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Study of Machinability in Drilling Operation of Enset–Sisal Hybrid Polyester Composite

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Abstract: Due to their light weight, low density, high-specificity strength, and ease of fiber surface treatment, natural-fiber-reinforced composites are recognized as the most suitable materials for interior part applications. Moreover, natural fibers are widely accessible and environmentally friendly. The fabricated parts are assembled predominantly by fastening using drilled holes, which makes drilling operations common machining processes for the composite parts. Damage occurs at the entry and exit surfaces of drilled holes. In this study, hand layup procedures are used to create unidirectional and woven forms of 1:1 ratio enset (false banana)/sisal hybrid polyester composites that have been treated with 5% NaOH. The drill operation was performed using a computer numerical control (CNC) drill machine with high-speed steel twist drill. A Taguchi design tool was used to complete the analysis. The experiments were conducted at different levels of drilling speeds: 600, 1200, and 1800 rpm. Feed rates of 0.1, 0.2, and 0.3 mm/rev and drill bit diameters of 6, 9, and 12 mm were used. These were determined to be the study parameters that influenced the delamination factors (F_d) and surface roughness (SR) of the hybrid composite drilled parts. Delamination occurred at the entry and exit surfaces of the drilled holes, and surface roughness occurred at the inner surface of the sectioned drilled hole. The quality of the drilled holes was compared based on the delamination factor and the surface roughness, as analyzed by the 3D optical surface profiles.

Keywords: natural-fiber-reinforced composite; drilling parameter; delamination factor; surface roughness; Taguchi; 3D optical surface profile

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1. Introduction

Natural fibers are a resource that are widely available and are utilized as reinforcement either alone or in a hybrid with nondegradable matrix materials, such as epoxy resin, unsaturated polyester, polypropylene, and polyethylene [1]. The properties exhibited by natural fibers complicate the manufacture of components from these materials. In particular, the machining of natural-fiber-reinforced composites (NFRCs) has been found to be difficult due to the mechanical anisotropy, inhomogeneity, and abrasive nature of the natural fiber reinforcement materials. Hence, the machining of NFRCs or fiber-reinforced polymer composites (FRPCs) differs from the machining of homogenous materials such as metals [1,2] and should be studied comprehensively. Extensive studies are available concerning the machining of isotropic materials such as metals compared with research concerning that of FRPC or NFRCs.

Post-processing operations such as machining or other finishing operations are required in order to meet assembly requirements and the dimensional accuracy of composite products. Machining composites is a complicated task due to their mechanically anisotropic and inhomogeneous structure. The comprehensive review article reported in [1] clearly indicated the challenges related with machinability of NFRCs with a focus on drilling operations. The present article highlights the need for research covering machinability, and the need for studies that can inform the selection of machining parameters in order to achieve higher-quality products from NFRCs in terms of surface finish, roundness of drilled holes, and residual stresses, etc. While the output parameters studied as a measure of machinability in NFRCs are similar to those in conventional materials, the main parameters investigated by researchers include the delamination factor, inner and outer surface roughness, cutting forces, torque, power, tool wear, and the life of the tools, etc. In addition to these conditions, the tool material and work material also influence the machinability [3]. The machinability of NFRCs can be achieved by proper selection of cutting parameters, such as feed rate, speed, drill diameter, and drill type; and proper selection of manufacturing parameters, such as fabrication methods, fiber volume fraction, fiber orientation, types of matrices and fibers, the interfacial bond between fiber and volume, and the surface characterization of fibers, etc. [4]. The interfacial bond between natural fibers and polymer matrices affects the mechanical properties of fiber composites and nanofiber composites [5,6].

After the fabrication of natural-fiber-reinforced composites, post-processing operation is required. Of machining operations, drilling is one of the most frequently used post-processing operations which is used to prepare parts for assembly. Drilling is also a more cost-effective process than other machining processes. For NFPCs, conventional drilling is the most widely used method to date. There are a lot of factors that affect the quality of the drill hole surface, such as the types of fibers used, the fiber orientation, the fiber volume, the types of matrices, the interfacial fiber matrix, voids, cracks, blisters, cutting parameters, tool material, and tool geometry. Those factors can cause defects to occur in and around drilled holes in the form of delamination, debonding, fiber pull-out, surface roughness, and thermal damage. In order to overcome these problems, it is essential to develop a proper procedure and to select appropriate cutting parameters [1,4].

Although a number of approaches have been used for making holes in composites, conventional radial drilling and CNC machining are the most widely used drilling methods presently [7,8]. Among other drill bits, twist drills consisting of HSS or carbide tool materials are the most popular for mechanically drilling NFRCs [4]. During assembly processes, delamination of drilled holes can lead to the rejection of the composite products. The damage (delamination) of the NFRCs can be measured either directly or indirectly. Direct measurements can be implemented using parameters such as delamination factor, damage width, surface roughness, and the chip type produced. Indirect measurements involve assessment of the damage on the basis of the thrust force, torque, or power generated during the machining operation. The machinability of drilling is influenced by a variety of elements; some crucial machining parameters include spindle speed, feed rate, and drill diameter [9,10]. Peel-up and push-down delamination develops during drilling operations, with push-down delamination being more susceptible to service failure than peel-up delamination [11,12].

The surface quality produced by machining has a significant impact on the quality and performance of a composite product. Surface roughness is defined as the average (mean) of the deviation of the roughness profile from the average line, within the estimated length. The resulting surface roughness has a significant impact on the functionality of the machined components as well as the cost of manufacture. Surface roughness in drilling is a sign of irregularity in the surface of the circumferentially drilled hole, which can cause the emergence of significant wear, fatigue, and corrosion mechanisms [4].

