Hindawi
Advances in Polymer Technology
Volume 2023, Article ID 6271115, 15 pages
https://doi.org/10.1155/2023/6271115

WILEY | Hindawi

Research Article

Influence of Drilling Parameters on the Delamination and Surface Roughness of Insulative-Coated Glass/Carbon-Hybrid Composite

Sarower Kabir[1] **Faiz Ahmad,**[2] **Chowdhury Ahmed Shahed,**[2] **and Ebru Gunister**[3]

[1]*Department of Mechanical and Production Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh*
[2]*Department of Mechanical Engineering, Universiti Teknologi PETRONAS (UTP), Perak, Malaysia*
[3]*Department of Mechanical Engineering, Istanbul Health and Technology University, TR-34015 Istanbul, Turkey*

Correspondence should be addressed to Sarower Kabir; sarower.mpe@aust.edu

Received 4 October 2022; Revised 4 May 2023; Accepted 21 May 2023; Published 2 June 2023

Academic Editor: Ngoc A. Nguyen

Drilling in synthetic fiber-reinforced polymer composites is facing challenges due to their anisotropic, inhomogeneity, and abrasive machining behavior. The joining of composite parts using fasteners is commonly done by the drilling, and the generated heat is one of the main causes to damage the drilled hole in the composite. Moreover, the quality of drilled hole is crucial for joining parts effectively. The paper presents the design, fabrication, and drilling of a hybrid fiber-reinforced polymer (HFRP) based on insulative coating. These composites were fabricated using vacuum infusion molding (VIM) and coated with different thicknesses to investigate the influence of drilling parameters and associated damages. Cutting speed, feed rate, and coating thicknesses were varied, and a full factorial design of the experiment was formulated. High-speed steel (HSS) twist drill bit was used to drill the coated composite and test samples, and delamination factor and surface roughness were measured. ANOVA and full factorial response optimizer were used to evaluate the influence and optimum drilling parameters. The delamination factor (DF) at the entry and surface roughness were found to decrease with the increasing cutting speed. However, the DF at the exit showed the opposite. Coating thickness influenced the delamination at the entry whereas delamination at the exit has been found insignificant. For drilling HFRP composite with 1 mm coating thickness, 3000 RPM spindle speed and 0.08 mm/rev feed rate were found optimum parameters in minimizing surface roughness and delamination damage. However, 6000 RPM and 0.02 mm/rev were found optimum parameters for drilling HFRP composite with 1.5 mm coating thickness.

1. Introduction

The fastest growth in the industrial revolution has driven the need for better materials in terms of strength, stiffness, resistance to fatigue, and corrosion with improved sustainability. Conventional materials are now being replaced by advanced composite materials due to their wide range of advantages in high-performance applications. It is not only found in racing cars, sporting goods, and airplanes but also in the low-cost high-volume industry like automotive [1]. Over the years, fiber-reinforced polymer (FRP) composites are getting huge attention due to their wide variety of applications in the field of aerospace constructions, transportation, sporting goods, chemical engineering, and foremost civil engineering application due to their superior advantages over traditional materials [2]. Moreover, the FRP composites are widely used in the vital dessign and structure for well-known companies such as Boeing and Airbus passenger plane's landing gears, and body parts of the racing cars [3–5]. Fibers are bounded by the polymer matrix, thus transferring the load to the fibers and also protecting fibers from environmental attack [6]. There are a wide variety of fibers and resin systems that can be used to fabricate FRP composite, each of these having its advantages and disadvantages. Besides that, the cost of the materials, their strength to mass ratio, stiffness, fatigue limit, and corrosion resistance are some other important requirements that must be met which is practically not possible to achieve in a single-type FRP composite. For example, having higher strength, stiffness, and lower density than glass fiber, using carbon fiber alone is not still recommended in the automobile industry as it incurs higher costs. Therefore, hybridization is an ideal concept that has been developed to attain desired properties in one single type of composite. The ultimate advantage of using hybrid composite in advanced applications lies in the synergistic effects of the constituent's materials. High-strength carbon fiber and high elongation glass fiber are popular choices in the manufacturing of composites [7, 8]. Manders and Bader [9] demonstrated and proved that using glass fiber and carbon fiber combination has better advantages due to higher specific strength, higher stiffness, higher elongation, and higher strain to failure. Moorthy et al. [10] found that the conglomeration of glass and carbon can significantly improve the mechanical properties compared to the single glass or carbon-based composites. Sayer et al. [11] reported that combining glass fiber reinforcement with carbon fiber in the automobile industry not only reduces the weight of the part but also maintains the overall cost. They also added that glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) composites can be an ideal option in the construction of wind turbine rotor blades. Drilling of FRP composites comes with a challenge due to the damaging tendency of the materials under various cutting parameters. However, to solve the drilling-generated damage incurred, many researchers have studied the optimization of the drilling process of single-type FRP composite [12–14]. Inappropriate selection of cutting parameters can lead to unacceptable damage in materials such as fiber pull out, matrix cratering, thermal damage, and delamination [15]. Drilling-generated damage such as fiber pull-out/push-out and delamination reduces the strength against failure hence degrading the longevity of produced parts [16]. Delamination is the most occurred damage when drilling FRP composites and reduces the mechanical strengths. Delamination occurs on both sides of the sample (entrance and exit), and investigation shows that push-out delamination (exit) is more drastic than peel up (entrance) [6]. Figures 1(a) and 1(b) shows a schematic diagram of geometrical damage and peel-up and push-out delamination, respectively. Surface finish is also a significant factor and focus study of many researchers [17]; quality surface finish is one of the main determinant factors when selecting or rejecting an engineered part. During the drilling, the cutting edges of the drill bit contact alternatively with the separate oriented reinforced fibers; thus, dynamic change of fiber cutting angle, distinct delamination profile, and mode of chip removal (Figure 1(c)) can be observed [18]. Most researchers observed mainly four types of cutting models for four relative fiber orientation angles with the cutting edge. Figure 1(d) illustrates the cutting mechanism where the bending-induced fractured type, compression and interlaminar shear type, crushing dominated type, and macro fracture type can be observed at 0°, 45°, 90°, and 135° angles, respectively.

Kilickap [19] investigated the effect of cutting parameters such as cutting speed, feed rate, and drill point angle on the delamination when drilling GFRP composite and concluded that the cutting speed is the main influential factor followed by feed rate. Köklü et al. [20] stated that the delamination has a proportional relation with feed rate and inversely associated with speed. The geometry of the drill bit played an important role in forming delamination when drilling CFRP composite, and an investigation reported that a 5 mm diameter is optimum in minimizing the delamination [21]. Feed rate has a proportional relationship with delamination while cutting speed is inversely related to delamination [22]. Kumar and Singh [23] studied and reported that increased feed rate also increases delamination on both sides of the composite. Fiber push-out delamination can occur when the drill bit is in contact with the workpiece due to higher applied forces generated [24]. Babu and Philip [25] observed the feed rate as the most significant; thus, the delamination was stepped high with the increase of cutting speed. Krishnamoorthy et al. [26] found feed rate as the most significant parameter that affects the delamination when drilling CFRP composite. Kılıçkap [27] concluded in his research that delamination was higher at the exit side in comparison to the entrance at a 13-30% rate and it can be minimized by setting a low cutting speed and feed rate. Wang and Feng [28] studied and reported that spindle speed plays a significant role in inducing roughness over the surface. Surface roughness is high when the feed rate is 0.010 mm/rev at a lower cutting speed, but roughness also increases when the cutting speed goes up [29]. Palanikumar et al. [30] investigated the effect of drilling parameters on surface roughness and concluded that feed rate is the most significant factor; using a small drill diameter reduces surface roughness. When cutting speed is high, surface roughness is low as higher cutting speed generates temperature which softens the work materials [31]. Feed rate and drill diameter were found to significantly affect the surface roughness followed by drilling speed [32]. Feed rate was found to influence the surface roughness followed by cutting velocity and was investigated by Shunmugesh and Panneerselvam [33]. Eneyew and Ramulu [5] reported that average surface roughness was affected by point angle and better hole quality can be achieved with higher cutting speed and lower feed rate. Feed rate was found the most prominent factor with 39% and speed with 24% that affects the delamination in order to achieve a 5% level of significance when drilled pultruded glass fiber polymer composite [34]. Margabandu and Subramaniam [35] found that the drilling speed was the most influencing factor that affects jute-/carbon-reinforced hybrid composite and suggested to drill at a speed of 1750 RPM and 0.03 mm/rev of feed.

