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STACKING EFFECT OF CARBON/GLASS FIBER DURING DRILLING OPERATION OF LAMINATED POLYMER COMPOSITE

Nowadays, fiber stacks are extensively used in the aircraft and structural component manufacturing industries. It is mainly due to their excellent mechanical and physiochemical performances. The different stacking sequences of fiber materials expand the structural properties due to high-strength carbon fiber and low-cost glass fiber. The fragile and anisotropic conduct of Carbon (Cf) and Glass (Gf) laminates generates different types of complex machining issues. This article focuses on the Drilling test of Carbon/glass fiber hybrid composites using different stacking sequences. The effect of varying stacking orders is explored in this study to identify a feasible composite. The control of varying constraints, namely, spindle speed (N), feed rate (f), and stacking sequence (SS) of carbon (Cf) and glass fiber (Gf) reinforcement, is performed to achieve the optimal parametric condition. The finding reveals that sample A (C4G4) stacking sequence provides an acceptable value for thrust force 59.05 N and delamination 1.0001 for high drilling efficiency. The stacking technique of carbon/glass layers can be endorsed to the manufacturing sector for cost-effective composite development and a defect-free machining environment.

Keywords: Stacking; Sequence; Thrust; Delamination; Carbon

1. Introduction

In structural components, lightweight and durable polymer composites are highly claimed due to their high fuel efficiency and cost-effectiveness compared to metallic alloys. The possibilities of searching for different polymer composites are emerging in manufacturing due to their outstanding physio-mechanical and chemical properties. The carbon/fiber polymer (CFRP) is broadly used to fabricate locomotive, spacecraft, chemical, and sports components. It consists of high elastic modulus and mechanical features. But the cost-effectiveness of CFRP is another critical challenge for polymer manufacturers compared to other fibers such as glass, basalt, etc. To overcome the complex issue of cost-effectiveness in laminate composites, the concept of hybrid composite has been preferred by production industries for the last decades. It is fabricated by using two or more reinforcements in a single matrix such as epoxy (resin). Hybrid laminates tend to combine the properties of two components and subsequently adjust the merits and demerits of each of them. Fiber laminate stacking sequences in hybrid composites lead to cost-effective, durable, high strength, etc., in complex structures [1]. At the same time, the composite material reinforced by glass fiber is also used in structural material, aircraft industries, marine, electronic gadgets, and automotive. Carbon fiber has limitations such as higher cost, low impact strength, low damage tolerance, etc. Nowadays, materials based on glass fiber are being used as an economical alternative to exotic materials. Here, replacing some carbon fabric layers through the glass fiber creates prospects for developing cost-effectual and improved mechanical hybrid laminate composites.

Recently, eminent scholars have investigated hybrid laminates effectively to extract advanced properties. The findings demonstrate that the hybrid laminate composites provide high strength, stiffness, tailored dimensions, corrosion endurance, and lowered preparation expense. Each reinforcing material has different properties, and its combination with other filler materials can expand the desired mechanical features. Such types of combined reinforcing material layers in the matrix phase could improve the overall product assembly. Several works are available on the synthesis and advanced characterization of hybrid laminate composites containing various reinforcements such as glass fiber, carbon fiber, and basalt. Sonparote and Lakkad [2]

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explored the filament winding (FW) method to fabricate the carbon and glass fiber-modified hybrid composites and examined their mechanical properties. The findings of the work show the feasibility of the hybrid composite in terms of mechanical properties. In another similar study, Kretsis [3] examined the mechanical characterization of unidirectional carbon/glass-reinforced hybrid laminate composites. The study defined a negative hybrid effect for the mechanical testing, such as tensile, compressive, and flexural strengths of the proposed composite.

Drilling is the primary machining procedure in manufacturing to create holes for riveting and fastening purposes of different laminates. During composite machining, intermittent thrust force and torque generation occur, which is essential in defining the material removal mechanism and surface characteristics. The drilling efficiency and machinability aspect of polymer laminates is passing through a transition phase. The evaluation of the drilling behavior of laminates requires more attention from academia and the manufacturing sector. For proper utilization of any developed material, it is crucial to realize the machinability aspect of the hybrid composites. In hybrid composite, the relation of machining parameters with respect to the reinforcement material, stacking sequence, matrix materials, etc., is the primary concern for product development. It has been remarked that the stacking configuration performs a considerable role in defining the properties of the hybrid composites and influences the machinability behavior [4]. Drilling operations on laminate composites have been prevalent in many studies investigating machinability. In this series, a survey of polymer composite machining was carried out by Bhatnagar et al. [5]. They have demonstrated the importance of thrust force and torque on the drilling-engendered delamination factor. Naveen et al. [6] examined the delamination phenomenon and the impact of varying cutting speed and feed rate while drilling the sandwich fibers reinforced composites with different volumetric ratios. The drilling test of laminate composite's structure creates several critical challenges such as delamination; fiber pull out, edge chipping, and uncut fibers [7]. These issues could be responsible for less assembly tolerance, low structural integrity, and deterioration of material in the long term.