Delamination is simply defined as the main form of failure of laminated composites, whereby the laminates or layers separate along the composite material's interfaces. Delamination in a composite material occurs when reinforced fiber plies separate, by either the peel-up phenomenon or the push-out phenomenon [13]. This defect can be improved by proper selection of cutting conditions, such as feed rate, speed, tool material, and tool geometry. Poor surface roughness of the hole wall and fiber/resin pull-out are among the issues associated with drilling, while delamination appears to be the most critical [14]. During drilling, damage occurs at both the entrance and the exit surfaces of a given work piece. The damage that occurs around a drilled hole is known as the damage factor, the delamination factor, or the defacement factor [15]. In machining processes, tool wear is one of the major features which can be used to assess the machinability of materials. In fact, minimum tool wear is an indicator of good surface finish and better tool life. However, as can be observed from the literature, tool wear is critical for hard materials and metal matrix composites. In NFRCs machining, however, insignificant tool wear is often observed since natural fibers are less abrasive due to their lower strength [16–19].

Drilling processes are influenced by the spindle speed, feed rate, drill geometry, and work material characteristics [20]. The delamination and surface roughness of the drilled surfaces of aloe-vera- and woven-sisal-fiber-reinforced polymer composites were analyzed and the results showed that less delamination occurred at high speeds and high feed rates [13]. The same findings were presented for the surface roughness parameter. Among the drilling parameters, feed rate and cutting speed affect the delamination and surface roughness of natural-fiber-reinforced composites. The effects of drilling parameters and fiber ratios on the delamination and surface roughness of hemp-fiber-reinforced polycaprolactone were studied in [15]; the results showed that the delamination and surface roughness reduced with increased cutting speed, whereas delamination and surface roughness increased with increased feed rate.

Therefore, several studies have been carried out to optimize process parameters in an effort to achieve the desired surface roughness for natural-fiber-reinforced composite materials [7]. Drilling hole damage was studied in a case of sisal-fiber-reinforced polylactic acid and Grewia-optiva-fiber-reinforced polylactic acid. The results showed that drilling-induced damage decreased with increased cutting speed and decreased feed rate. Drill geometry and feed rate are critical parameters for generating damage-free holes in the drilling of green composite laminates. The effects of drilling on treated woven and nonwoven coir mats were studied in [21]; the results showed that the woven sample showed low delamination when compared with the nonwoven coir-reinforced polyester composites. The fiber volume fraction of a fiber affects the machining of composites because increased fiber volume increases the torque [1]. It was found that composites with 30% roselle and sisal hybrid fiber content, with an 8 h alkali treatment of the fibers, resulted in a better dimensional accuracy during drilling than other fiber volume fractions and treatment times [22]. Minimum delamination was observed during the drilling of hemp-fiber-reinforced composites compared with the delamination that occurred during the drilling of jute-fiber-reinforced composite [23].

Machining parameters are frequently chosen based on various academic sources. According to the literature, cutting speeds between 20 and 60 m/min, feed rates between 0.1 and 0.3 mm/rev, and drill bit diameters between 6 and 12 mm are typically employed [18,19,24,25]. Furthermore, higher cutting speeds increase the temperature of materials; therefore, under high cutting speeds, polymer-based composite materials soften. Higher feed rates and drill diameters increase the damage around a drilled hole and are generally not recommended by various researchers. A study on the drilling of a coir-reinforced composite reported that a low drill size of 6 mm, a spindle speed of 600 rev/min, and a high feed rate of 0.3 mm/rev were found to be the optimum conditions for drilling the composite [15,18].

Since drilling is the final stage of production, poor hole quality of drilled parts leads to a very high rejection rate of around 60% in assembly operations. This results in a significant economic loss. Among other factors, delamination must be reduced in order for a drilled material to be accepted and for the rejection rate to be reduced. When the drilling process starts, the first layers of the fibers are compressed, and at the end of the drilling process, the last layer of the fibers is pushed down, stretching the laminate away from the hole edge. This increases the delamination factor of the composite as well as the surface roughness [26].

The assessment of delamination and surface roughness is necessary for the correction and improvement of the performance of parts during assembly operations [23]. Profile projections, microscopy, and image processing using a scanner are the most readily available and economically feasible techniques for measuring the diameter and radius of drilled holes, which can be used to calculate delamination [1,4]. In the study reported in [27], analysis of variance (ANOVA) was used to evaluate the influence of the factors over the response variable; that is, they used ANOVA to determine how different factors affected the response variable to different degrees.

Fibers and nanofibers are added to polymer resins to improve the mechanical properties and the machinability of the developed composite [3,28]. Using the same fiber ratio, a sisal fiber–polymer composite has better mechanical properties than enset fiber–polymer composites. This is likely due to the loss of matrix integrity and insufficient wetting between the fiber and the matrix [5]. The integrity of a fiber matrix affects both the mechanical properties and the machineability of composites [29,30]. As reported in [31], a lack of bonding between fibers and matrices creates voids in the drilled hole surface, leading to a rough surface. Simultaneously, the lack of bonding affects the machinability properties. The smoothness of inner wall surfaces is very important for the insertion of bolts, screws, or other components during assembly. Hence, a hole must be made with minimum delamination and surface roughness to reduce the secondary finishing operations.

In this study, the drilling of enset (or enset ventricosum)/sisal fibers–polyester hybrid composite is explored using a variety of process parameters, including cutting speed, feed rate, and drill bit diameter. We performed this experiment to understand the impacts of each parameter on the delamination and surface roughness of the drilled hole surface. The Taguchi Design of Experiment was used, and the findings were examined using ANOVA techniques. The design and analysis of the experiment data were performed using MINITAB 18 statistical analysis software. The aim of this work was to determine the optimal drill parameters for improving the quality of drilled hole surfaces.

