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Effect of drilling parameters on hole quality in drilling of pultruded GFRP composite material: Surface roughness, thrust force and delamination factor

Pultrüzyon ile üretilen GFRP kompozit malzemenin delinmesinde delme parametrelerinin delik kalitesine etkisi: Yüzey pürüzlülüğü, itme kuvveti ve delaminasyon faktörü

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Abstract

The use of fiber reinforced composite materials (FRP) has increased in many areas. These materials need to be processed with some machining methods according to their usage areas, but their machinability is difficult. In this study, surface roughness (SR), delamination factor (F_d) and thrust forces were investigated in the drilling of glass fiber reinforced composite material (GFRP) produced by pultrusion with a coated and uncoated drill. Microstructures of chips formed during drilling were investigated and their effects on surface roughness were determined. Three different cutting speeds (60, 70, 80 m/min) and feed rates (0.06, 0.09, 0.12 mm/min) were selected as machining parameters. At the end of the study, it was found that feed rate had a more significant effect on surface roughness, delamination factor and thrust force. It was observed that as the cutting speed increased, the surface roughness, thrust force and delamination factor decreased. The lowest thrust force and F_d occurred at a cutting speed of 80 m/min and a feed rate of 0.06 mm/min. However, the lowest SR was obtained at a cutting speed of 70 m/min and a feed rate of 0.06 mm/min.Better results were obtained with TiN coated drills compared to uncoated drills.

Keywords: GFRP, Drilling, Delamination factor, Thrust force, Surface roughness

Öz

Fiber takviyeli kompozit malzemelerin birçok alanda kullanımı artmıştır. Bu malzemeler kullanım alanlarına göre bazı talaşlı imalat yöntemleri ile işlenmesi gerekmektedir fakat işlenebilirlikleri zordur. Bu çalışmada pultrüzyon ile üretilmiş cam fiber takviyeli kompozit malzemenin kaplamalı ve kaplamasız matkap ile delinmesinde yüzey pürüzlülüğü, delaminasyon faktörü ve itme kuvvetleri incelenmiştir. Delme sırasında oluşan talaşların mikro yapıları incelenmiş ve yüzey pürüzlülüğüne etkileri belirlenmiştir. İşleme parametreleri olarak üç farklı kesme hızı (60,70, 80 m/dk) ve ilerme oranı (0.06, 0.09, 0.12 mm/dk) seçilmiştir. Çalışma sonunda, ilerleme oranı yüzey pürüzlülüğü, delaminasyon faktörü ve itme kuvveti üzerinde daha belirgin etki yaptığı bulunmuştur. Kesme hızı arttıkça yüzey pürüzlülüğü, itme kuvveti ve delaminasyon faktörünün azaldığı görülmüştür. İtme kuvveti ve delaminasyon faktörü en düşük 80 m/dk kesme hızı ve 0.06 mm/dk ilerleme oranında oluşmuştur. Ancak en düşük yüzey pürüzlülüğü 70 m/dk kesme hızı ve 0.06 mm/dk ilerleme oranında çıkmıştır. TiN kaplı matkaplarda kaplamasız matkaplara kıyasla daha iyi sonuçlar elde edilmiştir.

Anahtar kelimeler: GFRP, Delme, Delaminasyon faktörü, İtme kuvveti, Yüzey pürüzlülüğü

1 Introduction

Fiber-reinforced polymers (FRPs) have many advantages, but it is challenging to machine FRP composites due to their anisotropy. The drilling procedure for these materials presents distinct challenges that are not typically encountered in other material types. The delamination between layers, protrusion of fibers from the drilled hole edges of the composite, commonly referred to as fiber pull-out, spalling of the composite, hole shrinkage and thermal degradation are common defects that can occur during FRP composite drilling [1]. The presence of delamination in the drilled hole is widely recognized as a critical defect that can lower the strength of the material. This defect has the potential to adversely affect the durability of the composite, leading to a shortened service life when subjected to cyclic loading conditions. The phenomenon of delamination has the potential to impose restrictions on the utilization of FRPs in the domain of structural engineering [2-5].