Various studies remarked that the drilling process of laminated composites generates severe damage and surface defects like tool wear [8,9], delamination [10], hole tapered [11], hole circularity [12], hole cylindricity [7], fiber breakage [13], etc. It is mainly due to the anisotropic behavior of the composite structure and layered configuration [14]. Also, it is observed that such defects and damages could be controlled by selecting appropriate parametric conditions, tool geometry, cutting tool materials, and optimization modules [10,15]. The effects of wear factors on various drilling performances of CFRP laminates, such as drilling forces, interface temperatures, and machined surface indices, were discussed by Xu et al. [8]. Also, another work by Xu et al. [14] investigated the wear characteristics of two different types of drill bit during the machining of CFRPs. It has been concluded that the effectiveness of tool geometries is an essential factor in improving the wear resistance of drill bits during composite machining

Similarly, Poór et al. [13] critically explored the mechanism of burr formation and unique ways to reduce the burr and other defects in the materials. The machining of laminated polymers critically differs from particulate-reinforced composites. Xu et al. [7] investigated the machining characteristics of carbon/epoxy and carbon/polyimide composites using a TiAlN-coated drill tool to explore laminated polymer composite machining efficiency. The machining behavior of polymeric materials completely differs from metallic composites. It needs special types of designed and coated tools, cutting environment and machining temperature.

Apart from the experimental work, the outcome can be controlled by adequately selecting the constraints and their ranges. Therefore, the various studies explore the different optimization approaches for controlling process performance. In this series, Ekici et al. [12] studied the hole quality of Carbon Reinforced Aluminium Laminate (CARALL) composite. The values close to the nominal hole diameter were obtained using the uncoated drill tool and the delamination factor from observed between 1.174 and 1.804. Simultaneously in another study, Ekici et al. [56] optimized the parameters using the GRA-PCA approach. They found the enhanced response at optimum conditions as spindle speed 110 m/min, feed rate 0.1 mm/rev with an uncoated drill tool. The Taguchi theory was remarked as an efficient tool for parametric optimization during the machining of polymeric laminates [12,16-18].

The extensive literature survey demonstrated that renowned researchers staged much effort to characterize and develop hybrid laminate composites. A limited study exists on the drilling machinability of proposed stacking sequences laminate composites, although it is used in various structural components development. The exceptional features and cost-effectiveness of the hybrid laminates attract the manufacturing sector for their application in conventional and costly polymer composites. The present work explores the machinability behavior of hybrid laminate polymer composites. The drilling machinability of stacking carbon and glass fiber sequences with epoxy matrix composite passes through a transition phase. The different stacking sequences are utilized to fabricate the polymer composite using a low-cost development technique. The configuration used in this study has not been explored in a detailed manner in previous studies. The drilling test was executed by taking the process constraints, namely, speed (N), feed (f) and stacking sequences (SS). The thrust force and drilling-induced delamination are estimated to assess the capability of the developed composite. The scanning electron test of stacking polymer composites was performed to evaluate the defect and damage during the drilling process. An effort has been presented to appraise the optimum stacking sequences of carbon and glass fibers developed hybrid laminates.

2. Materials and Methods

For the fabrication of the laminate composites, the carbon fiber (density – 1.79 g/cc and thickness 0.42 mm) and glass fiber (density – 2.55 g/cc and thickness 0.55 mm) have bi-directional and plain weave as reinforcing materials. The epoxy (resin – LAPOX-12, density – 1.162 g/cm^3) was used as the matrix phase with hardener (K-6) and a hand layup technique was used to manufacture the laminate composite. Brief information on the used epoxy and hardener materials is mentioned in TABLE 1. Each glass/carbon fiber layer was cut into the desired dimension (26 cm × 17 cm). Firstly, a thin polyester film was spread in the open mold (acrylic sheet), and one layer of carbon/glass fiber was put. The matrix blend was developed using brushed above the layer of fiber (all laminates are at 0° angle). Hydraulic pressure is used for pressing the cured sample. Four types of stacking sequences, namely *C4G4*, *C5G3*, *C6G2*, and *CG*, were prepared and coded, as shown in Fig. 1. The samples to be machined were made in the dimension of 150 mm × 150 mm × 10 mm blocks for each material.

TABLE 1

Properties of Epoxy (LAPOX L-12), Hardener (K-6)

Epoxy					Hardener	
Tensile strength	**Tensile modulus**	**Strain**	**Density**	**Specific gravity**	**Type**	**Mixing ratio**
(MPa)	(GPa)	(%)	(g/cc)	(25ºC)		
110	4.1	4.6	1.162	1.1-1.2	K-6	10:1

The drilling process uses a rotating cutting tool to remove the unwanted material from the workpiece sample to create the desired hole. The cutting tool rotates and forms a hole throughout the laminate polymer composites. The drilling process creates low residual stresses around the hole to remove the material. The deformation produced during the drilling operation can cause variations in the machinability properties. The schematic plan of the drilling method execution is offered in Fig. 2. The drilling tests were performed on Knee type drilling set up with a vertical machining center (Fuel instrument & Engineers, UNITEK, MODEL NO: 9450). The drilling strategy was selected as unidirectional to understand the mechanism of stacking. Thrust force produced through the drilling test was recorded using systematic arrangements as shown in Fig. 2. The dry cutting condition was chosen to carry out the drilling operation. High-speed steel (HSS) drill tool with 8 mm diameter drill bit was used to perform drilling operations on the hybrid composite. The composition of chemical components and the physical properties are listed as TABLE 2. The thrust force is converted proportionally into a particular signal. This signal conversion is done using a suitable transducer. The thrust force in the drilling of carbon/glass fiber hybrid laminates was measured directly from the dynamometer (KISTLER, MODEL NO: 9257B) and mathematical values were obtained from the computer.

