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Research Article

Optimization of Drilling Parameters in Sisal-Human Hair Hybrid Composite Using Grey Relational Analysis

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Sisal is the most commonly used natural fiber in polymer composites due to its high strength, durability, and ability to stretch. In this present work, sisal and human hair were used as reinforcement for epoxy resin-based hybrid composites, and their effect on the mechanical properties was reported. Four composite plates with fiber volume fractions of 10%, 20%, 30%, and 40% were fabricated by the hand lay-up method. Chopped sisal fiber and human hair of 30 mm length were mixed with epoxy resin to fabricate the composites. In addition, high-speed steel (HSS) drills were used to study the influence of drilling parameters such as speed, feed, and drill point angle on the quality of the drilling. Three factors with three levels were considered for the design of the experiment. The drilling parameters were optimized using Grey Relational Analysis and the Taguchi method for the reduction of delamination. The experimental results indicate that a flexural strength of 38 MPa was achieved in a 60% epoxy, 20% sisal, and 20% human hair composite. NI vision assistant software was used to process the images taken on the drilled holes using the Matrix Vision camera. The optimization results showed that the feed rate played a pivotal role in deciding the delamination on the entry side of the hole. In contrast, the drill point angle significantly affects the delamination at the exit side of the hole. Better quality holes are achieved with a cutting speed of 2500 rpm and a feed rate of 50 m/min.

1. Introduction

Composites are fabricated using two or more different materials having distinctly different physical or chemical properties. They possess characteristics different from the individual components, and they are heterogeneous within the finished structure. Composite materials are normally preferred for reasons like being stronger, lighter, and cheaper than conventional materials. Composite materials have become the most popularly used materials in construction and structural elements such as automobile bodies, boat hulls, bathtubs, swimming pool panels, storage tanks, and cultured marble sinks. It is also widely used in challenging environments for applications like aircraft and spacecraft [1]. Natural fibers play a vital role in the environmental-friendly green composites. Plant-based fiber composites and animal-based fiber composites possess good mechanical properties due to the presence of cellulose, lignin, and proteins, respectively. In recent years, the usage of natural fiber polymer composites is on the upsurge because of their low cost and higher biodegradability. In this research work, the combination of animal-based and plant-based fibers was used for the production of hybrid composites.

Different machining processes are used in composites, such as drilling, milling, and laser cutting, because of the expertise requirements available. Among them, drilling is the most frequently used operation in fiber-reinforced composite materials, which is usually carried out as the final operation for assembling any structural components. Any kind of defect in the drilling process will result in the rejection of parts and lead to an expensive loss. Therefore, it is very important to study the impact of damage caused by drilling on the properties of fiber-reinforced laminate composites. The composite material contains a soft epoxy matrix and hard fibers reinforced in different directions, make it anisotropic. Therefore, a better understanding of the machining of such hybrid composites is needed to achieve high-quality and cost-effective machining and ensure a perfect fit in the assembly process. The drilling of composite materials is a very challenging process since it involves independent parameters like type of reinforcement, reinforcing method, volume fraction, the thickness of the laminate, drilling speed, feed, drill bit material, tool geometry, etc. The dependent variables, such as torque, thrust, delamination, surface roughness, tool wear, microcracks, fiber pull-out, and combustion of the matrix around the hole, are reliant on the independent variables, and eventually drilling causes a change in strength. The thrust force developed while drilling has a major impact on hole quality, whereas the thrust force is influenced by tool geometry, speed, and feed.

Vankanti and Ganta [2] carried out the experimentation as per the Taguchi experimental design and an *L*9 orthogonal array, which revealed the major stakeholders of the hole quality such as thrust force, point angle, cutting speed, and feed. Isik and Ekici [3] studied the effect of drilling on the hole quality in glass fiber-reinforced plastic composite (GFRP) for various point angles and the number of flutes in the drill bit. They concluded that the delamination rises with the increase in point angle and declines at the exit side with the increase in the number of flutes. Ragothaman and Unnikrishnan [4] analyzed the damage area and delamination in the GPRF composite using a digital image processing method. Also, they used the fuzzy logic model for validating the predicted delamination values. Surface roughness and produced thrust force while drilling woven fabric carbon fiber composites were studied by Tsao and Hocheng [5]. It was evident that the key parameters, like feed rate and drill bit diameter, affected the surface roughness and thrust force. The hole quality was analyzed by varying the drilling parameters in CFRP, and the drilling parameters were optimized by a genetic algorithm [6]. Zitoune et al. [7] used double cone drill bits to study the machining performance of sandwiched CFRP composites, and the tribological characteristics of drill bits at various speeds and feeds were also reported. The Taguchi method was adopted to optimize the machining parameters on the residual strength in drilled GFRP [8]. Grey relational analysis was used by Palanikumar [9] to optimize the machining parameters by considering characteristics such as surface roughness, thrust force, and delamination factor. Valarmathi et al. [10] developed a mathematical model for RSM to predict the thrust force depending on various cutting parameters. They found that the low feed rate and high drilling speed reduced the thrust force developed while drilling the particle board laminates. Sikiru Oluwarotimi Ismail et al. [11] found that the delamination and surface roughness increase with feed and thrust force on the drilling of two different composites. Apart from drilling parameters, drilling tool geometry and tool material play a significant role in the quality of the hole [12]. Luís Miguel evaluated the delamination using the digital radiography method and found that the risk of delamination can be reduced considerably with lower drilling thrust forces [13]. Also, the feed rate and drill point angle play an important role in deciding the adjusted delamination [14].