Glass fiber-reinforced polymer (GFRP) composites have become prevalent in a variety of technical fields, including the automotive, aircraft, and sea vehicle industries, as well as in the manufacture of spaceships. This is due to the several advantages that GFRP composites offer. GFRP composites possess a range of advantageous characteristics, including notable specific stiffness and strength, suitability for use in lightweight constructions, resistance to fatigue, and resilience to chemical exposure. The composites of FRPs also display a low level of thermal conductivity [6]. The aforementioned errors are relevant to GFRP composites and

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represent a significant area of investigation aimed at improving the drilled hole quality of GFRP materials.

In their study, Kılıçkap et al. [7] performed drilling on GFRP woven composites made of uni-directional (UD), ±45° and 0°/90° glass fibers. The findings put forward that different values of feed rate along with cutting speed exert notable impacts on the process outcomes. The temperature got lowered as the feed rate increased, whereas cutting speed rise resulted in an elevation of the cutting temperature. They also established the importance of delamination and composite strength's relation.

Chadha et al. [8], conducted an analysis for different parameters which have effects in the process of drilling GFRP's. The researchers examined multiple parameters, to analyze the delamination in the composite material. The study employed to achieve the objective of minimizing delamination.

The severity of residual tensile strength for unidirectional glass fiber embedded epoxy materials after drilling was assessed by Kishore et al. [9]. The investigation has established the most suited parameters of drill point geometry, cutting speed, and feed rate to attain the maximum residual tensile strength in drilled UD-GFRP laminates. The findings of the study indicate that the residual tensile strength of drilled laminates is notably influenced by the damage caused during drilling, particularly when higher cutting speeds are employed.

Mohan et al. [10], employed the Taguchi approach to enhance drilling performance in GFRP composite materials by optimizing cutting parameters. The impact of various factors on the drilling outcomes was assessed using ANOVA. Experiments were executed on a CNC machining center to investigate the correlation between material parameters and the process of cutting. According to the findings of the Taguchi method analysis, it was determined that the thrust force was more influenced by the speed and drill size rather than the thickness of the specimen and the feed rate.

Shunmugesh et al. [11], studied optimizing the GFRP composite drilling. The experiment utilized a drilling method that followed the L27(3^{13}) orthogonal array. The experiment sought to observe how various parameters have affected certain characteristics, namely the delamination factor and surface roughness (Ra and Rz). The feed rate parameter had the most dominant effects on the delamination factor and surface roughness (Ra and Rz) performance measures.

Bhat et al. [12], performed drilling operation on three different thicknesses. The purpose of this study was to assess the extent of damage caused to the workpiece. Thickness accounted for 21.30% of the total variance. When examining the impact of speed and feed variation, it became evident that the 8 mm thick composite laminate demonstrated superior performance.

Khashaba et al. [13], researched the effects of drilling parameters, experimentally and how they influenced mechanical and thermal aspects of GFRP workpieces. They utilized sensors and thermal cameras to observe the heat-affected zone (HAZ) and to measure the temperature at drill point. Then, with purpose of optimizing the process, they employed regression analysis to establish relationships between drilling factors and outcomes. It was noted that the thrust force is primarily affected by the feed rate, with a significant impact. On the other hand, the sway of cutting speed on the thrust force was observed to be minor and negligible. These findings highlight the importance of considering these factors when analyzing temperature variations in machining processes.

Erturk et al. [14], performed parameter optimization on the drilling process of continuous GFRP composite materials. The drilling capacity was assessed by utilizing a drilling system that incorporated different drill bit types, feed rates, and spindle speeds. The findings suggested that the effectiveness of the drilling operation is influenced by the type of coating applied to the tool.

Rubio et al. [15], used high-speed machining (HSM), particularly drilling GFRP composites utilizing three distinct geometries of drill bits. The researchers performed drilling experiments using a machining center equipped with 11kW of spindle power and 10,000 rpm of spindle speed. They used an aerostatic headstock having maximum rotational speed of 40,000 rpm. They manufactured laminates using hand lay-up method. Three cemented carbide drills that had a diameter of 5mm and different helical angles were used for the drilling experiments. They found that increasing the speed resulted in lowering of delamination. With increased feed rate, the incidence of delamination was seen to rise.

Studies show that drilling is generally done on hand lay-up FRP materials. In addition, in drilling operations, tool tip geometry is generally considered and drill coatings are not taken into account sufficiently.