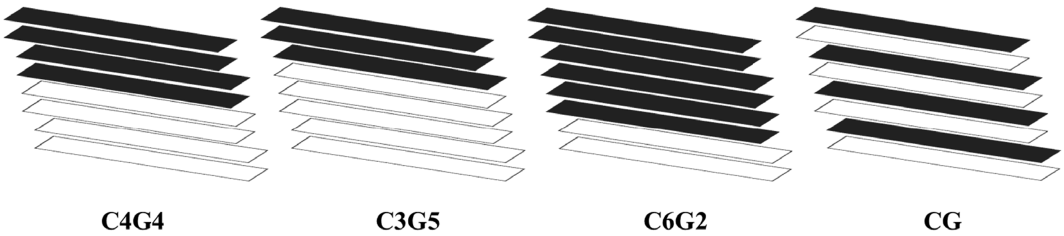

Fig. 1. Stacking sequence of the prepared sample

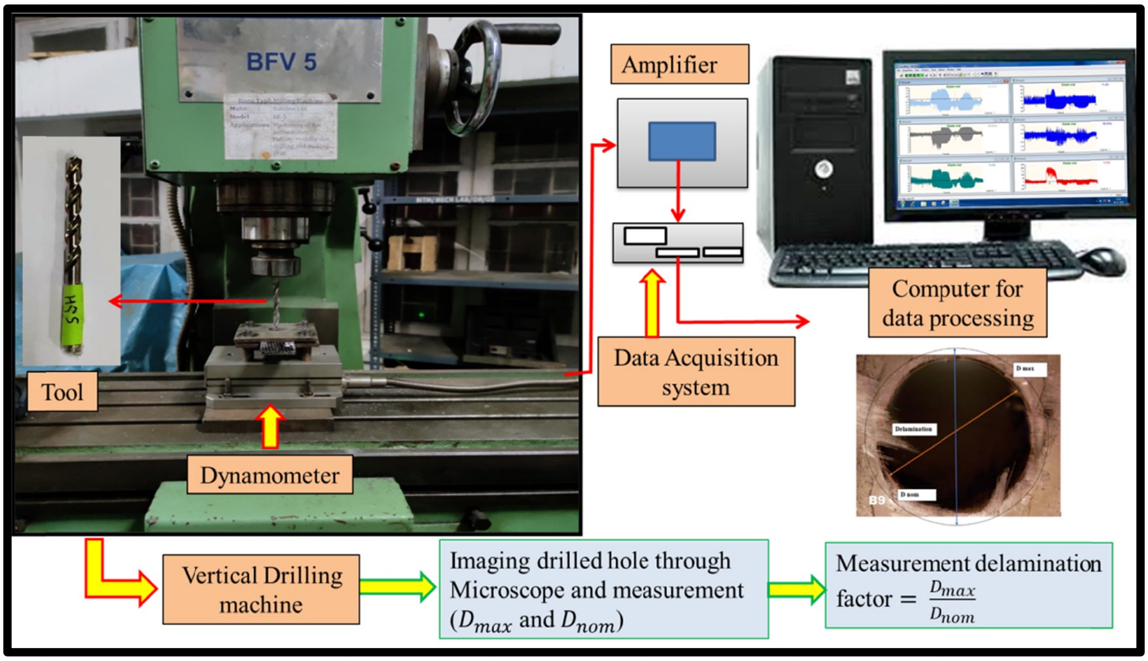

Fig. 2. Schematic diagram of the experimental setup

TABLE 2

Drill bit specifications

Properties					Chemical composition					
Type	**Point angle (°)**	**Helix angle (°)**	**Hardness (BHN)**	**Dia. (mm)**	**W**	**Cr**	**V**	**Co**	**Mo**	**C**
Twist	118	30°	290	8	18	4.3	1.1	5	0.65	0.75

Delamination measurements were done from the microscopic image taken of each hole (ANALYTICAL, MODEL NO: ZSM-3780T2). The ratio of the maximum diameter of the hole to the nominal diameter of the hole was measured as the delamination factor. However, in the current study, the average delamination (of inlet/outlet sides of hole) value was taken [19-22]. Fig. 2 shows the process of delamination measurements. Three process parameters were chosen to perform the drilling operation, i.e., spindle speed, feed rate and stacking sequence, as shown in TABLE 3. The experiments were made using the full factorial design approach. A total of thirty-six nos. of the drilling run were performed using various combinations of process parameters.

TABLE 3

Drilling factor and stacking summary

Factor	Notation	Type	Levels	Values	Repetitions
Spindle speed	N	Fixed	3	500, 1250, 2000 (rpm)	3
Feed rate	f	Fixed	3	50, 125, 200 (mm/min)	
Sequence	SS	Fixed	4	A, B, C, D	

3. Results and discussion

The obtained response was analyzed using two variable parameters, i.e., spindle speed and feed rate with a categorical predictor of stacking sequence. Since there are four different configurations, i.e., *C4G4*, *C5G3*, *C6G2*, and *CG*, these are non-mathematical values that can be used separately to determine machining operation performance. Fig. 3 shows the values and variation of thrust force and delamination with respect to each experiment. It can be remarked that minimum values of the thrust force are obtained at Exp. No. 4, 13, 16 and 19 are stacking sequences *C4G4* and *C5G3*. For stacking *C6G2* and *CG*, the maximum values were obtained at Exp. No. 18, 28, 29, 30.

Similarly, for delamination values, minimum values are obtained at Exp. No. 4, 13, 16 and 19 are also for the stacking sequence *C4G4* and *C5G3*. Thus, the experiment value from the graph analysis is significantly influenced by stacking sequences *C4G4* and *C5G3*. The stacking *C6G2* and *CG* show maximum values of thrust force and delamination, which is undesirable. Other related work findings reveal that the variation in stacking sequence could be one of the major causes of irregular thrust force and delamination effect [23,24].

