Journal of Materials and Manufacturing 5(2): 67-78 (2026)

JMM Materials and Manufacturing Journal of Materials and Manufacturing

Effect of Volume Fraction of Fiber Reinforced Plastics on Drilling Performance of GFRP and Hybrid Composites

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Abstract

In this study, the drilling performance of glass fiber-reinforced plastics (GFRP) and various hybrid composite materials was experimentally investigated. Within the scope of the research, the effects of fiber volume fraction (30%, 40%, 50%, and 60%), cutting speed, and feed rate on thrust force, torque, and delamination factor were analyzed in detail. Furthermore, the drilling behaviors of different 40% hybrid composite compositions consisting of binary combinations of glass, carbon, and Kevlar fibers were compared. Experimental results demonstrated that increasing the feed rate and fiber volume fraction (from 30% to 60%) elevated the thrust force and delamination values by increasing cutting resistance; conversely, increasing the cutting speed reduced the thrust force and torque, which is interpreted as a plausible mechanism associated with localized matrix softening driven by cutting zone temperatures, though thermal measurements were not performed. In terms of material composition, the lowest thrust force and delamination were obtained in the 40% glass fiber specimens, whereas higher forces and distinct force fluctuations were observed in the hybrid specimens containing Kevlar and carbon due to constituent modulus mismatches and the tough, ductile nature of Kevlar. The findings obtained provide an important resource for minimizing and optimizing drilling-induced damages in composite structures while explicitly noting experimental constraints such as the exclusion of post-manufacture volumetric characterization and unquantified tool wear across multi-specimen sequences.

Keywords: *Volume fraction, Drilling, Delamination, Glass fiber-reinforced plastics, Hybrid composite*

1. Introduction

Glass fiber-reinforced plastics (GFRP) are widely used in various industries ranging from liquid tanks to the manufacturing of marine and aerospace vehicles due to their superior properties such as high strength, excellent corrosion resistance, low thermal conductivity, high fatigue strength, and low cost [1-4]. The properties of fiber-reinforced composites can be improved by altering the fiber volume fraction within the structure. As the fiber volume fraction within the composite increases, its mechanical properties also increase to a certain extent. However, with the increase in the fiber volume fraction, the matrix amount decreases, and insufficient matrix leads to a deterioration of the composite material's properties. In addition, a high fiber volume fraction makes the machining of the material difficult. Therefore, depending on the targeted application, the optimum fiber volume fraction should be preferred [5-8].

Although fiber-reinforced polymers (FRP) are predominantly produced near net shape, they frequently require secondary finishing operations. In this context, drilling is the most commonly used operation during the

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DOI: 10.5281/zenodo.22772846
Received: 12 August 2026, Revised: 10 September 2026, Accepted: 15 September 2026
ISSN: 2822-6054 ©2026 The Author(s). Published by JMM under CC BY 4.0

assembly stage. Due to the anisotropic, heterogeneous, and abrasive structures of FRP, various problems arise during machining processes. Delamination, which is the most critical of these problems, causes a reduction in the bearing and fatigue strength of the holes, thereby shortening the service life of the components. Although frequent industrial claims cite significant financial losses and high component rejection rates due to delamination in aerospace manufacturing [9-11] specific scrap metrics vary depending on the assembly process, component class, and historical context.

Extensive research has investigated the machinability of fiber-reinforced composites. For instance, Khashaba et al. [12] investigated the effects of cutting parameters on thrust force, torque, and delamination in the drilling of composites with varying fiber volume fractions. They reported that the feed rate and fiber volume had a direct impact on thrust forces and torques. Furthermore, they observed that the size of delamination decreased with a reduction in the feed rate, whereas the cutting speed did not have a significant effect on the delamination size. Velayudham et al. [13] stated that the increase in the fiber volume fraction enhances the strength and rigidity of the material, while also increasing the cutting resistance and tool wear during drilling. El-Sonbaty et al. [14] investigated the effects of cutting speed, feed rate, drill diameter, and fiber volume fraction (V_f) on thrust force, torque, and surface roughness in the drilling of fiber-reinforced composites. They reported that cutting speed has a negligible effect on the thrust force and surface roughness of the epoxy matrix. For glass fiber-reinforced epoxy composites within a V_f range of 9.8% to 23.7%, it was determined that thrust force and torque decreased as the cutting speed increased, whereas they increased as the fiber volume fraction rose. Gill et al. [15] investigated the effects of fiber volume variations on mode I and mode II delamination behavior in satin woven carbon fiber/epoxy composites, determining that a higher fiber volume fraction and a greater number of transverse yarn bundles along the delamination plane provided higher fracture toughness. Abdullbudan et al. [5] demonstrated that an increase in the fiber ratio reduces hole quality by elevating tool wear, the delamination factor, and surface roughness. Mudegowdar [16] investigated the drilling behavior of titanium dioxide and zinc sulfide-filled glass fabric-reinforced polymer composites, reporting that filler content levels within the matrix (1%, 2%, and 3%) increased the damage factor.