2. Materials and Methods

2.1. Materials

The enset, also referred to as false banana or enset ventricosum, and sisal fibers used for this study were collected from Southeast Ethiopia. The sisal fibers were extracted from the leaves of the *Agava sisilana* plant, and the enset fibers were extracted from the Psuadustem portions of the enset plant. The composite samples were made using wax, hardener, and unsaturated polyester resin (topazo-1110 phthalic anhydride). These materials were bought from a local supplier in Addis Abeba, Ethiopia, called World Fiber Glass and Ethio-plastic Industry. Drilling was carried out using a CNC drill machine (XH7145, Shandong Schuler CNC Machinery Co., Ltd., Tengzhou, China) and the research was conducted to determine how drill parameters and fiber orientation affect the surface roughness and delamination of the drilled holes in an enset–sisal hybrid composite.

2.2. Methods

2.2.1. Composite Fabrication

The enset and sisal fibers were extracted and treated with 5% NaOH. Two types of composite samples (unidirectional and woven, Figure 1a) were prepared. The unidirectional samples (Figure 1a, top) were fabricated by orienting the fibers in one direction, while the woven composite samples (Figure 1a, bottom) had the fibers bidirectionally oriented in a mat form. The prepared resin at a 10:1 ratio with hardener was poured into the mold surface. The composites were prepared using a hand lay-up method. The samples were fabricated in 300 $\times$ 300 $\times$ 5 (mm) dimensions on a steel sheet plate. Both (unidirectional and woven) composite samples were prepared using layer-by-layer enset–sisal. A roller was used to distribute the resin and to spread the polyester and the fibers, and the process was repeated until the required lamina was obtained. To ensure that the polyester resin penetrated the pores of the fibers and samples, they were compressed using a load of 30 kg for 24 h. To ensure the strength of the matrix and the reinforcement, the samples were cured for 24–48 h. After the curing process, test samples were cut to the required test dimensions.

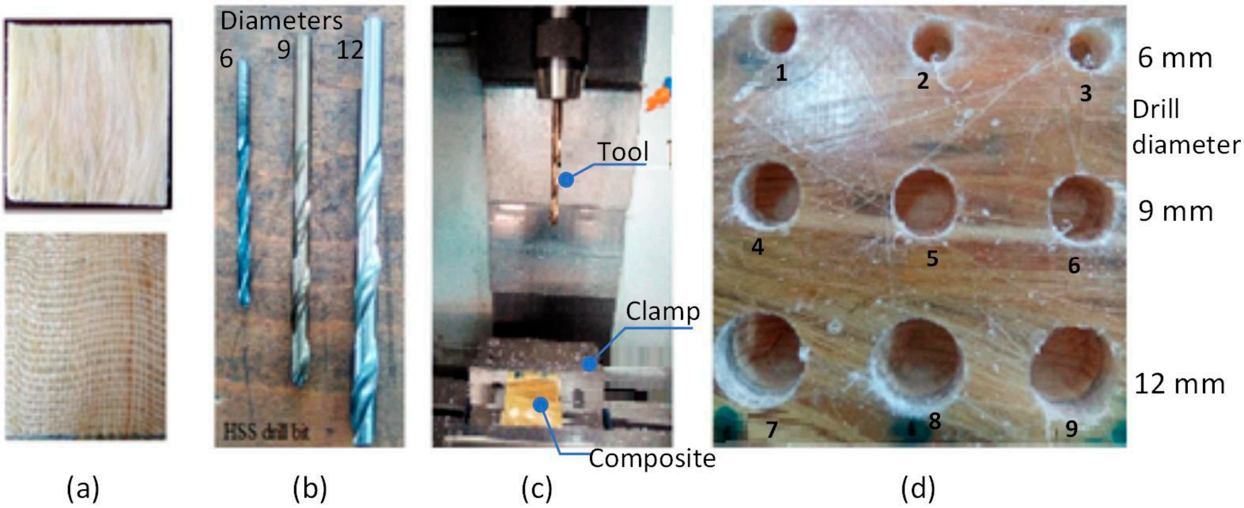

Figure 1. (**a**) Unidirectional (**top**) and woven (**bottom**) enset–sisal hybrid composite. (**b**) High-speed steel drill bit. (**c**) Drilling setup in CNC machine. (**d**) Drilled composite.

2.2.2. Drilling Operation and Equipment Used

The high-speed steel (HSS) drill bit was used to drill the woven and unidirectional enset–sisal hybrid composites on a CNC center-drill machine. The thickness of the prepared composites was 5 mm. The specimens were cut to a size of 100 × 50 × 5 (mm) and held in a rigid fixture attached to the machine table. The back of the specimen was supported (illustrated in Figure 1) by flat wood to avoid any damage during the drilling operation. The machining condition for the drilling operation in this work was the dry condition, and this was due to requirements for low abrasiveness and reduced wear, and the high liquid absorption properties (hydrophilic) of the natural fibers [1,4]. Less expensive alternatives would be a better choice for NFRCs. HSS and carbide tools are used frequently because of their low cost and low tool wear [32]. Natural fibers in general are less abrasive since their strengths are lower than those of synthetic materials [1]. Nine HSS twist drill bits with 118° point angle were chosen since these are commonly available at a cheaper price when compared with carbide tool materials. The drill sizes used, the CNC machine setup, and the samples of the drilled holes are illustrated in Figure 1b–d, respectively.

