*Journal of Applied Science, Engineering, Technology, and Education* *ISSN: 2685-0591 (online)*
*Vol. 6 No. 2 (2024)*
https://doi.org/10.35877/454RI.asci3471

# The Effect of Feed Rate Variation and Cooling on the Drilling Process of Carbon Fiber and Glass Fiber Composites

Rhesa Rama Reyhan, Andoko*, & Riduwan Prasetya

*Department of Mechanical Engineering, Universitas Negeri Malang, Malang, 65145, Indonesia*

## Abstract

Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) composites have extensive applications in the automotive, aerospace, and manufacturing industries due to their high strength and lightweight properties. However, machining processes such as drilling often encounter challenges such as delamination and tool wear due to the anisotropic nature and low thermal conductivity of these materials. This study evaluates the effect of varying feed rates and cooling methods on drilling quality and delamination levels in CFRP and GFRP composites. The cooling methods tested include dry, nanofluid, and cryogenic cooling. Experimental results indicate that cryogenic cooling produces the best hole quality with the lowest delamination levels, even at high feed rates. These findings provide valuable insights into the interaction between machining parameters and cooling methods, offering solutions to enhance the efficiency and quality of composite drilling processes in the manufacturing industry.

*Keywords:* carbon fiber, glass fiber, drilling, feed rate, cryogenic cooling

Received: 26 October 2024 Revised: 13 December 2024 Accepted: 27 December 2024

## 1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) composites are materials with superior properties, such as high strength, lightweight, and corrosion resistance, making them widely used in the automotive, aerospace, and construction industries (Ze et al., 2023). The use of these composites is increasing due to their ability to meet design demands requiring materials with high mechanical strength but minimal weight (Dalle Mura & Dini, 2021). However, machining these composites, particularly drilling, often encounters significant challenges, such as delamination, tool wear, and poor surface quality (Kumar & Verma, 2022). These issues are caused by the anisotropic nature of composites, which leads to more complex cutting behavior compared to conventional metallic materials.

More complex cutting operations are closely tied to the selection of machining parameters (Doluk et al., 2020). Although numerous studies have addressed parameters such as cutting speed and feed rate, there remains a lack of optimization in cooling methods to minimize structural damage, such as delamination (Bolar et al., 2024). Previous research has primarily evaluated individual parameters without considering the interaction between feed rate and cooling methods, both of which play a crucial role in enhancing the quality of the drilling process. A study by (Caggiano et al., 2019) revealed that improper feed rate settings could lead to high thrust forces, thereby increasing the risk of delamination in composite layers. Meanwhile, conventional cooling methods, such as dry cooling, are often inadequate for abrasive materials like CFRP and GFRP (Hoffmann et al., 2021). Furthermore, newer cooling methods, such as cryogenic cooling and the use of nanofluids, have yet to be thoroughly explored in the context of drilling CFRP and GFRP

---

* Corresponding author.
*E-mail address*: andoko.ft@um.ac.id

composites. Therefore, further research is needed to combine these parameters to optimize the quality of the drilling process.

The use of more efficient cooling methods, such as cryogenic cooling and nanofluids, is gaining attention as a potential solution to improve the quality of composite drilling (Pervaiz et al., 2020). Cryogenic cooling methods, for instance, have been proven to reduce tool and material temperatures, thereby decreasing thrust force and friction, which are the main causes of delamination (Venkatesh & Sikarwar, 2018). Additionally, nanofluids, which are a mixture of nanometer-sized particles with a base fluid, can reduce friction between the tool and the material, enhance lubrication, and extend tool life (Xiao et al., 2024). The selection of optimal methods and settings can contribute to advancing this research for composite machining processes.

The objective of this research is to evaluate the impact of feed rate variations and cooling methods on drilling quality and the delamination level of CFRP and GFRP composites. The focus of this study is to identify combinations of machining parameters and cooling methods that can minimize damage to the composites during the drilling process. By understanding the interaction between feed rate and cooling methods, it is expected to find optimal settings that can improve the efficiency and quality of composite machining results, which can ultimately be applied in the manufacturing industry. The primary contribution of this research is to provide a deeper understanding of the interaction between machining parameters and cooling methods in the composite drilling process. The potential benefits of this study include identifying optimal settings that can be utilized in the industry to minimize delamination and enhance the quality of the final product, thereby leading to increased efficiency and competitiveness in composite manufacturing applications.