While the applications of fiber-reinforced polymer composites in industrial fields are expanding, drilling-induced damages encountered during the assembly of hybrid composites consisting of different fiber combinations stand out as a critical research area. Although the machinability and delamination analyses of traditional glass fiber-reinforced plastics have been intensively investigated in the literature [1, 2, 17-19], interest in the behavior of hybrid composite structures where different fiber types are used together to enhance structural performance has increased in recent years [9]. Particularly during the drilling of hybrid composites consisting of binary combinations of glass, carbon, and Kevlar fibers, significant changes and force fluctuations occur in thrust force and delamination mechanisms due to the differing mechanical properties of each fiber [20]. While prior studies have separately addressed conventional GFRP machining and limited hybrid stacking behaviors, the concurrent evaluation of nominal target fiber volume fraction variations alongside glass/carbon, glass/Kevlar, and Kevlar/carbon hybrid configurations under dry drilling conditions remains less systematically explored. In this context, investigating and optimizing the drilling performance of hybrid composites with different fiber compositions alongside cutting parameters is of great importance for enhancing component quality in industries such as aerospace and automotive [21-24].

Although there are numerous studies in the literature investigating the effects of cutting parameters on thrust force, delamination, and surface quality in the drilling of GFRP, the number of studies addressing the effects of fiber volume fraction on drilling performance is quite limited. In this study, the drilling of glass fiber-reinforced plastics with four different fiber volume fractions using various cutting parameters was investigated and evaluated based on thrust force, torque, and delamination criteria. Furthermore, the drilling behaviors of different hybrid composite samples consisting of binary combinations of glass, carbon, and Kevlar fibers at a 40% volume fraction were compared.

2. Material and Method

Glass fiber-reinforced epoxy composite plates with varying fiber volume fractions were manufactured for machinability tests. For this purpose, 14-ply glass fiber fabrics with a 0°/90° fiber orientation were utilized, and

composite plates with a thickness of approximately 4 mm were prepared at nominal target fiber volume fractions of 30%, 40%, 50%, and 60%. To investigate the effect of hybridization on machinability behavior, the total number of plies and the fiber volume fraction were kept constant at 14 and 40%, respectively; symmetric hybrid composite plates featuring Kevlar/glass (K/G), carbon/glass (C/G), and Kevlar/carbon (K/C) combinations were prepared. The exact individual ply-by-ply stacking sequences and constituent-level fiber volume contributions for each hybrid variant were not recorded during original manufacturing; hence, hybrid panels are evaluated based on their overall symmetric 14-ply and 40% nominal composition framework. All specimens were fabricated using the vacuum bagging method, and the primary stages of the manufacturing process are schematically illustrated in Fig. 1.

In the initial stage of production, glass, carbon, and Kevlar fiber fabrics were cut in accordance with the specified plate dimensions. The masses of the fiber fabrics were measured using a precision balance, and the required amounts of epoxy resin and hardener were determined based on the targeted fiber volume fractions. After homogenizing the resin and hardener with the aid of a mechanical stirrer, the layering process was initiated. The composite plies were placed sequentially onto a heatable aluminum mold, and each fiber layer was uniformly wetted with the epoxy matrix using a roller. Following the placement of a total of 14 fiber layers, a peel ply, a release film, and a breather were laid over the laminate in that order. Subsequently, a vacuum bag was positioned to cover the entire lay-up system and sealed tightly to the aluminum mold using sealant tape to prevent air leakage, thereby establishing a controlled vacuum environment along the laminate.

The application of vacuum ensured the homogeneous distribution of the epoxy matrix within the fiber layers, eliminated potential voids formed during lamination, and aimed to maintain the targeted fiber/matrix ratio through the extraction of excess resin. After confirming that the resin had sufficiently permeated all layers, the specimens were cured under a vacuum bag at 80 °C for 8 hours. In this study, the 30%, 40%, 50%, and 60% fiber volume fractions represent the nominal target fiber volume fractions specified during laminate manufacturing. Post-manufacturing experimental verification of the fiber volume fraction via burn-off tests, laminate density, void content, and thickness was not performed; therefore, these values are designated strictly as nominal target parameters, and unquantified variations in tool wear across multi-specimen drilling sequences are acknowledged as an experimental limitation. Upon completion of the curing process, the composite plates were demolded and cut into the required dimensions for machinability tests. The fiber wetting, layering, vacuum bagging, and curing stages performed during the production process are illustrated in Fig. 1.