The current investigation pertains to the drilling procedure of a GFRP composite of 25 mm thickness, which was fabricated using the pultrusion technique. The drilling procedure was conducted utilizing an uncoated solid carbide and a solid carbide drill that was coated with Titanium Nitride (TiN). The drilling procedure entailed the creation of perforations throughout the material, extending from one end to the other under dry condition. The study utilized three discrete sets of cutting speeds (60, 70, 80 m/min) and three different feed rates (0.06, 0.09, 0.12 mm/rev). The data collected encompassed the experimental outcomes, specifically the measurements of thrust force, surface roughness (SR), and delamination factor (F_d).

2 Material and methods

2.1 *Production of the composite*

The GFRP composites employed in the experiments were produced using the pultrusion method. This involved preheating uni-directional multi-end continuous glass rovings weighing 600 Gram per Square Meter (GSM), composed of E-glass fibers. These rovings were then pulled by a puller and drawn into the melt impregnated epoxy reinforcement at a velocity of 100 m/s. Subsequently, the composite material was cooled utilizing a die, thereby imparting the ultimate form and dimensions. Subsequently, the fabricated composite material was divided into the desired lengths through the utilization of a pelletizing system.

Pultruded solid composite was manufactured with high-volume fraction of fibers, specifically 60%, to enhance its resistance to variations in cutting speeds and feed rates during drilling experiments. The composite exhibited fiber orientation of 90° indicating that the fibers were positioned perpendicular to feed direction. The rectangular shaped composite used for drilling operations had the dimensions of 60x190x25 mm. The illustration of the composite workpiece was given in Figure 1. Additionally, the microstructures of the composite material are shown in Figure 2.

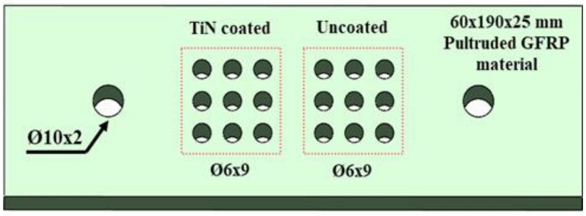
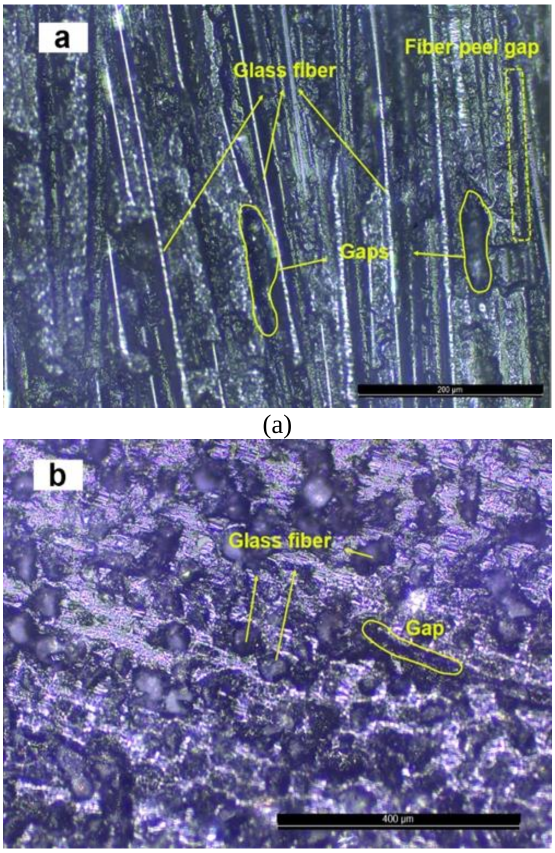


Figure 1. Illustration of pultruded composite workpiece and related hole diameters



(a)

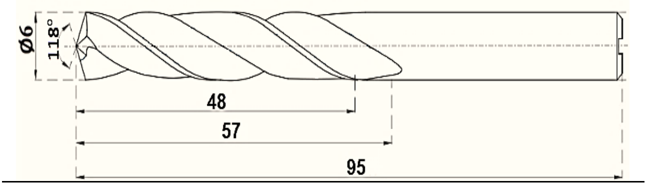
(b)

Figure 2. Microstructures of the composite material, (a) parallel view to glass fibers, (b) perpendicular view of glass fibers

2.2 *Specifications of drill bits*

The experiments employed two types of drill bits: an uncoated solid carbide drill bit and a titanium nitride (TiN) coated solid carbide drill bit. Both drills were acquired from the Karcan Cutting Tools company and shared common specifications, including a diameter of 6 mm and a tip angle of 118°. Table 1 displayed the specifications of the drill utilized in the experimental procedures.