Many researchers have attempted the usage of natural fibers for improving the mechanical properties of composite materials in many applications. Choudhry and Pandey [15] used human hair as a reinforcing material at four different levels of weight percentage (3, 5, 10, and 15) in polypropylene polymeric composites. The reinforcement of human hair up to 5% weight shows an enhancement in flexural and impact strength, and vice versa. Ganiron [16] revealed that the addition of human hair improved the load-bearing capacity of pavements when added to the conventional cement-asphalt mixture. Ramesh indicated that sisal fiber-reinforced GFRP possesses superior tensile properties than jute-reinforced GFRP [17]. Munde and Ingle [18] used theoretical models such as parallel and series, Halpin-Tsai, modified Halpin–Tsai, and the Hirsch model for evaluating the mechanical properties. The results of theoretical models were compared with the experimental results to ensure the correctness of mechanical properties. Also, they claimed that better tensile strength in coir fiber polypropylene composite was achieved with 30 mm length fiber reinforcement and tensile strength is increased till 30% volume fraction of fibers.

The literature on hybrid composites consisting of human hair was inadequate. An attempt to optimize the machining parameters on the sisal, or human hair, is required for a better-assembled finish. So, the proposed work demonstrates the effect of the weight percentage of sisal-human hair on the mechanical properties of the hybrid composites. Also, the influence of drilling parameters on the delamination has been studied using GRA and Taguchi analysis.

2. Materials and Methods

Composite materials consist of two different phases, such as the discontinuous phase and the continuous phase. The reinforcement material represents the discontinuous phase, and the matrix represents the continuous phase. In this work, sisal fiber (Agave Sisalana) and human hair are used as reinforcements with the epoxy matrix to fabricate natural fiber hybrid composites. Sisal fiber is coarse and inflexible. It is preferred for cordage usage because of its high strength, ability to stretch, durability, and resistance to deterioration in saltwater. Also, sisal is used in the manufacturing of paper, carpets, ropes, etc. [19].

Human hair is mainly composed of 95% keratin, which is highly elastic in nature and can be used as the reinforcement material in composite materials. It creates an environmental problem as it is biologically nondegradable in nature [20], and this issue can be addressed by using human hair as the reinforcement for the manufacturing of composites. The chemical composition of the hair fiber is mainly composed of about 45% carbon, and the remaining are oxygen, nitrogen, hydrogen, and sulfur. The present work concentrates on short fiber reinforcement using sisal fiber and human hair cut into 30 mm length [21]. Epoxy resin is widely used in many advanced composite materials due to its excellent bonding with a variety of fibers, low shrinkage, good corrosion resistance, and high-temperature performance. Epoxy LY 556 (bisphenol-A-diglycidyl ether) was selected as the matrix material. The epoxy resin and the corresponding curing agent, HY-951, are taken in 10 : 1 ratio to prepare the composite plates. Due to low tooling cost and simple method, composite plates were fabricated using the hand lay-up method. The tools used are silicone rubber with a thickness of 3 mm, polyester laminate, plywood, rollers and weights for setting. Sisal fiber and human hair are thoroughly mixed in equal proportions, and this fiber mixture is used to mould composite plates. Four different composite plates were fabricated with different fiber volume fractions of 10%, 20%, 30%, and 40%. The composition and designation details of these composite plates are given in Table 1. Composite plates were fabricated in the size of 300 × 300 mm with 3 mm thickness using the hand lay-up method [20]. Each composite mould was cured for 24 hours under a load of approximately 25 kg before being removed from the mould. After removing the casting from the mould, it was allowed to cure in the air for another 24 hours.

2.1. Testing of Mechanical Properties. A vertical cutting machine has been employed to cut the sample into appropriate dimensions in accordance with ASTM standards for mechanical performance testing (Figure 1). The tensile test (ASTM D 638, 1996) and a three-point bending test (ASTM D790) [22] are carried out in a universal testing machine with a crosshead speed of 2 mm/min. The Charpy impact test (ASTM D 256) was performed on the composite materials and compared with the different reinforcement percentages.

2.2. Drilling. The drilling operation was performed in the V-510 VERTIMACH CNC vertical milling centre at RAA TECH CNC, Chennai, India. The drilling operation was performed with a 10 mm diameter HSS drill bit in dry cutting condition in the hybrid composite plate *D*, which possesses better mechanical properties. An attempt has been made to understand the effect of varying the drill point angle on the delamination of composite plates. Therefore, three different drill point angles were used in the present work.