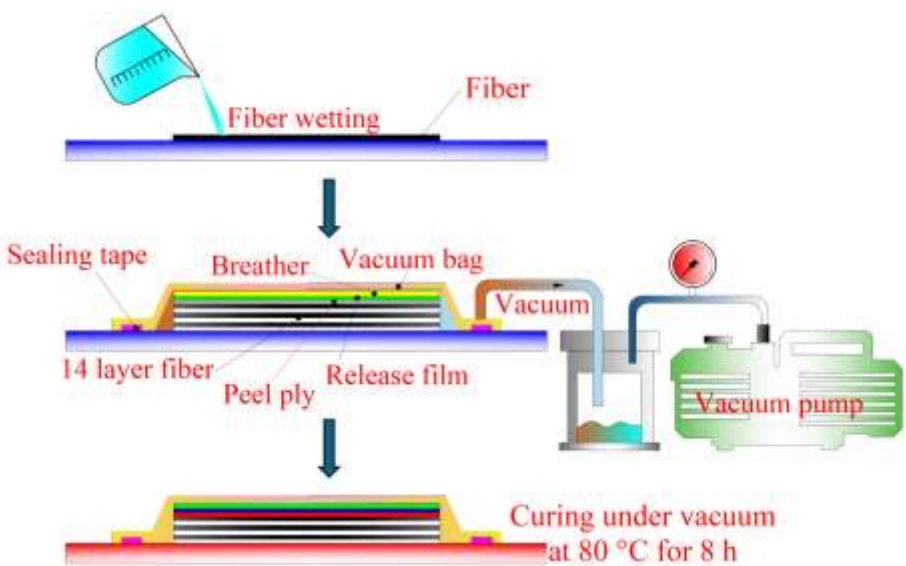

Fig. 1. Schematic representation of the vacuum bagging and curing process used for manufacturing the composite laminates.

As detailed in the experimental procedure, the produced laminates include GFRP panels with four distinct volume fractions (30%, 40%, 50%, and 60%) as shown in Figure 2a, along with three binary hybrid combinations (Kevlar/glass, carbon/glass, and Kevlar/carbon) maintained at a 40% fiber content (Figure 2b).

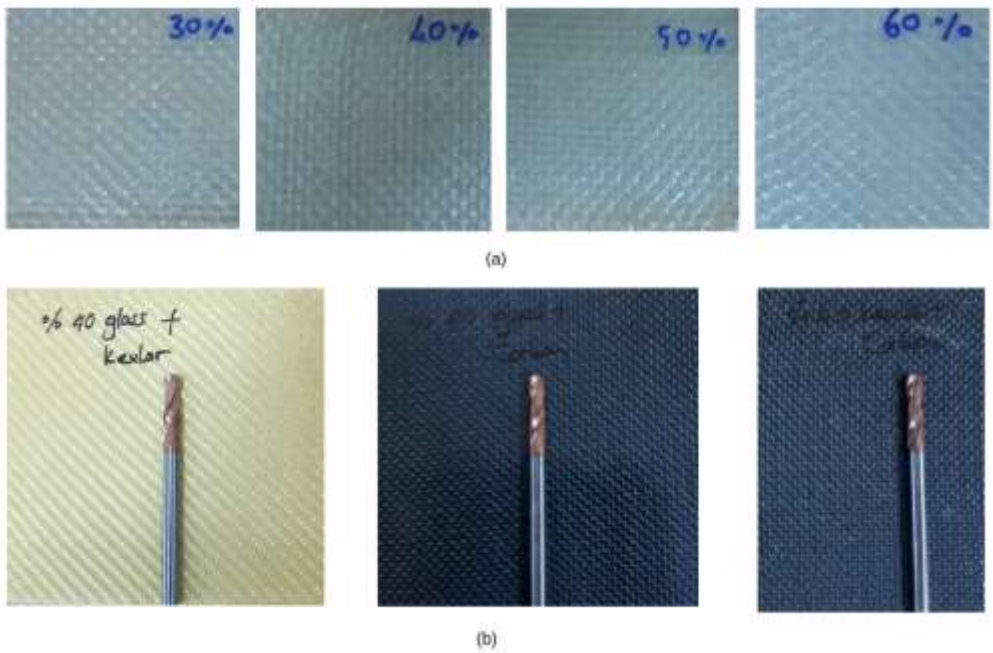

Fig. 2. (a) GFRP that have different volume fractions and (b) different hybrid composite materials used in the experiments

In this study, experimental work was carried out on a Quaser MV154 C three-axis vertical machining center with a maximum spindle speed of 10,000 rpm (Figure 3a). All drilling tests were performed under dry cutting conditions. To mitigate cumulative tool wear effects, a fresh drill bit was implemented per material group. Carbide cutting tools with a diameter of 6 mm, a 140° point angle, a 30° helix angle, and a TiAlN coating, as shown in Figure 3b, were used in the drilling process. Thrust forces were measured using a three-component dynamometer (Kistler type 9257B) mounted on the CNC machine table (Figure 3c). In addition to the thrust force, the drilling torque (M_z) was directly measured using the Kistler 9257B piezoelectric dynamometer. The dynamometer was connected to a Kistler 5070A charge amplifier and a Kistler 5697A data acquisition system, and the acquired signals were monitored and processed using DynoWare software. The torque response was obtained from the M_z channel of the dynamometer. The delamination factor (F_d), defined as the ratio of the maximum damaged diameter to the nominal hole diameter (6 mm), was evaluated for both entrance and exit regions using an Olympus SZX7 stereo microscope with digital image processing. Three different cutting speeds (57, 94, and 132 m/min, corresponding to spindle speeds calculated for a 6 mm diameter) and three different feed rates (150, 250, and 350 mm/min) were selected under axial feed control. The experimental parameters are shown in Table 1.