## 2. Materials and Methods

This study employs two types of composites commonly used in the automotive and aerospace industries, namely Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP), with dimensions of 30 x 30 x 5 mm as shown in Figure 1. These composites have a fiber-to-matrix ratio of 60:40, providing high mechanical strength and load durability. The CFRP composite consists of 15 layers of Twill 3k carbon fiber (240 gsm), while the GFRP uses woven roving (800 gsm). The matrix for both composites is an epoxy resin reinforced with multi-walled carbon nanotubes (MWCNT) to enhance the material's mechanical and thermal properties (Mirsalehi et al., 2021). The fabrication of the composites was carried out using the hand lay-up technique, where carbon and glass fiber layers are manually arranged, followed by the injection of epoxy resin to bind the fibers. The addition of MWCNT aims to improve the thermal conductivity and strength of the composites, which are critical in machining applications under extreme conditions. The composite composition is detailed in Table 1.

**Table 1.** Composite Composition

| Input | Description |
|---|---|
| Carbon fibre | Twill 3k 240 gsm |
| Glass fibre | Woven roving 800 gsm |
| Ratio of fibre and matrix | 60:40 |
| Matriks | Epoxy resin + MWCNT |
| Ratio of resin and hardener | 2 : 1 |

Drilling test process was conducted using a 3-axis CNC milling machine equipped with a 6 mm diameter High-Speed Steel (HSS) twist drill bit (Figure 2). The spindle speed was maintained at 3000 RPM, while feed rate variations were applied at three levels: 20, 30, and 40 mm/min. These parameters were selected to examine the effect of cutting speed on the drilling quality, particularly regarding delamination on the composite surface. Three different cooling methods were employed during the drilling process to evaluate their impact on the drilling quality and the extent of composite delamination (Figure 3). The methods included: (1) Dry Cooling, where no coolant was used to observe the effects of cutting conditions without external cooling intervention; (2) Nanofluid Cooling, which involved a nanofluid consisting of a mixture of palm oil and SiO2 particles at a concentration of 1 wt%, aimed at enhancing lubrication and heat removal during drilling; and (3) Cryogenic Cooling, utilizing liquid nitrogen ($LN_2$) at a temperature of -196°C to cool the drill bit and material during the drilling process, expected to lower the temperature of the tool and material, as well as reduce thrust force and friction, thereby minimizing delamination.

This experiment involved a total of 9 trials, consisting of three variations of feed rate (20, 30, and 40 mm/min) and three different cooling methods (dry, nanofluid, cryogenic). Each experiment was conducted using a new cutting tool to ensure the consistency and validity of the results. In addition, the delamination factor was calculated to measure the extent of composite layer damage on the drilled surface, which was determined by comparing the maximum delamination diameter ($D_{max}$) to the nominal hole diameter ($D_0$) according to the Equation 1:

$$F_d = \frac{D_{max}}{D_0} \tag{1}$$

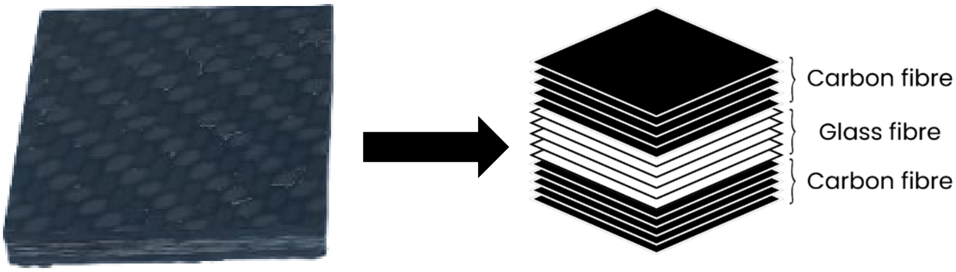


**Figure 1.** Specimen

**Figure 2.** HSS twist drill

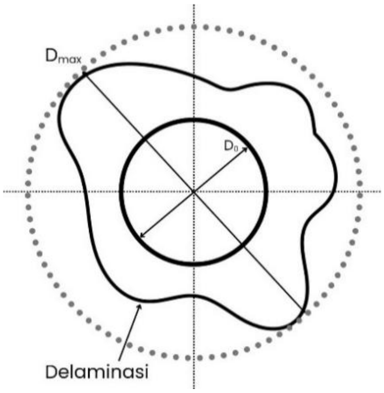


**Figure 3.** Delamination schematic

## 3. Results and discussions

Experimental testing has been conducted using three cooling methods and three different feed rates, resulting in data shown in Table 2.

**Table 2.** Delamination factor value

| No. | Cooling Method | Feed rate (mm/min) | $F_d$ entry | $F_d$ exit |
|---|---|---|---|---|
| 1 | Dry | 20 | 1.120 | 1.178 |
| 2 | Dry | 30 | 1.142 | 1.225 |
| 3 | Dry | 40 | 1.155 | 1.285 |
| 4 | Nanofluid | 20 | 1.113 | 1.167 |
| 5 | Nanofluid | 30 | 1.130 | 1.183 |
| 6 | Nanofluid | 40 | 1.147 | 1.233 |
| 7 | Cryogenic | 20 | 1.077 | 1.125 |
| 8 | Cryogenic | 30 | 1.107 | 1.150 |
| 9 | Cryogenic | 40 | 1.118 | 1.182 |

### *3.1. Factor delamination on entry*

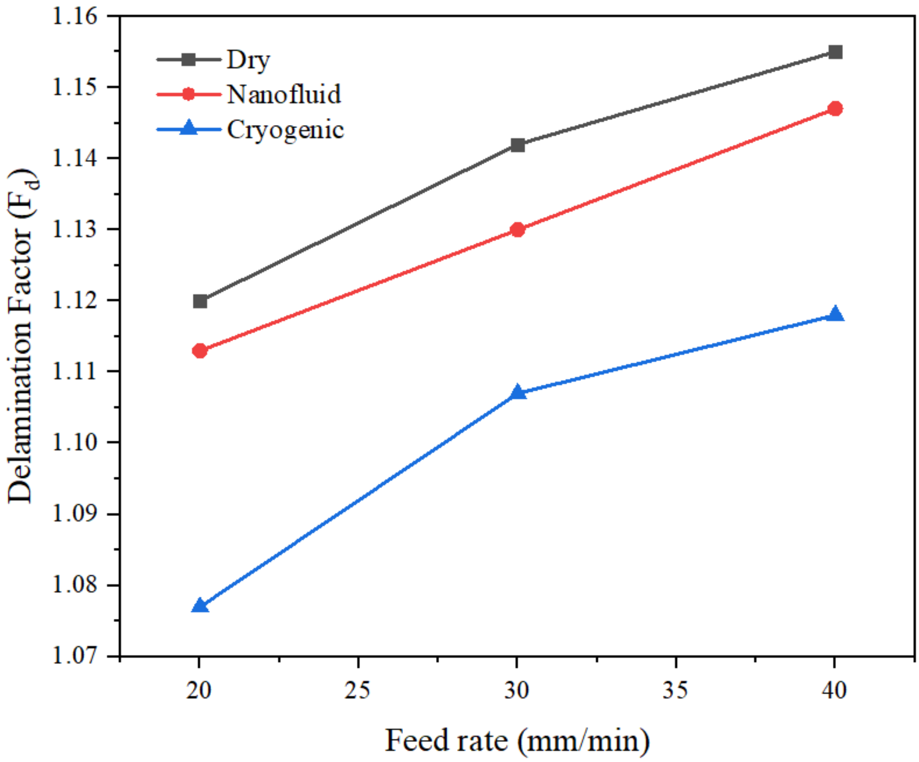


**Figure 4.** Comparison graph of $F_d$ values on entry

Based on the experimental results shown in Figure 4, the delamination factor at the entry ($F_d$ entry) indicates that the feed rate has a significant effect on the level of damage to the composite layer at the hole entry surface. The higher the feed rate, the greater the thrust force experienced by the cutting tool, which in turn increases the friction between the tool and the material. This leads to a higher delamination level on the composite surface (Ghafarizadeh et al., 2016). In the dry method, the delamination factor increases progressively with an increase in feed rate. At a feed rate of 20 mm/min, the delamination factor was recorded at 1.120, which then increased to 1.142 at a feed rate of 30 mm/min and reached 1.155 at a feed rate of 40 mm/min. This increase indicates that without cooling, higher cutting speeds result in greater thrust forces, causing more significant damage to the composite layer due to high friction between the tool and the material.