Taguchi orthogonal arrays have been used to identify the most critical factors that influence the process by performing a minimum number of experiments to save time and money. In addition, this approach is used to increase the efficiency of any process or product by optimizing parameters.

Three machining parameters, namely speed, feed, and drill point angle, with three levels each, are used here. Table 2 shows the values of the parameters and levels. A full factorial design (L_{27}) is used in this work to understand the effect of every possible combination of machining parameters. The angles of drill bits were ground to 105°, 118°, and 135° using a bench grinder, and the values were ensured by a toolmaker's microscope. Drilling was done with the 27 combinations of machining parameters with 2 trials.

Table 1: Composition and designation of composites.

Composite designation	Volume fraction		
	Resin (%)	Sisal fiber (%)	Human hair (%)
A	90	5	5
B	80	10	10
C	70	15	15
D	60	20	20

2.3. Delamination. During drilling operation, damages are being occurred around the hole, as shown in Figure 2(a), generally called as delamination. Delamination occurs whenever the hole diameter reaches the desired diameter. The drilling mechanism is different on the entrance and exit sides of the composite laminate, since the tool should drill thicker material at the entrance and thinner material at the exit. The delamination at the entrance and exit of the hole are called peel-up delamination and push-down delamination, respectively [23].

Delamination of a drilled hole can be calculated [20] using the relation shown in

$$F_d = \frac{D_{\max}}{D}, \quad (1)$$

where F_d = delamination factor. $D_{\max}$ = actual hole diameter. D = intended hole diameter.

To measure the delamination factor, the actual diameters of the holes were quantified by the machine vision technique. Images of the drilled holes were captured using a Matrix Vision camera that is connected to a computer. After this, the images were further processed using Measurement and Automation Explorer software in the subsequent steps, namely image processing, thresholding, and particle analysis. Figure 2(b) shows the machine vision setup used for this work.

2.4. Taguchi Analysis. Taguchi analysis is a set of general design guidelines for factorial studies that encompass a broad variety of topics. Many researchers used the Taguchi method to design experimental work [2, 19, 20], which is a vital tool for optimizing the process parameter to achieve robust design. It is used to enhance the process conditions and products that are least sensitive to the cause of change. Taguchi involves the choice of parameters and levels, selecting orthogonal arrays, and analyzing the data to determine the best parameter levels. In this work, the Taguchi method was used to find the optimized processing parameters to achieve the smallest delamination.

2.5. Grey Relational Analysis. When compared to a single response characteristic, optimizing multiple response characteristics is challenging. Grey relational analysis (GRA) is an effective tool to optimize multiple response

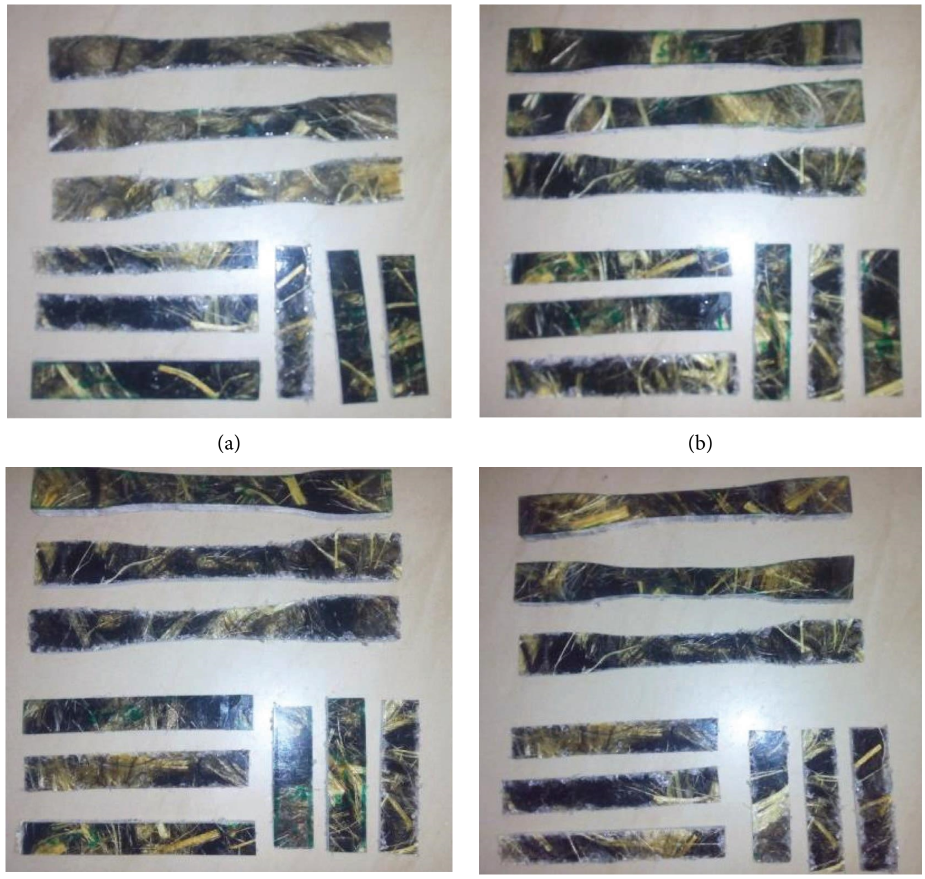


Figure 1: Test specimens for mechanical properties as per ASTM standards. (a) Composite A. (b) Composite B. (c) Composite C. (d) Composite D.