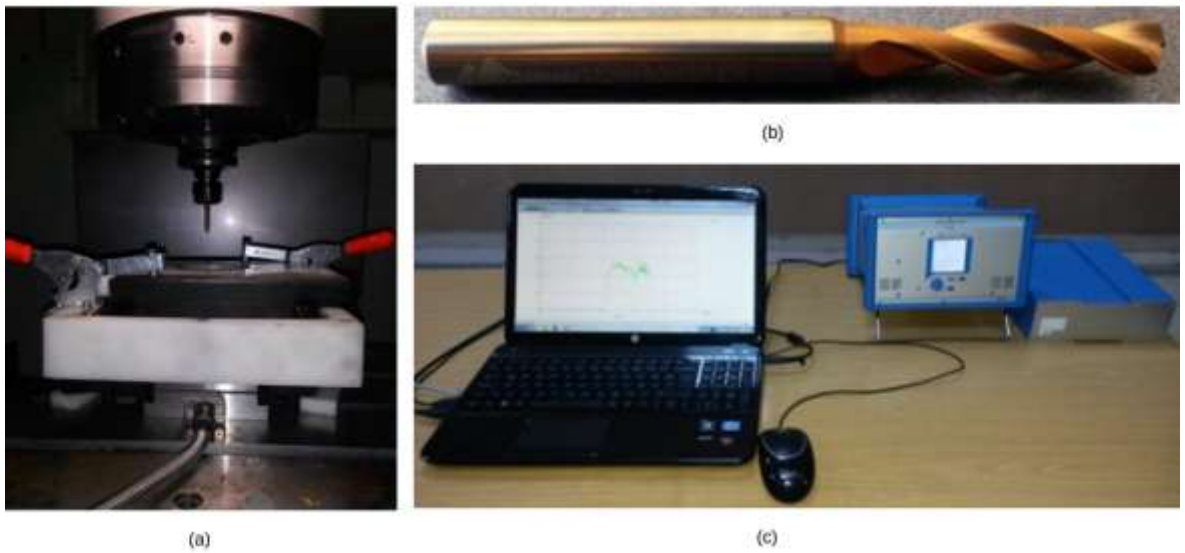

Fig 3. (a) Experimental set-up, (b) drill, and (c) PC and force measurement equipment

Table 1. Experimental parameters

Fiber volume fraction	Feed rate (mm/min)	Cutting speed (m/min)
30% glass		
40% glass		
50% glass		
60% glass	150, 250, 350	57, 94, 132
40% carbon + glass		
40% Kevlar + glass		
40% Kevlar + carbon		

3. Results and Discussion

3.1. The effect of % fiber volume fraction on thrust force, torque and delamination

In the drilling process, the forces in the X and Y directions are very small compared to the axial force (Z direction); therefore, only the thrust force was considered. The variations in thrust force and delamination factor for volume fractions (30%, 40%, 50%, and 60%) at a constant cutting speed of 57 m/min are shown in Figure 3. It is observed that the thrust force increases with an increase in feed rate. Furthermore, as the fiber volume fraction increases (from 30% to 60%), higher thrust force is required to drill the composite plate. Quantitatively, increasing the nominal fiber volume fraction from 30% to 60% at a feed rate of 150 mm/min resulted in an approximately 35% increase in peak thrust force. This increase in thrust force values is attributed to the increase in the mechanical properties and, consequently, the cutting resistance of the GFRP. These obtained results are consistent with the studies of Khashaba et al. [12] and El-Sonbaty et al. [14].

The delamination factor (F_d) is defined as the ratio between the maximum damaged diameter and the drilled hole diameter. Figure 4 illustrates the effect of feed rate and fiber volume fraction (30%, 40%, 50%, and 60%) on delamination at a constant cutting speed of 57 m/min. It is observed that the delamination factor increases with an increase in feed rate. Furthermore, the lowest delamination occurred in the sample with a 30% fiber volume fraction, whereas the highest delamination took place in the sample with a 60% fiber volume fraction. Minimum thrust force and delamination factor values were observed in the sample with 30% fiber content at a feed rate of 150 mm/min. These values increased with the increase in fiber percentage and reached their maximum level in the sample with 60% fiber content at a feed rate of 350 mm/min. Consequently, at high fiber concentrations, the decrease in the matrix ratio and the increased susceptibility of inter-fiber interfacial bonds

to localized fractures accelerate the tendency for interlayer separation (delamination) at the drill exit. In GFRP composites, an increase in the proportion of glass fiber within the material enhances its mechanical properties and, consequently, its cutting resistance against the cutting tool. This situation leads to an increase in the thrust force exerted by the drill on the material during the drilling process; this increased thrust force triggers the tendency for layer separation at the hole exit, resulting in an increase in delamination.

