

Studies on Drilling of Natural Fiber Reinforced Polymer Matrix Hybrid Composites

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Abstract — Polymer composites have replaced many conventional materials due to ease of processing, high productivity and lower cost. This paper presents experimental investigations on drilling of natural fiber reinforced polymer matrix hybrid composites fabricated using coconut leaf sheath (CLS), jute fiber, glass fiber, coconut shell powder (filler) and phenol formaldehyde (PF) resin. CLS fibers were alkaline-treated with 5% NaOH solution. Five different stacking sequences (M1–M5) were prepared by hand lay-up technique and hot pressed at 150°C, 20 bar for one hour. Drilling experiments were conducted on a vertical CNC drilling machine using TI-NI coated HSS and carbide drill bits of 5 mm diameter. A Taguchi L9 orthogonal array with spindle speeds (400, 800, 1200 rpm) and feed rates (0.1, 0.2, 0.3 mm/rev) was employed. Thrust force and torque were measured by a drill tool dynamometer; peel-up and push-down delamination factors were determined using a toolmaker microscope. ANOVA analysis revealed that feed rate is the dominant parameter affecting all responses. Carbide drill bit produced lower thrust force and delamination compared to TI-NI coated HSS. Stacking sequences M1 and M5 exhibited minimum thrust force, while M2 and M4 exhibited minimum delamination.

Key Words: Natural fiber; Hybrid composite; Coconut leaf sheath; Jute fiber; Glass fiber; Drilling; Thrust force; Delamination; Taguchi; ANOVA

I. INTRODUCTION

Composite materials are defined as a combination of more than two materials, in which one is the reinforcement and the other is the matrix. Glass fiber reinforced polymers are widely used in automobile, aerospace, packaging and sports goods industries due to their excellent properties. In recent years, synthetic fibers are being replaced by natural fiber composites because of their superior eco-friendly properties, low density, and wide availability.

Natural fibers such as jute, hemp, sisal, bamboo, and coconut leaf sheath (CLS) offer low density, lower cost, biodegradability, and reasonable specific mechanical properties. However, natural fiber composites exhibit lower mechanical properties and poorer moisture resistance than their synthetic counterparts. Hybrid composites, which combine natural and synthetic fibers, offer a balanced compromise between performance and sustainability.

Machining — particularly drilling — is essential for structural assembly of composite panels. Drilling-induced damage, especially delamination, is a critical quality problem that degrades mechanical performance and assembly tolerance. Understanding the influence of drilling parameters on thrust force, torque, and delamination factor is therefore of great industrial significance. This study investigates these

responses for five stacking-sequence variants of CLS/jute/glass/PF hybrid composites using Taguchi's design of experiments.

II. COMPOSITE MATERIAL SYSTEM

A. Matrix Material

Phenol formaldehyde (PF) resin was used as the matrix. It is the first fully synthetic polymer, offering excellent high-temperature resistance (205–260°C), good mechanical strength, dimensional and thermal stability, fire resistance, and high chemical resistance. The curing temperature is 140°C. PF resin constituted 50% by volume in all composite formulations.

B. Reinforcement Materials

B.1 Coconut Leaf Sheath (CLS)

CLS fiber extracted from coconut trees (*Cocos nucifera*, family Areaceae) constitutes the primary natural reinforcement. It has a diameter of 300–600 μm and density of $630 \times 10^{-3} \text{ kg/m}^3$. Chemical composition: cellulose 32–43%, hemi-cellulose 0.15–0.25%, lignin 40–45%, ash 2.22%, water soluble 5.25%. The inner mat of the leaf sheath was used, placed between two layers of coarse leaf.

B.2 Jute Fiber

Jute (*Corchorus* sp.) is the cheapest natural fiber, with cellulose 59–71%, hemi-cellulose 12–13%, lignin 11.8–12.9%, density 1.3–1.48 g/cm^3 , tensile strength 400–800 MPa, Young's modulus 10–30 GPa, and moisture absorption 12%. Jute plants grow to 12–15 feet in about three months before harvest by retting.