Shafi et al. [36] investigated the effects of silica gel as a heat insulation layer on silica aerogel/glass fiber composites and concluded that the compressive strain was improved. C-bonded C-fiber-reinforced composites were fabricated and coated with novel carbon aerogel to improve the heat insulation properties [37]. Flammability was reduced for a sustainable composite made of wool, canola oil, and sulphur, and the composite was considered favorable for future energy conservation [38]. Khalili et al. [39] approached the investigation of improving flame retardancy of Elium reinforced natural fiber composite made of intumescent mats with consisting expandable graphite. They concluded that the flame retardancy was significantly enhanced due to the

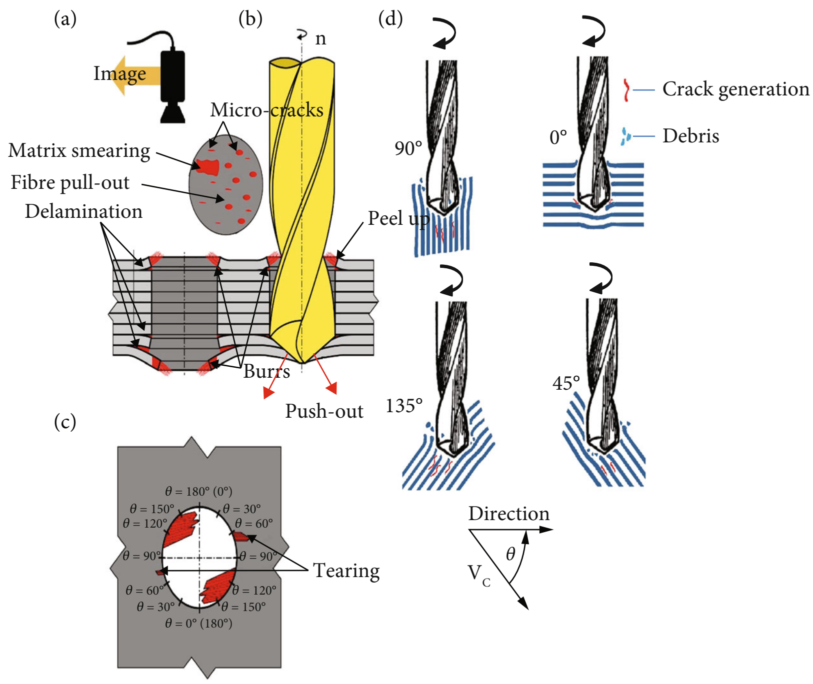


Figure 1: Schematic drilling challenges in CFRP: (a) macro and micro geometrical damages, (b) peel-up and push-out delamination, (c) burr characteristics [18], and (d) material removal and delamination for different fiber orientation.

expansion of expandable graphite flakes. However, lack of study was noticed on the machining performance of hybrid/composites when coated with insulative materials.

In this study, we are aimed to investigate the effects of drilling parameters on the insulative-coated HFRP composite and expected to obtain an impact on the delamination behavior of the drilled materials. In addition, it is also important to look at the scope of composite materials in heat-resistant applications in various sensitive industries.

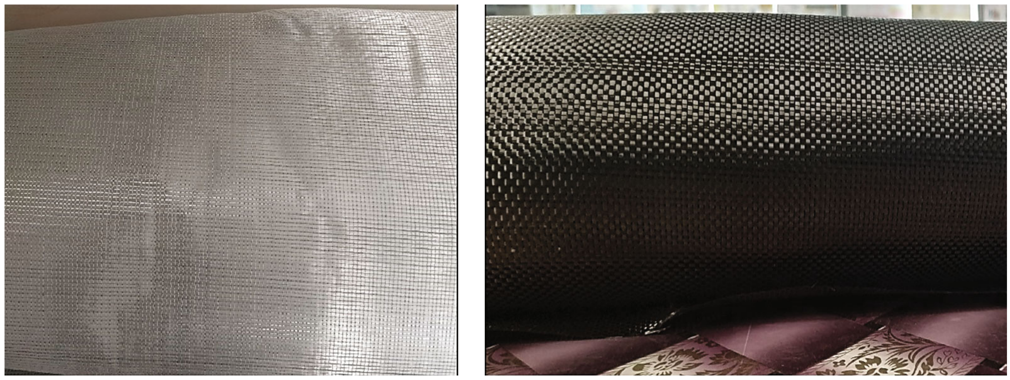
2. Experimental

2.1. Fabrication of Hybrid Fiber-Reinforced Polymer (HFRP) Composite. Carbon and glass fibers in the woven form were used as the reinforcement materials (Figure 2) and epoxy as the matrix material in this investigation and purchased from RP Products Sdn. Bhd. and Advance Altimas Sdn. Bhd., Malaysia, respectively. The mechanical properties of glass and carbon fibers are given in Table 1 according to the spreadsheet provided by the supplier. Other accessories such as peel plies, mesh, spiral tubes, hose pipes, and vacuum bags required to manufacture the composite laminate were also purchased from UK Composite, UK.

The hybrid composite was fabricated using the vacuum infusion molding method in the lab. Orientation of fiber materials was maintained at 0/90°, and the lamina stacking sequence (C-G-G-G-C-G-G-G-C) (Figure 3) was selected to measure delamination and average roughness on the surface of the drilled component. Stacking carbon fiber at the exterior helps the bending deformation, and stacking in core reduces delamination during drilling [40]. Placing glass fiber right after carbon fiber helps reducing the propagation of microcracks at the interface [41]. The thickness of glass fiber and carbon fiber was 0.31 mm and 0.16 mm, respectively. Carbon fiber was taken first to achieve a higher flexural modulus [42], and the experimental setup is given in Figure 4. The vacuum pressure was kept at 80 kPa to produce a bubble-free sample with a fiber resin ratio of 46 : 54.

2.2. Preparation of Insulative Coating. The constituent materials required to formulate the coating were purchased from different suppliers. Zirconium phosphate (ZrP) was purchased from Sichuan HongChang Plastics Indus. Co. Ltd., China. Expandable graphite (EG), boric acid (BA), ammonium polyphosphate (APP), melamine (MEL), and halloysite nanotube (HNT) were purchased from Sigma-Aldrich (M) Sdn Bhd., Malaysia. Epoxy resin BE-188 (BPA) and hardener H-2310 polyamide amine were brought from McGrowth Chemical Sdn Bhd., Malaysia. The detailed formulation ingredients are given in Table 2.

All the ingredients such as APP, BA, MEL, HNT, and ZrP were mixed according to formulations given in Table 2 and ground in a shear mixer for about 90 seconds with 21000 RPM to make it homogenous. EG was later added to the mixture and stirred a little with a spoon to prevent the EG from grinding, as bigger EG flakes are responsible for better expansion. After that, epoxy (BE-188) was added to the mixture followed by the hardener (H-2310) and stirred at about 40 RPM for 15 min and then 5 min at 60 RPM, respectively, by using an automatic shear mixer CAFRAMO (BDC 6015-220). A total of 24 samples of 70 mm × 25 mm was used as substrate, and coating was applied (Figure 5) using a hand lay-up technique with the help of a specially designed mold with a 1 mm pitch screw where every half turn of the screw makes the 0.5 mm vertical displacement (Figure 6) which ensures the desired thickness of 0.5, 1.0,



(a) (b)

Figure 2: Woven fibrous materials used in this investigation: (a) E-glass and (b) carbon.

Table 1: Mechanical properties of woven glass and carbon fibers.

Properties	Glass fiber	Carbon fiber
Tensile strength (ksi)	360	512
Tensile modulus (msi)	11.4	33.4
Strain to failure (%)	3.0	1.5

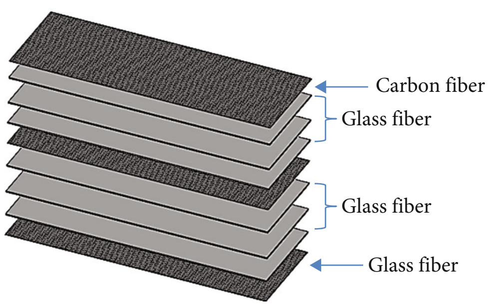


Figure 3: Fiber's orientation.

1.5, and 2.0 mm and the curing time was a day at the ambient room temperature.

2.3. Drilling of HFRP Composite. A drill bit with a 5 mm diameter of high-speed steel (HSS) was selected in this study to investigate the effect of drilling parameters on the delamination and surface roughness of coated HFRP composite with various coating thicknesses. To perform the drilling operation, Mazak variaxis 630 CNC machines were used without pouring out coolant to avoid moisture absorption which may affect the microstructure, dimensional accuracy, and mechanical properties of the composite [43]. The sample size selected was 70 mm in length and 25 mm in width. The samples were clamped by the fixture. Each sample had undergone drilling operation on it using a 5 mm HSS drill bit shown in Figure 7.

3. Characterizations

The quality of drilled hole was evaluated based on the delamination factor and surface roughness of the HFRP composite. Figures 8(a) and 8(b) show drilled holes obtained for uncoated and coated HFRP composites, respectively.

3.1. Measurement of Delamination Factor (DF). Delamination factor (DF) is considered the major and well-known tool to determine the drill hole quality at the entrance and exit. DF of the drilled hole was identified according to equation (1) and Figure 9(a).

$$\mathrm{DF} = \frac{D_{\mathrm{max}}}{D_{\mathrm{hole}}}, \tag{1}$$

where D_{max} is the maximum diameter after drilling and D_{hole} is the nominal diameter of the hole.