3.1. Thrust force analysis

The second-order regression models for thrust were intended from the experimental data. The adequacy of the proposed models has been examined by determining the significant factors identified using the variance approach (ANOVA) technique, taking a confidence level of 95% [25]. The regression equation for Thrust force for configuration sequence:

$$A_f = 195.6 - 0.1422 \times N + 0.221 \times f + 0.000038 \times N^2 + \\ + 0.00002 \times f^2 + 0.000135 \times N \times f \tag{1}$$

$$B_f = 321.5 - 0.2004 \times N + 0.042 \times f + 0.000038 \times f^2 + \\ + 0.00002 \times f^2 + 0.000135 \times N \times f \tag{2}$$

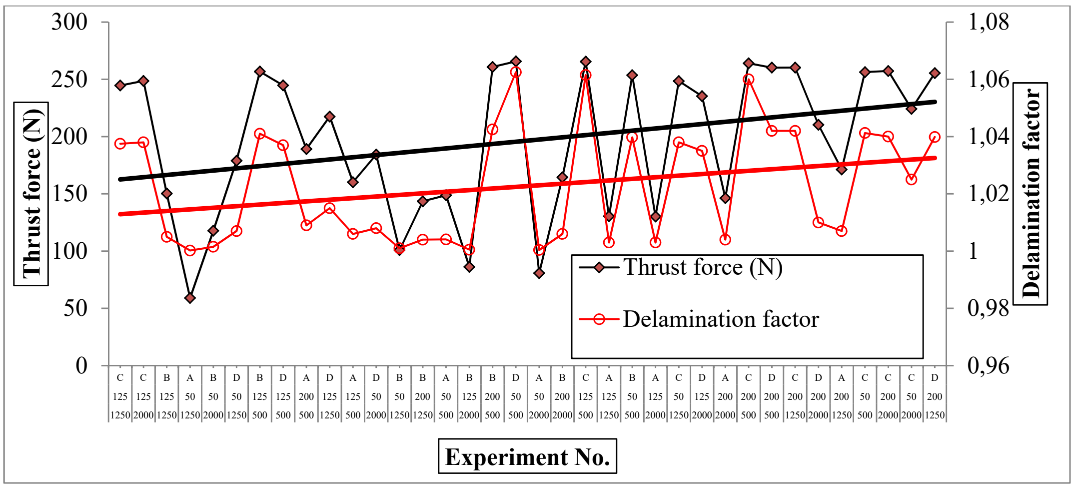

Fig. 3. Thrust force and Delamination variation

$$C_f = 318.9 - 0.1233 \times N - 0.056 \times f + 0.000038 \times N^2 + \\ + 0.00002 \times f^2 + 0.000135 \times N \times f \quad (3)$$

$$D_f = 306.1 - 0.1422 \times N + 0.043 \times f + 0.000038 \times N^2 + \\ + 0.00002 \times f^2 + 0.000135 \times N \times f \quad (4)$$

(Here, unit of N – rpm, f = mm/min).

TABLE 4 indicates that the R-squared value of the developed model is relatively high at 92.47, which suggests that the developed thrust force model is adequate and can predict the output response with fair accuracy. The p values of the model, spindle speed, feed rate, and stacking sequence have values less than 0.05. Thus they are significant parameters in the case of thrust analysis.

Fig. 4 shows the thrust force variation regarding spindle speed and fe rate over different stacking sequences. The sequence analysis of *C4G4* shows the value of the feed rate rises, and the thrust force value also increases. As the feed rate is high, a higher vibration is developed during the time of contact between the composite laminate and the tool. In relation to the lower feed rate, the trend for thrust force at higher speed has increased with respect to the *C5G3* sequence [23]. However, the minimum value of thrust is obtained at a feed rate of 50 mm/min for a speed of 1250 rpm. There is an increasing trend in thrust force variation for *C6G2* and *CG* stacking sequences obtained with respect to feed rate value at slight variations of lower speed [26]. The value of thrust forces decreases as the spindle speed increases [4,27,28]. The *C4G4* sequence achieves the lowest thrust force, while the *C5G3* sequence comes in second. The maximum thrust force, denoted by the green line, has been consistently produced by a low spindle speed and a high feed rate.

3.2. Delamination analysis

The drilling-induced delamination was investigated by simultaneously altering feed rate and speed value. In TABLE 5, R square (coefficient of determination) values of 86.55% indicate

TABLE 4

ANOVA for Thrust force

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
Model	14	119369	119369	8526.4	18.43	0.000	92.47%
Linear	5	102176	102176	20435.3	44.17	0.000	79.16%
N	1	22814	22814	22813.6	49.32	0.000	17.67%
f	1	7452	7452	7452.2	16.11	0.001	5.77%
SS	3	71910	71910	23970.2	51.82	0.000	55.71%
Square	2	3581	3581	1790.4	3.87	0.037	2.77%
$N \times N$	1	3581	3581	3580.7	7.74	0.011	2.77%
$F \times F$	1	0	0	0.1	0.00	0.991	0.00%
2-Way Interaction	7	13612	13612	1944.6	4.20	0.005	10.55%
$N \times F$	1	922	922	922.0	1.99	0.173	0.71%
$N \times C$	3	11345	11345	3781.7	8.17	0.001	8.79%
$F \times C$	3	1345	1345	448.3	0.97	0.426	1.04%
Error	21	9715	9715	462.6			7.53%
Total	35	129084					100.00%
$S = 21.5083$, $R^2 = 92.47\%$, $R^2_{adj} = 87.46\%$							