2.2.3. Drilling Parameters

Three parameters—(a) speed, (b) feed rate, and (c) drill bit diameter—and three levels in each category were considered in this work. An L9 orthogonal array [18] was developed to analyze the 3 variables and 3 levels in each variable. It is important to select the optimal parameters during machining to reduce the operating and labor costs of manufacturing industries. Hence, in order to find the optimal conditions, several studies have been carried out. The effects of spindle speed, feed rate, and diameter were used to determine the delamination.

2.2.4. Design of the Experiment

The tools used in the experiment play a vital role in determining the best combination of parameters. Several tools were utilized to optimize the machining parameters. The cutting speed, feed rate, and drill bit diameter are the most important parameters that can be used to characterize drilling operations and these were selected for this investigation. In this research work, the Taguchi method was used to determine the desired optimum cutting parameter and drill bit diameter for minimizing the appearance of delamination and surface roughness in drilled enset–sisal hybrid woven and unidirectional orientation natural-fiber-reinforced composites. The experimental results were transformed into *signal-to-noise ratios (S/N)*, which were used to reflect the deviation of the quality characteristics from or to the desired value. There are three main categories of quality characteristics in the analysis of S/N ratios, i.e., (1) the higher the better, (2) the more nominal the better, and (3) the lower the better [8,33]. For the lower the better quality characteristic, the formula is given in Equation (1), as follows:

$$\frac{N}{S} ratio\ (\eta) = -10 log_{10} \frac{1}{n} \sum_{i=1}^{n} y_i^2 \tag{1}$$

where $\sum$ is the observed response value and η is the number of replications.

The data given in Table 1 show the factors to be studied. The assignment of the corresponding levels [34]. The analysis was performed using MINITAB18 software [13].

Table 1. Levels of the variables used in the experiment.

Parameters	**Levels**		
	1	**2**	**3**
Speed (rpm)	500	1000	1500
Feed rate (mm/rev)	0.10	0.20	0.30
Drill diameter (mm)	6	9	12

2.2.5. Surface Analysis and Surface Roughness Measuring System

The damage around the entrance of the drilled holes, known as delamination damage, is shown in Figure 2a. After the drilling operation, the damage around the holes at the entrance and exit were pictured using a digital camera, and the damage was measured using "ImageJ" processing software (National Institute of Health). The average of two values was taken as the process response. To obtain easy access to the machined surface after drilling, the drilled samples were sectioned, and a 3D optical surface profiler (Zeta-20, San Jose, CA, USA) was used to measure the roughness value in an Ra scale. The final average delamination was calculated using Equation (2) [10]. The damage zone around the hole was clearly visible for the unidirectional and woven enset–sisal composites, as shown in Figure 2b,c, respectively. Each test was replicated twice. The drilled hole surface roughness was analyzed using a 3D optical surface profiler. It was observed and measured using a zeta instrument optical microscope operated at 25× magnification.

$$\text{Delamination factor } F_d = \frac{D_{max}}{D_{nom}} \tag{2}$$

where F_d is delamination factor, and D_{max} and D_{nom} are the maximum damage diameter and the nominal or actual diameter, respectively.

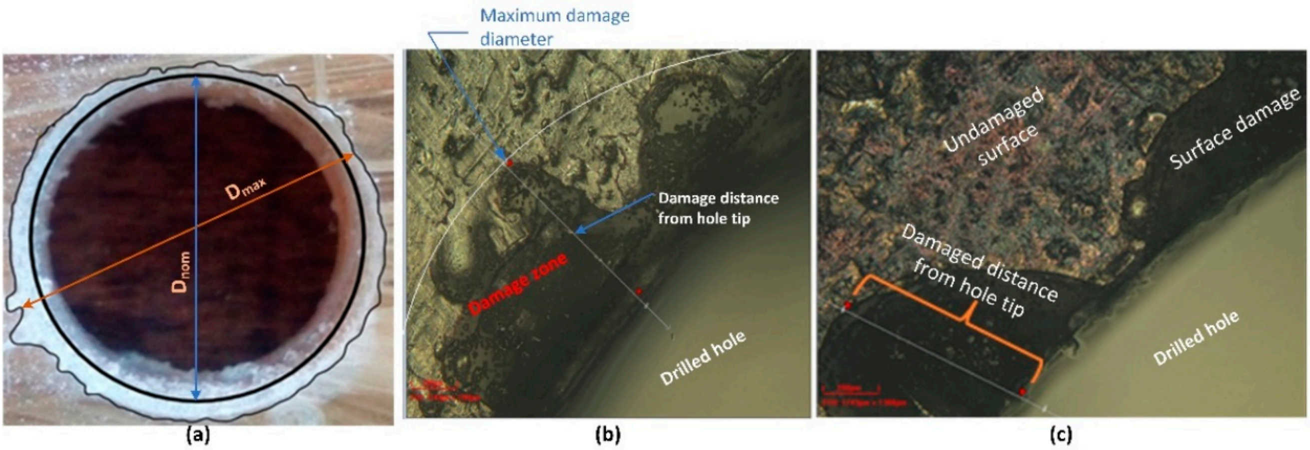

Figure 2. Measured image of delamination: (**a**) entrance damage at drill hole; (**b**) unidirectional and (**c**) woven orientation enset–sisal hybrid composite by 3D optical surface profiler.

3. Result and Discussion

In the drilling process of the enset–sisal hybrid composites, the parts can be rejected due to defects such as tearing along the entry and exit and poor surface finish. It was identified that delamination factors and surface roughness have been the causes of such defects. The selected L9 orthogonal array values with the experimental results of this study are given in Table 2, where two responses are reported: (1) the delamination factor (F_d) and (2) the surface roughness (SR). For both F_d and SR, smaller values indicate better quality characteristics. The S/N ratio was analyzed using Equation (2).

Table 2. L9 orthogonal array and the desired parameter value.