Leica LX 00971A optical microscope was used to identify the delamination on the drilled samples (Figure 9(b)). The microscope magnified 5 times of 1 mm resolution. Maximum diameter and nominal diameter were evaluated through the images by using smart dimensioning tool of SOLIDWORKS software.

3.2. Measurement of Surface Roughness. The surface topology of the drilled HFRP composites was obtained by employing scanning electronic microscopy (SEM, Phenom, Pro-X, Netherlands). Samples were first cut at a dimension of 1 mm × 1 mm using an abrasive cutter. The average roughness (R_a) and roughness height (R_z) were assessed from 3D images based on "shape from shading" technology. The device was operated at 15 kV, and the field of view was 964 μm. The images were captured at different magnifications to obtain clear surface roughness information.

4. Results and Discussion

The procedure discussed above was repeated corresponding to the experimental sequence provided in Table 3 according to the ANOVA full factorial analysis, and the measured values are shown in the table.

4.1. Analyzing the Effects of Drilling Parameters on the Delamination at the Entrance and Exit. Effects of cutting parameters on the delamination at the entry and exit were observed and analyzed after drilling. DF at the entry was found to decrease with the increasing cutting speeds shown in Figures 10(a) and 10(b). This scenario can be elucidated

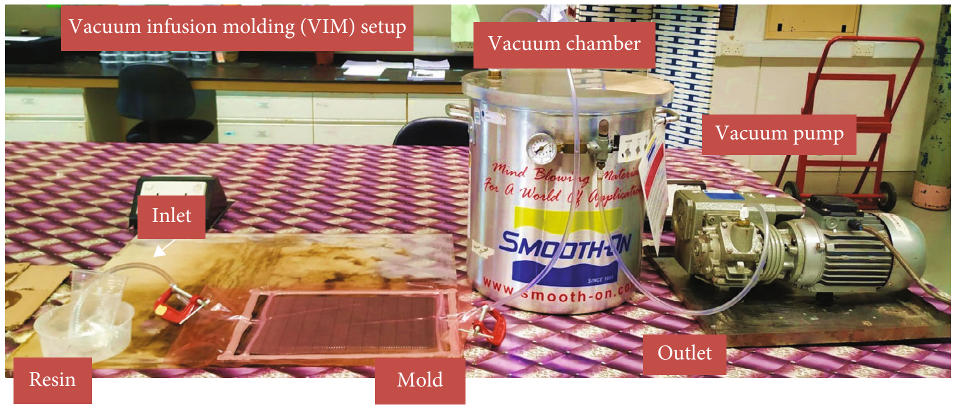


Figure 4: Vacuum infusion molding (VIM) setup used in the lab.

Table 2: Formulation of insulative coating used in this study (gm).

APP	MEL	BA	EG	HNT	ZrP	Epoxy resin	Hardener
11.36	5.5	11	5.5	0.5	0.5	41.94	19.72

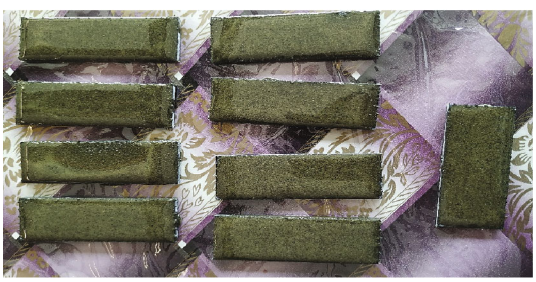


Figure 5: Coated HFRP composite samples.

by relating to the temperature generated during the drilling. Higher cutting speed produces heat at the drilling zone which soften the composites, and thus, reduced delamination factors can be observed [44]. On the other hand, this scenario can be illustrated as the high spindle speed producing high shear force; therefore, the composites undergo a shear deformation, thus reducing delamination. Again, delamination had shown a proportional relationship with the feed rate as it increased with the increase of the feed rate. Thrust force increased when feed rate is increased due to expanding cross-sectional area thus producing more delamination [45]. DF at the entry ranges from 1.020 to 1.178, as presented in Table 3. The lowest DF value at the entry was obtained at the drilling condition of 3000 RPM, 0.02 mm/rev, and 2.0 mm thick coating; meanwhile, the highest delamination onset was obtained at 6000 RPM, 0.08 mm/rev, and 2.0 mm thick coating. This is because when an overly brittle coating of 2.0 mm thick drilled at a high speed and feed, it could not take much compressive force that leads to the delay in damping effect and fracture and finally resulted higher delamination at the entrance. However, delamination at the exit showed the opposite behavior. DF was found to increase with the cutting speeds shown in Figures 10(c) and 10(d). DF at the exit has higher delamination damages than at the entrance. DF at the exit ranges from 1.076 to 1.220. The lowest DF value at the exit was obtained at 4500 RPM, 0.08 mm/rev, and 0.5 mm thick coating. The highest delamination damage at the exit was obtained at the drilling condition of 6000 RPM, 0.08 mm/rev, and 2.0 mm thick coating. This could be happened due to the different states of the top and bottom surfaces of the composites. At the entry, the composites were experiencing compression, and at the exit, those were in tension. Coating thicknesses have played a vital role in the damage factor at the entry. It has been observed that the delamination was found to increase with the increased cutting speeds on exit sides for a 2.0 mm thickly coated sample. This is because the coating agitated the fiber push out at the exit; however, the coating thickness had no significant impact on DF. This happened because of the brittle nature of the coating as brittle materials have a lack of ductility in tension and they will fail prematurely [46]. Therefore, the changes in the thickness of the coating failed to show any significant improvements. On the other hand, delamination at the entry was reduced with the increase of the coating thickness. DF at the entry was 5.5% and 2.7% less in comparison to the 0.5 mm thick coated samples while drilling at 3000 and 4500 RPM, respectively. This was presumable that the entry point is in compression and brittle materials under compressive load tend to close up the transverse crack; therefore, the delamination was lesser [47].

4.2. Optimized Drilling Parameters for Delamination. The influence of speed, feed rate, and coating thickness on the delamination at the entry of coated HFRP composite was calculated using ANOVA and presented in Table 4. ANOVA table suggested that the interactions between speeds and coating thicknesses are the most important factor that affects the delamination at the entry followed by coating thickness alone and the interactions between feed rate and coating thicknesses. F value is $> F_{0.05}$ for both the interactions obtained, and the corresponding P value is less than 0.05. Feed rate alone is found insignificant since the F value and

Figure 6: Especially designed adjustable mold used in this study to maintain coating thickness.

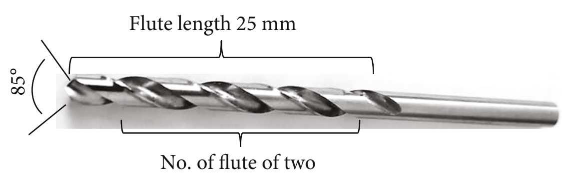


Figure 7: HSS twist drill bit geometry used in this study.

P value are showing opposite results to the others. Table 4 illustrates that the 98.90% variations in the response are explained by the model and it is considered significant. Moreover, the difference between the *R*-square value and *R* -square (predicted) value is acceptable which gives us the idea that all the parameters involved are significant.

Similarly, the influence of speed, feed rate, and coating thickness on the delamination at the exit of coated HFRP composite was calculated using ANOVA and presented in Table 4. ANOVA table suggested that the cutting speed is the major factor that is affecting the delamination at the exit followed by coating thickness. Feed rate has been found nonsignificant, and no interaction effects were present. This could be happened due to the notch sensitivity of the brittle materials. Table 4 illustrates that 82.72% of variations in the response are explained by the model and the difference between the *R*-square value and *R*-square (predicted) value is quite high enough (17.16%) to give us the idea that some of the important factors like temperature, the bonding strength between layers, axial thrust force, and drill geometry are missing.

Figure 11 presents the residual plots for both delamination at the entry and exit for coated HFRP composite. In both cases, the normal probability plot shows that all the points are close to the straight line meaning no unusual observations. The residual vs. fit graph shows that all the data are nearly distributed evenly and randomly below and above the straight line. Bell shape curve is obtained for delamination at the exit shown in the histogram. No specific pattern is shown in the residual vs. observation graph meaning no biasness involved in the data set.

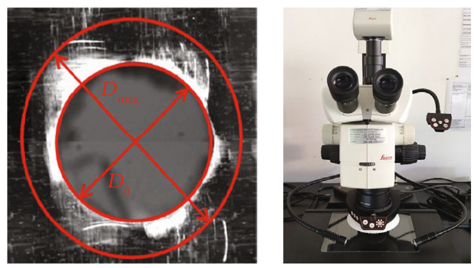
S/N ratio, a systematic approach to analyze the response parameters, has been used in this study. The greater is the value of S/N ratio, the lesser is the variance in the optimum values. Table 5 shows the response table of S/N ratio for the delamination at the entry and exit, and Figure 12 illustrates the main effects obtained from the S/N plots and highlights that coating thickness and cutting speed played the vital role in the delamination factor at the entrance and exit. Feed rate was found to be less significant compared to speed and coating thickness.

