling, the tool-cutting lips actively engage in material removal, resulting in a rapid increase in thrust force until it reaches its peak. The thrust force is predominantly influenced by the chisel edge of the tool and the cutting lips, as they play a crucial role in material removal [17,18]. It should be noted that the chisel edge of the tool does not directly cut the material, but instead aids in the extrusion action to remove the formed chip material. Once the drilling operation is completed, the cutting lips and chisel edge of the tool are no longer engaged in machining, causing the thrust force to decrease and eventually reach zero. From Figure 4, it is clear that there is an increase in the spindle feed and feed increased the thrust force. The feed rate resulted in an increase in thrust force. This was due to the chip formation's higher resistance encounter. The material removal process becomes less efficient as feed rates increase, resulting in chip formation. As a result, a resistance force was developed against the tool, resulting in an increase in thrust force. Similarly, increasing the spindle speed increased the thrust force. One possible explanation is within the composite matrix, which acts as an impediment to the drilling tool's progress and shows the presence of red mud particles [19,20]. This impediment contributes to increased thrust force even at higher speeds. Furthermore, higher spindle speeds can generate more heat during the drilling process. Because of the accumulated heat in the drilling area, the matrix and red mud particles can adhere to the tool, forming a build-up edge. This build-up edge may also contribute to the increased thrust force observed at higher speeds.

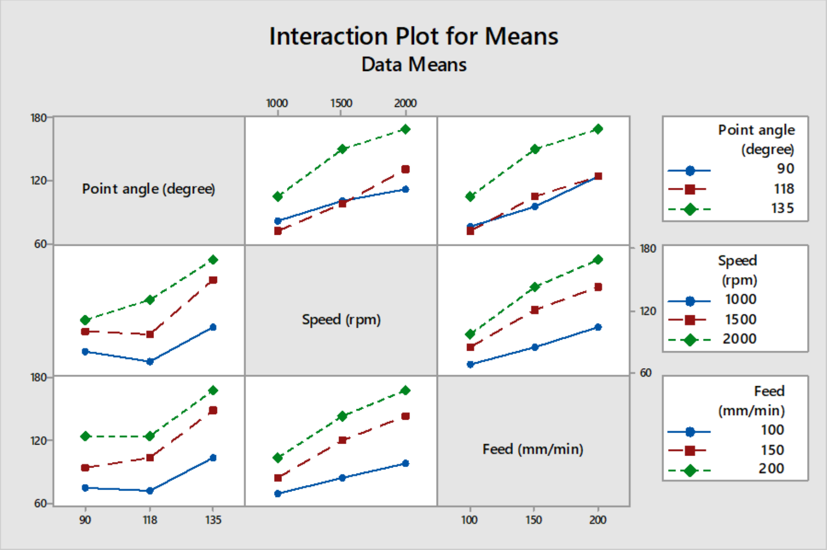

Fig. 4. Thrust force variation with respect to drilling parameters

3.2. *Delamination analysis*

Figure 5 illustrates the delamination factor variation with respect to the drilling parameters change. It was found that increasing both feed rate and spindle speed causes an increase in delamination. Delamination is closely subjected to thrust force. Higher feed rates result in more thrust development, which increases resistance to tool penetration. When the tool reaches the exit point, the increased stress in the tool is transferred to the surface, resulting in high delamination [21,22]. Furthermore, the increased feed rate was frequently accompanied by the built-up edge formation on the tool as a result of increased heat generation. This, in turn, contributed to more delamination. Higher spindle speeds are typically expected to result in less delamination in fiber composites. In our case, the opposite trend was observed, with increased spindle speed the delamination was increased. This is due to the brittleness developed in the composite as a result of the addition of red mud addition. Further, it is clear that increasing the point angle causes an increase in delamination. The delamination factor is relatively less at lower point angles. This could be attributed to a thrust force decrease at low point angles, which reduces the extent of delamination damage.