The use of the nanofluid method shows a reduction in the delamination factor at each feed rate level compared to the dry method. At a feed rate of 20 mm/min, the delamination factor for the nanofluid method was recorded at 1.113, which is lower than that of the dry method (1.120). Although the delamination factor increases with the increase in feed rate, the rate of increase observed in the nanofluid method is smaller compared to the dry method. This indicates that the lubrication and friction reduction provided by nanofluid can decrease the level of damage occurring on the composite surface, even though greater thrust forces still play a role (Duc et al., 2020).

The cryogenic cooling method showed the most effective results in reducing the delamination factor. At a feed rate of 20 mm/min, the lowest delamination factor value was recorded at 1.077, which is lower than that of the other two methods. The use of liquid nitrogen at -196°C to cool the cutting tool and material helps lower the temperature, reduce friction, and decrease the thrust force experienced by the cutting tool (Balan et al., 2021). Although the delamination factor increases at a feed rate of 30 mm/min (1.107) and 40 mm/min (1.118), these increases are still smaller compared to those observed with the dry and nanofluid methods. This indicates that the cryogenic cooling method is more effective in reducing composite layer damage across all feed rate levels tested.

### *3.2. Delamination factor on exit*

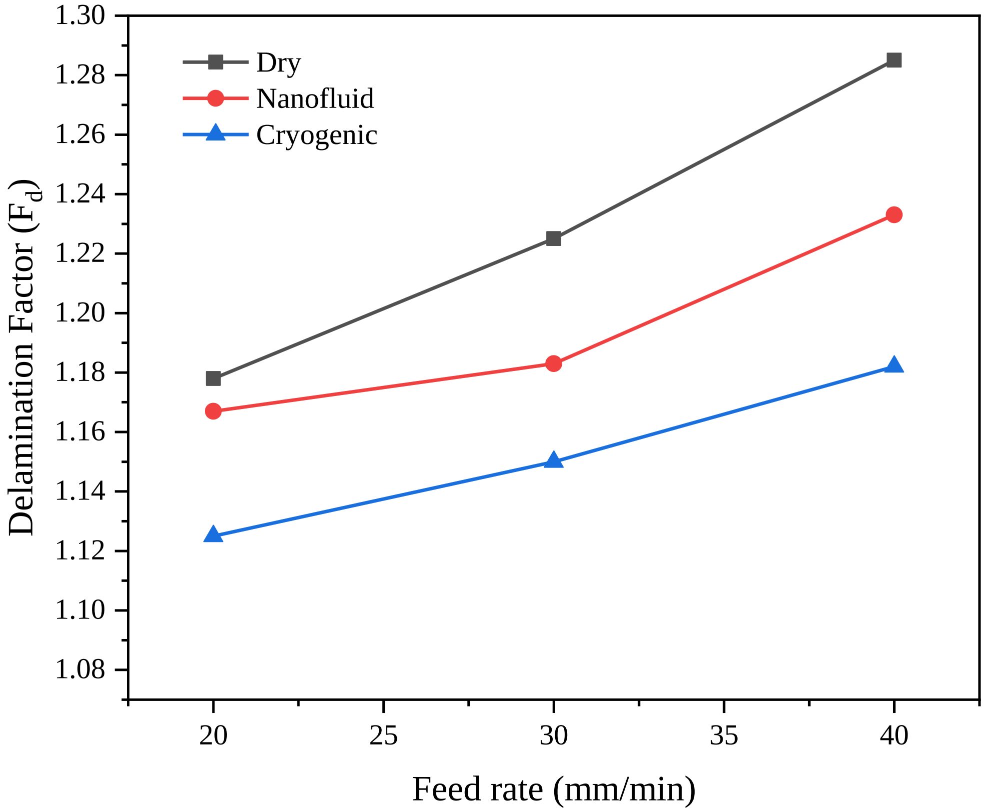


**Figure 5.** Comparison graph of $F_d$ values on exit

The test results shown in Figure 5 indicate that feed rate remains the primary factor influencing the level of delamination at the hole exit surface. The higher the feed rate, the greater the thrust force generated, which can lead to increased damage to the material surface as the cutting tool exit (Elgnemi et al., 2021). In the dry method, the delamination factor increases progressively with the increase in feed rate. At a feed rate of 20 mm/min, the delamination factor was recorded at 1.120, which then increased to 1.142 at a feed rate of 30 mm/min and reached 1.155 at a feed rate of 40 mm/min. This increase indicates that under cooling-free conditions, higher cutting speeds lead to increased thrust forces, which in turn cause greater damage to the composite layer due to the friction that occurs during the drilling process.

In the nanofluid method, the delamination factor at the exit is lower compared to the dry method, although there is an increase as the feed rate rises. At a feed rate of 20 mm/min, the delamination factor for the nanofluid method was recorded at 1.113, which is lower than that of the dry method (1.120). Although the delamination factor increases with increasing feed rate, the rate of increase is smaller compared to the dry method. This indicates that the lubrication and friction reduction provided by nanofluid can reduce damage to the composite surface, even though the thrust force still plays a role in increasing the level of delamination.