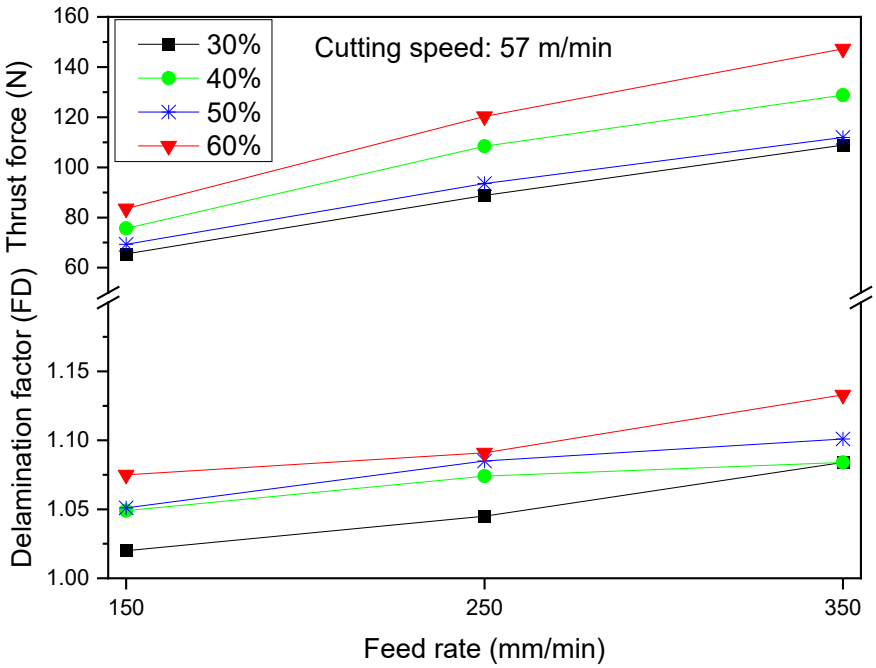

Fig. 4. Thrust force and delamination factor variations with feed rate and fiber content

The effect of fiber volume fraction and cutting speed on thrust force and torque is illustrated in Figure 5. As the cutting speed increased, the thrust force and torque rapidly decreased. Although direct thermal measurements were not performed in this study, this behavior is interpreted as a plausible mechanism grounded in prior literature, wherein local temperature elevation in the cutting zone at higher cutting speeds induces matrix softening, thereby reducing material resistance against cutting. To minimize cutting forces and torque in the drilling of GFRP composites, high spindle speeds should be preferred. These results are consistent with the findings of the studies by Babu and Philip et al. [25] and Campos Rubio et al. [26]. Higher thrust force and torque were measured in the drilling of material produced at a higher fiber concentration.

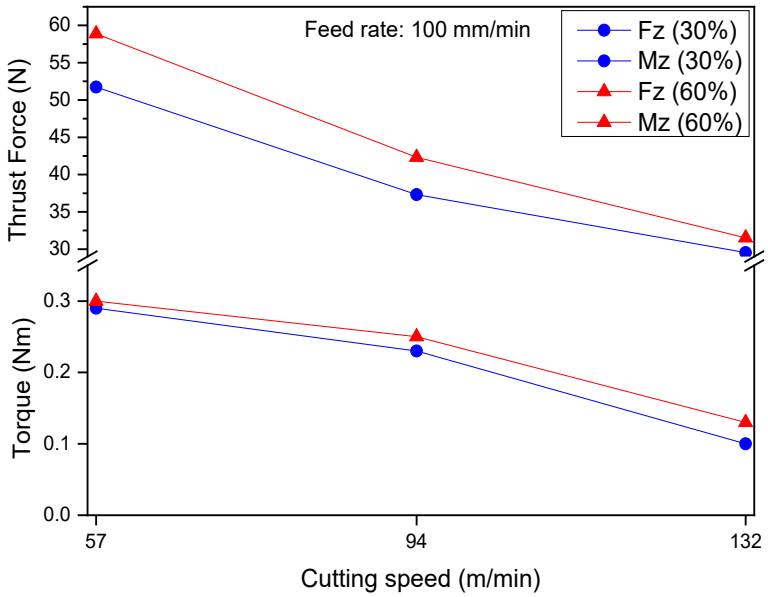

Fig. 5. The effect of cutting speed and volume fraction on thrust force and torque

When examining the images of the drilled samples given in Figure 6, it is clearly seen that the amount of damage and delamination around the holes changes significantly depending on both the feed rate and the fiber volume fraction. When the feed rate is increased from 150 mm/min to 350 mm/min, an increase in layer separations and surface distortions is observed at the hole exit. This situation supports the theoretical inferences that the axial thrust force increases with the increasing feed rate and, accordingly, the tendency for delamination accelerates. Similarly, the increase in the volumetric fiber ratio from 30% to 60% negatively affected the hole exit quality because it increased the material's resistance to cutting and the required thrust force. The visual data are consistent with the mechanical behavior and cutting resistance analyses expressed in the text.