Table 1. Illustration of the drill's employed in the experiments



Helix angle	30°	30°
Coating type	TiN	Uncoated
Point angle	118°	118°
Coating thickness	0.25-1.2 Micron	-
Coating method	PVD	-
Coating melting Temperature	2950 °C	-

The TAKUMA brand JVH710 CNC vertical machining center, which is under the maintenance of Amasya University, was utilized for conducting experiments. The experiments employed a bench and a test set, as depicted in Figure 2. The adjustment of drilling factors was based on the specifications provided in the cutting tool catalog and the findings obtained from relevant literature. The drilling operation was conducted at a cutting depth of 25 mm, employing three distinct cutting speeds (60, 70, and 80 m/min) and three feed rates (0.06, 0.09, 0.12 mm/rev). The cutting parameters employed for hole drilling are presented in Table 2.

Table 2. Drilling factors and factor levels

Factors	**Unit**	**Code**	**Factor levels**		
Cutting speed (Vc)	m/min	B	60	70	80
Feed rate (f)	mm/min	C	0.06	0.09	0.12

2.3 *Thrust force*

The measurement of thrust forces during the drilling process was conducted using a S type load cell manufactured by Puls Elektronik as given in Figure 3. The Newton (N) is the accepted unit for expressing values of thrust force. Given that the study also involved the calculation of delamination factors at the hole entrance, the experiments were conducted without replication.

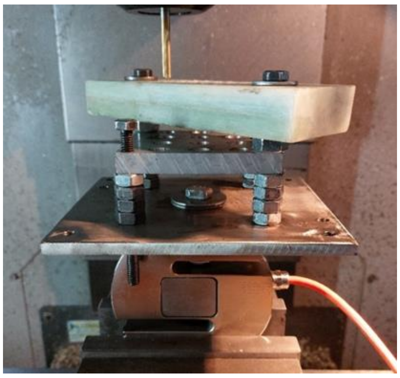


Figure 3. Thrust force measurement setup for drilling

2.4 *Surface roughness measurements*

The measurements of surface roughness (SR) were carried out using a Mitutoyo surface roughness measuring device. The drilled holes were bisected, and measurements were obtained from the interior hole surface.

Similar to the approach taken in the determination of thrust force, the measurements were carried out without replication owing to the consideration of delamination factors at the hole entrances.

2.5 *Delamination factor (F_d)*

Minimizing delamination damages at the entrances of holes is significant in the context of working with GFRP materials. In instances where there are significant delamination damages present, the progressive nature of the damage inhibits the material's ability to effectively carry out its intended function, resulting in a shortened lifespan.

The calculation of the delamination factor on the surfaces of hole entrances is determined using Equation 1 as;

$$F_d = \frac{D_{max}}{D} \tag{1}$$

where, F_d is the delamination factor; D_{max} indicates the maximum damage diameter at the hole entrance and D indicates the drilling diameter [16].

The measurement of the maximum damage diameter was done to determine the delamination factors. Images capturing the hole entrances were acquired during the experimental procedures, and subsequently, the maximum diameters of deformation were determined through the utilization of computer-aided design (CAD) software. The images underwent a conversion process, resulting in the transformation of the images into negatives. Consequently, the damage to the entrances of the holes became more pronounced and apparent as depicted for experiment no: 16 in Figure 4.

