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Microstructural investigation and hole quality evaluation in S2/FM94 glass-fibre composites under dry and cryogenic conditions

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Keyword:	Drilling, Cryogenic, Surface roughness, Hardness, Scanning Electron Microscopy, Composites
Abstract:	S2/FM94 glass-fibre reinforced epoxy is an aerospace-grade composite currently installed in parts of the Airbus A380 fuselage. In addition to its abrasive and hard nature, it is sensitive to thermal effects developed during the drilling process and therefore, using coolants becomes necessary. However, conventional oil and water-based coolants are not suitable for drilling of composites. Cryogenic coolants on the other hand are an attractive choice for machining composites and are environmentally friendly. In this study, a new, environmentally friendly cryogenic cooling technique in a liquid nitrogen bath was used for the drilling of S2/FM94 glass fibre reinforced epoxy composite. The aim was to investigate the effect of drilling parameters and cryogenic cooling on cutting forces, surface roughness, hardness and delamination factor at hole entry and exit sides. The workpiece was drilled within a cryogenic bath. In this way, both cryogenic workpiece cooling and tool cooling were obtained. The results indicate that the spindle speed and cryogenic cooling had the most significant influence on the cutting forces and surface roughness parameters (Ra and Rz), while the use of cryogenic cooling had the most significant influence on increasing the hardness and size of delamination at entry and exit sides of the holes.

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Dear Prof. Narongrit Sombatsompop

I would like to take this opportunity to sincerely thank all reviewers and yourself for the time and effort in reviewing the previous version of the manuscript. Your suggestions/ comments have certainly helped to improve the quality of the manuscript. All queries are responded, and corresponding amendments made to the revised manuscript; the amendments are highlighted in yellow throughout the revised manuscript.

Comments:

Reviewer: 1

Line #54: I suggest reviewing the data about the expected value that composites market can to reach by 2022. This value maybe is wrong, due the pandemic crisis. The reference used is from 2017.

Thank you for your observation, we have updated the expectations on composite market based on the pandemic impact and added extra sentences in the introduction.

However, the outbreak of COVID-19 virus has adversely impacted the aviation industry leading to shut down of aircraft production and cancellation of new orders. Before the unanticipated pandemic outbreak, it was estimated that the aerospace composites market will have a constant annual growth rate of 8.5% from 2016 to 2021[2]. Due to the COVID-19 pandemic, the global composites market size is now expected to decline from $90.6 billion in 2019 to $82.9 billion by 2021, a 4.4% negative growth rate. However, the market will witness recovery after the year 2021 with an estimated 5-7% growth by 2025[3]. The gradual slowing down of aerospace manufacturing industries will undoubtedly impose limits on the estimated demand on composites. Nevertheless, composites remain an attractive choice in aerospace industry due to the increased usage in the latest models of commercial aircrafts such as A350XWB and B787 compared to older aircraft programs[2].

Line #60: In SI units, "kilogram" is not plural, like "Kgs". The correct is "kg".

Thank you for observing the typo. The unit Kgs is corrected to Kg

I suggest the authors include the reference "Machining process of glass fiber reinforced polyamide 6,6 composites: Pathways to improve the drilling of recycled polymers", from authors Harrison L. Corrêa, Rafaela Rodrigues and Dalberto da Costa. It is a recent article about drilling and evaluation of hole in polymer composite.

The reference was considered in the manuscript

I suggest the authors include the reference "Adhesion of glass/epoxy composites influenced by thermal and cryogenic environments" and "Effects of thermal and cryogenic conditionings on mechanical behavior of thermally shocked glass fiber-epoxy compositse", both from Ray Bankim. They must be used to complement the discussion about hardness under cooling conditions.

The reference was considered in the manuscript

I suggest the authors include another reference to discuss the surface roughness in polymer composites. They are: "Roughness of holes in metal and polymer composite bags" (Chashhin, Sturov and Ivanov).

The reference was considered in the manuscript

Reviewer: 2

The sentence:

"S2 glass fibers are characterised by high compressive and tensile strength, coupled with temperature and impact resistance making it an attractive choice for aeronautical structures." is not correct. Please rewrite it. Composite aeronautical structures are by far made of carbon fiber. S2 glass fibers are barely used compared to carbon. S2 fibers are much more expensive that E glass and their modulus and strength are much lower than carbon.

The suggestion to change the paragraph was considered in the manuscript

Composite aeronautical structures are by far made of carbon fibre. S2 glass fibres are much less used compared to carbon due to their higher costs. Nevertheless, they are characterised by high compressive and tensile strength, coupled with temperature and impact resistance making it an attractive choice for aeronautical structures that undergo impact loadings[5]. In the aerospace industry, CFRPs (Carbon Fibre Reinforced Plastics) are mainly used in the primary structural components of an aircraft such as the wing aileron, flaps, spoilers, tailplane and main landing gear fairings [13, 26], while GFRPs (Glass Fibre Reinforced Plastics) are used in primary and secondary structural components such as the radome (the dome-like shell that protects a radar assembly in aircraft), belly fairing skins, floor panels, and passenger compartments. GFRPs are bonded with metals to create a hybrid fibre metal laminates used in sections of the fuselage [13, 26]. Moreover, GFRPs can be also bonded with metals to create hybrid fibre metal laminates used in sections of the fuselage.

Please review the references, some key references are missing. Add their description including the differences with the present work.

Thank you for your recommendation, we have revised all the references and discussed them in more details as highlighted in yellow in several places in the manuscript. We also added other important references and highlighted the differences with present work.

A backup plate is a standard device used to reduce cutting forces and exit delamination, please explain why it was not used in the present work.

Authors thanks the reviewer for his pertinent comment. as you suggested, the effects of backup plate on hole exit delamination is well-known to reduce delamination. There are many studies on this subject. However, it's important to know that, in the industrial field, during the drilling operation of the fuselage, the bottom face (hole exit) of the panels are not accessible. Therefore, machining with a backing plate cannot be performed. In addition, the aim of the current study is to evaluate the impact of cryogenic cooling of the workpiece on delamination without the aid of a backup plate to specifically determine its impact without any other supporting equipment or setup. Indeed, your suggesting is interesting, and we will aim to conduct further tests in the future to further investigate the effect of backup plate as well as cryogenic bath on the delamination and other hole quality metrics.