A full factorial response optimizer was used to determine the optimum cutting condition in drilling coated HFRP composite and presented in Figure 13. 3000 RPM, 0.08 mm/rev feed rate, and 1.0 mm coating thickness are considered the optimum cutting condition.

4.3. Analyzing the Effects of Drilling Parameters on the Surface Roughness. Understanding the precision of the drilled hole part and measurement of roughness is important, and it is occurred due to the inappropriate fracture of fiber leading to the sharp end in the inner surface, failure under fatigue load, high friction, and generation of heat at the drilled wall [35]. The surface roughness (R_a) of the drilled hole wall has been found to decrease with increasing cutting speeds shown in Figure 14(a). Surface roughness values range from 1.30 μm to 1.82 μm, as highlighted in Table 3. The lowest roughness value was obtained at the drilling condition of 6000 RPM, 0.02 mm/rev, and 1.5 mm thick coating. This might be happened due to the smearing effect in the fiber-matrix composite at the elevated temperature. The highest roughness value was noticed at the drilling condition of 3000 RPM, 0.08 mm/rev, and 0.5 mm thick coating. It has been observed that 0.5 mm thick coating samples showed a 3.8% increment in roughness value when the feed rate increased from 0.02 mm/rev to 0.08 mm/rev at 3000 RPM. However, the roughness value was reduced by approximately 20% and 16% when the cutting speed increased from 3000 RPM to 6000 RPM for the similar condition of 0.02 and 0.08 mm/rev feed rate and 0.5 mm thick coating, respectively. Comparably, measured roughness value (R_a), while drilling at 3000 RPM and 0.02 mm/rev feed with 1.0 mm thick coating, was obtained as 1.69 μm, but it has decreased to 1.33 μm when speed increased to 6000 RPM. In all the cases, the surface roughness of the drilled holes shows an inverse relationship with cutting speeds. This scenario is common in other machining

(a) (b)

Figure 8: Drilled HFRP composite: (a) uncoated; (b) coated.



(a) (b)

Figure 9: (a) Microscopic view of damaged HFRP composite surface. (b) Optical microscope to identify delamination.

Table 3: Experimental sequence followed to drill the HFRP composite samples using full factorial design of experiment.

Sample no.	Spindle speed (RPM)	Feed rate (mm/rev)	IC thickness (mm)	Delamination (entry)	Delamination (exit)	Surface roughness (μm)
1	3000	0.02	0.5	1.080	1.086	1.75
2			1.0	1.070	1.090	1.69
3			1.5	1.060	1.100	1.56
4			2.0	1.020	1.160	1.47
5		0.08	0.5	1.080	1.080	1.82
6			1.0	1.050	1.108	1.71
7			1.5	1.068	1.078	1.52
8			2.0	1.038	1.080	1.61
9	4500	0.02	0.5	1.080	1.100	1.63
10			1.0	1.068	1.110	1.58
11			1.5	1.060	1.120	1.61
12			2.0	1.050	1.158	1.42
13		0.08	0.5	1.064	1.076	1.70
14			1.0	1.052	1.110	1.63
15			1.5	1.062	1.102	1.62
16			2.0	1.080	1.128	1.53
17	6000	0.02	0.5	1.052	1.116	1.41
18			1.0	1.040	1.150	1.33
19			1.5	1.026	1.166	1.30
20			2.0	1.140	1.206	1.35
21		0.08	0.5	1.034	1.116	1.52
22			1.0	1.040	1.150	1.47
23			1.5	1.026	1.160	1.46
24			2.0	1.178	1.220	1.49

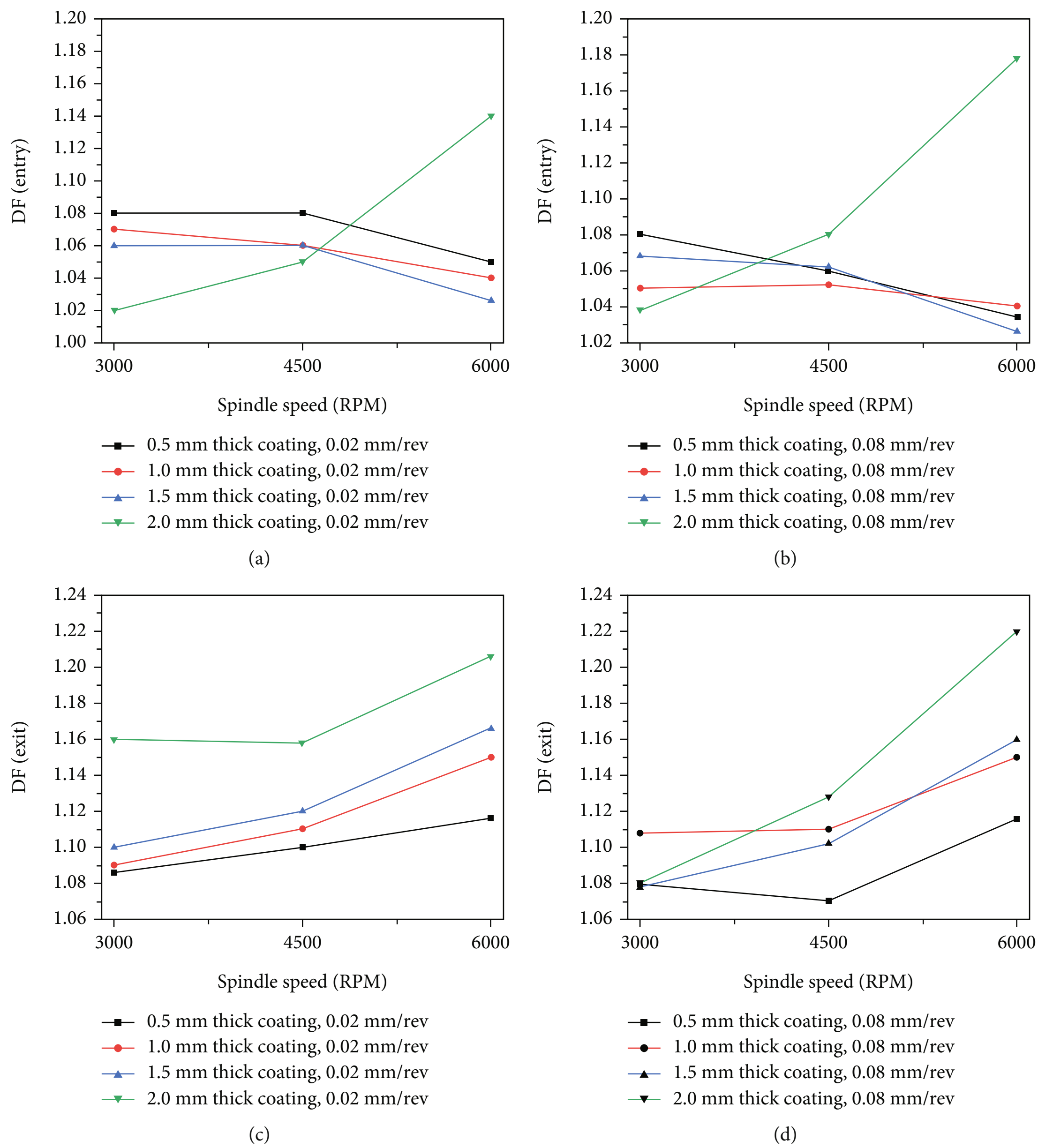


Figure 10: DF: at the entry (a) 0.02 mm/rev and (b) 0.08 mm/rev and at the exit (c) 0.02 mm/rev and (d) 0.08 mm/rev.

methods as well. According to Ghani et al., the cutting process becomes stable more at the high cutting speed [48]. Also, researchers showed that the interactions and the adherence between the composites and cutters are more at the lower cutting speeds, thus creating a built-up edge that may lead to a rough surface [49]. This scenario is more likely here. However, keeping the speed (3000 and 6000 RPM) and coating thickness (1.0 mm) constant, the roughness value was found higher for the 0.08 mm/rev feed rate. Composite laminates when drilling at higher spindle speeds and feed rate, increases the temperature of the accumulated heat around the drill cutting edges due to the low thermal coefficient and destroys the matrix stability, and produces rough cuts around the wall which leads to the surface roughness [50]. This can be distinguished differently from the smearing effects mentioned earlier because of the large vertical displacement component due to the high feed rate. Exactly similar behavior was noticed when coating thickness varied between 1.5 mm and 2.0 mm. In Figure 15(b), the 3 K, 4.5 K, and 6 K indicate the spindle speed in RPM and the 0.02 and 0.08 represent the feed rate in millimeters. It is clear that the coating thickness has been slightly significant to reduce the surface roughness at a lower cutting speed. However, it was not found significant at a relatively higher cutting speed. Among all, 6000 RPM has given the U-shaped curve with the lowest roughness values with different coating thicknesses. And overall, 1.5 mm coating thickness has been found optimum for R_a.