Table 2: Machining parameters and its levels.

Parameters/level	Drill point angle	Speed	Feed
	$P1$	$P2$	$P3$
Unit	Degree	RPM	mm/min
1	105	1500	50
2	118	2000	75
3	135	2500	100

characteristics [23–25]. In GRA, the experimental values are first normalized (eq. (2)) to lower the best condition since the delamination should be reduced.

$$x_i(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)}. \quad (2)$$

The absolute difference between the referential series and the compared series was calculated by eq. (3), and then the maximum and minimum differences were calculated.

$$\Delta x_i(k) = \left| x_0(k) - x_i(k) \right|. \quad (3)$$

Grey relational coefficient ξ can be expressed as follows:

$$\xi_i(k) = \frac{\Delta_{\min} + p\,\Delta_{\max}}{\Delta x_i(k) + p\,\Delta_{\max}}, \quad (4)$$

where $\Delta_{\min}$ and $\Delta_{\max}$ are minimum and maximum differences; p coefficient, whose value is normally selected as 0.5.

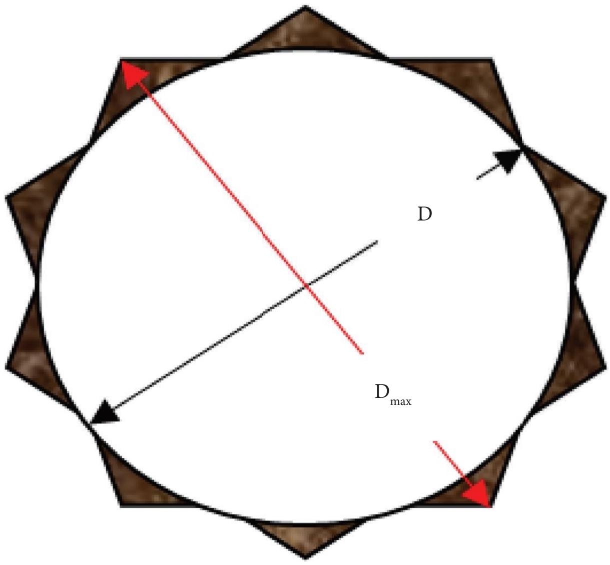
The relational degree can be calculated by

$$r_i = \sum [w(k)\xi(k)]. \quad (5)$$

In this equation, ξ is the Grey relational coefficient and (k) represents the proportion of the number k influence factor to the total influence indicators. Relation degree r_i will be ranked based on the highest values.

3. Results and Discussion

3.1. Tensile and Flexural Test. The results of the tensile and flexural tests are shown in Figures 3(a) and 3(b), which show an increase in tensile and flexural strengths with the increase in fiber volume. This confirms the effective bonding of sisal fiber and human hair with the matrix material. Tensile strength increased from 9 MPa~16 MPa with the increase in fiber volume. Flexural strength also reached its peak (~38 MPa) in the 60% epoxy and 40% fiber hybrid composites, which has been a considerable achievement over the earlier research work. [15] Because the fibers effectively absorb the impact load, the composites with a higher fiber weight percentage exhibited good impact resistance (Figure 3(c)).



(a)

(b)

Figure 2: (a) Delamination in a drilled hole. (b) Machine vision set up.

Figure 4(a) shows the SEM image of the fractured surface of composite *D* after the tensile test. It is evident that the fibers are properly distributed in this laminate since it possesses good mechanical properties compared to the other three laminates. Also, the density of the fiber volume was higher (Figure 4(a)) in 40% fiber composites when compared to the 10% hybrid fiber composite. Figures 4(b)–4(d) show the different modes of failure, such as fiber pull-out and breakage of the matrix in composite A (90% epoxy and 10% fiber composite). Voids were found to be high in composite A due to the meager amount of fiber volume (10%). In addition to this, fiber pull-out and matrix failure readily occurred on the application of load, which manifested the lowest strength value.

3.2. Delamination. The peel-up and push-down delamination for the drilled composite were measured using equation (1). The maximum deviated (D_{max}) diameter values were measured by using Figure 5, captured by the machine vision system and LabVIEW software. The values of delamination factors for both the entry and exit sides of holes are indicated in Table 3. It is evident that the delamination factor on the entry side is slightly greater than the delamination factor on the exit side due to the reduction in thickness while drilling the composite from the entry side to the exit side. The thrust force that developed was found to be higher due to the absence of support. Due to this, the delamination increased at the exit side of the hole.