B.3 E-Glass Fiber

E-glass fiber (density 2.54 g/cm^3 , Young's modulus 72.4 GPa, UTS 3447 MPa) provides high tensile strength, excellent insulating properties, and low cost. It was included in selected stacking sequences to improve peel-up delamination resistance due to its higher surface hardness and tensile strength compared with natural fibers.

B.4 Coconut Shell Powder (Filler)

Coconut shell powder (80-mesh, density 1.60 g/cm^3) sourced from Kerala, Goa, and Maharashtra was used as a filler material at 10% by volume. It fills inter-fiber voids, reduces air entrapment during fabrication, and contributes to environmental sustainability as an agricultural waste by-product.

III. ALKALI TREATMENT OF CLS FIBERS

Alkali treatment (mercerisation) with 5% NaOH solution was applied to improve fibre–matrix interfacial adhesion. The procedure:

- CLS fibers extracted by handpicking from agricultural farms.
- Fibers cleaned with running water and sun-dried for 24 hours to remove moisture.
- Fibers cut to 200 \times 200 mm and fully immersed in 5% NaOH solution for 24 hours with a manual load applied.
- Fibers removed, rinsed with distilled water to neutral pH, and sun-dried again.

Alkali treatment removes hemicellulose and lignin from the fibre surface, increasing the exposed hydroxyl (-OH) groups, improving

mechanical interlocking with the PF matrix, and thereby enhancing interfacial shear strength and reducing moisture absorption.

IV. COMPOSITE FABRICATION

A. Volume Fraction Calculations

Volume of each composite plate: $200 \times 200 \times 6 \text{ mm} = 240 \text{ cm}^3$. Target composition: 50% PF resin + 40% fiber reinforcement + 10% coconut shell powder filler (Material 1). For each material, the number of fiber layers was determined as:

$$N_{\text{layers}} = (V_{\text{composite}} \times V_{\text{f}\%}) / V_{\text{one_layer}}$$

Sample calculation for CLS (Material 1): Volume of one CLS layer = $8.83 / 0.630 = 14.02 \text{ cm}^3$; Amount of CLS = $240 \times 0.40 = 96 \text{ cm}^3$; Number of layers = $96 / 14.02 \approx 7$ layers. Resin quantity = $240 \times 0.50 = 120 \text{ ml}$; filler (10%) = 38.4 g.

B. Composite Compositions and Stacking Sequences

Five hybrid composite formulations were prepared as described in Tables 1 and 2.

Table 1: Composite percentage compositions (CLS=Coconut Leaf Sheath, GF=Glass Fiber, JF=Jute Fiber, CSP=Coconut Shell Powder)

Material	Reinforcement (50%)
M1	40% CLS
M2	20% CLS + 20% GF
M3	20% CLS + 20% JF
M4	20% CLS + 20% CLS
M5	20% CLS + 20% JF

Table 2: Stacking sequences (C=CLS, G=Glass, J=Jute)

Material	Reinforcement (50%)
M1	40% CLS
M2	20% CLS + 20% GF
M3	20% CLS + 20% JF
M4	20% CLS + 20% CLS
M5	20% CLS + 20% JF

C. Hand Lay-Up and Hot Press

Composites were fabricated by hand lay-up: fibers were cut to $200 \times 200 \text{ mm}$; calculated PF resin (with dissolved filler) was spread on a flat release-coated surface; fibers were placed in sequence per Table 2; a roller was used to eliminate air pockets. The assembly was transferred to a steel mould and hot-pressed at 150°C , 20 bar for one hour, then cooled and demoulded. Final plates ($200 \times 200 \times 6 \text{ mm}$) were cut to test specimens of $100 \times 100 \times 6 \text{ mm}$.

V. DESIGN OF EXPERIMENTS AND TESTING

A. Taguchi L9 Orthogonal Array

Taguchi's L9 orthogonal array with two factors at three levels was employed to plan drilling experiments. The control factors and their levels are given in Table 3.