* Significant term

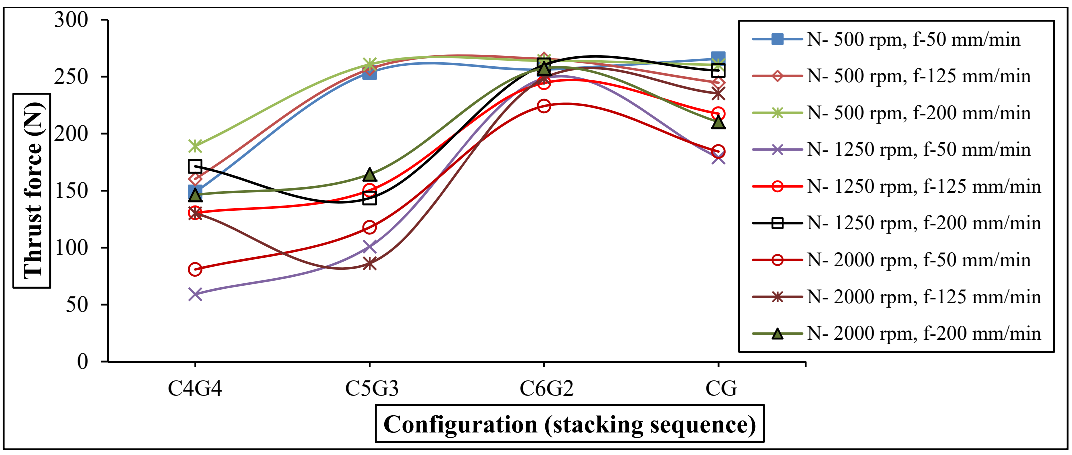

Fig. 4. Thrust force for *C4G4*, *C5G3*, *C6G2*, and *CG* stacking

TABLE 5

ANOVA for Delamination factor

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
Model	14	0.012411	0.012411	0.000886	9.73	0.000	86.65%
Linear	5	0.010697	0.010697	0.002139	23.49	0.000	74.68%
N	1	0.003163	0.003163	0.003163	34.72	0.000	22.08%
f	1	0.000231	0.000231	0.000231	2.54	0.126	1.61%
SS	3	0.007304	0.007304	0.002435	26.73	0.000	50.99%
Square	2	0.000632	0.000632	0.000316	3.47	0.050	4.41%
$N \times N$	1	0.000622	0.000622	0.000622	6.83	0.016	4.34%
$F \times F$	1	0.000010	0.000010	0.000010	0.11	744	0.07%
2-Way Interaction	7	0.001082	0.001082	0.000155	1.70	0.164	7.56%
$N \times F$	1	0.000024	0.000024	0.000024	0.26	0.615	0.17%
$N \times C$	3	0.000976	0.000976	0.000325	3.57	0.031	6.81%
$F \times C$	3	0.000083	0.000083	0.000028	0.30	0.823	0.58%
Error	21	0.001913	0.001913	0.000091			13.35%
Total	35	0.014324					100.00%
$S = 0.009536$, $R^2 = 86.65\%$, $R^2_{adj} = 77.74\%$							

*Significant

the independent variable's ability to predict the variance of output significantly. It is apparent from the analysis that the model is precise and appropriate for delamination. ANOVA table shows that spindle speed and configuration sequence have been the most significant parameters.

The regression equation for the delamination factor

$$A_d = 1.0241 - 0.000045 \times N + 0.000049 \times f + \\ + 0.0000 \times N^2 - 0.000 \times f^2 + 0.000 \times N \times f \quad (5)$$

$$B_d = 1.0645 - 0.000068 \times N + 0.000045 \times f + \\ + 0.000 \times N^2 - 0.000 \times f^2 + 0.000 \times N \times f \quad (6)$$

$$C_d = 1.0683 - 0.000055 \times N + 0.000106 \times f + \\ + 0.000 \times N^2 - 0.000 \times f^2 + 0.00000 \times N \times f \quad (7)$$

$$D_d = 1.0687 - 0.000062 \times N + 0.000054 \times f + \\ + 0.000 \times N^2 - 0.000 \times f^2 + 0.000 \times N \times f \quad (8)$$

(Here, unit of N – rpm, f = mm/min).

For Fig. 5, the *C4G4* stacking analysis, trends for delamination values also increase with the feed rate increase. The delamination decreases as the spindle value increases showing similar trends as thrust values from the *C5G3* stacking analysis. There is again a clear trend for the variation with respect to the feed rate. In the case of stacking sequence *C6G2* and *CG*, a higher value of delamination factor was obtained at a feed rate 200 mm/min. The maximum amount of delamination is generated by higher feed rates as the lowest spindle speed due to the last lamina fracture, with no uniform stress distribution [29]. The delamination factor value is lower at the higher speed at 2000 rpm,