3.3. Taguchi Method. To investigate the effect of drilling parameters on the delamination factor, Minitab 16.5 statistical software was used to calculate the signal-to-noise ratio (S/N) on the entry and exit sides. The most important machining factors can be obtained from the response table, which leads to delamination. Also, the delta value given in this table indicates the order of contribution of machining parameters.

Table 4 demonstrates response data for peel-up delamination. It is understood from the table that feed is the most important contributing factor for delamination, followed by speed and drill point angle. Table 5 shows the response data for push-down delamination and demonstrates that the drill point angle is the most prominent factor in deciding the push-down delamination. Speed and feed are having less contribution in the formation of push-down delamination. From the main effects plot for the S/N ratio (Figure 6), the optimum values of speed (2500 rpm), feed (50 mm/min), and drill point angle (105°) were obtained. It is understood that the optimum values of machining parameters remain the same for push-down delamination as well (Figure 7).

3.4. Grey Relational Analysis. To optimize the drilling condition, grey relational analysis was also employed. The multiple responses (delamination on the entry and exit) were converted into a single response by GRA grade. The calculated values of the grey relation coefficient ξ and relational degree γ are shown in Table 6.

The optimum cutting condition was selected based on the higher-grade relational degree value. According to GRA, the optimum cutting conditions were selected as drill point angle level 1 (105°); speed level 3 (2500 rpm); and feed level 1 (50 mm/min).

Similarly, the worst condition was observed in experiment number 12, and the respective parameters were drill point angle-level 2 (118°), speed-level 1 (1500 rpm), and feed-

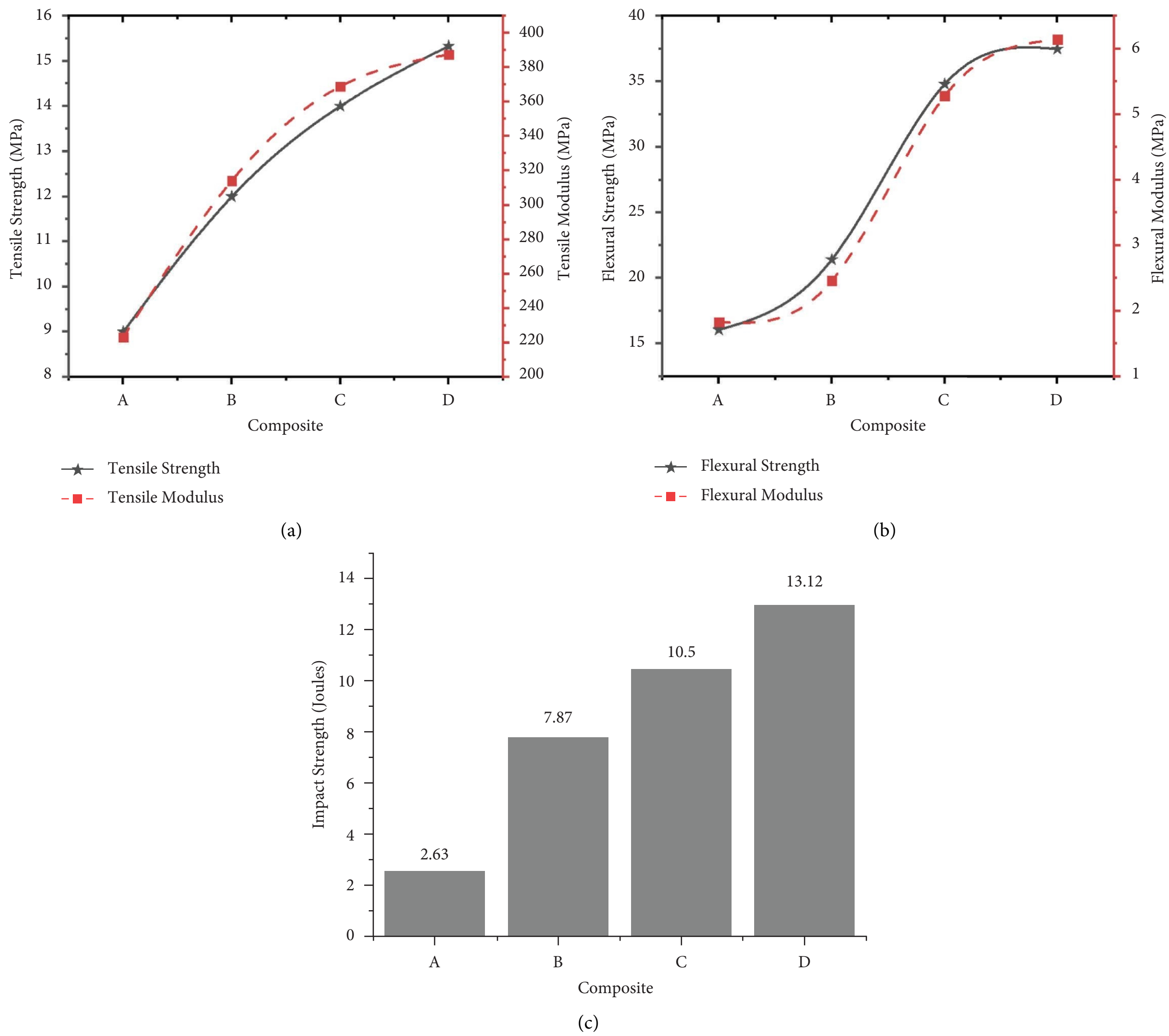
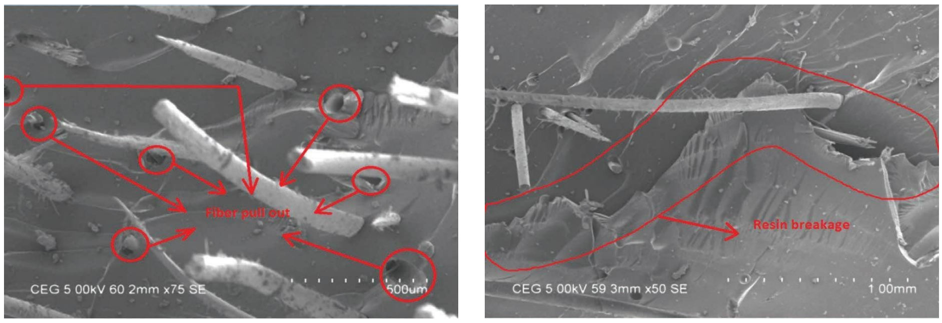