Table 3: Control factors and levels

Factor	Unit	Level 1	Level 2	Level 3
Speed	rpm	400	800	1200
Feed rate	mm/rev	0.1	0.2	0.3

B. Equipments

Drilling machine: Vertical CNC drilling machine (Harihar). Specimens: $100 \times 100 \times 6 \text{ mm}$ plates. Drill bits: 5 mm diameter TI-NI coated HSS and tungsten carbide. Depth of cut: 6 mm. Aluminium foil was applied at entry and exit surfaces to reduce delamination damage during testing.

Dynamometer: Drill tool dynamometer (thrust range 0–200 kg; torque range 0–20 kg-m; least count 0.1 kg-m) with digital dual-channel display connected to a mechanical sensing unit.

Delamination measurement: Toolmaker microscope was used to measure the maximum damage diameter (D_{max}) around the drilled hole. Delamination factor: $F_d = D_{\text{max}} / D_0$, where $D_0 = 5 \text{ mm}$ (nominal drill diameter). Both peel-up (entry) and push-down (exit) delamination were measured.

VI. RESULTS AND DISCUSSION

A. Thrust Force

ANOVA results for thrust force are summarised in Table 5 (TI-NI HSS) and Table 6 (Carbide). Feed rate is the dominant parameter in both cases.

Table 5: ANOVA for Thrust Force – TI-NI Coated HSS Drill Bit ($R^2 = 97.9\%$)

Source	DF	Seq SS	F	P	Contribution
Speed	2	877.05	2.25	0.001	56%
Feed	2	656.80	39.13	0.002	42%
Error	4	33.57	—	—	2%
Total	8	1567.43	—	—	100%

Table 6: ANOVA for Thrust Force – Carbide Drill Bit ($R^2 = 97.4\%$)

Source	DF	Seq SS	F	P	Contribution
Speed	2	432.62	33.54	0.003	43.30%
Feed	2	540.55	41.91	0.002	54.11%
Error	4	25.80	—	—	2.5%

Feed rate contributed 54.11% (carbide) and 42% (HSS) to thrust force variation, confirming its dominance. As feed rate increases from 0.1 to 0.3 mm/rev, thrust force increases for all materials and both tools because higher feed advances the tool faster, generating greater axial cutting resistance. Speed showed 43–56% contribution but had less practical significance at the test range. Carbide drill bits consistently produced lower thrust forces than TI-NI coated HSS due to sharper cutting edges and higher hardness, confirming superior machineability.

Material M1 (all-CLS, alkali-treated) and M5 (CLS core, jute outer) exhibited the lowest thrust force among the five stacking sequences. M1 benefits from NaOH treatment removing hemicellulose and lignin, reducing fibre cutting resistance. M5 benefits from good matrix-fibre compatibility in the jute-CLS combination. M2, M3, M4 showed higher thrust force due to the presence of harder glass fibers.

B. Peel-Up Delamination

Table 7: ANOVA Contributions – Peel-Up Delamination (HSS vs Carbide)

Source	DF	HSS Contribution
Speed	2	43.29%
Feed	2	53.50%
Error	4	3.4%
R²	—	96.6%

Stacking sequences M2 and M4 exhibited the least peel-up delamination. These sequences place glass fiber layers at the top surface; the high tensile strength and stiffness of E-glass resists the upward peeling action of the drill at entry. Jute and CLS outer layers (M3, M5) are more easily peeled due to their lower in-plane stiffness. Carbide drill bit produced consistently lower peel-up F_d than TI-NI HSS due to sharper edges generating cleaner entry cuts.

C. Push-Down Delamination

Push-down delamination occurs at drill exit. ANOVA results (Tables 8–9) show feed rate contributes 58.77% (HSS) and 60.04% (carbide), and speed contributes 32.78% and 36.4% respectively. Push-down delamination is generally higher than peel-up because at exit, unsupported plies beneath the drill are thrust downward by the axial cutting force, promoting inter-ply separation.