Figures 15(a) and 15(b) present the SEM texture obtained for drilled hole wall of insulative-coated HFRP

Table 4: ANOVA table for delamination factor.

Source	At the entry Degree of freedom	F value	P value	At the exit Degree of freedom	F value	P value
Model	15	47.75	0.001	6	13.56	0.001
Linear	6	20.90	0.001	6	13.56	0.001
Spindle speed (*S*)	2	4.70	0.045	2	23.18	0.001
Feed rate (*F*)	1	0.35	0.573	1	2.46	0.135
Coating thickness (*C*)	3	38.55	0.001	3	10.86	0.001
2-way interactions	9	65.66	0.001	—	—	—
S^*C	6	91.53	0.001	—	—	—
F^*C	3	13.92	0.002	—	—	—
Error	8	—	—	17	—	—
Total	23	—	—	23	—	—
Standard deviation		0.0062452			0.0189956	
R-square		98.90%			82.72%	
R-square (adjusted)		96.82%			76.62%	
R-square (predicted)		90.06%			65.56%	

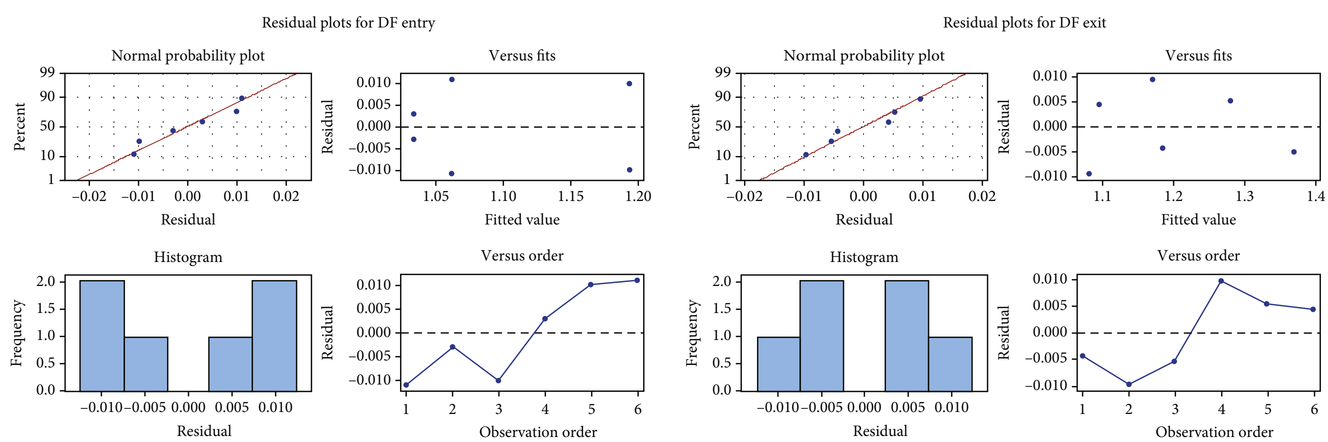


Figure 11: Residual plots obtained for delamination at the entry and exit.

Table 5: Response table for delamination at the entry and exit (S/N ratio); smaller is better.

Level	Cutting speed	Feed rate	Coating thickness
1	-0.6552	-0.8014	-0.6728
2	-0.7409	-0.7549	-0.7254
3	-0.9384		-0.7204
4			-0.9941
Delta	0.2832	0.0465	0.3213
Rank	2	3	1

composite when drilling at 6000 RPM at varied feed and thickness of coating due to the lower roughness value obtained for these two drilling conditions. Morphology is shown in Figure 15(a) which illustrates that good fiber-matrix interfacial bonding is present and no matrix cracking and push-/pull-out damage is observed. However, Figure 15(b) shows fiber pull out and matrix crack in the SEM image indicating surface damage. This damage resulted from the loose fibers at the exit wall which occurred due to the higher speed and feed exerted on the overly brittle coating that also delayed the damping effect.

4.4. Optimized Drilling Parameters for Surface Roughness. The influence of cutting speeds and feed rates on the surface roughness of coated HFRP composite was calculated using ANOVA and presented in Table 6. ANOVA table suggested that cutting speed has the most impact on the surface roughness followed by feed rate, coating thickness, and speed interaction with coating thicknesses. The combined effect of speed and feed rate has nonsignificant interaction since their *P* value is slightly over 0.05. Table 6 illustrates that the 97.32% variations in the response are explained by the model and it is considered significant. Moreover, the difference between the *R*-square value and *R*-square (predicted) value is quite high (16.4%) which gives us the idea that some of the important factors such as temperature and machine vibration are missing that are not considered in this research.

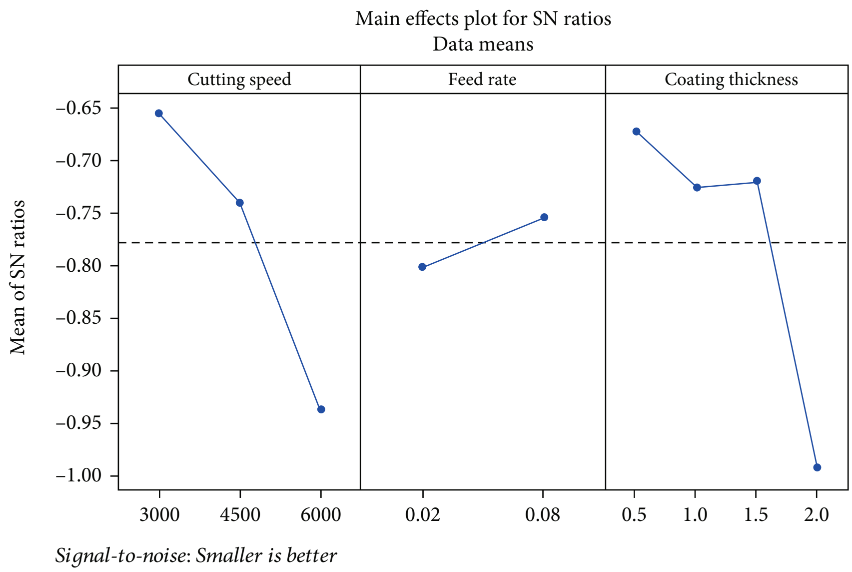


Figure 12: S/N ratio plots for delamination at the entry and exit.

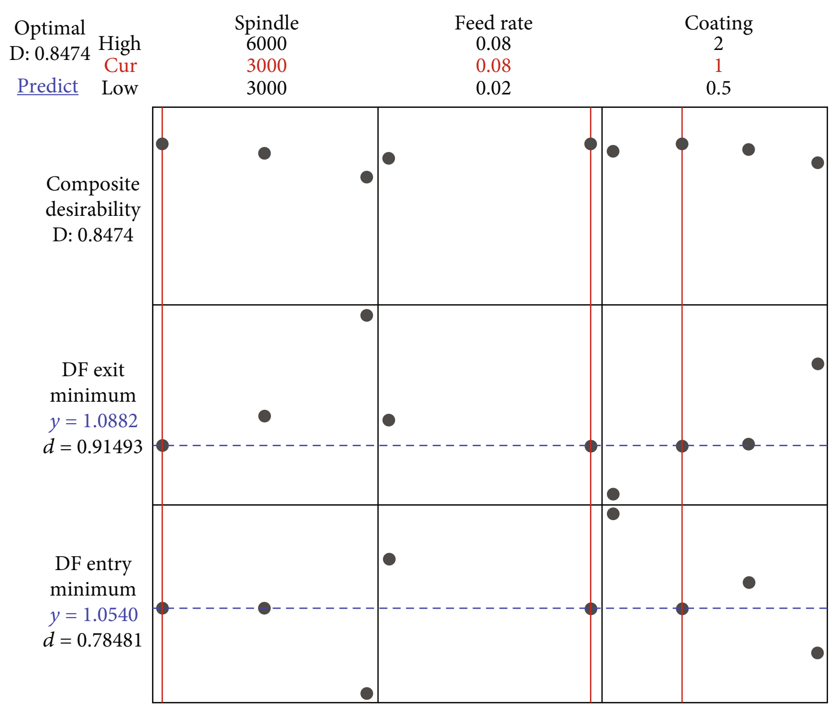


Figure 13: Optimized cutting speed, feed rate, and coating thickness achieved to minimize delamination for coated HFRP composite.

Figure 16 presents the residual plots for surface roughness of coated HFRP composite. Normal probability plot shows that all the points are close to the straight line meaning no unusual observations. The residual vs. fit graph shows that all the data are distributed evenly below and above the straight line. Bell shape curve is obtained in the histogram. No specific pattern is shown in the residual vs. observation graph meaning no biasness involved in the data set.