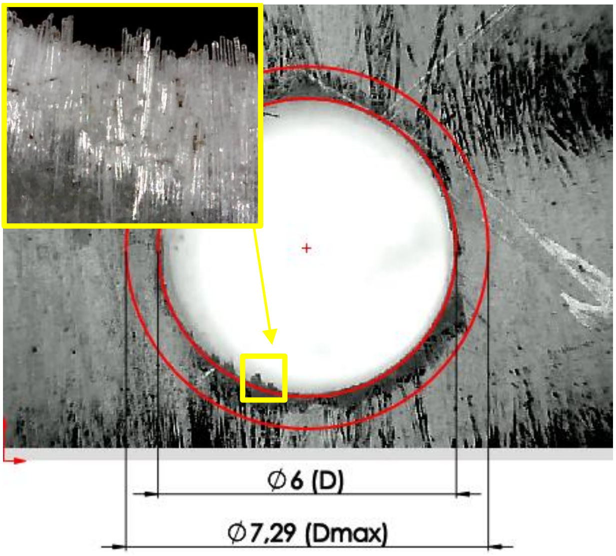


Figure 4. Delamination factor measurement for experiment no: 16

3 Results and discussion

The experimental procedure involved the implementation of cutting parameters in a total of 18 trials. The measurement of maximum thrust forces was obtained. Following the conclusion of the drilling operations, the surface roughness (SR) of the hole surfaces and the delamination factors at the hole entrances were measured. The delamination factors were computed for each experiment based on the maximum delamination measurements observed at the conclusion of the drilling procedures. Table 3 presents the experimental data pertaining to the surface roughness (SR), delamination factors (F_d), and thrust forces.

Table 3. Experimental measurements of SR, F_d, and thrust force values

Exp, No	A	B	C	SR	D_{max} (mm)	F_d (Delamination Factor)	Thrust Force
E1	Coated	60	0.06	3.12	7.72	1.31	33.1
E2	Coated	60	0.09	3.98	8.59	1.43	51.2
E3	Coated	60	0.12	4.65	8.86	1.54	61.2
E4	Coated	70	0.06	2.84	7.77	1.29	27.8
E5	Coated	70	0.09	3.62	8.2	1.37	33.1
E6	Coated	70	0.12	4.11	9.26	1.48	49.78
E7	Coated	80	0.06	3.21	7.66	1.28	23.4
E8	Coated	80	0.09	3.58	7.75	1.29	28.2
E9	Coated	80	0.12	3.77	8.71	1.45	38.1
E10	Uncoated	60	0.06	2.93	8.93	1.49	46.9
E11	Uncoated	60	0.09	4.62	8.66	1.55	64.4
E12	Uncoated	60	0.12	5.33	7.63	1.64	96.9
E13	Uncoated	70	0.06	2.81	7.59	1.34	39.3
E14	Uncoated	70	0.09	4.22	8.47	1.48	57.2
E15	Uncoated	70	0.12	5.32	7.82	1.51	67.4
E16	Uncoated	80	0.06	3.13	7.29	1.22	33.6
E17	Uncoated	80	0.09	3.51	9.27	1.41	40.2
E18	Uncoated	80	0.12	4.03	9.81	1.43	54.8

3.1 *Thrust force results*

Figure 5 presents the thrust force outcomes for two distinct types of drill bits operating under various cutting conditions.

As depicted in Figure 5, the thrust values exhibited a positive correlation with the feed rate values for both drill bits. In contrast, an rise in cutting speed led to a fall in thrust forces. This result was a predictable outcome that had been previously documented in the existing body of literature. The elevation in speed provided a rise of temperature between the contacting areas of drill bit and composite surfaces. The heat generated due to this contact causes an elevation of temperature in the surrounding area, which subsequently affects the material behavior of the matrix resin. The matrix resin undergoes a transition from a glassy state to an elastic state, resulting in a softening of the contacted area and a subsequent reduction in the thrust force [17, 18]. However, it should be noted that slower cutting velocities result in colder surface contact areas, which hinders heat generation. Therefore, the composite material exhibited increased resistance to drilling deformation at lower cutting speed values, leading to the generation of higher thrust forces [19, 20].

Furthermore, the feed rate values, and the magnitude of the thrust force values were observed to be closely related.

Shear area of the drill bit and its increase can be attributed to this phenomenon. When conducting drilling operations at elevated feed rates, the self-generated feed angle experiences an elevation, resulting in the drop of the angle of effective clearance. This circumstance leads to the occurrence of uncut fibers, subsequently facilitating the flow of chips more challenging due to the polymer's softening. As a result, the challenges experienced during the process of chip evacuation resulted in a subsequent augmentation of the thrust force [13, 21].