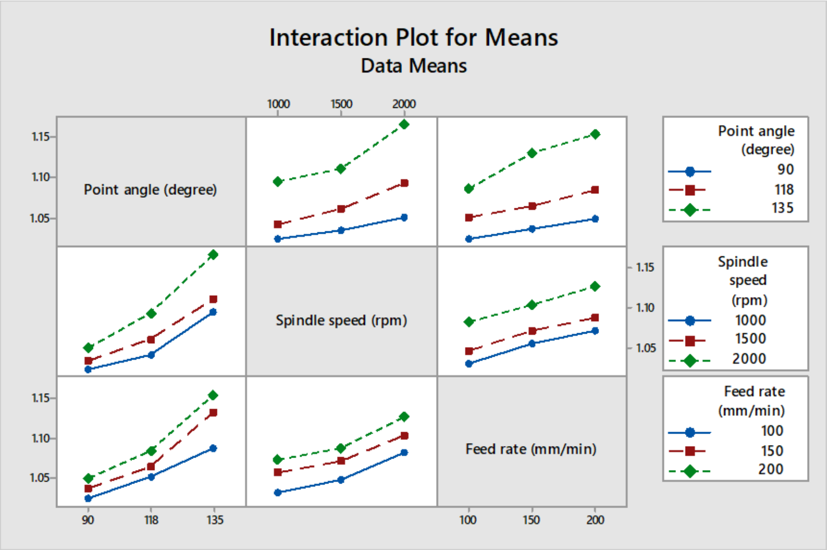

Fig. 5. Delamination factor variation with respect to drilling parameters

3.3. Drilled Hole Surface Analysis

Figure 6 depicts the surface morphology of the composite's drilled walls. Matrix cracks were visible on the surface (Figure 6a), which can be attributed to the increased stress generated at the drill face while penetrating the material. The insistent drilling action resulted in fiber extraction from the matrix and subsequent debonding, resulting in fiber protrusion and matrix detachment. Furthermore, the fibers were found to be fractured and fragmented in some areas. Furthermore, the considerable during the drilling process heat generation resulted in the melting and smearing of the matrix on the walls of the cut surface (Figure 6b). This occurrence was apparent as a coating of melted matrix material on the surface. Cutting forces generated during drill tool penetration created stress concentrations in the composites, resulting in fiber separation (Figure 6c). These variations in cutting mechanisms, such as fragmentation, fiber pull-out, matrix cracking, and matrix melting, collectively contribute to a poor drill wall surface. Surface irregularities and inconsistencies, such as matrix cracks, fiber protrusion, and melted matrix smearing, can compromise the overall integrity and quality of drilled fiber composites. However, by optimizing drilling parameters, carefully selecting tools, and implementing effective cooling methods, it is possible to alleviate these concerns and improve the surface finish and quality of drilled holes in fiber composites. These measures can help to reduce the aforementioned issues while also improving the overall surface integrity and quality of drilled fiber composites.

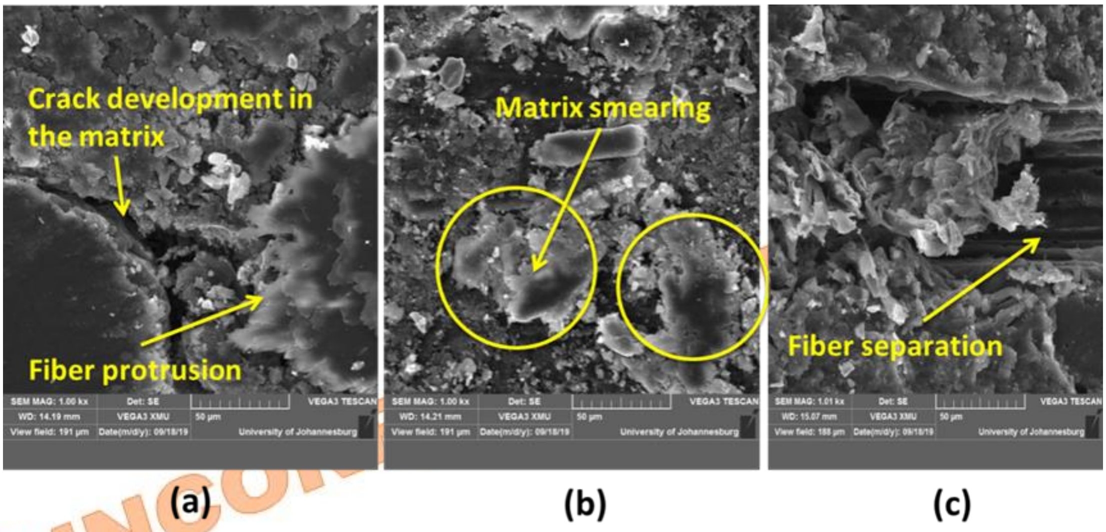

Fig. 6. SEM morphology of red mud/coconut sheath composite

4. Conclusion

The feed rate and spindle speed had a direct impact on the thrust force, with higher values resulting in increased thrust force. The red mud particles' presence in the composite matrix contributed to higher thrust forces, possibly due to their hindrance to the progress of the drilling tool. Increasing feed rate and spindle speed led to higher delamination, primarily driven by increased thrust force and resistance to tool penetration. Unexpectedly, higher spindle speeds resulted in increased delamination, possibly due to the brittleness induced by the red mud addition. The point angle of the tool also influenced delamination, with higher point angles resulting in increased delamination. The analysis of the drilled hole surface morphology revealed fragmentation, fiber pull-out, melted matrix smearing, and matrix cracks all contributing to increased surface roughness. These surface irregularities and discontinuities can negatively impact the overall quality and integrity of the drilled fiber composite.

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