Table 7 shows the response table of S/N ratio for the surface roughness, and Figure 17 illustrates the main effects obtained from the S/N plots and highlights that the cutting speed contributed highest in the roughness occurred in the surface of the composites followed by the coating thickness and feed rate.

A full factorial response optimizer was used to determine the optimum cutting condition in drilling coated HFRP composite and presented in Figure 18. 6000 RPM, 0.02 mm/rev feed rate, and 1.5 mm coating thickness are considered the optimum cutting condition for minimizing surface roughness.

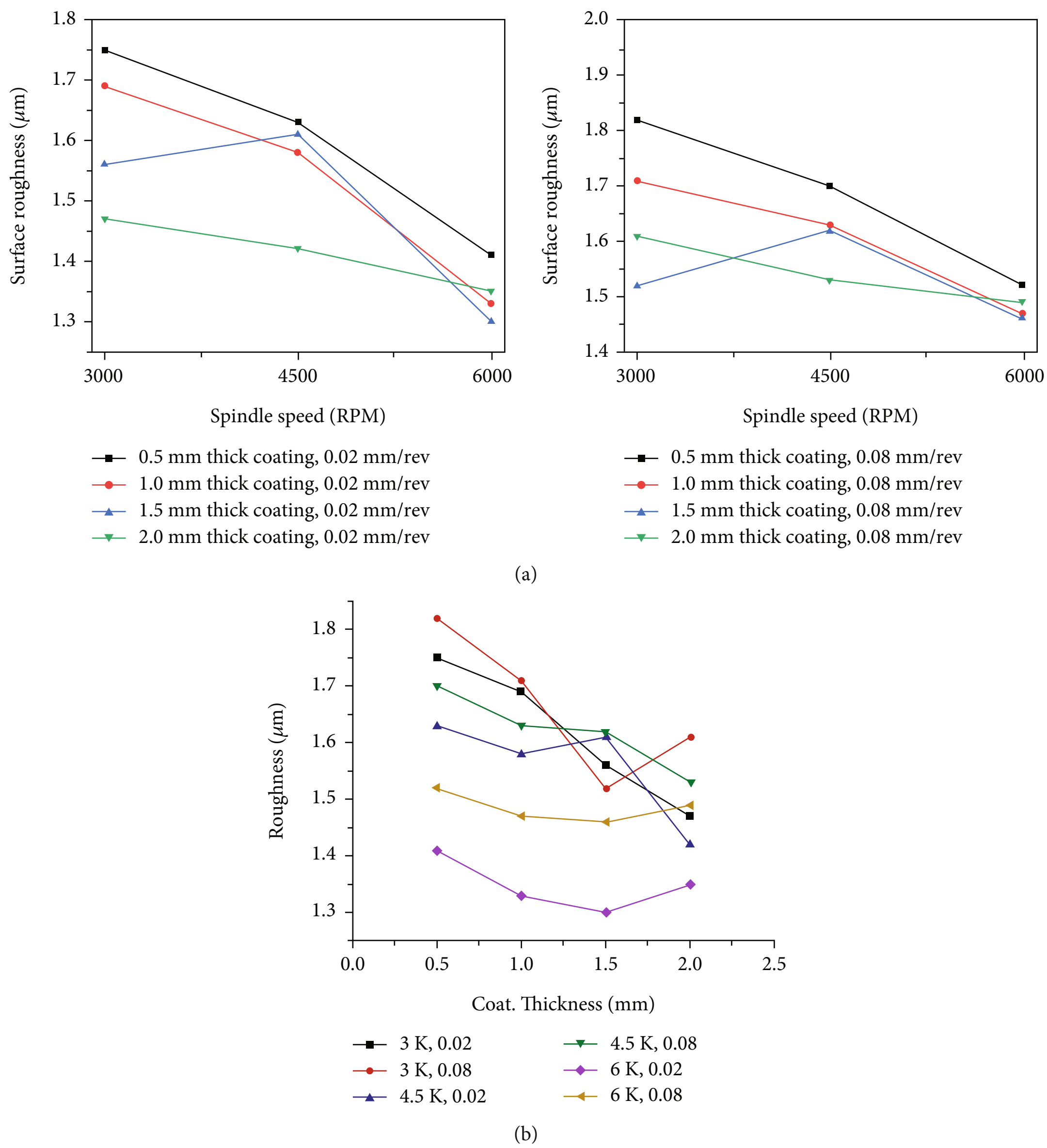


Figure 14: (a) Surface roughness (R_a) for varied drilling parameters and (b) roughness and coating thickness comparison plot.

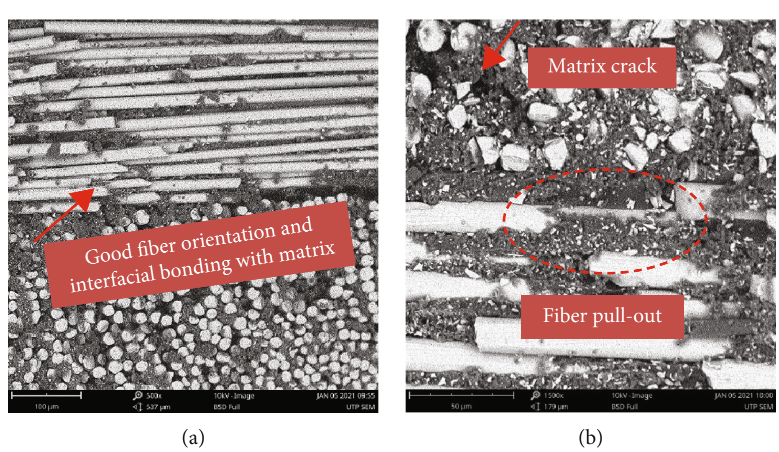


Figure 15: Microscopic image of drilled hole wall: (a) 6000 RPM, 0.02 mm/rev, and 1.5 mm thick coating; (b) 6000 RPM, 0.08 mm/rev, and 2.0 mm thick coating.

Table 6: ANOVA table for surface roughness.

Source	Degree of freedom	*F* value	*P* value
Model	14	23.38	0.001
Linear	6	46.95	0.001
S	2	90.68	0.001
F	1	31.07	0.001
C	3	23.10	0.001
2-way interactions	8	5.71	0.009
S^*F	2	4.03	0.056
S^*C	6	6.26	0.008
Error	9	—	—
Total	23	—	—
Standard deviation		0.0351584	
R-square		97.32%	
R-square (adjusted)		93.16%	
R-square (predicted)		80.97%	

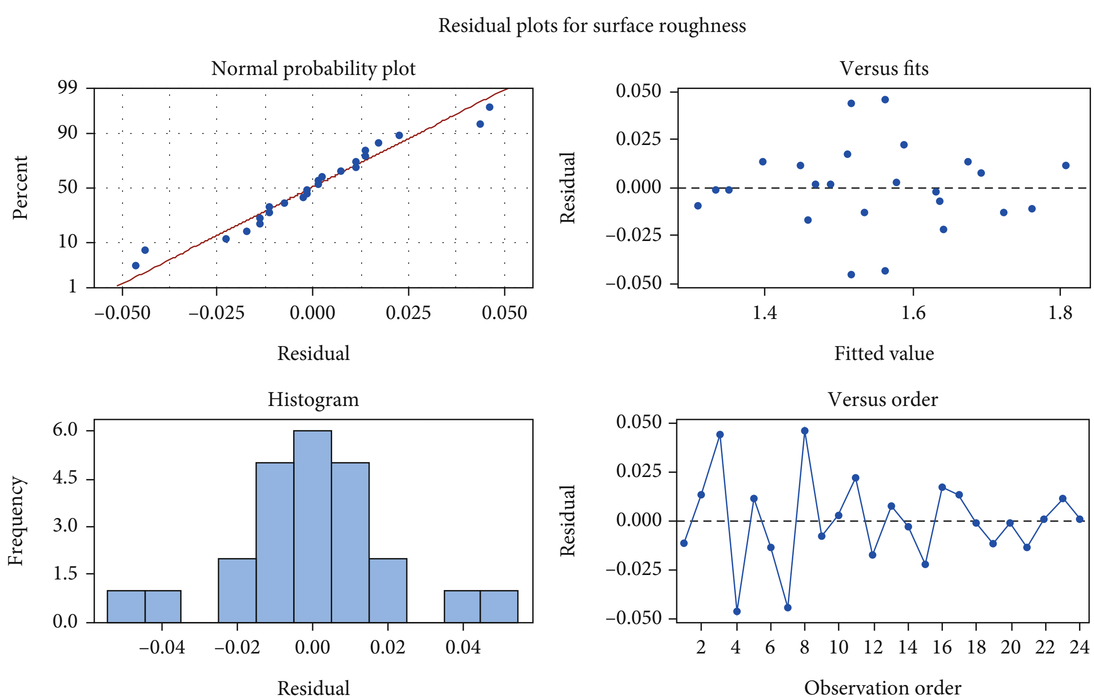


Figure 16: Residual plots obtained for surface roughness.

Table 7: Response table for surface roughness (S/N ratio); smaller is better.