Abstract

S2/FM94 glass fibre reinforced epoxy is an aerospace-grade composite currently bonded with aluminium alloys and installed in parts of the Airbus A380 fuselage. In addition to its abrasive and hard nature, S2/FM94 glass fibre is sensitive to thermal effects developed during the drilling process and therefore, using coolants becomes necessary. However, conventional oil and water-based coolants are not suitable for drilling of composites. Cryogenic coolants on the other hand are an attractive choice for machining composites and are environmentally friendly. In this study, a new, environmentally friendly cryogenic cooling technique in a liquid nitrogen bath was used for the drilling of S2/FM94 glass fibre reinforced epoxy composite. The aim was to investigate the effect of drilling parameters and cryogenic cooling on cutting forces, surface roughness, hardness and delamination factor at hole entry and exit sides. The workpiece was drilled within a cryogenic bath. In this way, both cryogenic workpiece cooling and tool cooling were obtained. In addition, the drill geometry is fixed and only the cutting parameters (i.e. spindle speed and the feed rate) are varied under dry and cryogenic conditions. The results indicate that the spindle speed and cryogenic cooling had the most significant influence on the cutting forces and surface roughness parameters (R_a and R_z), while the use of cryogenic cooling had the most significant influence on increasing the hardness and size of delamination at entry and exit sides of the holes.

Keywords: Cryogenic cooling; Drilling; S2/FM94; Cutting forces; Hardness; Roughness.

1. Introduction

The demand on composite materials for aerospace applications is consistently growing due to their excellent strength to weight ratio compared to metals. A main driver for that is because the world passenger air traffic is set to grow at 4.4% per year in the next two decades adding more than 37400 new aircraft within that period[1]. However, the outbreak of COVID-19 virus has adversely impacted the aviation industry leading to shut down of aircraft production and cancellation of new orders. Before the unanticipated pandemic outbreak, it was estimated that the aerospace composites market will have a constant annual growth rate of 8.5% from 2016 to 2021[2]. Due to the COVID-19 pandemic, the global composites market size is now expected to decline from $90.6 billion in 2019 to $82.9 billion by 2021, a 4.4% negative growth rate. However, the market will witness recovery after the year 2021 with an estimated 5-7% growth by 2025[3]. The gradual slowing down of aerospace manufacturing industries will undoubtedly impose limits on the estimated demand on composites. Nevertheless, composites remain an attractive choice in aerospace industry due to the increased usage in the latest models of commercial aircrafts such as A350XWB and B787 compared to older aircraft programs[2]. At the same time, the increasing demand on commercial aircraft means that the contribution of aviation to global warming phenomena and CO_2 emissions will lead to more strict regulations aiming to reduce aviation carbon footprint. Therefore, lightweight materials such as composites becomes more attractive choice for use in aircraft structures and aircraft engines than ever before in order to reduce the overall weight, cut fuel emissions as well as noise reduction[4]. Indeed, because of all the above reasons, the composite market is expected to reach a value of 115.43 billion USD by 2022 from 72.58 billion back in 2016[5]. The first commercial aircraft to use composite materials in its structure was the Boeing 707 in the 1950s with 2% glass fibre material[6]. In 1995, 10% of Boeing 777 structural weight was made from composites. The first Boeing 787 Dreamliner which entered the service in 2011 contained 32,000 Kg (50% by weight) of composite materials[7-10]. Composite materials such as carbon and glass fibre reinforced polymers are mainly used in the aircraft airframe, sections of the fuselage, wings, tail surfaces, doors, crater and fan of the engine [4, 11, 12]. Such areas of the aircraft usually undergo drilling and milling processes for riveting and assembly purposes. In fact, 1.5- to 3 million holes are drilled in a single commercial aircraft using conventional process of machining. However, with this process of machining poor hole quality can be obtained which represents the main reason for part rejection prior assembly accounting for 60% of all rejected parts[13-17]. Therefore, proper hole drilling plays a critical role in defining longevity and structural integrity of future aircraft structures[18-21]. In addition, the drilling process becomes more challenging as some of those composite materials are bonded with metallic structures to enhance the impact and fatigue resistance of the aircraft structures[22, 23]. In this context, the most prominent composite material is S2/FM94 glass fibre reinforced epoxy composites which is integrated in fuselage panels made of GLARE® fibre metal laminates[23, 24]. S2/FM94 glass fibre reinforced epoxy composites have less strength and stiffness than carbon fibre reinforced composites, however, they are extremely hard, cheaper, less brittle and can be easily formed[5]. S2 glass fibres are made of magnesium alumina-silicate glasses attenuated at higher temperatures into fine fibres ranging from 5 to 24 µm[5, 25]. Composite aeronautical structures are by far made of carbon fibre. S2 glass fibres are much less used compared to carbon due to their higher costs. Nevertheless, they are characterised by high compressive and tensile strength, coupled with temperature and impact resistance making it an attractive choice for aeronautical structures that undergo impact loadings[5]. In the aerospace industry, CFRPs (Carbon Fibre Reinforced Plastics) are mainly used in the primary structural components of an aircraft such as the wing aileron, flaps, spoilers, tailplane and main landing gear fairings [13, 26], while GFRPs (Glass Fibre Reinforced Plastics) are used in primary and secondary structural components such as the radome (the dome-like shell that protects a radar assembly in aircraft), belly fairing skins, floor panels, and passenger compartments [13, 26]. Moreover, GFRPs can be also bonded with metals to create hybrid fibre metal laminates used in sections of the fuselage.

There have been numerous studies on drilling different types of glass fibre materials as shown in Table 1. The past studies in the open literature investigated the machinability of unidirectional and woven E-glass and none on S2 glass fibre composites. The studies usually used HSS or carbide drills which were coated and uncoated, while their size ranged between 4-12 mm which is common hole size range used in aerospace structures. Previous studies also agree that minimal delamination and cutting forces on the GFRP work piece can be achieved using lower feed rates [27-29]. It can be also observed that the order of the importance for the controllable cutting factors when drilling GFRPs is feed rate followed by spindle speed[27, 28, 30-32]. Although the feed rate seems to be the most critical parameter that should be selected carefully in order to reduce all kinds of damages. Nevertheless, most studies only investigated two input parameters which are the feed rate and the spindle speed. Additional, input parameters such as the drill coating, size or geometry have shown that they could significantly impact hole quality metrics and cutting forces [33, 34], while only few of the previous studies in the open literature studied the effect of environmentally friendly coolants such as MQL (Minimum Quantity Lubrication) and cryogenics (LN_2 and CO_2) on drilling GFRP mainly in composite metal stack structures [35-38]. The aim in the current study is to fill this gap in the literature and highlight the impact of using cryogenic cooling environment when drilling GFRPs.