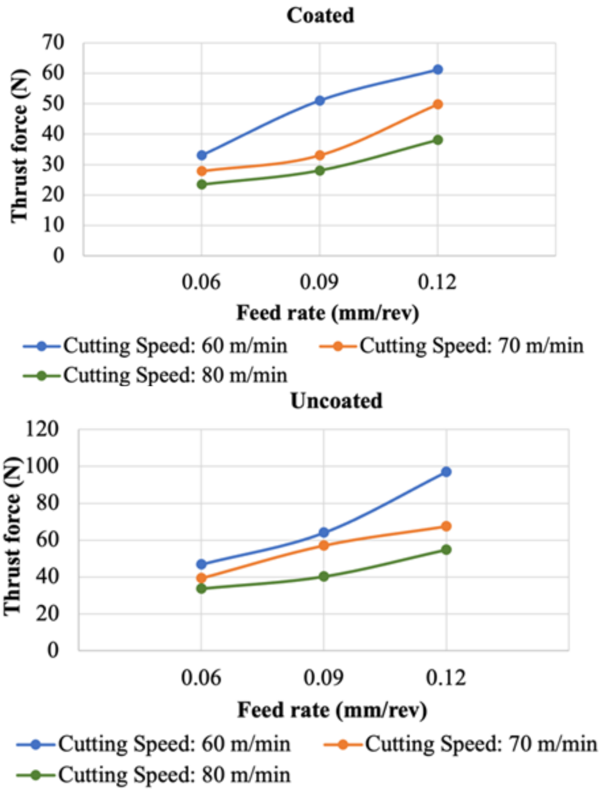


Figure 5. Thrust force values under different cutting conditions for coated and uncoated drill bits

The disparity of the values of thrust force between solid carbide and TiN drill bits can also be explained by the heat generation and subsequent temperature increase observed during the drilling process. As mentioned earlier, a rise in temperature induces a transformation of the matrix resin from a solid, glassy phase to a more flexible, elastic phase. However, if the temperature continues to rise, the matrix resin undergoes a phase transition to a viscous-flow state. This transition results in a splitting or detachment of the fibers from the matrix resin, accompanied by an adhesive-style deformation of the polymeric material during the contact of the drilling bit [22, 23]. Higher contact temperatures have effect on the thrust force. The utilization of TiN coated solid carbide drills offers several advantages over uncoated solid carbide drills, including increased hardness, enhanced wear resistance, reduction in thermal conduction, and improved rate of heat dissipation. Due to the heat generation capabilities, noticeable disparities in thrust forces were observed between the two types of drills.

The chip formations observed subsequent to the drilling procedure were presented in Figure 6. As previously stated, the size and continuity of chip formations exhibited a rising pattern as the feed rate increased.