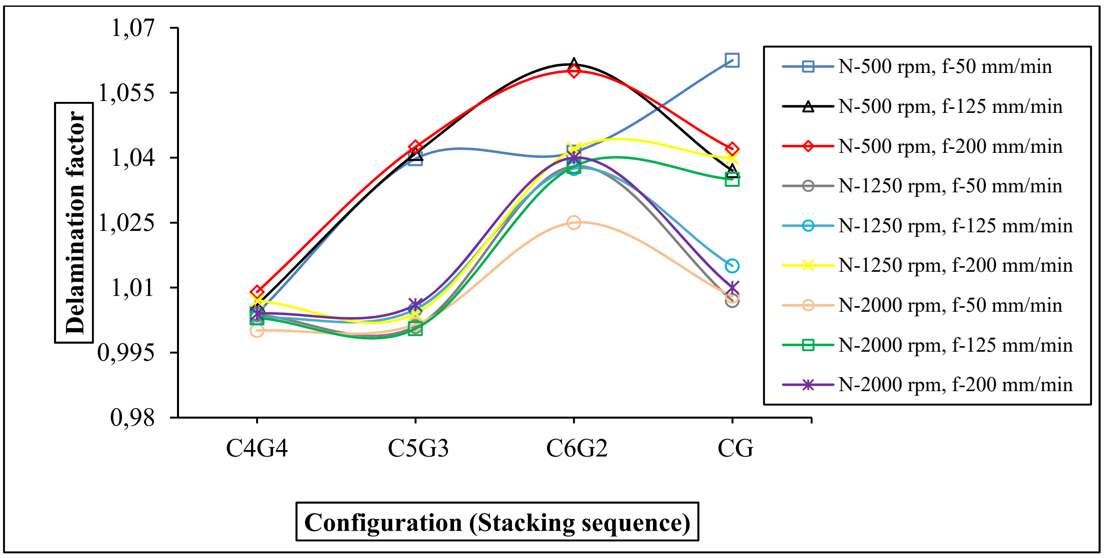

Fig. 5. Delamination for *C4G4*, *C5G3*, *C6G2*, and *CG* stacking

and at the lower feed at 50 mm/min. As the carbon layer has more impact on the thrust force, the stacking sequence has been an efficient parameter to produce delamination. The carbon layer being more rigid helps in preventing bending deformation in the composite [4]. Other similar studies have found lower delamination measurements at higher speeds and lower feed rate value [30].

Prediction with a categorical predictor of stacking sequence was analyzed for appraisal during the drilling of polymer composites reinforced by Carbon/Glass fiber. The desired possible setting for minimum thrust force for a stacking sequence *C4G4* is initiated as the speed of the spindle (*N*-1250 rpm) at level-2 and the tool feed rate (*f*-50 mm/min) at level-1. The desired best possible setting for minimum delamination factor for a stacking sequence *C4G4* is found as the speed of the spindle (*N*-2000 rpm) at level-3 and tool feed (*f*-50 mm/min) at level-1. Due to higher thrust force & delamination factor generation, the undesirable stacking sequences *C5G3*, *C6G2*, and *CG* were addressed.

An in-depth literature search reveals a similar trend in altering thrust force (T_h) as a feed rate (f) change function. The punch effect varies the thrust force directly with the increase in feed rate. Here, the drill bit acts as a punch over the composite surface in an impactful way as the feed rate increases. In turn, the growth of the undeformed chip cross-sectional area increases the thrust value as the feed rate increases. It directs to greater resistance in chip formation for the duration of cutting. The tool feed is essential in the thrust and the experimental results show that the thrust force is increased proportionately with the feed rate. In addition, since the temperature between the tool and the workpiece material increased with medium spindle speed, a lower thrust force was found [7]. Similarly, at a higher spindle speed, the delamination factor drops and results in the efficient cutting of composite materials. Furthermore, the carbon fiber material of the laminated composite serves as a lubricant to reduce the friction force at the chip edges of the drill and reduce surface roughness and damage. Therefore, the findings indicate that a lower delamination factor is observed at an increased spindle speed, confirming a close relationship with polymer machining. Delamination can result from a rise in uncut chip thickness and higher effects of the polymer matrix with an increased feed rate. In addition, the punching effect at higher feed rates increases considerably, leading to damage to delamination at the end of the ply lamina. The fiber layer configuration impacts thrust force generation, and the carbon layer has a larger effect than the glass fiber layer [4].

3.3. Confirmatory test

The optimum value of thrust force and delamination is preferable, as mentioned in TABLE 6. Stacking sequence, A (*C4G4*) is preferable for lower thrust results and delamination. From analysis, it can be concluded that sequence A shows the best results for the responses and among the non-categorical predictor, with a low feed rate.

TABLE 6

Optimal test result

Responses	Optimal setting			Optimal value
	N (rpm)	*f* (mm/min)	*SS*	
Thrust force (newton)	1250	50	*C4G4*	59.05
Delamination factor	2000	50	*C4G4*	1.0001

3.4. Scanning electron microscopy (SEM) analysis

The high-resolution photographs was taken to understand the machining behavior of polymeric stacked composites and drilling-induced damage and defects generation. In its compelling aspect, the sample from the machine, including the inlet, outlet, and boreholes, failed in three different areas. It can see from Fig. 6 that the type of reinforcement used has a strong correlation with the failure mode at the hole inlet. As presented in Fig. 6, the carbon laminate fracture surface is critical, corresponding to fragmentation. At the same time, the fibers in the outlet of a hole broke due to the applied tool motion. The circumferential fibers take a large portion of the applied load and cause fiber failures.

SEM microstructural analyses were conducted on glass/carbon epoxy laminates to understand the degradation mechanisms involved during the drilling test. The form of fiber damage, cavity, fiber, breakage, uncut fibers, fiber protrusions, uneven cut fibers, fiber frying, fiber residues, etc., are observed in the case of carbon/glass epoxy laminate. The finding of the microscopy test investigates the quality of holes drilled and damages induced during the drilling of hybrid composites (Fig. 7). This shows that failure marks and cracks occur due to the effect of thrust force and cutting tool edge. The compressive side is subjected to the development of cracks and the delamination obtained is significant on the top surface. Along with the results, fiber pullout is another effect observed from the periphery in the SEM images. At the top surface, fiber de-bonding has been detected and is the straight result of composites developed by using different layers/stacking of glass and carbon fibers. [4].