Generally, previous studies on drilling GFRPs have looked into the effect of cutting parameters, nature of the process of manufacturing of the composite, drill geometry, drill coating and coolants on the developed cutting forces and hole quality as depicted in Table 1. Previous studies reported that the feed rate had a major influence on the hole quality, thrust force and torque. Moreover, abrasion wear in the cutting tool is usually present when drilling GFRP composites and usually increases the thrust force and torque especially when low feed rates are employed. Also, the low thermal conductivity of the GFRP is a drawback for the machining process. For example, using low feeds and high speeds will considerably increase the friction and induce high temperatures on the material which causes severe delamination and premature wear of the tool. Previous studies showed that HSS and coated HSS tools wear quickly and therefore not suitable for drilling GFRP[39]. Cemented carbide or diamond coated tools, on the other hand, are recommended due to their high wear resistance[40, 41]. Hole quality parameters such as surface roughness and delamination were the most analysed parameters due to their importance in defining the quality of machined holes. The main challenge when machining composites made of glass fibre is the thermal-induced damage caused by the interaction between the cutting tool and the workpiece. Excessive heat during drilling could cause significant delamination and worsen the dimensional accuracy of the holes due to the difference in mechanical and thermal properties of the matrix and the fibre[42]. Conventional coolants can be used to overcome and improve the machinability of composite materials by reducing the friction between the tool, chip and workpiece[15]. Some previous studies reported that the composite materials tend to expand when in contact with lubricant or any fluid due to moisture absorption by the matrix[43, 44]. However, other authors have mentioned that, specimens machined with abrasive water jet process are characterized by high limit endurance compared to other specimens machined by conventional cutting tool and without lubricant[19, 20]. This in return will increase the mechanical damage and cause rapid deterioration of the composite structure during its service[43, 44]. In addition, previous reports showed that the use of lubricants contributes by around 7.5% to 20% of the total manufacturing costs, while the cutting tools contributed by 4% to 8% beside[45-47]. The machined parts with the presence of coolants require cleaning from oils and contamination which makes coolants less desirable especially with composite materials due to increased costs.

Table 1: Summary of previous research conducted on drilling of glass fibre composites

Material	Drill bit information	Drilling parameters	Output parameters	Ref.
GFRP	8 mm diameter HSS drill	455, 875, 1850 (rpm) 0.03, 0.08, 0.15, 0.23, 0.3 (mm/rev)	CF, T, DF	48
GFRP	4, 6, and 8 mm diameter solid carbide drills 4-facet, 8-facet, parabolic point, and Jobber drill	750, 1500, 2250 (rpm) 10, 15, 20 (mm/min)	CF, T, DiD	49
GFRP	2, 3, and 4 flute carbide drills with 60˚, 90˚ and 120˚ - point angle, and 8 mm diameter	50, 70, 90 (m/min) 0.06, 0.12, 0.18 (mm/rev)	DiD, TW	50
GFRP	12 mm WC tipped drill	600, 900, 1200, 1600 (rpm) 0.04, 0.08, 0.12, 0.16 (mm/rev)	CF, DF, SR	51
GFRP	3, 6, 10, and 12 mm diameter carbide-coated drills	600, 900, 1200, 1500 (rpm) 50, 75, 100, 125, 150 (mm/min)	DF	29
GFRP	6 mm diameter HSS drill, 90°, 104°, and 118°-point angle	375, 938, 1500 (rpm) 0.075, 0.188, and 0.300 (mm/rev)	CF, T, DiD	52
GFRP	5 mm stub length and Brad & Spur cobalt grade drills	55, 71, 86 (m/min) 0.05, 0.1, 0.2 (mm/rev)	SCP, CF, DiD, SR	31
GFRP	6 mm diameter, HSS, TiN coated HSS and tipped tungsten carbide drills	9.43, 18.85, 23.56, 30.16 (m/min) 0.02, 0.04, 0.06, 0.08 (mm/rev)	CF, TW, DF, P, AE	39
GFRP	8 mm diameter cemented carbide drills	6.41, 12.71, 20.25, 32.03, 50.63 (m/min) 0.056, 0.112, 0.22, 0.315, 0.45 (mm/rev)	CF, T, DF, SR	53
GFRP	6, 8- and 10-mm diameter step and multifaced drills	500, 1500, 2500 (rpm) 100, 300, 500 (mm/min)	CF	54
GFRP	7 mm diameter with high speed steel (HSS) point angles of 118° and 135˚, helix angle of 30˚	5, 10, 15, 20, 25 (m/min) 0.1, 0.2, 0.3, 0.4 (mm/rev)	DF, SR	32
GFRP	5 mm HSS drills	50, 80 and 110 (mm/min), 355, 710 and 1000 (rpm), A =5, 10 and 15 µm	CF, D	55
GFRP	6 mm HSS drill	0.04 (mm/rev), 630 (rpm), $F=$ 220 Hz	CF, P, W	56
GFRP	7 mm carbide 25˚ helix angle, 120˚-point angle 7 mm tungsten carbide multifaceted micro grain drill with 30˚ rake angle and 30˚ helix angle	0.03,0.05, 0.07, (mm/rev) 9550, 24100, 38650 (rpm)	CF, W	57
Woven E-GFRP	10 mm	25, 50, 75, 100, 125 (m/min) 1000, 1200, 1400 (rpm)	DF	58
Woven E-GFRP	8 mm cemented carbide drill	0.56, 0.112, 0.22, 0.315, 0.45 (mm/rev) 255, 505, 805, 1275, 2015 (rpm)	CF, DF, SR, W	53
Woven GFRP	6 mm cemented carbide drill	0.02, 0.05, 0.1, 0.2, 0.3 (mm/rev) 600, 800, 1000, 2000, 3000 (rpm) Conditions of curing of the composite	DF, SR	59

E-GFRP	5 mm Cemented carbide (grade K20) twist drills 25º helix angle 130˚, 118˚, 85˚-point angle	1000, 3000, 6000, 9000 (mm/min) 4000, 8000, 40000 (rpm)	DF	60
Woven E-GFRP	8- and 13-mm cemented carbide drills with point angle of 120˚ and flute angle of 30˚	0.056, 0.112, 0.22, 0.315, and 0.45 (mm/rev) 6.41, 12.70, 20.23, 32.04, 50.64 (m/min)	CF, DF, R, TW	61, 62
E-GFRP	10 mm coated cemented carbide drill 140˚-point angle, 30˚ helix angle	0.05, 0.10, 0.15 (mm/rev) 750, 1000, 1250 (rpm)	CF	63
GFRP	10 mm twist drill, point drill and multi facet drill	0.02, 0.03, 0.04, 0.05 (mm/rev) 500, 1000, 1500, 2000, 14000, 16500 19000 (rpm)	DF, R	64
Woven GFRP	6 mm HSS TiN coated HSS and tipped tungsten carbide drills	0.02, 0.04, 0.06, 0.08 (mm/rev) 9.43, 18.85, 23.56, 30.16 (m/min)	CF	39
E-GFRP	PCD	0.048, 0.096, 0.143, 0.191, 0.238 (mm/rev) 54, 82, 126, 194, 302 (m/min)	SR	65
Polyamide GFRP	8 mm HSS TiN coated drills with 118˚ and135˚ point angle	0.1,0.2,0.4 (mm/rev) 1500, 3000, 6000 (rpm)	HS, HC, B, DiD	66
E-GFRP	Twist drill	400, 800, 1200 (rpm) 50, 100, 150 (mm/min)	DF	27
E-GFRP	6, 8, 10 mm carbide K10 drills	500, 1000, 1500 (rpm) 50, 100, 150 (mm/min)	DF	67
E-GFRP	2, 4, 6, 8, 10 mm brad and spur drills	500, 1000, 1500, 2000, 25000 (rpm) 50, 100, 150, 200, 250, 300 (mm/min)	SR	68
GFRP	8 mm brad and spur drills	1000, 1500, 2000, 2500 (rpm) 100, 200, 300, 400 (mm/min)	CF, DF SR	30
E-GFRP	Diamond core drills	1000, 1200, 1400 (rpm) 30, 50, 70 (mm/min)	CF	69