Level	Cutting speed	Feed rate	Coating thickness
1	-4.283	-3.531	-4.256
2	-4.017	-4.009	-3.876
3	-3.010		-3.565
4			-3.382
Delta	1.273	0.478	0.874
Rank	1	3	2

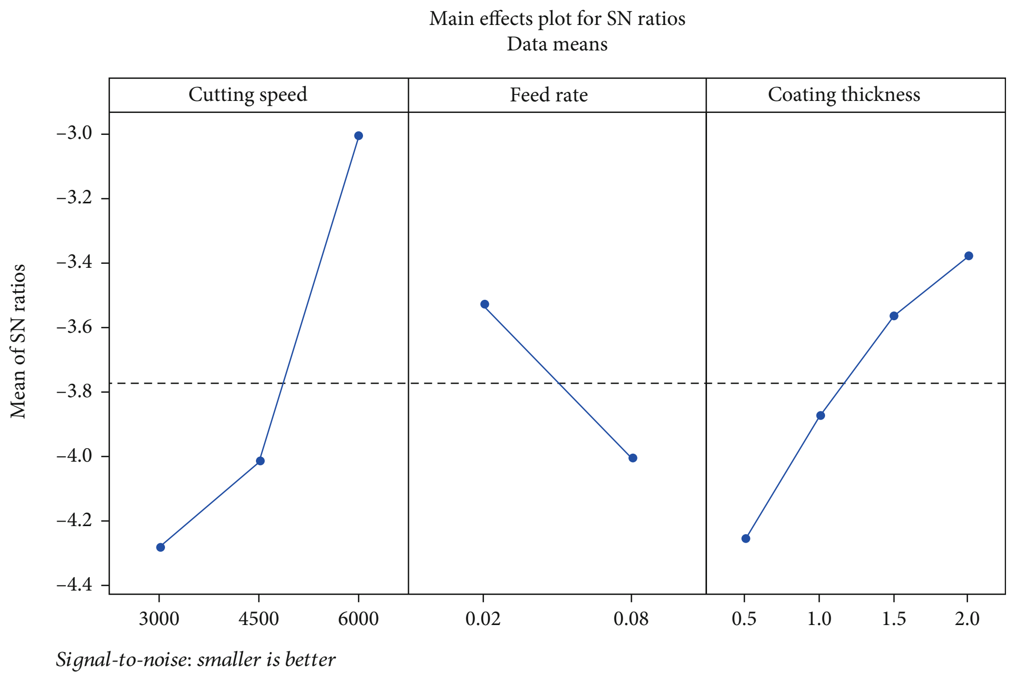


Figure 17: S/N ratio plots for surface roughness.

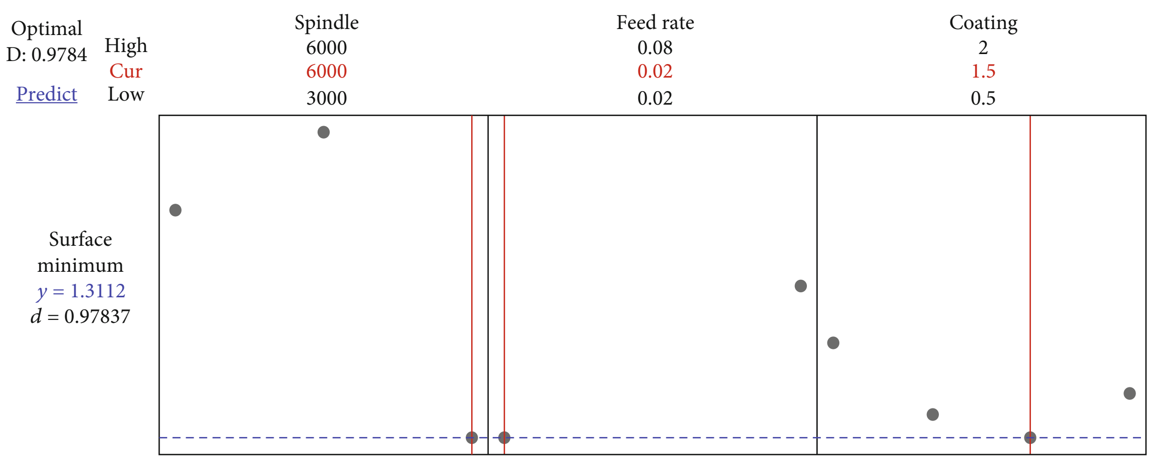


Figure 18: Optimized cutting speed, feed rate, and coating thickness achieved to minimize surface roughness for coated HFRP composite.

5. Conclusions

This study has successfully fabricated HFRP composite, and the influence of drilling parameters such as cutting speed and feed rate on delamination and surface roughness on insulative-coated HFRP composite has been investigated and well presented. In general, it can be concluded from the discussion that the delamination factor (DF) at the entrance decreases with the increasing cutting speeds. On the other hand, the delamination factor at the exit showed the opposite manner. However, coating thickness played an important role in delamination at the entrance. The DF was found higher with increasing cutting speeds especially when the coating thickness was higher. But the exit side of the hole showed no significant difference in this manner. S/N plot has been used to analyze the response parameters, and it is clearly visible that coating thickness and speed have the dominant effect on delamination. For coated HFRP composite, a coating thickness of 1 mm, cutting speed of 3000 RPM, and feed rate of 0.08 mm/rev are the optimized parameters for minimizing delamination based on the full factorial response optimizer. Similarly, surface roughness was found to have decreased with the increasing cutting speeds. Lower cutting speed generates higher roughness whereas higher cutting speed incurs lower roughness. S/N plots also showed that cutting speed is pivotal in occurring roughness on the wall of drilled composites. However, based on the full factorial response optimizer, cutting speed of 6000 RPM, feed rate of 0.02 mm/rev, and coating thickness of 1.5 mm are considered optimum in minimizing surface roughness when drilling coated HFRP composites.

Data Availability

All data including figures, tables, and experimental results are available.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge the laboratory support provided by the Advanced Materials Processing under Corrosion Research Center, Mechanical Engineering Department, and Engineering Prototyping and Innovation Center (EPIC) of Universiti Teknologi PETRONAS (UTP). We would also like to express our appreciation for giving financial support through FRGS Grant No. 0153AB-L68 by MOHE, Malaysia.

References

[1] C. Boeing, "Boeing 787 from the ground up," *Aero*, vol. 24, pp. 1–32, 2006.

[2] J. Zhu, K. Chandrashekhara, V. Flanigan, and S. Kapila, "Manufacturing and mechanical properties of soy-based composites using pultrusion," *Composites Part A: Applied Science and Manufacturing*, vol. 35, no. 1, pp. 95–101, 2004.

[3] J. Summerscales and D. Short, "Carbon fibre and glass fibre hybrid reinforced plastics," *Composites*, vol. 9, no. 3, pp. 157–166, 1978.

[4] C. Soutis, "Fibre reinforced composites in aircraft construction," *Progress in Aerospace Sciences*, vol. 41, no. 2, pp. 143–151, 2005.

[5] E. D. Eneyew and M. Ramulu, "Experimental study of surface quality and damage when drilling unidirectional CFRP composites," *Journal of Materials Research and Technology*, vol. 3, no. 4, pp. 354–362, 2014.

[6] D. Liu, Y. Tang, and W. Cong, "A review of mechanical drilling for composite laminates," *Composite Structures*, vol. 94, no. 4, pp. 1265–1279, 2012.

[7] C. Dong and I. J. Davies, "Flexural and tensile strengths of unidirectional hybrid epoxy composites reinforced by S-2 glass and T700S carbon fibres," *Materials & Design (1980-2015)*, vol. 54, pp. 955–966, 2014.

[8] S.-F. Hwang and C.-P. Mao, "Failure of delaminated interply hybrid composite plates under compression," *Composites Science and Technology*, vol. 61, no. 11, pp. 1513–1527, 2001.

[9] P. W. Manders and M. Bader, "The strength of hybrid glass/carbon fibre composites," *Journal of Materials Science*, vol. 16, no. 8, pp. 2246–2256, 1981.

[10] P. S. Moorthy, G. B. Bhaskar, N. Raja, V. Ramnath, and S. Gowri, "Mechanical properties and microstructure of glass carbon hybrid composites," *Materials Testing*, vol. 60, no. 11, pp. 1131–1137, 2018.

[11] M. Sayer, N. B. Bektaş, E. Demir, and H. Çallioğlu, "The effect of temperatures on hybrid composite laminates under impact loading," *Composites Part B: Engineering*, vol. 43, no. 5, pp. 2152–2160, 2012.

[12] P. Benardos and G.-C. Vosniakos, "Predicting surface roughness in machining: a review," *International Journal of Machine Tools and Manufacture*, vol. 43, no. 8, pp. 833–844, 2003.

[13] A. M. Abrão, J. C. C. Rubio, P. E. Faria, and J. P. Davim, "The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite," *Materials & Design*, vol. 29, no. 2, pp. 508–513, 2008.