However, the cryogenic cooling method demonstrated the most advantageous results in reducing the delamination factor at the exit surface. At a feed rate of 20 mm/min, the delamination factor was recorded at 1.125, which is the lowest value compared to the other two methods. Although there was a slight increase in the delamination factor at feed rates of 30 mm/min (1.150) and 40 mm/min (1.182), these values remained lower compared to those of the dry and nanofluid methods at the same feed rates. The success of cryogenic cooling in reducing delamination at the exit surface can be explained by its ability to lower the temperature of the cutting tool and material. This reduction in temperature helps decrease the thrust force and friction that occur during drilling, which in turn reduces damage to the composite layer, particularly at the exit surface, which is more prone to delamination caused by thrust force and friction (Kamaruzaman et al., 2022).

### *3.3. Macro image of the drilling results*

A visual analysis of the drilling results for CFRP and GFRP composites was conducted using macro images of the hole surfaces produced under various cooling methods and feed rate variations. These images provide a clear representation of the quality of the hole surfaces and the level of delamination occurring under each experimental condition, as shown in Table 3. The image results indicate that the cooling method used, as well as the applied feed rate, has a significant impact on composite surface damage.

In the dry method, the drilling images show the most significant level of damage. At a feed rate of 20 mm/min, the hole surface remains relatively smooth, although some signs of delamination begin to appear at the entry surface. However, as the feed rate increases to 30 mm/min and 40 mm/min, damage to the hole surface becomes more evident. At a feed rate of 40 mm/min, delamination becomes more extensive, and the hole surface appears rough, indicating that increased cutting speeds without adequate cooling lead to higher thrust forces and friction. Ultimately, this results in more severe damage to the composite layer (Basmaci et al., 2017).

Nanofluid results in better outcomes in reducing damage to the hole surface. The images for the nanofluid method show that although damage still occurs at higher feed rates, the level of delamination is better controlled. At a feed rate of 20 mm/min, the produced hole surface is relatively smooth, with minimal damage. Although damage increases at feed rates of 30 mm/min and 40 mm/min, the delamination levels at both the entry and exit surfaces remain lower compared to the dry method. This indicates that the use of nanofluid can reduce friction and improve hole quality, even though the effects of higher thrust forces at higher feed rates still play a role (Xie et al., 2016).