Trial	Parameters			Delamination Factor (F_d)		Surface Roughness (SR) (μm)		Signal-to-Noise (S/N) Ratio			
	Drill Diam. (mm)	Speed (rpm)	Feed Rate (mm/rev)	UF_d	WF_d	USR	WSR	UF_d	WF_d	USR	WSR
1	6	600	0.1	1.154	1.165	3.452	4.152	−1.252	−1.33	−10.8	−12.52
2	6	1200	0.2	1.162	1.176	3.794	4.490	−1.309	−1.41	−11.7	−13.08
3	6	1800	0.3	1.157	1.181	3.533	4.513	−1.268	−1.63	−11.0	−13.12
4	9	600	0.2	1.163	1.173	3.582	4.167	−1.44	−1.48	−11.1	−12.40
5	9	1200	0.3	1.148	1.153	3.059	4.203	−1.261	−1.24	−9.83	−12.60
6	9	1800	0.1	1.129	1.133	2.954	4.148	−1.057	−1.11	−9.46	−12.58
7	12	600	0.3	1.193	1.202	3.728	4.615	−1.578	−1.60	−11.6	−13.32
8	12	1200	0.1	1.136	1.145	3.126	4.216	−1.111	−1.21	−10.2	−12.65
9	12	1800	0.2	1.159	1.173	3.519	4.287	−1.283	−1.39	−11	−12.84

UF_d—unidirectional delamination factor; WF_d—woven delamination factor; USR—unidirectional surface roughness; WSR—woven surface roughness.

The main effect for the mean and the S/N ratios for WF_d, WSR, UF_d, and USR are shown in Figure 3a–d, respectively. Table 3 and Figure 3a show the effect of drilling parameters for WF_d. The optimum process parameters for WF_d were obtained at level 1 speed (600 rpm), level 1 feed (0.1 mm/rev), and level 1 drill diameter (6 mm). Table 4 and Figure 3b show the influence of the process parameters on WSR. The optimum process parameters for WSR were obtained for level 3 speed (1800 rpm), level 3 feed (0.3 mm/rev), and level 1 drill diameter (6 mm). Moreover, Table 5 and Figure 3c show the influence of cutting parameters on UF_d. The optimum process parameters for UF_d were obtained for level 1 speed (600 rpm), level 3 feed (0.3 mm/rev), and level 3 drill diameter (12 mm). Table 6 and Figure 3d show the influence of the cutting parameters on USR. The optimum process parameters for USR were obtained for level 1 speed (600 rpm), level 2 feed (0.2 mm/rev), and level 1 drill diameter (6 mm). The obtained experimental results show a similar trend as that reported in [35].