CF: Cutting Forces, T: Torque, P: Power, AE: Acoustic Emission, B: Burrs, DF: Delamination Factor, DiD: Drilling-induced Damage, TW: Tool Wear, TEMP: Temperature, SCP: Specific cutting pressure, SR: Surface roughness, HS: Hole Size, HC: Hole circularity.

Alternative methods to minimise machining temperatures were proposed by using cryogenic cooling techniques[70]. Cryogenic machining is the process of using liquids that have sub-zero boiling temperatures as coolants for machining instead of conventional coolants to study their impact on different machined materials[5, 38]. Cryogenic coolants are environmentally friendly, do not leave any signs of contamination on the machined parts and can save costs as the produced chips are clean and can be easily recycled. Moreover, they evaporate at room temperatures and therefore do not require handling and disposal similar to conventional machining coolants[71, 72]. Most commonly used cryogenic coolants in machining processes are carbon dioxide (CO_2) and liquid nitrogen (LN_2)[38, 72]. The majority of research on cryogenic machining was conducted using turning operations on different types of steel, nickel, Inconel and titanium alloys. This was mainly due to their high hardness, good failure strength and low thermal conductivity which causes excessive temperatures in the tool-workpiece during machining[38]. There has also been an increasing interest in using cryogenics in machining composite materials in the past two decades[73-80]. A large number of researchers looked into a different method of applying cryogenic coolants to the machining process either through direct cooling of the cutting zone or precooling the workpiece/cutting tools. For example, previous study showed that applying LN_2 when drilling Kevlar composites reduced the surface roughness and improved the hole accuracy[73]. However, applying cryogenic coolants directly tends to increase the workpiece hardness which causes a significant rise in cutting forces and therefore increasing the delamination size and microcracking [5, 36, 38, 73, 81]. In contrast, other studies reported that cryogenically pre-cooling the cutting tool or direct cryogenic spraying tended to reduce the cutting forces stating that it provided lubrication between the drill and the workpiece[74, 76]. Drilling studies on CFRP agree that using cryogenic coolants tend to reduce surface roughness and increase cutting forces and delamination factor [77, 82, 83]. While previous studies on drilling GFRP in cryogenic environment are limited and reported that using them increased the cutting forces and reduced delamination factor and surface roughness[35]. None of the previous studies in the open literature reported the drilling of S2 glass fibre composites or the impact of cryogenic cooling in particular. Therefore, the purpose of the current work is to fill this gap in the literature. The study evaluates the impact of drilling parameters (spindle speed (n), feed rate (f)) and cryogenic cooling of the workpiece/drill using LN_2 on the developed cutting forces (thrust force and torque), hole roughness parameters (R_a and R_z), hole hardness and area delamination factor (F_a) at the hole entry and exit sides. To eliminate any influence on the study arising from other factors, the same cutting tool geometry was used for all tests with fixed drill size, point angle and helix angle. Moreover, a full factorial design of experiments was employed in the study. The design consists all possible combinations of three factors (spindle speed, feed rate and dry or cryogenic coolant) at different levels. The results were further analysed using Analysis of Variance (ANOVA) statistical method to evaluate the percentage contribution of cryogenic coolant, cutting parameters and their interactions on the measured hole metrics.

2. Materials and methods

2.1 Workpiece and cutting tools

S2/FM94 glass fibre prepreg workpiece of 240 mm x 240 mm x 7.18 mm thick (54 layers) was used in the drilling studies. The workpiece consisted of FM-94 film adhesive embedded with S2 glass fibres in the form or prepregs having a thickness of 0.133 mm[14, 16, 36, 40, 84]. The fibres were delivered as a prepreg including the FM94 adhesive system (Cytec®) from Cytec, U.K [40]. The S2/FM94 glass fibre adhesive epoxy material is of particular interest as it is the fibre reinforcing material used in fibre metal laminates[85]. The material is mainly used in aerospace structural applications such as Airbus A380 fuselage as part of a fibre metal laminate material commercially known as GLARE®. Table 2 shows the mechanical properties of the glass fibre prepregs used in the current study.

Table 2: Mechanical properties of unidirectional S2 Glass/FM 94 epoxy prepreg[86-90]

Mechanical property		**UD S2 Glass/FM 94 Epoxy Prepreg $V_F = 60\%$**	**Units**
Young Modulus (E)	E_L	54-55	GPa
	E_T	9.4-9.5	
Ultimate tensile strength (σ_{ult})	σ_L	2640	MPa
	σ_T	57	
Ultimate strain % (ε_{ult})	ε_L	3.5-4.7	-
	ε_T	0.6	

Shear Modulus (G)	G_{LT}	5.55	GPa
	G_{TL}	3	
Poisson's ratio (ν)	υ_{LT}	0.33	-
	υ_{TL}	0.0575	
Density (ρ)	-	1980	kg/m^3
Thermal expansion coefficient(α)	α_L	3.9-6.1	$(1/°C) \cdot 10^{-6}$
	α_T	26.2-55.2	
Thermal conductivity (K)	λ_L	1.1-1.4	W/m-K
	λ_T	0.43-0.53	

The symbols L and T stand for longitudinal (the rolling direction for the metal) and transverse directions respectively.