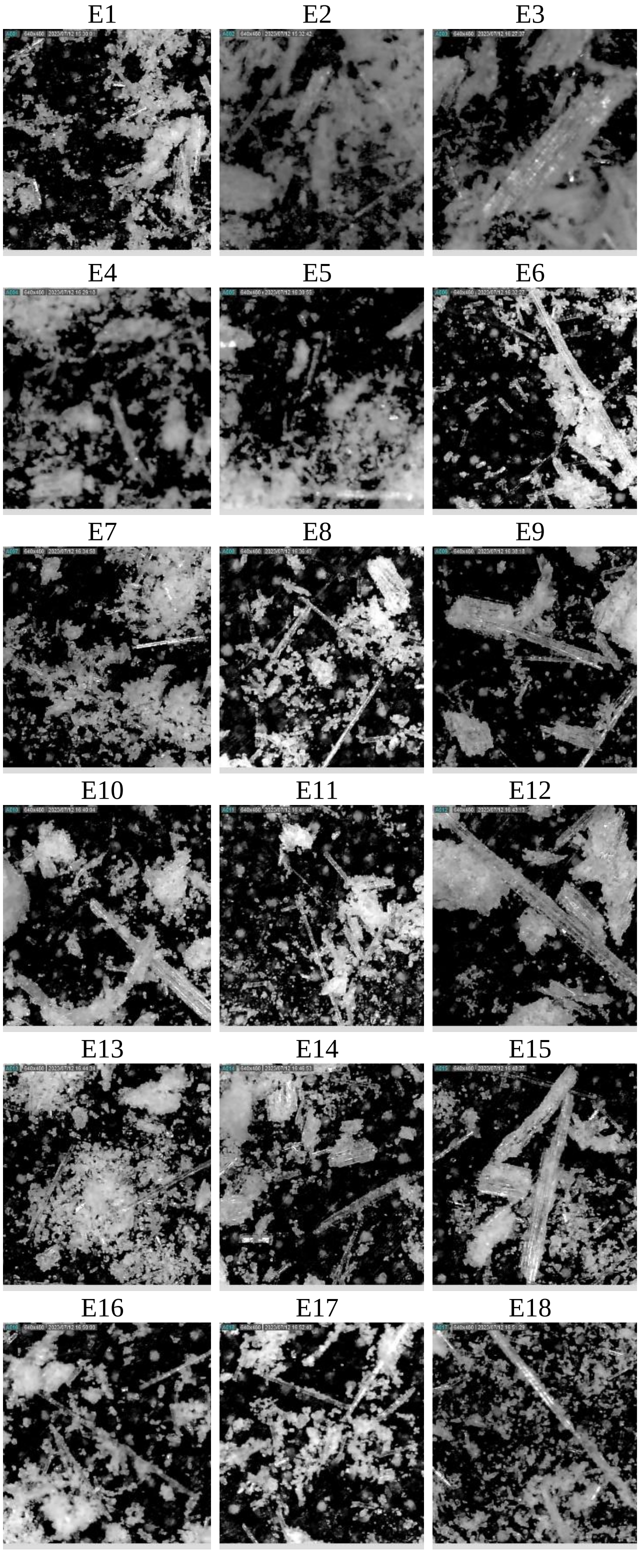


Figure 6. Images of chip formations in relation to conducted experiments

3.2 *Delamination factor (F_d) results*

Upon conducting drilling on the specimens, the presence of delamination damage was observed at the surface of the samples. Drilling provided an external force that can separate neighboring plies near the drill's entry. Measured delamination factors were given in Figure 7.

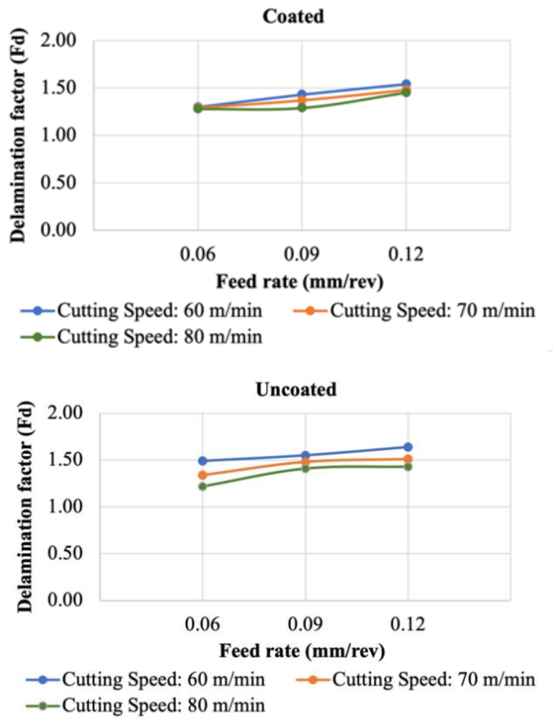


Figure 7. Delamination factor values under different cutting conditions for coated and uncoated drill bits

The analysis of the observed delamination damage suggested that the delamination caused by drilling is positively correlated with the feed rate, while it exhibits a negative correlation with the cutting speed. Furthermore, it was noted that the impact of cutting speed on delamination was comparatively less significant in comparison to the effect of feed rate. This phenomenon may be correlated with the escalation of axial thrust force as the feed rate increases. [24].

Additionally, that the utilization of TiN drill bits resulted in a slightly reduced occurrence of F_d as depicted in Figure 7. The likely cause of this situation can be attributed to the reduced heat generation and temperature increase between the tool and matrix.

The utilization of an uncoated solid carbide drill has the potential to generate elevated levels of heat, which may reach a critical threshold leading to adhesive-induced deformation. Consequently, this phenomenon can result in an increased occurrence of delamination damage [15].

3.3 *Surface roughness (SR) results*

The output of cutting parameters and tool performance that holds the highest significance is surface roughness. The operational effectiveness and mechanical properties of a set of components involving pins, bolts, and screws are influenced by SR values of the holes. The measured SR values were given in Figure 8.