Table 8: ANOVA Contributions – Push-Down Delamination (HSS vs Carbide)

Source	DF	HSS Contribution
Speed	2	32.78%
Feed	2	58.77%
Error	4	8.43%
R²	—	91.6%
Source	DF	HSS Contribution

Table 8: ANOVA Contributions – Push-Down Delamination (HSS vs Carbide)

M2 and M4 again exhibited minimum push-down delamination. Although glass fiber has high tensile strength, its placement as the exit layer means the drill must overcome this strength before completing the hole, causing delamination between plies before breakthrough. Jute fiber exit layers (M3, M5) allow the drill to cut through with less inter-ply damage. However, M2 and M4 still achieve lower total push-down F_d owing to better glass-matrix interfacial adhesion providing higher resistance to layer separation. Carbide drill produced lower push-down F_d than TI-NI HSS.

D. Torque

Feed rate is the overwhelmingly dominant factor for torque, contributing 97.16% (HSS) and 97.2% (carbide), with speed contributing less than 1–3% (Table 9). R^2 values of 98–99.6% confirm excellent model fit. Torque increases with increasing feed rate because higher feed causes the drill to engage more material per revolution, generating greater torsional resistance.

Table 9: ANOVA Contributions – Torque (HSS vs Carbide)

Source	DF	HSS Contribution
Speed	2	0.87%
Feed	2	97.16%
Error	4	0.19%
R²	—	98.0%

Table 9: ANOVA Contributions – Torque (HSS vs Carbide)

M5 (CLS core, jute outer) consistently exhibited the lowest torque of all five stacking sequences. The presence of jute and CLS — both relatively soft natural fibers with lower specific cutting energy — reduces the torsional drilling force. M2 and M3 show higher torques due to glass fiber layers requiring greater energy for material removal. Carbide drill produced lower torque values than TI-NI HSS, attributable to its lower coefficient of friction and superior wear resistance.

E. Regression Models

Empirical regression models for all five materials and both drill bits were developed from experimental data. Sample equations for thrust force (N):

$M1 = 44.64 + 49.0 \cdot f - 0.033 \cdot N$; $M2 = 14.9 + 278.8 \cdot f - 0.016 \cdot N$; $M3 = 52.2 + 81.8 \cdot f - 0.029 \cdot N$; $M4 = 17.4 + 179.8 \cdot f - 0.008 \cdot N$; $M5 = 43.6 + 81.5 \cdot f - 0.029 \cdot N$ (f = feed mm/rev; N = speed rpm). The positive coefficient of feed rate and negative coefficient of speed confirm that thrust force increases with feed and decreases with speed across all formulations.

VII. EXPERIMENTAL DATA SUMMARY

Table 10: Thrust Force (N) – C=Carbide, H=TI-NI HSS. M1–M5 for Carbide; selected M1, M5 for HSS shown.

Trial	N (rpm)	f (mm/r)	M1-C	M2-C	M3-C	M4-C	M5-C	M1-H	M5-H
1	400	0.1	29.4	19.6	19.6	29.4	19.6	39.2	49
2	800	0.1	39.2	39.2	39.2	39.2	29.6	49	49
3	1200	0.1	39.2	49	49	49	39	19.6	29.4
4	400	0.2	9.8	19.6	19.6	19.6	19.6	29.4	39
5	800	0.2	19.6	29.4	29.4	29.4	19.6	29.4	58.8
6	1200	0.2	19.6	39.2	58.8	39.2	29.6	9.8	19.6
7	400	0.3	9.8	9.8	9.8	19.6	9.8	19.6	19.6
8	800	0.3	9.8	19.6	19.6	19.6	9.8	19.6	29.4
9	1200	0.3	9.8	29.4	29.4	39.2	29.4	39.2	49