The workpiece was made using unidirectional (UD) prepregs with symmetric stacking sequence of $[0°/90°]_{27s}$ similar to those used in GLARE® laminates as shown in Figure 1.a which can found in aircraft structures. The workpiece was cured in an autoclave for around 300 minutes at elevated temperatures of 120°C and under a pressure of six bars according to the manufacturer's instructions as shown in Figure 1.b. A ∅6 mm TiAlN coated carbide drill bit with a point angle of 140° and a helix angle of 30° was used for drilling tests as shown in Figure 1.c. The drill has a shank length of 28 mm and a flute length of 75 mm long. The drill is suitable for general use on materials up to 55 HRC. The specific selection of the drill geometry and coating was based on previous studies shown previously in Table 1 and previous literature[5, 16, 40, 91]. Besides, the choice of the drill bit size was based on previous studies on and typical 4.8-10 mm hole size commonly used for rivets in aerospace structures[5, 16, 33, 84].

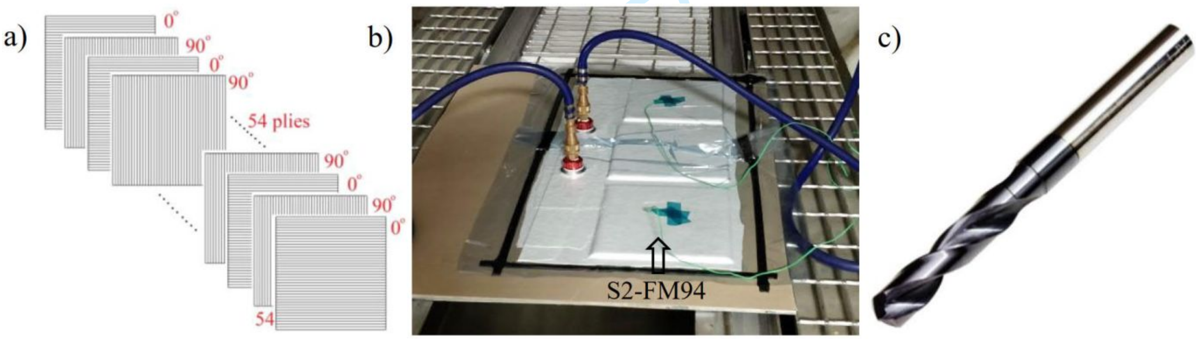

Figure 1: (a) Fibre orientation system of S2/FM94 glass fibre composite workpiece (b) Manufacturing the workpiece in the autoclave (c) Cutting tool used in the study

2.2 Cutting parameters

Drilling tests have been conducted using full experimental design with three levels of spindle speed and three levels of feed rate. Besides, two cooling strategies (with and without cooling) and one cutting tool type (i.e. fixed coating, size and geometry). Each test run produced a set of nine holes, which was repeated two additional times to confirm repeatability. Therefore, all values reported in this study represent the mean values of the three runs. A fresh drill bit was used in each run to eliminate any impact of tool wear[33, 92]. The full factorial design technique with three factors (i.e. spindle speed, feed rate and presence/absence of cooling) was carried out for both dry and cryogenic cooling tests, thus requiring a total number of 54 holes (27 holes for dry tests and 27 holes for cryogenic tests). Table 3 shows the levels of the spindle speeds and feed rates used in the study. The full factorial study can determine the impact of the three factors and their levels on measured outputs, which were the cutting forces (F_z, M_z), surface roughness (R_a, R_z), hardness and delamination factor (F_a). The collected data was analysed using a statistical approach. For this MINITAB®18 software was employed to determine the significance of each of the three factors and their interactions. The factorial analysis was carried out using a Prob>F less than 0.05 which means that the effect of the model, the input parameters on the output parameters (F_z, M_z, R_a, R_z, *hardness and* F_a) are significant at 95% confidence level[33]. The spindle speed and feed rate levels were chosen according to previous literature on drilling different types of glass fibre composites and based on recommendations of tool manufacturers. Current literature reported that a typical feed rate ranging from 0.05 to 0.3 (mm/rev) can be used for drilling glass fibre reinforced plastics (GFRP). Similarly, the choice of spindle speeds - depends on the drill size and can be anything from 1000 to 9000 rpm[5, 16, 33, 36, 38, 91, 93-96]. Table 3 shows the levels of the spindle speeds and feed rates used in the study.

Table 3: Spindle speed and feed rate levels used in the study

Factor	Low level	Medium level	High level
Spindle speed (rpm)	3000	5000	7000
Feed rate (mm/min)	300	500	700
Cooling	No (Dry)	Cryogenic bath of tool and workpiece	

2.3 Experimental machine setup and procedure

The drilling tests were carried out on a Quaser MV 154-C - CNC milling machine and the drilling tests were programmed using a Mitsubishi M70 Series controller. This CNC machine is characterised by a maximum spindle speed of 10000 rpm. Some of the most commonly used cryogenic machining techniques include cryogenic workpiece cooling, cryogenic jet cooling, and cryogenic cutting tool cooling. In this study, with a different approach, the workpiece was drilled within a cryogenic bath. In this way, both cryogenic workpiece cooling and tool cooling were obtained. The workpiece was placed in a polyamide fixture that was full of liquid nitrogen as shown in Figure 2. The fixture provides thermal insulation to minimise the impact of low temperature effects of LN_2 on the dynamometer or damaging the CNC machine[97]. The detailed information about the fixture and the method were given in a previous study[70].