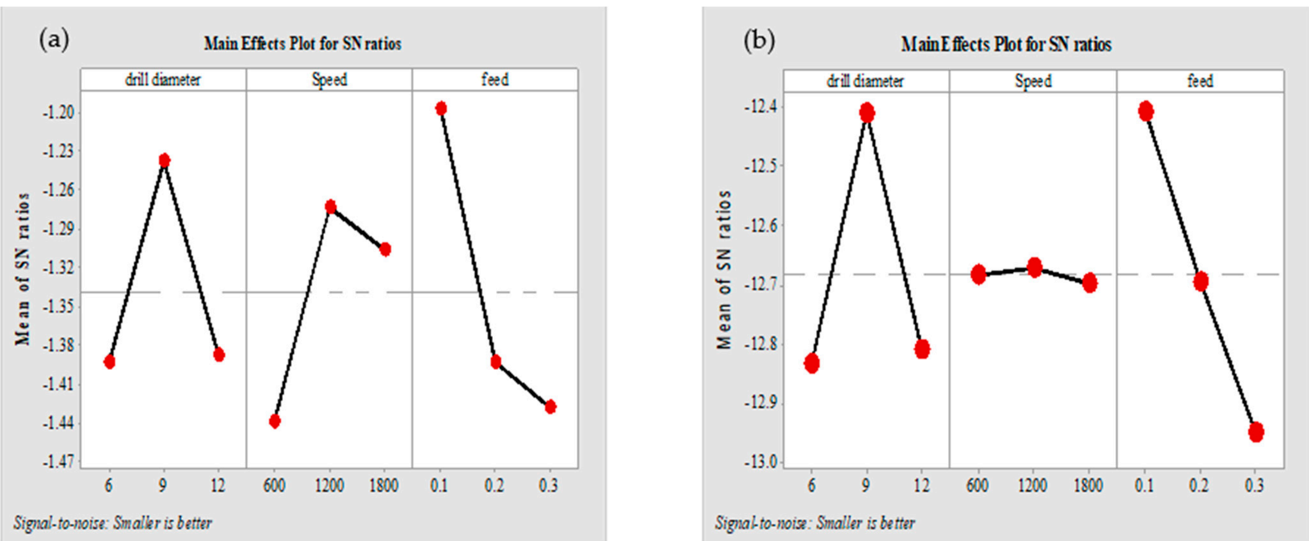

Figure 3. *Cont.*

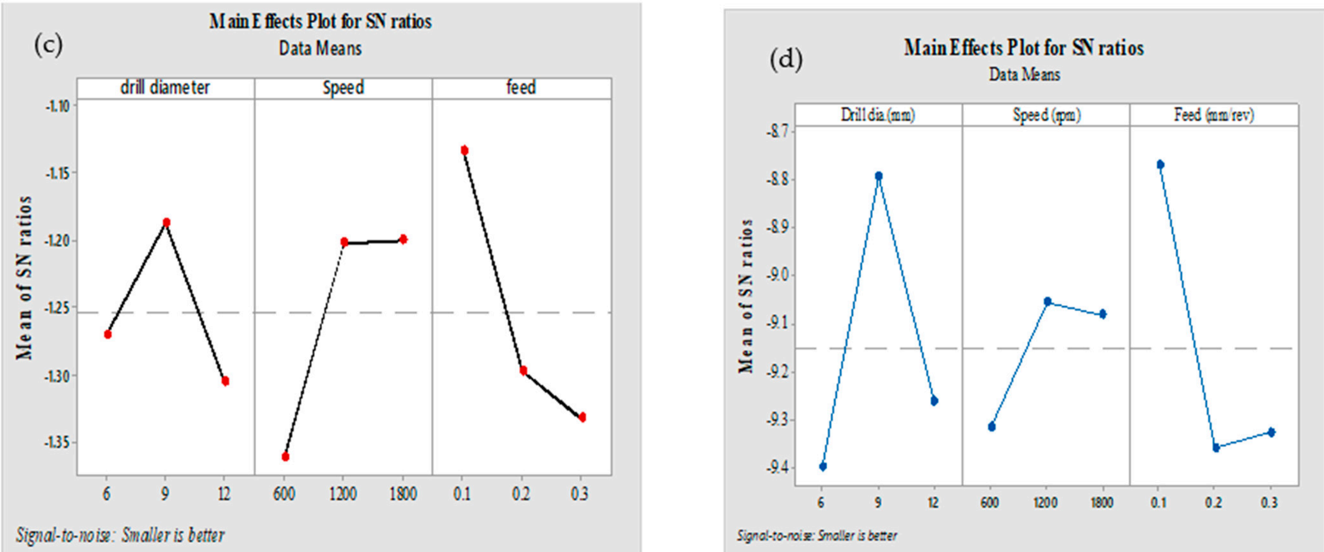

Figure 3. Main effects plot for S/N ratio of (**a**) WF_d, (**b**) WSR, (**c**) UF_d, and (**d**) USR composites.

Table 3. Response table for S/N ratios for WF_d.

Level	Drill Diam. (mm)	Speed (rpm)	Feed Rate (mm/rev)
1	−11.10	−11.09	−10.02
2	−10.07	−10.40	−11.20
3	−10.75	−10.43	−10.70
Delta	1.03	0.69	1.18
Rank	2	3	1

Table 4. Response table for S/N ratios for WSR.

Level	Drill Diam. (mm)	Speed (rpm)	Feed Rate (mm/rev)
1	−1.271	−1.361	−1.134
2	−1.187	−1.203	−1.297
3	−1.306	−1.200	−1.333
Delta	0.118	0.161	0.199
Rank	3	2	1

Table 5. Response table for S/N ratios for UF_d.

Level	Drill Diam. (mm)	Speed (rpm)	Feed Rate (mm/rev)
1	−12.83	−12.68	−12.41
2	−12.41	−12.67	−12.69
3	−12.81	−12.70	−12.95
Delta	0.43	0.03	0.54
Rank	2	3	1

Table 6. Response table for S/N ratios for USR.

Level	Drill Diam. (mm)	Speed (rpm)	Feed Fate (mm/rev)
1	−1.393	−1.439	−1.198
2	−1.238	−1.274	−1.393
3	−1.388	−1.306	−1.428
Delta	0.155	0.166	0.231
Rank	3	2	1

The delamination factor increased with increased feed rate and speed. As feed rate increased, the thrust force increased, and this led to increased delamination. Furthermore, lower feed rate reduced the tool wear, resulting in reduced cutting force, which helped to reduce the delamination and surface roughness. Smaller diameter helped to reduce the cutting force and wear, which helped in minimizing the delamination. This was expected to happen because higher speed reduces the cutting force and torque and results in continuous chip, ensuring drilled holes are free of cracks and sub-cracks. Similarly, the obtained experimental results show a similar trend to that which has been reported elsewhere [35,36].

3.1. Influence of the Operational Parameters

The degree of importance of each parameter is considered, namely speed, feed, and drill diameter, for each result, as given in Tables 7–10, respectively. From Table 7, it can be observed that the feed rate made a major parameter contribution (44.93%) for UF_d, followed by speed and drill bit diameter, with 34.31% and 14.90% contributions, respectively. From Table 8, it can be seen that feed rate made a major parameter contribution (43.48%) for USR, followed by drill bit diameter and speed, with 33.56% and 18.34% contributions, respectively. Similarly, Table 9 shows that feed rate made a major parameter contribution (48.98%) for WF_d, followed by speed (24.65%) and drill bit diameter (24.44%). It can be observed from Table 10 that feed rate was the major parameter contribution (42.73%) for WSR, followed by drill bit diameter (32.93%) and speed (0.11%). This appears to be the main parameter influencing both types of composites (unidirectional and woven) and both responses (delamination and surface roughness). On the other hand, speed was the second main parameter influencing the surface roughness of unidirectional and woven types of composites, and drill diameter was the second parameter influencing the delamination of unidirectional and woven types of composites. This means that speed and drill diameter were less influential on delamination and surface roughness, respectively, than feed rate.

Table 7. ANOVA for UF_d.

Source	DF	Seq SS	%Contribution	Adj SS	MS	*f*-Value	*p*-Value
Drill diameter (d)	2	0.000397	14.90	0.000397	0.000199	2.54	0.282
Speed (v)	2	0.000915	34.31	0.000915	0.000458	5.85	0.146
Feed rate (f)	2	0.001199	44.93	0.001199	0.000599	7.67	0.115
Error	2	0.000156	5.86	0.000156	0.000078		
Total	8	0.002667	100.00				

DF—degrees of freedom; SS—sum of squares; MS—mean squares; *f*- and *p*-values.

Table 8. ANOVA for USR.