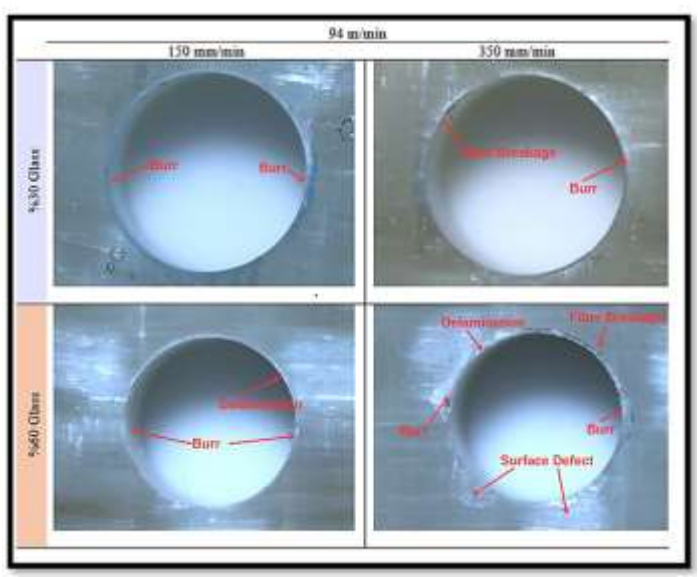

Fig. 6. Bore hole quality images of composite specimens with different glass fiber ratios and feed rates (94 m/min cutting speed)

3.2. The effect of carbon + glass, Kevlar + glass and Kevlar + carbon content on thrust force and delamination

In the second part of the experiments, the drilling performance of three different polymer composite materials with various compositions was investigated. The experiments were carried out using the cutting parameters in Table 1. The effect of cutting speed and feed rate on the thrust force during the drilling of 40% glass, 40% carbon + glass, 40% Kevlar + glass, and 40% Kevlar + carbon samples is shown in Figure 7. The experimental results show that the thrust force increases with an increase in the feed rate for all samples. Increasing the cutting speed from 57 m/min to 94 m/min, on the other hand, reduces the thrust forces. It was observed that combinations of higher cutting speed and lower feed rate significantly decrease the thrust forces. When evaluated in terms of material composition, the lowest thrust force was obtained in the sample with a 40% glass fiber volume fraction, while the highest thrust force was obtained in the 40% Kevlar + carbon fiber sample. Particularly at low feed rates, the thrust force generated during the drilling of the 40% Kevlar + carbon fiber was approximately twice as high compared to the 40% glass fiber. This situation stems from the high mechanical properties of Kevlar fibers and their high resistance to shear stresses. Since Kevlar fibers undergo elastic deformation rather than being easily cut by the cutting tool edge and resist through a fiber breakage mechanism, they significantly increase the axial thrust force and torque. As can be seen from the graph, the thrust forces of the 40% glass and 40% carbon + glass samples turned out to be close to each other. Similarly, the fact that groups containing Kevlar (40% Kevlar + glass and 40% Kevlar + carbon) exhibited similar force values among themselves is an indicator of the mechanical superiority and dominant role of the Kevlar phase in cutting resistance. The addition of Kevlar to the composite structure makes the drilling process more difficult by increasing the thrust force.