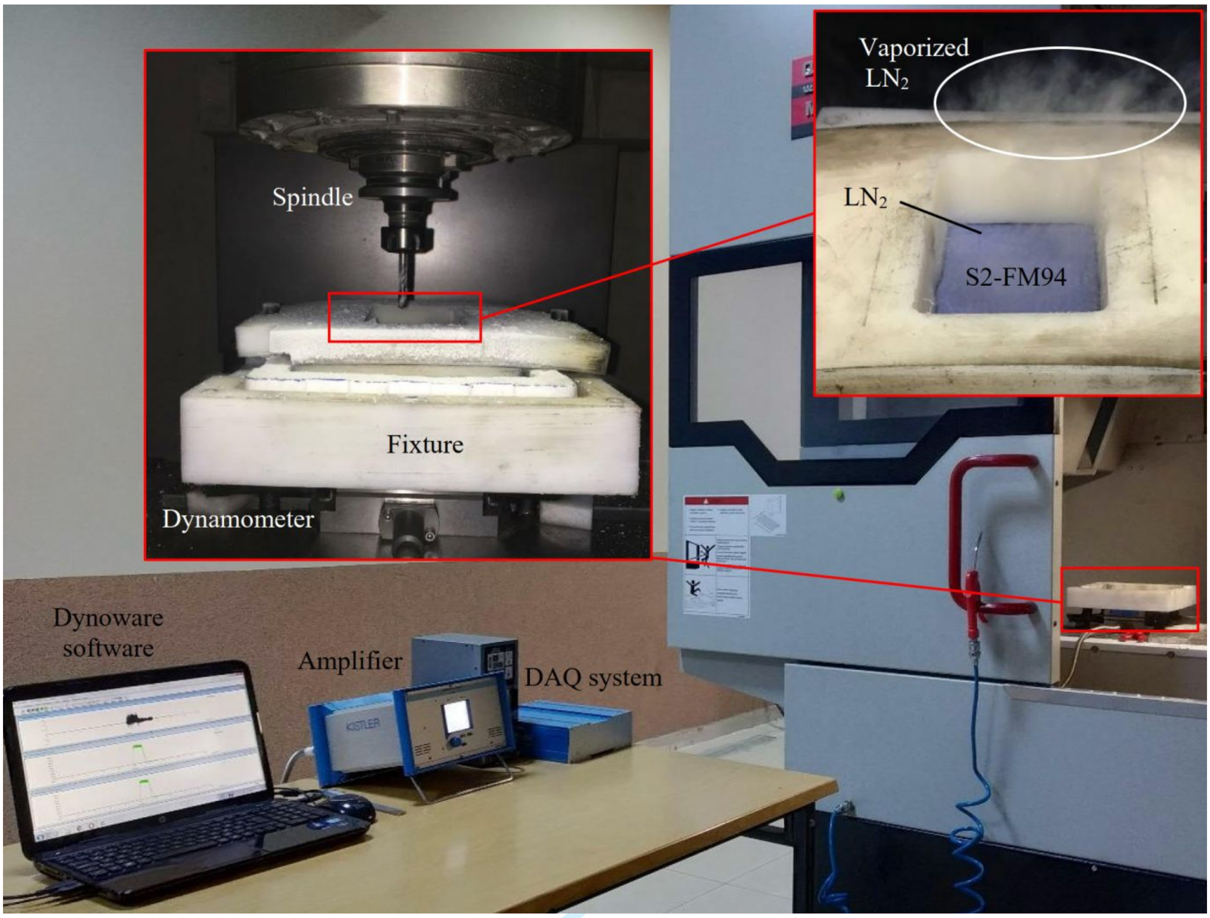

Figure 2: Details of the experimental setup for the drilling tests, cutting force and torque measurement instruments

2.4 Measurement of thrust force and torque

The cutting forces (thrust force F_z and torque M_z) were measured using a piezoelectric 6-component force measurement (F_x, F_y, F_z, M_x, M_y, M_z) KISTLER 9257B dynamometer which is suitable for milling and drilling experiments. This dynamometer is based on the instrumentation by four piezoelectric sensors. DynoWare software, KISTLER 5697A data acquisition system and 5070A 8-channel charge amplifier were used for measurement and data acquisition as shown in **Error! Reference source not found.**2. a sampling frequency of 8000 Hz and 10 to 20 seconds measuring range were predefined in the software before the drilling process.

2.5 Surface roughness measurements

The machining quality of the wall of the hole can influence the performance of the machined structure in service. Therefore, for the qualification of the drilled holes, the choice focuses on the determination of the surface roughness. There are many criteria for the qualification of surface quality. The arithmetic average roughness, R_a and the ten-point mean roughness R_z were measured in the current study using a Zygo Zegage optical surface profilometer as shown in Figure 3a[20, 98]. ZeMaps and MetroPro software surface analysis software was used to monitor surface topography and determine the surface roughness data. All holes were divided into two part from the radial axis and the wall of the hole was examined using a contactless surface profilometer.

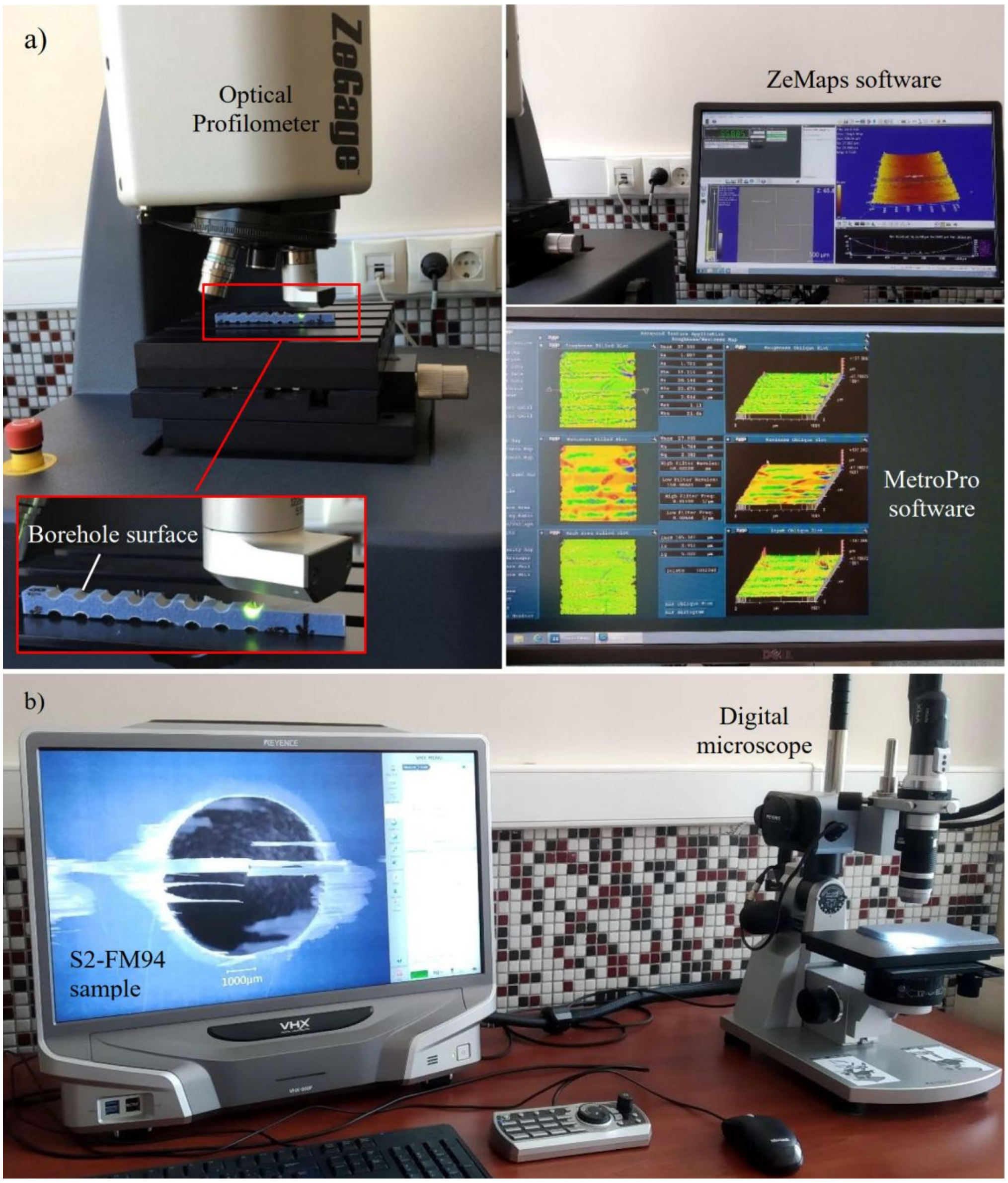

Figure 3: (a) Details of borehole surface roughness measurement and (b) observation of the drilled sample