Source	DF	Seq SS	%Contribution	Adj SS	MS	*f*-Value	*p*-Value
Drill diameter (d)	2	0.24119	33.56%	0.24119	0.12059	7.25	0.121
Speed (v)	2	0.13179	18.34%	0.13179	0.06589	3.96	0.202
Feed rate (f)	2	0.31250	43.48%	0.31250	0.15625	9.40	0.096
Error	2	0.03326	4.63%	0.03326	0.01663		
Total	8	0.71874	100.00%				

DF—degrees of freedom; SS—sum of squares; MS—mean squares; *f*- and *p*-values.

Table 9. ANOVA for WF_d.

Source	DF	Seq SS	%Contribution	Adj SS	MS	*f*-Value	*p*-Value
Drill diameter (d)	2	0.000831	24.44	0.000831	0.000415	12.64	0.073
Speed(v)	2	0.000838	24.65	0.000838	0.000419	12.75	0.073
Feed rate (f)	2	0.001665	48.98%	0.001665	0.000833	25.33	0.038
Error	2	0.000066	1.93%	0.000066	0.000033		
Total	8	0.003400	100.00%				

DF—degrees of freedom; SS—sum of squares; MS—mean squares; *f*- and *p*-values.

Table 10. ANOVA for WSR.

Source	DF	SS	%Contribution	Adj SS	MS	*f*-Value	*p*-Value
Drill diameter(d)	2	0.085429	32.93	0.085429	0.042715	1.36	0.424
Speed (v)	2	0.000276	0.11	0.000276	0.000138	0.00	0.996
Feed rate (f)	2	0.110878	42.73	0.110878	0.055439	1.76	0.362
Error	2	0.062881	24.24	0.062881	0.031441		
Total	8	0.259464	100.00%				

DF—degrees of freedom; SS—sum of squares; MS—mean squares; *f*- and *p*-values.

Generally, all parameters had statistically and physically significant effects on delamination factors and surface roughness in both types of composites. From the results presented above, the feed rate is seen to make the largest contribution to the delamination and surface roughness. It is also observed that the results obtained in this study are in good agreement with those reported in [13]. In general, as the speed increased and the feed rate decreased, the delamination and surface roughness reduce in both types of the composite surfaces. This result is similar to those reported in [37]. Higher delamination was observed on both unidirectional and woven fiber composite orientations at 1200 rpm. It is also observed from the data that the effect of feed rate on the delamination and surface roughness decreased. In general, as the speed increased and feed rate decreased, the delamination and surface roughness were reduced in both types of composite surfaces.

3.2. Regression (Model Equation)

The correlation equations were developed to calculate delamination and surface roughness in terms of speed, feed rate, and drill bit diameter. ANOVA was used to statistically analyze the effect of input process parameters both individually and in interaction on the delamination and surface roughness factors for both unidirectional and woven types of enset–sisal fiber composites. The ANOVA data are shown in Tables 7–10. Mathematical regression equations for unidirectional delamination and surface roughness as well as woven delamination and surface roughness have been developed with the help of ANOVA—these are given in Table 11. The correlation between the factors v, f, and d, the responses of the unidirectional and woven delamination factors (UF_d and WF_d), and the surface roughness (USR and WSR) of fiber orientation in enset–sisal fiber hybrid polyester composites were determined by multiple linear regression using Minitab18 software.

The linear regression models as functions of the factors v, f, and d for the above-mentioned parameters are described by the equations given in Table 11. The effectiveness of the developed model is measured by "R-sq" values. The R-sq values indicate the closeness of the developed model with respect to real experimental values. When the values are equal to 1, this indicates that the model's result is the same as the experimental result—it is 100% accurate. Two models show R-sq values greater than 0.95, which indicates that the models are very effective in predicting the responses. For one model, the R-sq value was 0.9414, indicating that the model was effective in the prediction. Furthermore, one model had an R-sq value of 0.7576 with no effect with respect to the machining variables.

A similar result was obtained for milled natural-fiber-reinforced composites in [37]. In general, the correlation between the factor (v, f, and d) responses for unidirectional and woven delamination factors (UF_d and WF_d), the surface roughness (USR and WSR), and the fiber orientation of enset–sisal fiber hybrid polyester composites was determined by multiple linear regression using Minitab18 software.

The results of this work are useful for industries in the selection of process parameters in the drilling of natural-fiber-reinforced composite materials for improving the quality of the drilled holes by reducing the delamination and surface roughness.

Table 11. Regression models for predicting delamination and surface roughness.

S. No.	Response	Regression Equations	R-Sq
1	Delamination (UFd)	1.1432 − 0.000018v + 0.1328f + 0.00081d	0.9414
2	Delamination (WFd)	1.1432 − 0.000018v + 0.1328f + 0.00081d	0.9807
3	Surface Roughness (USR)	3.609 − 0.000210v + 1.3f − 0.0226d	0.9537
4	Surface Roughness (WSR)	4.053 + 0.000004v + 1.359f − 0.0021d	0.7576

3.3. Validation of the Regression Model

The predicted or theoretical values of various parameters obtained using regression equations are shown in Table 11. The comparison plot for the experimental and predicted values of unidirectional and woven delamination factors and the surface roughness of the L9-drilled enset–sisal-fiber-reinforced polyester composites is included in the table. The experimental values were obtained from the confirmation tests, and the predicted values obtained from the regression models were compared as shown in Figure 4a–d.