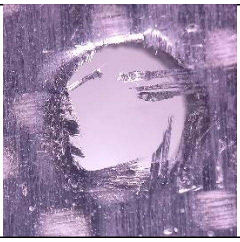
Cryogenic cooling shows the best results in reducing damage to the hole surface. The resulting images indicate that delamination is very minimal even at higher feed rates. At a feed rate of 20 mm/min, the hole surface shows almost no damage, with a smooth surface and only slight signs of delamination. Even at a feed rate of 40 mm/min, although there is a slight increase in delamination, the quality of the hole surface remains better compared to the other two methods. This demonstrates that cryogenic cooling can significantly reduce the temperature of the cutting tool and material, which in turn reduces thrust force and friction, thereby maintaining the integrity of the composite layer during the drilling process (Iqbal et al., 2021).

**Table 3.** Drilling results on the entry surface

| Feed rate (mm/min) | Dry | Nanofluid | Cryogenic |
|---|---|---|---|
| 20 |  |  |  |
| 30 |  |  |  |
| 40 |  |  |  |

**Table 4.** The results of the drilling on the surface has emerged.

| Feed rate (mm/min) | Dry | Nanofluid | Cryogenic |
|---|---|---|---|
| 20 |  |  |  |
| 30 |  |  |  |

| Feed rate (mm/min) | Dry | Nanofluid | Cryogenic |
|---|---|---|---|
| 40 |  |  |  |

## 4. Conclusion

The aim of this study is to evaluate the effect of feed rate variations and cooling methods on delamination and the quality of drilling results on CFRP and GFRP composites. The research findings indicate that feed rate has a significant effect on delamination, where an increase in feed rate leads to an increase in delamination, especially in the dry method. The cryogenic cooling method was proven to be the most effective in reducing delamination and maintaining the quality of the hole surface across all feed rate levels, thanks to its ability to lower the temperature of the cutting tool and material, thereby reducing thrust force and friction. Nanofluid also showed better results compared to the dry method, although it was not as effective as cryogenic cooling in controlling damage. Overall, cryogenic cooling provides the best solution for improving the drilling quality of CFRP and GFRP composites, particularly under high feed rate machining conditions. These findings are expected to be applied to improve efficiency and quality in the composite machining industry.

## References

Balan, A. S. S., Kannan, C., Jain, K., Chakraborty, S., Joshi, S., Rawat, K., Alsanie, W. F., & Thakur, V. K. (2021). Numerical modelling and analytical comparison of delamination during cryogenic drilling of cfrp. *Polymers*, *13*(22). https://doi.org/10.3390/polym13223995

Basmaci, G., Yoruk, A. S., Koklu, U., & Morkavuk, S. (2017). Impact of cryogenic condition and drill diameter on drilling performance of CFRP. *Applied Sciences (Switzerland)*, *7*(7). https://doi.org/10.3390/app7070667

Bolar, G., Dinesh, A. A., Polishetty, A., Shetty, R., Hiremath, A., & Neelakantha, V. L. (2024). Performance Analysis of Helical Milling and Drilling Operations While Machining Carbon Fiber-Reinforced Aluminum Laminates. *Journal of Manufacturing and Materials Processing*, *8*(3). https://doi.org/10.3390/jmmp8030113

Caggiano, A., Nele, L., & Teti, R. (2019). Drilling of Fiber-Reinforced Composite Materials for Aeronautical Assembly Processes. *Characterizations of Some Composite Materials*. https://doi.org/10.5772/intechopen.80466

Dalle Mura, M., & Dini, G. (2021). Drilling carbon fiber reinforced plastics with pre-cooling treatment by cryogenic fluid. *Journal of Manufacturing Processes*, *68*(PA), 23–31. https://doi.org/10.1016/j.jmapro.2021.05.030

Doluk, E., Rudawska, A., Kuczmaszewski, J., & Pieśko, P. (2020). Milling of an Al/CFRP sandwich construction with non-coated and TiAlN-coated tools. *Materials*, *13*(17). https://doi.org/10.3390/MA13173763

Duc, T. M., Long, T. T., & Van Thanh, D. (2020). Evaluation of minimum quantity lubrication and minimum quantity cooling lubrication performance in hard drilling of Hardox 500 steel using Al2O3 nanofluid. *Advances in Mechanical Engineering*, *12*(2), 1–12. https://doi.org/10.1177/1687814019888404