2.6 Delamination factor measurement

Drilling induced delamination in fibre reinforced composites reduce the service life of the parts during compressive loading. In fact, delamination is one of the most critical drilling induced damage in composite materials [99]. Surface delamination, which occurs around the hole edges at entry and exit sides can be inspected using an optical microscope. The delamination factors - F_A (ratio of delaminated area to the nominal hole area) or F_D (ratio of the diameter of delamination considering the extremities of surface damage contour to the nominal hole diameter) are often used to quantify delamination defect after drilling of composites[100]. F_A is a more accurate method to evaluate surface delamination, however, the majority of previous studies employ the conventional delamination factor F_D to assess surface delamination due to the difficulty in measuring the delamination area[101-103]. In this study, both entry and exit sides of the drilled composites were inspected using Keyence VHX-900F digital microscope as illustrated in Figure 3b and delamination factor F_A for each hole was determined with digital image processing to give an accurate evaluation of delamination defect. Hole images at the entry and exit sides were processed using ImageJ software to measure the delamination area. Full details of the steps undertaken to measure area delamination factor were reported in previous work[104]. The area delamination factor F_A was calculated using the equation shown below:

$$F_A = \frac{A_{nom}}{A_{max}}$$

Where

- A_{nom} is the nominal area of the hole
- A_{max} is the area of the hole and delamination area around it.

2.7 Hardness measurement

It is well known that the hardness of the material changes due to the machining process. Vickers hardness testing is the commonly used method for evaluating hardness in metals [105], while for hardness testing of composite materials, it is most commonly measured by the Shore (Durometer). Shore hardness is mainly used to measure the resistance of soft rubber-like or rigid plastic materials to indentation. A ZwickRoell analogue shore D hardness tester with a drag-pointer was used to measure the hole hardness prior and after the drilling tests as shown in Figure 4. The hardness value determination was taken after a dwell time of three seconds (ISO 7619-1) and 1 second (ISO 868) can be accommodated with digital hardness testing instruments. The post-machining hardness for each hole was measured near the entry and exit sides at room temperature T = 23 °C. The hardness of the top and bottom surfaces of the workpiece before machining were found to be 82 and 78, respectively.

Figure 4: Hole surface hardness measurement

2.8 Scanning Electron Microscopy (SEM)

A Hitachi SU5000 field emission Scanning Electron Microscope (SEM) equipped with Energy-dispersive X-ray spectroscopy (EDX) mapping was accessed to inspect the wall quality of the drilled holes as shown in Figure 5. Each hole was cut in two from its centre and throughout its thickness. The cut holes were cleaned using an ultrasonic bath to remove any dust or debris followed by a sputter coating process. Magnifications of 30-5000X and 10 keV voltage were applied to visualise the walls damage induced by the interaction cutting tool /composite as necessary.

Figure 5: Photos showing (a) the Hitachi SU5000 SEM microscope (b) the outer view of the SEM interlock (c) inside the main chamber with the specimen (d) image from the monitor

3. Results and Discussion

3.1 Analysis of hole hardness

All holes machined under dry and cryogenic conditions showed a change in the surface hardness due to the cutting process and developed temperatures in the workpiece/cutting tool zone. Figure 6 shows the average shore hardness measured near the hole entry and exit sides versus cutting parameters. The hardness of the holes under cryogenic conditions was always greater than those drilled under dry condition for the same cutting parameters. Dynamic recrystallization effect, which is a significant mechanism for metals, may be not valid for GFRP. The reason of strength and therefore hardness increase due to cryogenic treatment can be attributed to matrix hardening caused by more densely polymer structure based on exposing the material to low temperatures. In addition, cryogenic hardening may alter the local threshold required for breaking of adhesion bondage at the fibre/matrix interface which in return would cause reduced strength properties [81]. It was also observed that the hole hardness decreased with the increase of the feed rate under dry and cryogenic conditions with an exception for holes drilled at $n = 3000$ rpm under cryogenic conditions. This could be attributed to the generation of uncut chips at higher speed. Another reason could be related to the time of exposition to the low temperature from the first drilled holes till the ninth one when the spindle speed is $n = 3000$ rpm. In addition, the cutting temperatures at the tool-chip interface increase due to the drilling process while the workpiece remains exposed to sub-zero cryogenic temperatures. At this instant, very large thermal expansion mismatch within the workpiece itself may result in weakening the fibre–matrix interface and/or a possible matrix cracking due to thermal shock stress[106].

Additionally, the percentage change in hardness under dry condition at entry and exit sides ranged between -1.83% and 3.67%, while under cryogenic condition ranged between 0% and 3.6%. This indicates that cryogenic bath provided a thermally stable environment which allowed for uniform hardness across the hole and somewhat better than that obtained under dry drilling conditions. The largest increase in hole hardness under cryogenic conditions compared to dry condition occurred at $f = 700$ mm/min at all spindle speeds due the generation of uncut chips at higher speed as mentioned earlier. The maximum hardness on the cryogenically machined holes was 62.5 and 61 in Shore D hardness, which was 16.8% and 11.9% higher than dry machining at entry and exit sides at $f = 700$ mm/min and $n = 3000$ rpm, respectively. Structural materials used in aerospace applications must satisfy the crashworthiness and impact energy absorption conditions. Since S2/FM94 glass fibre is installed in areas of the aircraft that are subjected to low or high impact energy levels, therefore, it is speculated that an increase in the material hardness due to cryogenic machining would result in brittle fracture during impact. However, this claim needs to be confirmed in a future study.