[14] S. Karnik, V. N. Gaitonde, J. C. Rubio, A. E. Correia, A. M. Abrão, and J. P. Davim, "Delamination analysis in high speed drilling of carbon fiber reinforced plastics (CFRP) using artificial neural network model," *Materials & Design*, vol. 29, no. 9, pp. 1768–1776, 2008.

[15] V. K. Vankanti and V. Ganta, "Optimization of process parameters in drilling of GFRP composite using Taguchi method," *Journal of Materials Research and Technology*, vol. 3, no. 1, pp. 35–41, 2014.

[16] R. Mishra, J. Malik, I. Singh, and J. P. Davim, "Neural network approach for estimating the residual tensile strength after drilling in uni-directional glass fiber reinforced plastic laminates," *Materials & Design*, vol. 31, no. 6, pp. 2790–2795, 2010.

[17] D. Kumar, K. Singh, and R. Zitoune, "Experimental investigation of delamination and surface roughness in the drilling of GFRP composite material with different drills," *Advanced Manufacturing: Polymer & Composites Science*, vol. 2, no. 2, pp. 47–56, 2016.

[18] N. Geier, J. Xu, C. Pereszlai, D. I. Poór, and J. P. Davim, "Drilling of carbon fibre reinforced polymer (CFRP) composites: difficulties, challenges and expectations," *Procedia Manufacturing*, vol. 54, pp. 284–289, 2021.

[19] E. Kilickap, "Optimization of cutting parameters on delamination based on Taguchi method during drilling of GFRP composite," *Expert Systems with Applications*, vol. 37, no. 8, pp. 6116–6122, 2010.

[20] U. Köklü, M. Mayda, S. Morkavuk, A. Avcı, and O. Demir, "Optimization and prediction of thrust force, vibration and delamination in drilling of functionally graded composite using Taguchi, ANOVA and ANN analysis," *Materials Research Express*, vol. 6, no. 8, article 085335, 2019.

[21] J. P. Davim and P. Reis, "Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments," *Composite Structures*, vol. 59, no. 4, pp. 481–487, 2003.

[22] T. Rajamurugan, K. Shanmugam, and K. Palanikumar, "Analysis of delamination in drilling glass fiber reinforced polyester composites," *Materials & Design*, vol. 45, pp. 80–87, 2013.

[23] D. Kumar and K. Singh, "An approach towards damage free machining of CFRP and GFRP composite material: a review," *Advanced Composite Materials*, vol. 24, Supplement 1, pp. 49–63, 2015.

[24] W.-C. Chen, "Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates," *International Journal of Machine Tools and Manufacture*, vol. 37, no. 8, pp. 1097–1108, 1997.

[25] J. Babu and J. Philip, "Experimental studies on effect of process parameters on delamination in drilling GFRP composites using Taguchi method," *Procedia Materials Science*, vol. 6, pp. 1131–1142, 2014.

[26] A. Krishnamoorthy, S. Rajendra Boopathy, K. Palanikumar, and J. Paulo Davim, "Application of grey fuzzy logic for the optimization of drilling parameters for CFRP composites with multiple performance characteristics," *Measurement*, vol. 45, no. 5, pp. 1286–1296, 2012.

[27] E. Kılıçkap, "Investigation into the effect of drilling parameters on delamination in drilling GFRP," *Journal of Reinforced Plastics and Composites*, vol. 29, no. 23, pp. 3498–3503, 2010.

[28] X. Wang and C. Feng, "Development of empirical models for surface roughness prediction in finish turning," *The International Journal of Advanced Manufacturing Technology*, vol. 20, no. 5, pp. 348–356, 2002.

[29] K. Palanikumar, L. Karunamoorthy, and R. Karthikeyan, "Assessment of factors influencing surface roughness on the machining of glass fiber-reinforced polymer composites," *Materials & Design*, vol. 27, no. 10, pp. 862–871, 2006.

[30] K. Palanikumar, B. Latha, V. S. Senthilkumar, and J. P. Davim, "Analysis on drilling of glass fiber–reinforced polymer (GFRP) composites using grey relational analysis," *Materials and Manufacturing Processes*, vol. 27, no. 3, pp. 297–305, 2012.

[31] H. Takeyama and N. Iijima, "Machinability of glassfiber reinforced plastics and application of ultrasonic machining," *CIRP Annals*, vol. 37, no. 1, pp. 93–96, 1988.

[32] B. Latha and V. Senthilkumar, "Modeling and analysis of surface roughness parameters in drilling GFRP composites using fuzzy logic," *Materials and Manufacturing Processes*, vol. 25, no. 8, pp. 817–827, 2010.

[33] K. Shunmugesh and K. Panneerselvam, "Optimization of machining process parameters in drilling of CFRP using multi-objective Taguchi technique, TOPSIS and RSA techniques," *Polymers and Polymer Composites*, vol. 25, no. 3, pp. 185–192, 2017.

[34] A. Gupta, R. Vaishya, R. Kumar et al., "Effect of drilling process parameters on delamination factor in drilling of pultruded glass fiber reinforced polymer composite," *Materials Today: Proceedings*, vol. 64, pp. 1290–1294, 2022.

[35] S. Margabandu and S. Subramaniam, "An experimental investigation of thrust force, delamination and surface roughness in drilling of jute/carbon hybrid composites," *World Journal of Engineering*, vol. 17, no. 5, pp. 661–674, 2020.

[36] S. Shafi, R. Navik, X. Ding, and Y. Zhao, "Improved heat insulation and mechanical properties of silica aerogel/glass fiber composite by impregnating silica gel," *Journal of Non-Crystalline Solids*, vol. 503-504, pp. 78–83, 2019.

[37] C. Ye, Z. An, and R. Zhang, "Super-elastic carbon-bonded carbon fibre composites impregnated with carbon aerogel for high-temperature thermal insulation," *Advances in Applied Ceramics*, vol. 118, no. 5, pp. 292–299, 2019.

[38] I. Bu Najmah, N. A. Lundquist, M. K. Stanfield et al., "Insulating composites made from sulfur, canola oil, and wool," *ChemSusChem*, vol. 14, no. 11, pp. 2352–2359, 2021.

[39] P. Khalili, B. Blinzler, R. Kádár et al., "Ramie fabric Elium® composites with flame retardant coating: flammability, smoke, viscoelastic and mechanical properties," *Composites Part A: Applied Science and Manufacturing*, vol. 137, article 105986, 2020.

[40] L. Gemi, U. Köklü, Ş. Yazman, and S. Morkavuk, "The effects of stacking sequence on drilling machinability of filament wound hybrid composite pipes: part-1 mechanical characterization and drilling tests," *Composites Part B: Engineering*, vol. 186, article 107787, 2020.

[41] K. Nagaraja, S. Rajanna, G. S. Prakash, P. G. Koppad, and M. Alipour, "Studying the effect of different carbon and glass fabric stacking sequence on mechanical properties of epoxy hybrid composite laminates," *Composites Communications*, vol. 21, article 100425, 2020.

[42] L. M. P. Durao, "Machining of hybrid composite in mechanical engineering and industrial management," University of Porto, 2005.

[43] S. Jahanmir, M. Ramulu, and P. Koshy, "Machining of ceramics and composites," Marcel Dekker, 1999.

[44] J. C. Rubio, A. M. Abrao, P. E. Faria, A. E. Correia, and J. P. Davim, "Effects of high speed in the drilling of glass fibre reinforced plastic: evaluation of the delamination factor," *International Journal of Machine Tools and Manufacture*, vol. 48, no. 6, pp. 715–720, 2008.

[45] A. Velayudham, R. Krishnamurthy, and T. Soundarapandian, "Evaluation of drilling characteristics of high volume fraction fibre glass reinforced polymeric composite," *International Journal of Machine Tools and Manufacture*, vol. 45, no. 4-5, pp. 399–406, 2005.

[46] I. Crouch, "Laminated materials and layered structures," in *The Science of Armour Materials*, pp. 167–201, Elsevier, 2017.

[47] B. W. Darvell, "Materials Science for Dentistry," Woodhead Publishing, 10 edition, 2018.

[48] A. K. Ghani, I. A. Choudhury, and Husni, "Study of tool life, surface roughness and vibration in machining nodular cast iron with ceramic tool," *Journal of Materials Processing Technology*, vol. 127, no. 1, pp. 17–22, 2002.

[49] P. Parhad, A. Likhite, J. Bhatt, and D. Peshwe, "The effect of cutting speed and depth of cut on surface roughness during machining of austempered ductile iron," *Transactions of the Indian Institute of Metals*, vol. 68, no. 1, pp. 99–108, 2015.

[50] B. S. Rao, R. Rudramoorthy, S. Srinivas, and B. N. Rao, "Effect of drilling induced damage on notched tensile and pin bearing strengths of woven GFR-epoxy composites," *Materials Science and Engineering A*, vol. 472, no. 1-2, pp. 347–352, 2008.