Figure 3: Mechanical properties of hybrid composite.

Figure 4: Continued.



(c) (d)

Figure 4: SEM image of (a) 60% epoxy and 40% fiber after tensile fracture; (b) 90% epoxy and 10% fiber-presence of void; (c) 90% epoxy and 10% fiber-fiber pull out; and (d) 90% epoxy and 10% matrix breakage.

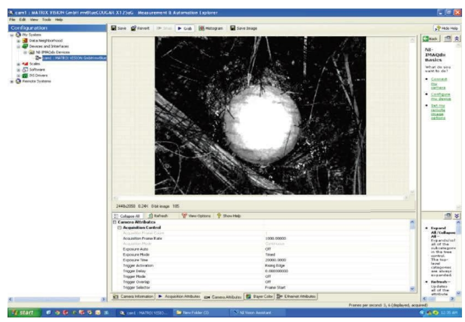


Figure 5: Image processing in LabVIEW.

Table 3: S/N ratio for peel up and push down delamination.

Ex. no.	Drill point angle (degree)	Speed (rpm)	Feed (mm/min)	F_d-entry	F_d-exit
1	105	1500	50	1.0007	1.0024
2	105	1500	75	1.0024	1.0038
3	105	1500	100	1.0047	1.0058
4	105	2000	50	1	1.0024
5	105	2000	75	1.0019	1.0036
6	105	2000	100	1.0044	1.0053
7	105	2500	50	1	1.002
8	105	2500	75	1.0019	1.0033
9	105	2500	100	1.0024	1.0037
10	118	1500	50	1.0013	1.7523
11	118	1500	75	1.0024	1.6981
12	118	1500	100	1.0048	1.5578
13	118	2000	50	1.0012	1.6571
14	118	2000	75	1.0023	1.5245
15	118	2000	100	1.0048	1.4677
16	118	2500	50	1.0011	1.14
17	118	2500	75	1.0023	1.2537
18	118	2500	100	1.0046	1.3134
19	135	1500	50	1.0007	1.0288
20	135	1500	75	1.0024	1.0414
21	135	1500	100	1.0047	1.122
22	135	2000	50	1.0001	1.0269
23	135	2000	75	1.0021	1.0396
24	135	2000	100	1.0045	1.0973
25	135	2500	50	1	1.0238
26	135	2500	75	1.002	1.038
27	135	2500	100	1.0024	1.0907

Table 4: Signal-to-noise ratios response table.

Peel up delamination-SN ratio			
Level	Drill point angle (degree)	Speed (rpm)	Feed (mm/min)
1	−0.017799	−0.02317	−0.004922
2	−0.023874	−0.020505	−0.018942
3	−0.018182	−0.01618	−0.03599
Delta Δ	0.006075	0.00699	0.031068
Rank	3	2	1

Table 5: Signal-to-noise ratios response table.