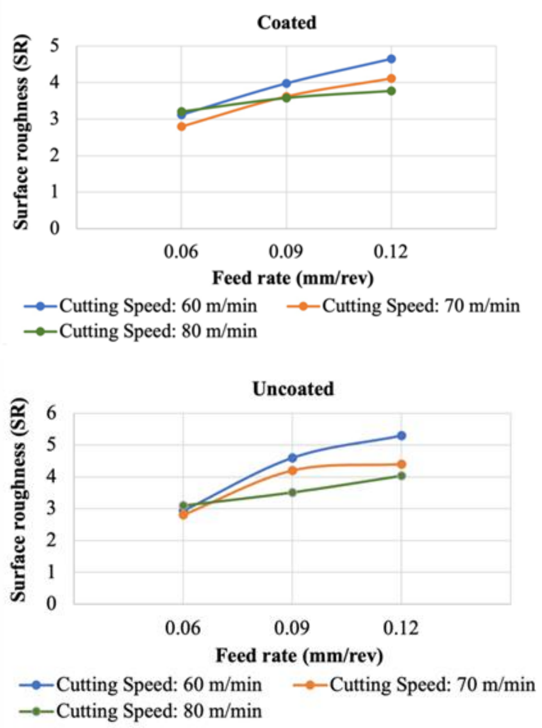


Figure 8. SR measurements obtained from distinct cutting conditions in relation to both coated and uncoated drill bits

The examination of Figure 8 has demonstrated that the feed rate had effects on the measurements of SR. The rationale behind this phenomenon is that at elevated feed rates, the propagation of cracks becomes more severe and less manageable because of the increased strain rate [25, 26]. The results presented in Figure 8 demonstrate a modest reduction in SR measurements with an increase in cutting speed. The observed phenomenon can be ascribed to the thermal-induced reduction in the rigidity of the matrix resin. Nevertheless, it was apparent that the rate at which the material was fed had an additional impact on the roughness of the surface in comparison to the influence exerted by the speed at which the cutting process was carried out. The utilization of TiN coating on solid carbide drill bit yielded superior surface roughness outcomes in comparison to uncoated solid carbide drill bit. The SR values were observed to be the lowest when employing a moderate cutting speed of 70 m/min and a feed rate of 0.06 mm/rev.

4 Conclusion

The pultrusion method was employed to manufacture a GFRP composite with 25 mm thickness, high-volume fraction of fibers (60%), and fiber orientation of 90°. Then the drilling process was performed using an uncoated solid carbide drill and a solid carbide drill coated with Titanium Nitride (TiN). The drilling process involved the formation of perforations across the material, spanning from one end to the other while maintaining a dry environment. The research employed three distinct sets of cutting speeds (60, 70, 80 m/min) and three varying feed rates (0.06, 0.09, 0.12 mm/rev). The findings are below;

- Feed rate values and thrust force values had a positive correlation for both TiN coated and uncoated drill bits. The study found that there was a negative relationship between cutting speed and thrust forces. In particular, as the cutting speed was increased, there was a corresponding reduction in the magnitude of the thrust forces. The rise in speed led to a temperature increase in the contacting regions of the drill bit and the drilled surface of the GFRP composite. The drilling process generated heat that resulted in elevated temperatures in the surrounding region. These increased temperatures had an impact on the matrix resin and its mechanical properties.
- The examination of the observed delamination damage indicated a positive correlation between the delamination caused by drilling and the feed rate, while a negative correlation was observed with the cutting speed. Moreover, it was observed that the influence of cutting speed on F_d was relatively less pronounced in comparison to the impact of feed rate.
- The feed rate profoundly impacted the SR measurements. The outcomes of the study revealed a modest decrease in surface roughness measurements at elevated cutting speeds. Nevertheless, it was apparent that the feed rate exerted a more pronounced effect on SR in comparison to the influence of cutting speed.
- The utilization of TiN-coated solid carbide drills has demonstrated better results in terms of thrust force, F_d, and SR than uncoated solid carbide drills. This reason of this situation is the increased hardness, enhanced wear resistance, reduced thermal conductivity, and improved heat dissipation rate provided by the TiN coating.

Conflict of interest

The authors declare that there are no conflicts of interest related to the study, including financial, personal, or professional relationships and affiliations.

Similarity rate (iThenticate): %16

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