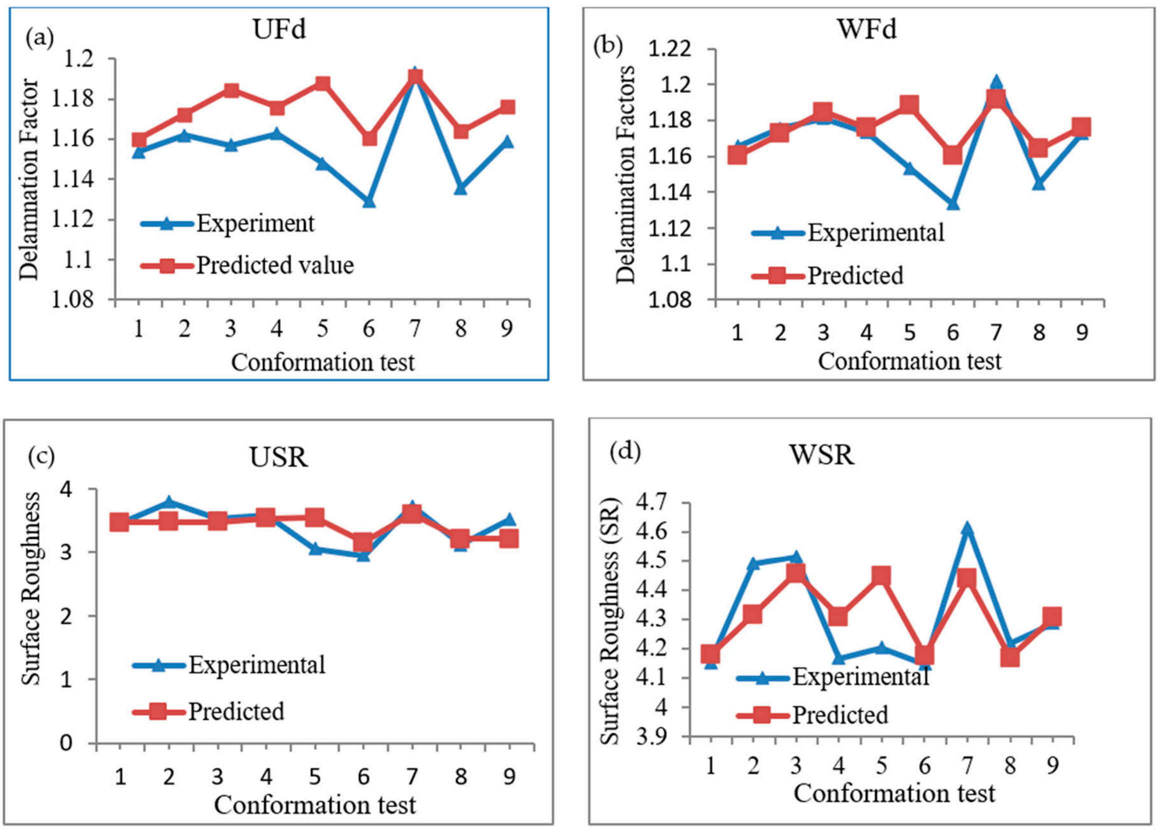

Figure 4. Comparation experimental results and predicted values for (**a**) UF_d, (**b**) WF_d, (**c**) USR, and (**d**) WSR.

The average absolute percentage error for the UF_d, WF_d, USR, and WSR factors of the enset–sisal-fiber-reinforced polyester composites (tabulated using ANOVA; Tables 7–10) were 5.86, 1.93, 4.63, and 24.24, respectively. The low values of percentage errors witnessed a close prediction of the Taguchi analysis. This study obtained similar trends as those reported in [36] for the drilled hole delamination factors of carbon-fiber-reinforced polymer composites. The predicted and experimental values are quite close, and in most cases, the predicted values are higher those reported in [38]. Otherwise, similar results were obtained in this study. From the researchers' point of view, this work is useful for industries in the selection of process parameters in the drilling of natural-fiber-reinforced composite materials, and for improving the quality of drilled holes by reducing delamination and surface roughness. In order to evaluate the prediction level of the developed models, confirmation experiments were carried out on the predicted set of conditions.

4. Conclusions

The objective of this study was to analyze the influence of cutting parameters and fiber orientation on the delamination and surface finish for drilling 5% NaOH-treated woven and unidirectional fiber orientation composites. Two cutting parameters (speed and feed rate) with three levels were tested and analyzed. Based on the obtained results, the following conclusions were drawn:

- ✓ Visual and microscopic analyses of cut sections of the drilled holes showed that higher cutting speed together with higher feed rate should be avoided because these give poor surface finish.
- ✓ The ANOVA results showed that feed rate and speed are the most significant influencing factors of the delamination and feed rate, and drill diameter is the most significant factor for surface finish of both unidirectional and woven types of enset–sisal fiber hybrid composites.
- ✓ The following optimal parameters were found: speed at 1800 rpm, feed rate of 0.3 mm/rev, and drill diameter of 6 mm for WSR; speed of 600 rpm, feed rate at 0.2 mm/rev, and drill diameter of 6 mm for USR.
- ✓ The following optimal parameters were found: speed at 600 rpm, feed rate of 0.1 mm/rev, and drill diameter of 6 mm for WF_d; speed 600 rpm, feed rate at 0.3mm/rev, and drill diameter of 12 mm for UF_d.
- ✓ In both composite cases, better delamination factor and surface finish of drilled holes were obtained with medium speed, medium drill diameter, and lower feed rate.
- ✓ Regression analysis of the data showed that the feed rate was the most influential control parameter affecting the surface roughness and delamination.
- ✓ Lastly, based on the ANOVA and other statistical results obtained, the unidirectional enset–sisal hybrid polyester composite sample had the lowest surface roughness (better surface finish) and the lowest drilling-induced delamination damage. Both samples were considered and analyzed within the same drilling conditions and parameters. Hence, the choice of their engineering applications should depend on their responses to this damage.

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