Push down delamination-SN ratio			
Level	Drill point angle (degree)	Speed (rpm)	Feed (mm/min)
1	−0.03122	−1.66943	−1.23764
2	−3.35269	−1.42841	−1.25915
3	−0.47291	−0.75899	−1.36004
Delta Δ	3.32147	0.91044	0.12241
Rank	1	2	3

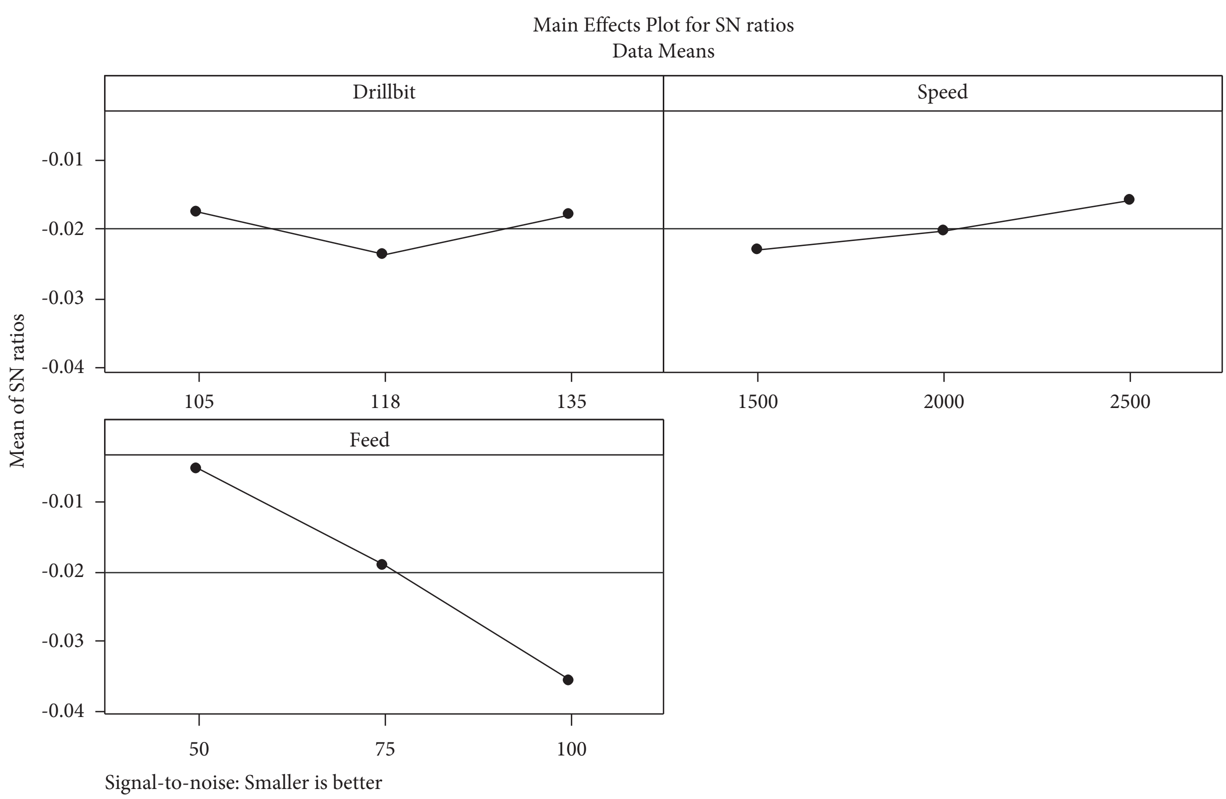


Figure 6: Plot of SN ratios' key effects-peel up delamination.