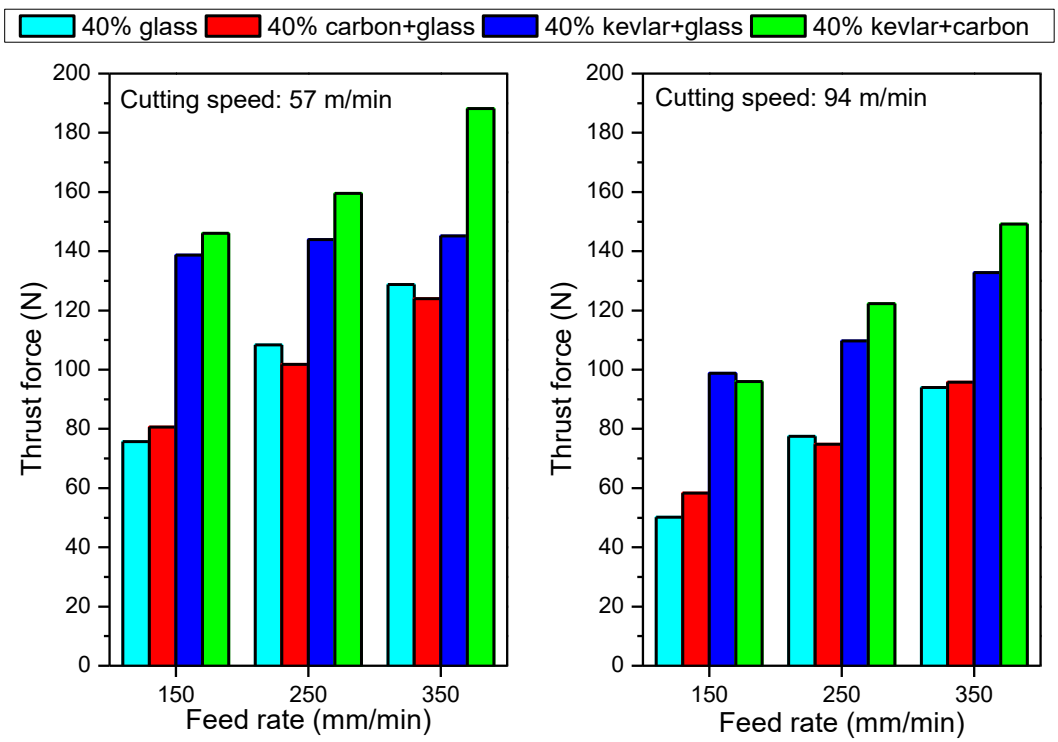

Fig. 7. Effect of material composition on thrust force

The variation curves of the thrust force over time for all samples during the drilling of a hole are shown in Figure 8. The thrust force variation during the drilling of the sample with a 40% glass fiber volume fraction exhibited a stable trend, excluding the entry and exit of the cutting tool. The thrust force variation in the drilling of the 40% carbon + glass fiber sample showed slight fluctuations. However, high-amplitude force fluctuations were obtained during the drilling of the 40% Kevlar + glass and 40% Kevlar + carbon samples. In the absence of micrographic fracture inspection of the chips, the reason for these fluctuations is the high toughness of the Kevlar fiber and the inter-fiber strength mismatch; the difference in the modulus of elasticity among the matrix, carbon, glass, and Kevlar phases leads to instantaneous resistance changes as the drill bit advances and, consequently, to axial force oscillations [27, 28]. The observed force fluctuations and fiber pull-out tendencies are consistent with the results of drilling studies conducted by Pathak et al. [29] on carbon-Kevlar hybrid composites, confirming the decisive role of the ductile and tough structure of Kevlar in the cutting mechanisms.

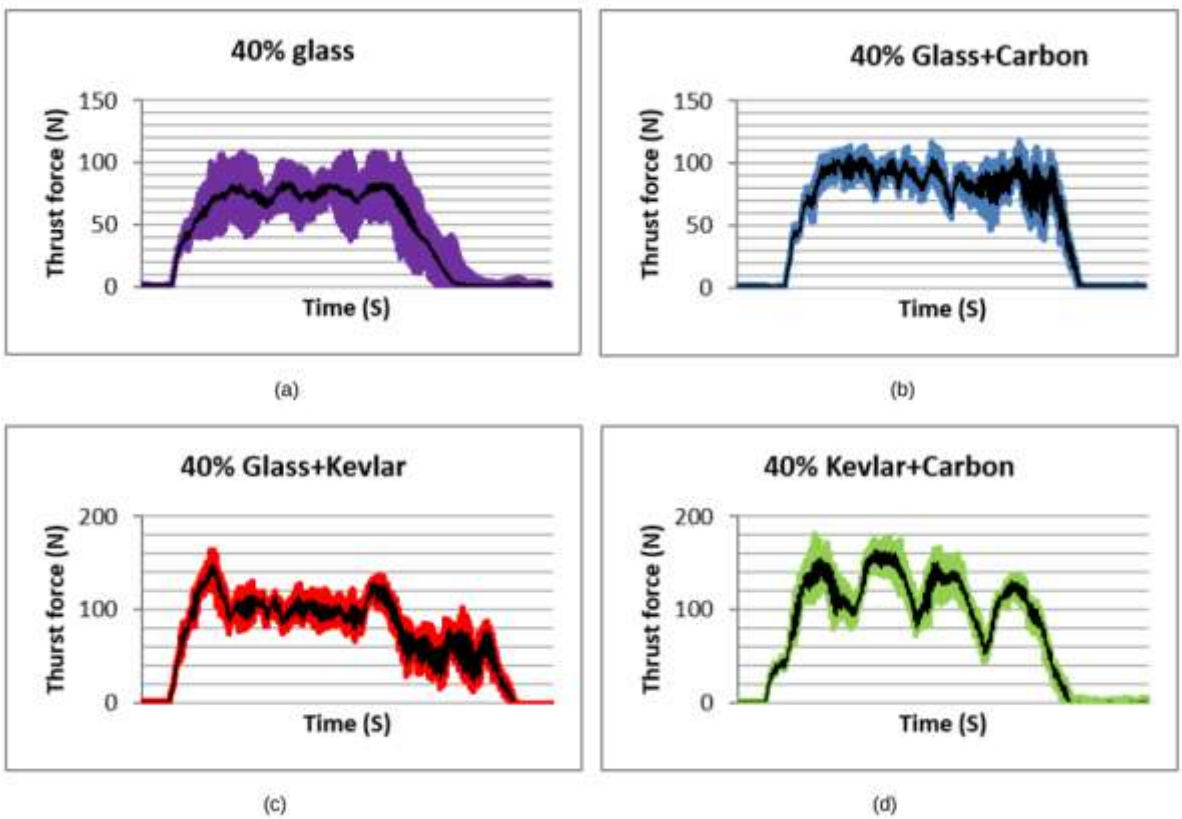

Fig. 8. Thrust force variation with time for all specimens

As shown in Figure 9, the smallest delamination was obtained in the drilling of the 40% glass fiber, while the largest delamination occurred in the 40% Kevlar + glass sample. The delamination generated in the drilling of the samples containing 40% glass and 40% carbon + glass fibers is at lower levels. However, quite high levels of delamination were calculated in the 40% Kevlar + glass and 40% Kevlar + carbon samples. In traditional glass- and carbon-reinforced composites, as the drill bit exits from the bottom surface, opening in the final layers becomes dominant due to the effect of the axial thrust force; therefore, exit delamination are larger than entrance delamination. In all samples, exit delamination were greater than entrance delamination.