Elgnemi, T., Songmene, V., Kouam, J., Jun, M. B. G., & Samuel, A. M. (2021). Experimental investigation on dry routing of cfrp composite: Temperature, forces, tool wear, and fine dust emission. *Materials*, *14*(19). https://doi.org/10.3390/ma14195697

Ghafarizadeh, S., Chatelain, J. F., & Lebrun, G. (2016). Effect of cutting tool lead angle on machining forces and surface finish of CFRP laminates. *Science and Engineering of Composite Materials*, *23*(5), 543–550.

https://doi.org/10.1515/secm-2013-0188

Hoffmann, N., Souza, G. S. C., Souza, A. J., & Tita, V. (2021). Delamination and hole wall roughness evaluation in air-cooled drilling of carbon fiber-reinforced polymer. *Journal of Composite Materials*, *55*(23), 3161–3174. https://doi.org/10.1177/00219983211009281

Iqbal, A., Zhao, G., Zaini, J., Gupta, M. K., Jamil, M., He, N., Nauman, M. M., Mikolajczyk, T., & Pimenov, D. Y. (2021). Between-the-holes cryogenic cooling of the tool in hole-making of Ti-6Al-4V and CFRP. *Materials*, *14*(4), 1–19. https://doi.org/10.3390/ma14040795

Kamaruzaman, M. F. S., Hassan, M. H., & Razali, M. F. (2022). Hole Quality Assessment of Drilled Carbon Fiber Reinforced Polymer (CFRP) Panel Using Various Custom Twist Drill Geometries. *Pertanika Journal of Science and Technology*, *30*(4), 2603–2612. https://doi.org/10.47836/pjst.30.4.17

Kumar, K., & Verma, R. K. (2022). Measurement and evaluation of delamination factors and thrust force generation during drilling of multiwall carbon nanotube (MWCNT) modified polymer laminates. *Archive of Mechanical Engineering*, *69*(2), 269–300. https://doi.org/10.24425/ame.2022.140417

Mirsalehi, S. A., Youzbashi, A. A., & Sazgar, A. (2021). Enhancement of out-of-plane mechanical properties of carbon fiber reinforced epoxy resin composite by incorporating the multi-walled carbon nanotubes. *SN Applied Sciences*, *3*(6). https://doi.org/10.1007/s42452-021-04624-2

Pervaiz, S., Kannan, S., Huo, D., & Mamidala, R. (2020). Ecofriendly inclined drilling of carbon fiber-reinforced polymers (CFRP). *International Journal of Advanced Manufacturing Technology*, *111*(7–8), 2127–2153. https://doi.org/10.1007/s00170-020-06203-y

Venkatesh, B., & Sikarwar, R. S. (2018). Drilling of carbon fibre reinforced polymer materials - A review. *International Journal of Mechanical and Production Engineering Research and Development*, *8*(2), 157–166. https://doi.org/10.24247/ijmperdapr201817

Xiao, B., Zhang, C., & Cao, X. (2024). The Effect of MoS2 and MWCNTs Nanomicro Lubrication on the Process of 7050 Aluminum Alloy. *Processes*, *12*(1). https://doi.org/10.3390/pr12010068

Xie, H., Jiang, B., Liu, B., Wang, Q., Xu, J., & Pan, F. (2016). An Investigation on the Tribological Performances of the SiO2/MoS2 Hybrid Nanofluids for Magnesium Alloy-Steel Contacts. *Nanoscale Research Letters*, *11*(1). https://doi.org/10.1186/s11671-016-1546-y

Yaşar, N., Korkmaz, M. E., & Günay, M. (2017). Investigation on hole quality of cutting conditions in drilling of CFRP composite. *MATEC Web of Conferences*, *112*, 3–9. https://doi.org/10.1051/matecconf/201711201013

Ze, G. K., Pramanik, A., Basak, A. K., Prakash, C., Shankar, S., & Radhika, N. (2023). Challenges associated with drilling of carbon fiber reinforced polymer (CFRP) composites-A review. *Composites Part C: Open Access*, *11*(March), 100356. https://doi.org/10.1016/j.jcomc.2023.100356