Fiber pullout and de-bonding is the most common damage mode obtained in several stacking sequences. A higher feed rate is one of the main factors for heavy surface damage due to increased contact pressure and increased last lamina breakage along the machining zone [31]. Cracks formation may result from strain hardening during the drilling operation. Its rotation produces a moment that pushes the lamina in a downward direction. This bending of the lamina is one of the main reasons for damage and delamination. The fibers are pulled out in the direction of the screw moment [32]. The failure to improperly select process constraints is caused by delamination caused by the presence of a hole. In addition, a constant speed 2000 rpm, feed rate 50 mm/min and a different stacking sequence was observed. It is significant to mention that the initiation of the thrust force is spread through the development of the delaminated zone to a minimum of a broken zone in sequence *C4G4*. But the delaminated areas are increasing in other stacking sequences

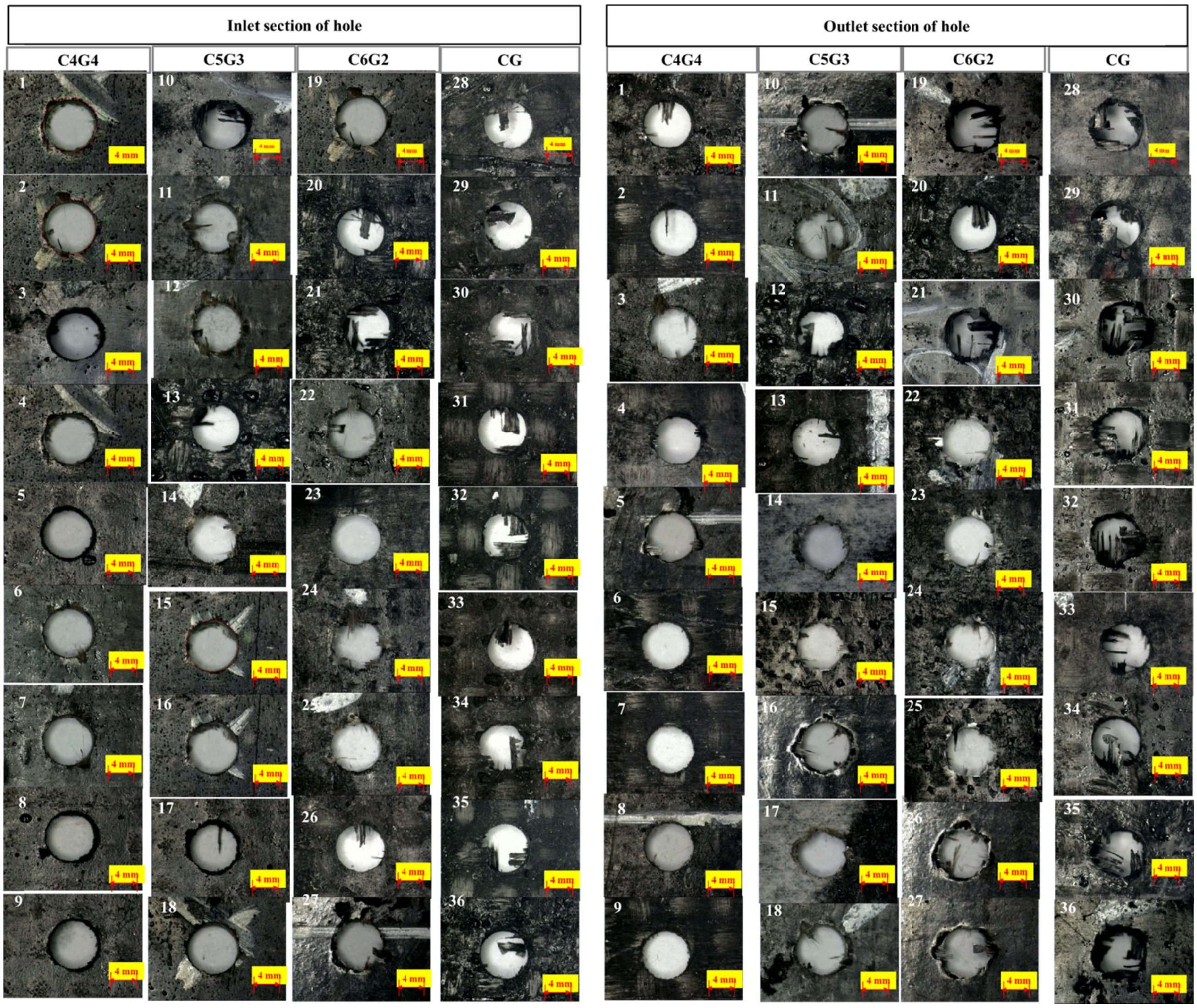

Fig. 6. Drilled hole images at inlet and outlet

because of their stacking configuration, which subsequently precipitates early specimen failure. According to the drilling results, the increase in delamination contributes significantly to the material's work-life being reduced.