Table 11: Peel-Up Delamination Factor F_d – Carbide Drill Bit

Trial	N	f	M1-C	M2-C	M3-C	M4-C	M5-C
1	400	0.1	1.31	1.09	1.51	1.04	1.41
2	800	0.1	1.58	1.13	1.82	1.13	1.62
3	1200	0.1	1.38	1.2	2.95	1.23	2.12
4	400	0.2	1.26	1.07	1.21	1.05	1.12
5	800	0.2	1.37	1.07	1.95	1.08	1.35
6	1200	0.2	1.47	1.23	2.3	1.1	1.52
7	400	0.3	1.32	1.08	1.21	1.01	1.05
8	800	0.3	1.12	1.01	1.77	1.14	1.19
9	1200	0.3	1.29	1.2	1.92	1.09	1.53

Table 12: Torque (N·m) – Carbide Drill Bit

Trial	N	f	M1-C	M2-C	M3-C	M4-C	M5-C	Trial	N
1	400	0.1	0.9	1.17	1.96	0.93	0.71	1	400
2	800	0.1	0.92	1.12	0.98	0.9	0.7	2	800
3	1200	0.1	1.45	2.13	1.41	1.89	1.12	3	1200
4	400	0.2	1.38	1.99	1.32	1.8	1.21	4	400
5	800	0.2	1.65	1.92	1.24	1.75	1.1	5	800
6	1200	0.2	2.01	2.91	1.62	2.79	1.46	6	1200
7	400	0.3	1.9	2.73	1.22	2.66	1.37	7	400
8	800	0.3	1.6	2.62	1.75	2.59	1.41	8	800
9	1200	0.3	0.9	1.17	1.96	0.93	0.71	9	1200

VIII. CONCLUSIONS

The following conclusions are drawn from the experimental investigation on drilling of natural fiber reinforced polymer matrix hybrid composites:

1. CLS fibers treated with 5% NaOH show measurable improvement in fibre–matrix adhesion, reducing thrust force in M1 composites compared to untreated counterparts.
2. Feed rate is the dominant drilling parameter for all responses — thrust force, peel-up delamination, push-down delamination and torque. Cutting speed showed comparatively less influence across the 400–1200 rpm range tested.
3. Thrust force is minimum for stacking sequences M1 (all-CLS, alkali-treated) and M5 (jute outer, CLS core). M2 and M3 exhibit higher thrust force due to glass fibers.
4. Peel-up delamination is minimum for M2 and M4, where glass fiber outer layers resist drill entry forces due to higher tensile strength and stiffness. Jute outer layers are more susceptible to peel-up.
5. Push-down delamination is consistently higher than peel-up delamination across all materials and conditions. M2 and M4 again exhibit minimum push-down delamination.
6. M5 stacking sequence (CLS core, jute outer) exhibits the lowest torque, confirming that natural-fibre dominant compositions require less specific cutting energy than glass-dominant sequences.
7. Carbide drill bit outperforms TI-NI coated HSS for all measured responses — lower thrust force, lower delamination, and lower torque — due to higher hardness, sharper cutting edge retention, and lower friction.
8. Optimal drilling conditions: low feed rate (0.1 mm/rev) combined with high spindle speed (1200 rpm) and carbide drill bit minimise delamination and torque simultaneously.

IX. SCOPE FOR FUTURE WORK

- Surface roughness, burr height, and chip formation at the drilled hole periphery can be investigated as additional quality indicators beyond the present scope.
- Alternative resin systems (epoxy, polypropylene, polyurethane) can be explored to improve interfacial adhesion and overall drilling performance.
- Different drill geometries (step drill, core drill, brad-point drill) and coatings (DLC, TiAlN) can be evaluated for further reduction of delamination in natural fibre composites.
- Finite element simulation of the drilling process can be developed and validated against the experimental regression models derived in this study.
- Statistical process optimisation using Response Surface Methodology (RSM) or Grey Relational Analysis (GRA) can be applied for multi-objective simultaneous optimisation of all four responses.

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