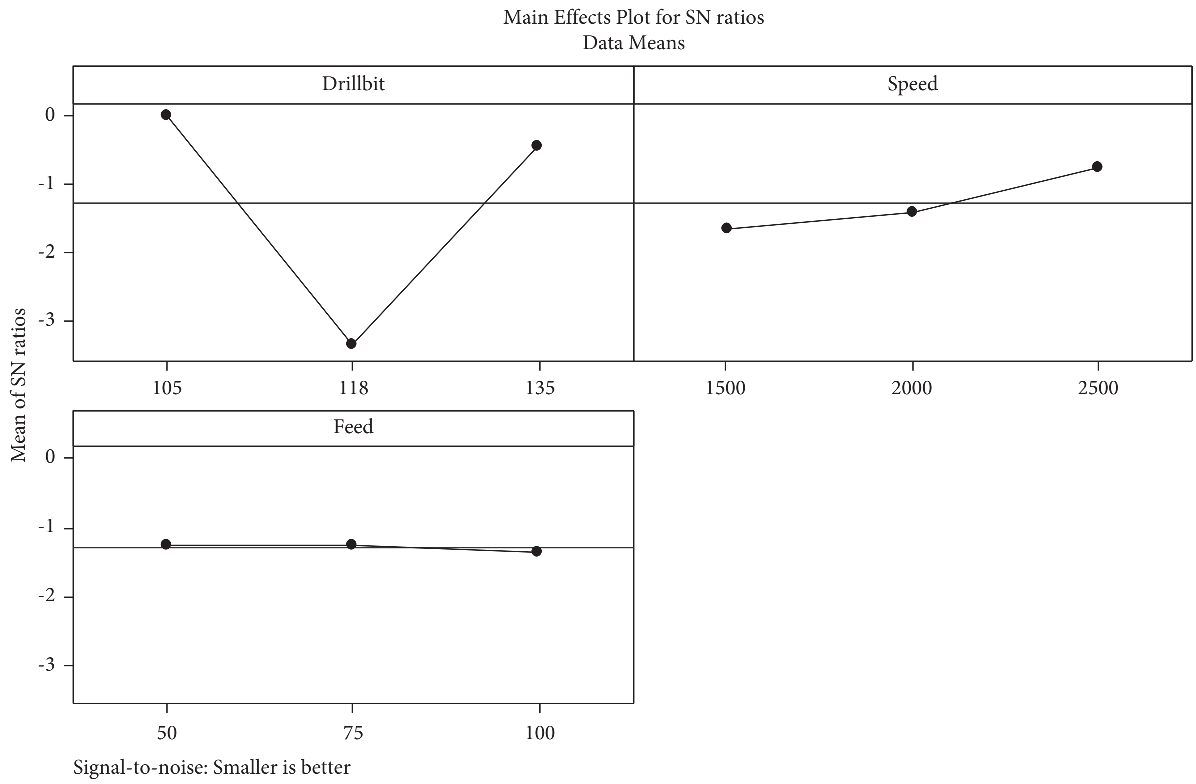


Figure 7: Plot of SN ratios' key effects-push down delamination.

Table 6: Grey relational analysis for delamination.

Ex. no.	F_d-entry	F_d-exit	ξ_i (1)	ξ_i (2)	Υ_i	GRA
1	1.00065	1.00245	0.7896	0.99875	0.89417	5
2	1.00238	1.00375	0.50434	0.99529	0.74982	9
3	1.00469	1.00585	0.33996	0.9898	0.66488	16
4	1.00002	1.00239	0.99509	0.9989	0.997	2
5	1.00195	1.00363	0.55468	0.99563	0.77516	8
6	1.00442	1.00534	0.35348	0.99111	0.67229	15
7	1.00001	1.00198	1	1	1	1
8	1.0019	1.0033	0.56074	0.9965	0.77862	7
9	1.00245	1.00373	0.49721	0.99535	0.74628	10
10	1.00128	1.75229	0.65526	0.33333	0.4943	22
11	1.00239	1.69812	0.50315	0.35019	0.42667	25
12	1.00483	1.5578	0.33333	0.40297	0.36815	27
13	1.00115	1.65713	0.67826	0.36412	0.52119	21
14	1.00229	1.52449	0.51404	0.41793	0.46598	23
15	1.00481	1.46775	0.33419	0.44612	0.39016	26
16	1.00114	1.14004	0.68023	0.73099	0.70561	13
17	1.00229	1.25368	0.51408	0.59847	0.55627	19
18	1.00459	1.31338	0.34502	0.54643	0.44573	24
19	1.00072	1.02881	0.77252	0.93325	0.85289	6
20	1.0024	1.04142	0.50207	0.90487	0.70347	14
21	1.0047	1.12196	0.33947	0.75769	0.54858	20
22	1.0001	1.02691	0.96373	0.93768	0.95071	4
23	1.00206	1.03965	0.54043	0.90876	0.72459	12
24	1.00448	1.09727	0.35061	0.79745	0.57403	18
25	1.00001	1.02383	0.99839	0.94495	0.97167	3
26	1.00199	1.038	0.54919	0.9124	0.7308	11
27	1.0024	1.09073	0.50184	0.80868	0.65526	17

level 3 (100 mm/min). The GRA order indicated a piece of interesting information: the lower feed (50 mm/min) appeared at top order levels. This reveals the importance of lower feed in the drilling of composite laminates.

4. Conclusions

Sisal fiber-human hair reinforced hybrid composite plate is made with four different fiber volume combinations. Their mechanical properties were tested, and an attempt was made to optimize drilling parameters to reduce the delamination factor on the entry and exit sides of the hole. The Taguchi method is used to find the parameters that have the most influence on delamination. GRA is used to find the best cutting conditions by converting multiresponse output to single-response output. The following conclusions can be drawn based on the obtained data:

(i) Increasing the fiber content in composite plates increases their mechanical properties.

(ii) best mechanical properties were found in composite *D* (20% sisal fiber, 20% human hair, and 60% epoxy).

(iii) Less delamination at higher cutting speed and lower feed.

(iv) Feed and cutting point angle are the most prominent parameters to decide the delamination on the entry and exit sides, respectively.

(v) Optimum drilling parameters were identified as speed (2500 rpm), feed (50 mm/min), and drill point angle (105°) using the Taguchi method.

(vi) From the results obtained in GRA, better performance is noticed in experiment number 7 and poor performance in experiment number 12.

(vii) Optimum speed, feed, and drill point angles derived from GRA were matched with results obtained using the Taguchi method (2500 rpm, 50 mm/min, and 105°).

Data Availability

All the dateas are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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