4. Conclusions

The stacking of glass and carbon fiber significantly enhances the machinability aspect of the laminate polymers. This article highlights the development of different stacking sequences hybrid composites and their effect on drilling machinability. The thrust force and delamination factor were explored by varying drilling parameters. The following conclusion can be drawn from the obtained results:

- The proposed hybrid laminates composites show that stacking sequences play a significant role in drilling machinability. The stacking process can lower the thrust and delamination generation in the case of hybrid composites.
- Since A (*C4G4*) and D (*CG*) are stacked in the laminate composite, each has four carbon fiber and glass fiber layers. However, the results were entirely different and defined the stacking sequence's positive effect on the response.
- The second-order regression model developed for thrust force and delamination during the drilling of hybrid composite is adequate, and the experimental data well fitted the model.
- The ANOVA for Thrust and delamination indicate that spindle speed (N) and the stacking sequence play a significant role.
- The confirmatory test analyzed and identified stacking sequence A (*C4G4*) to provide optimum thrust and delamination response.
- The findings of the SEM test for breakage analysis show that lower feed rate minimum breakage was found, while higher feed rates a severe breakage found.

The present work findings perceived that the current technique for fabrication (hand layup) is a multi-faceted and broad strategy for laminate production with enhanced machinability due to the stacking of layers (Cf/Gf). In addition, the composite materials in this research article may be improved with the addition of nanofiller such as carbon nanotube, graphene, carbon nanosheets, etc., and stacking of other laminates such as basalt

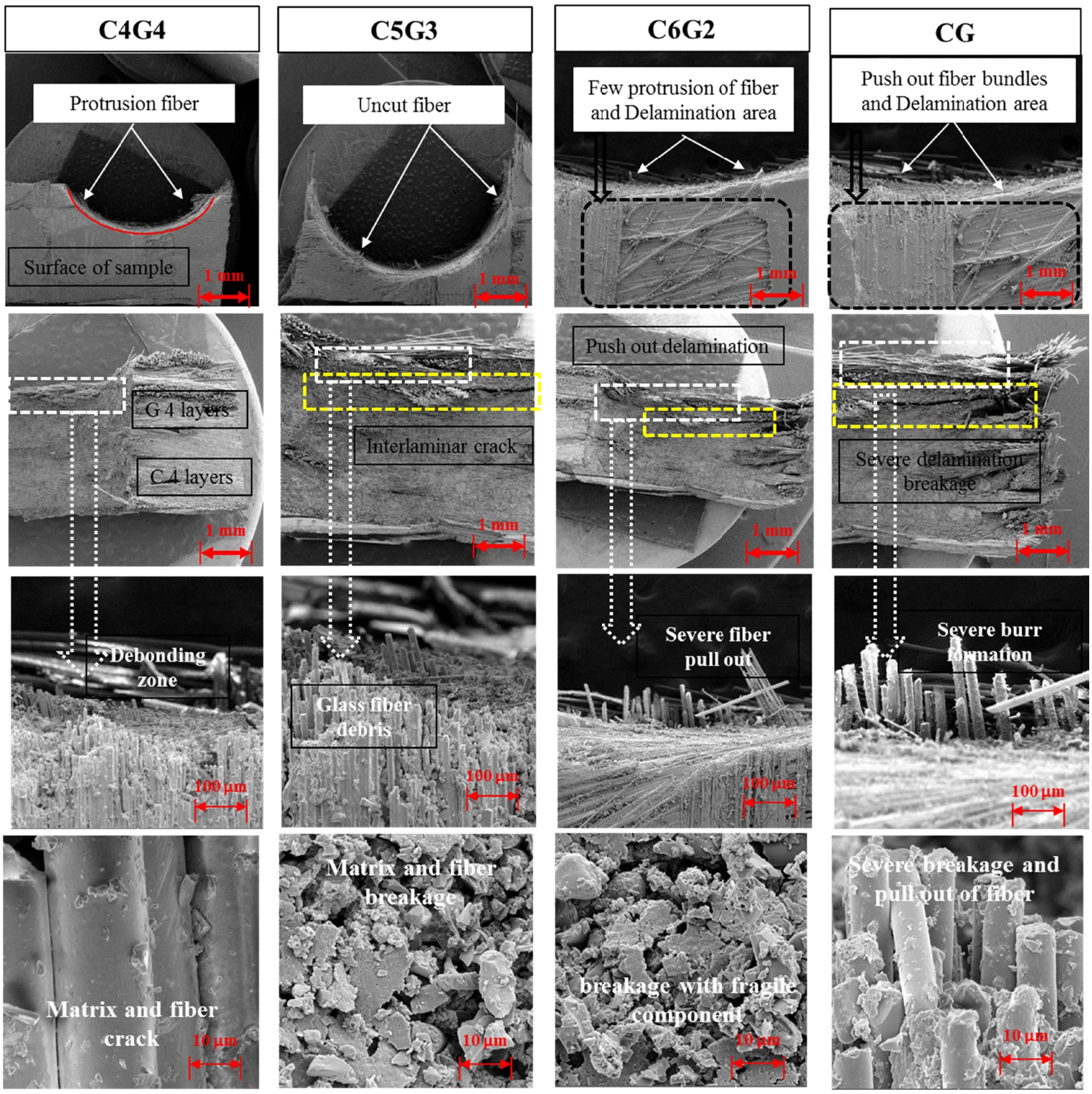

Fig. 7. Borehole damages: Effect of *N*-2000 rpm, *f*-50 mm/min over the *SS*

fabric and aramid. Therefore, this experimentation can lead to a new range of functional material manufacturing at an affordable cost.

Declaration of conflicting interests

There was no potential conflicts of interest were declared by the authors.

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