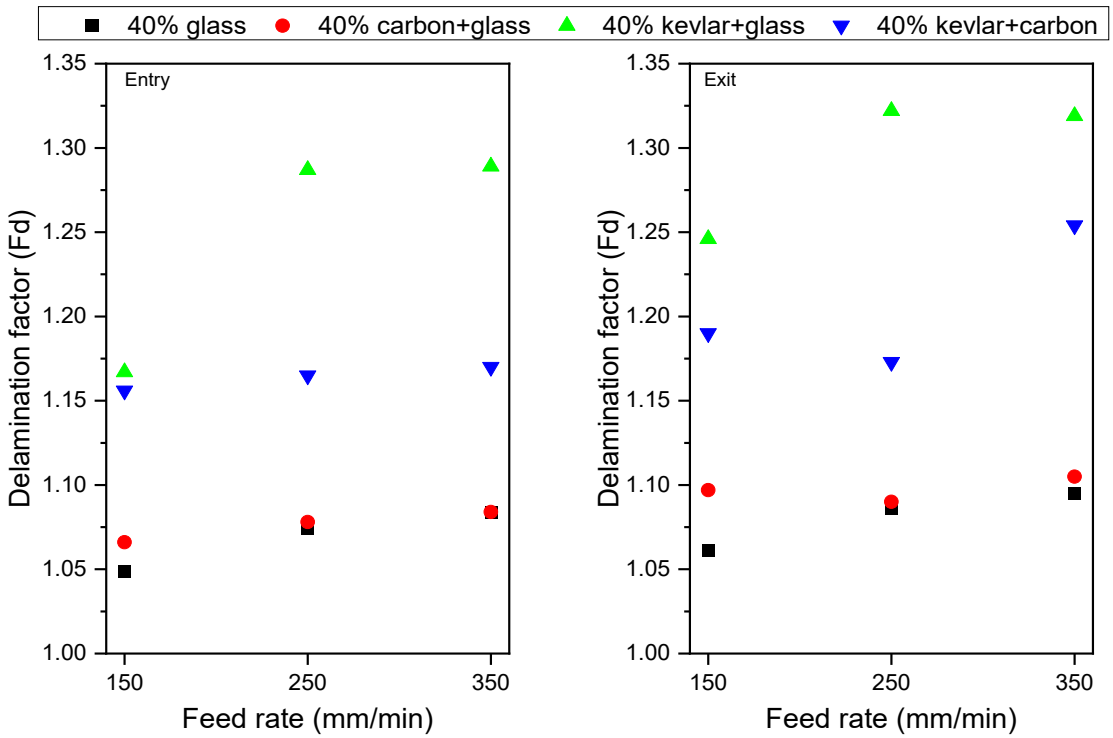

Fig. 9. Effect of material composition on delamination damage

4. Conclusions

In this study, the drilling performance of GFRP and hybrid composite materials was investigated experimentally, and the effects of cutting speed, feed rate, fiber volume fraction, and material composition on thrust force, torque, and delamination factor were examined. The main conclusions obtained are as follows:

- In all samples, the increase in feed rate and fiber volume fraction increased the thrust force and delamination due to the rise in cutting resistance. While the minimum thrust force and delamination values occurred in the sample with a 30% fiber ratio at a feed rate of 150 mm/min, the maximum values were obtained in the sample with a 60% fiber ratio at a feed rate of 350 mm/min.
- Increasing the cutting speed resulted in a decrease in thrust force and torque values within the investigated range, attributed to plausible matrix softening mechanisms. To obtain low cutting force and torque in GFRP drilling operations, high spindle speeds should be preferred.
- In the second stage, where hybrid composites were investigated, the lowest thrust force was observed in the 40% glass fiber sample, while the highest thrust force was obtained in the 40% Kevlar + carbon fiber sample. The addition of Kevlar to the composite structure made the drilling process more difficult by increasing the cutting resistance and thrust force.
- While the drilling of the 40% glass fiber sample exhibited a stable thrust force trend, prominent force fluctuations occurred in the hybrid composites containing Kevlar.
- This study has clearly demonstrated the critical role of cutting parameters and fiber combinations on the drilling performance of composite plates within the tested experimental boundaries (6 mm drill diameter, dry drilling, specific feed and speed ranges). The findings serve as a targeted guide for selecting optimal parameters (such as high cutting speed and low feed rate) to minimize delamination damage, while acknowledging constraints such as nominal target volume fractions and unquantified tool wear.

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