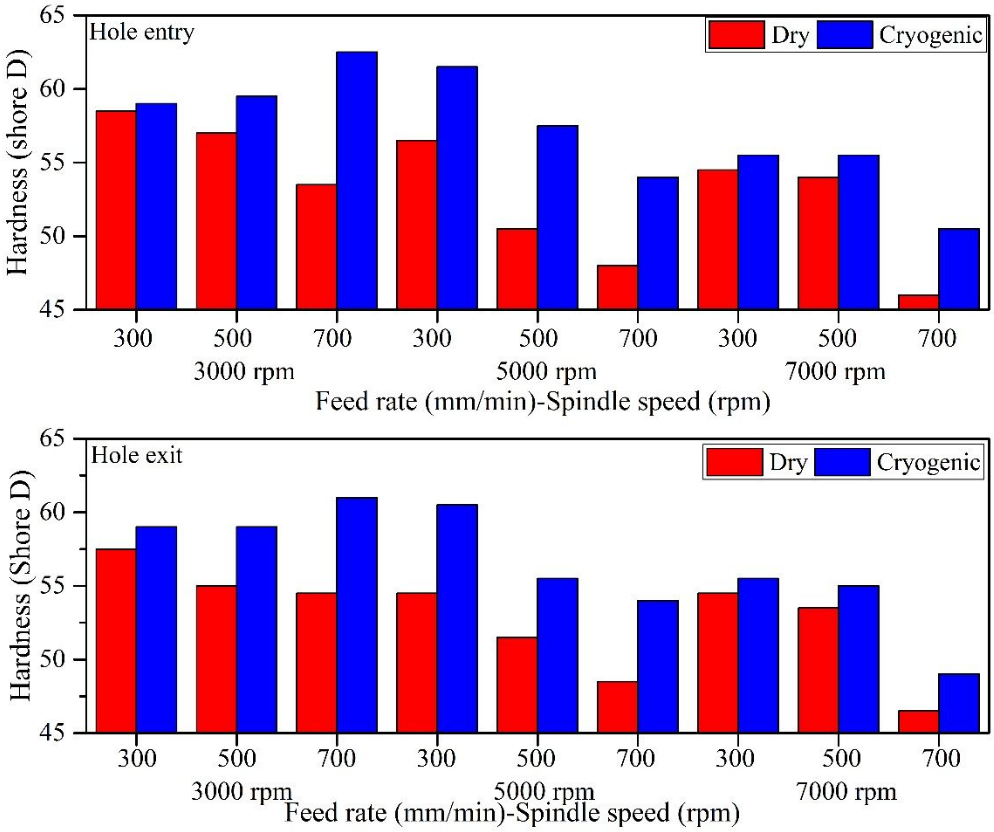

Figure 6: Shore hardness of holes at entry and exit sides under dry and cryogenic conditions

3.2 Thrust force and torque analysis

Figure 7 shows a thrust force profiles recorded during drilled under dry and cryogenic conditions. The thrust force profiles show several stages which indicate the interaction of the chisel edge and the main cutting edges of the cutting tool with the workpiece during the drilling process. The first stage occurs by the first contact of the chisel edge with the workpiece and is achieved when the corner of the cutting tool reaches the first layer or the of the laminate therefore, the thrust force is zero followed by rapid increase in the thrust force. This stage can be defined as the entry-stage since the chisel edge is not fully in contact with the workpiece. Once the chisel edge becomes in full contact with the workpiece, the thrust force reaches a maximum and steady value throughout the hole drilling process. The final stage occurs when the cutting tool represented by the chisel edge begins to exit the workpiece from its bottom side hence the thrust force drops down. This stage resembles the first stage observed when the drill enters the workpiece indicating the end of hole-making process.

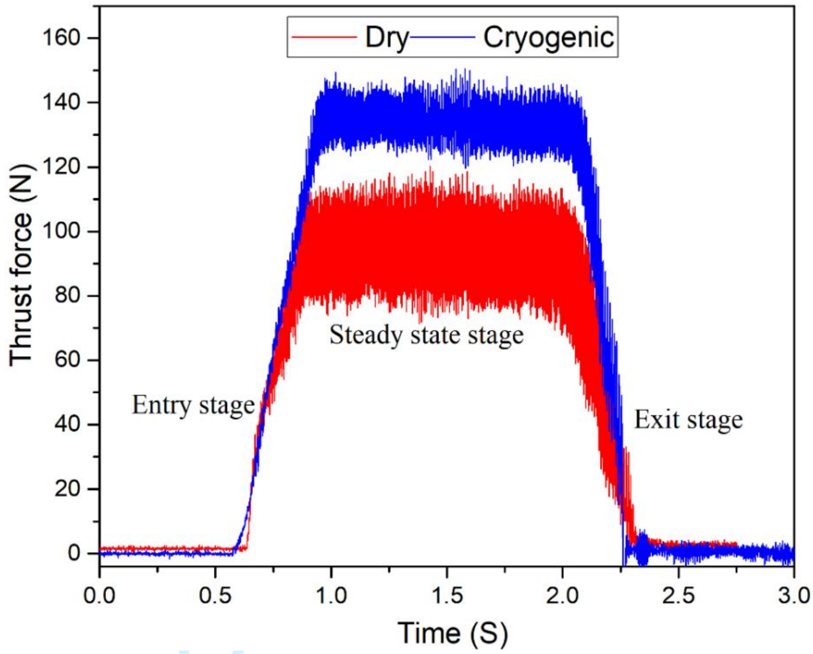

Figure 7: Thrust force diagram using a spindle speed of n =3000 rpm and a feed rate of f =300 mm/min

Figure 8 shows the cutting forces results obtained under different cutting parameters. The results showed that the cutting forces decreased with the increase of the spindle speed and increased with the increase of the feed rate. This augmentation can be explained by the fact that, when the feed rate increases the uncut chip thickness increases too [4, 97]. However, the reduction of the cutting forces when the spindle speed increases can be related the thermal phenomenon. In fact, when the temperature of machining increases the composite material (epoxy) softens and its strength is reduced. In addition, from Figure 8, it can be noticed that the cutting forces generated using cryogenic bath were always greater than those generated under dry drilling. This result is in good agreement with previously reported studies of using cryogenic liquid nitrogen as a coolant during drilling and milling of composites, metals and composite metal stacks alike[38, 70, 80, 97, 107]. Indeed, drilling in dry conditions generates lower cutting forces perhaps due to the softening of the matrix by the heat generated during the drilling process[108], yet cryogenic bath drilling lowers temperature in the cutting zone, therefore, higher cutting forces are produced[38, 97].

It was also observed that the rise in cutting forces under cryogenic cooling increased with the increase of the feed rate. For example, the thrust force and torque recorded under cryogenic conditions occurs when drilling at f =700 mm/min and n =3000 rpm were 69% and 35% higher than that under dry conditions, respectively. The difference could be attributed to the increase in hardness of the hole as shown previously in Figure 8. It was also observed that the difference in cutting forces between dry and cryogenic conditions becomes smaller when drilling is conducted with a higher spindle speed. This could be due to the counter-effect of cutting temperatures rise with spindle speed which reduces the effect of cryogenic coolant on the hardness of the hole and its mechanical properties. This also indicates that perhaps cryogenic cooling is more suitable for high-speed drilling applications where temperatures play a more significant role on hole quality and premature tool wear.

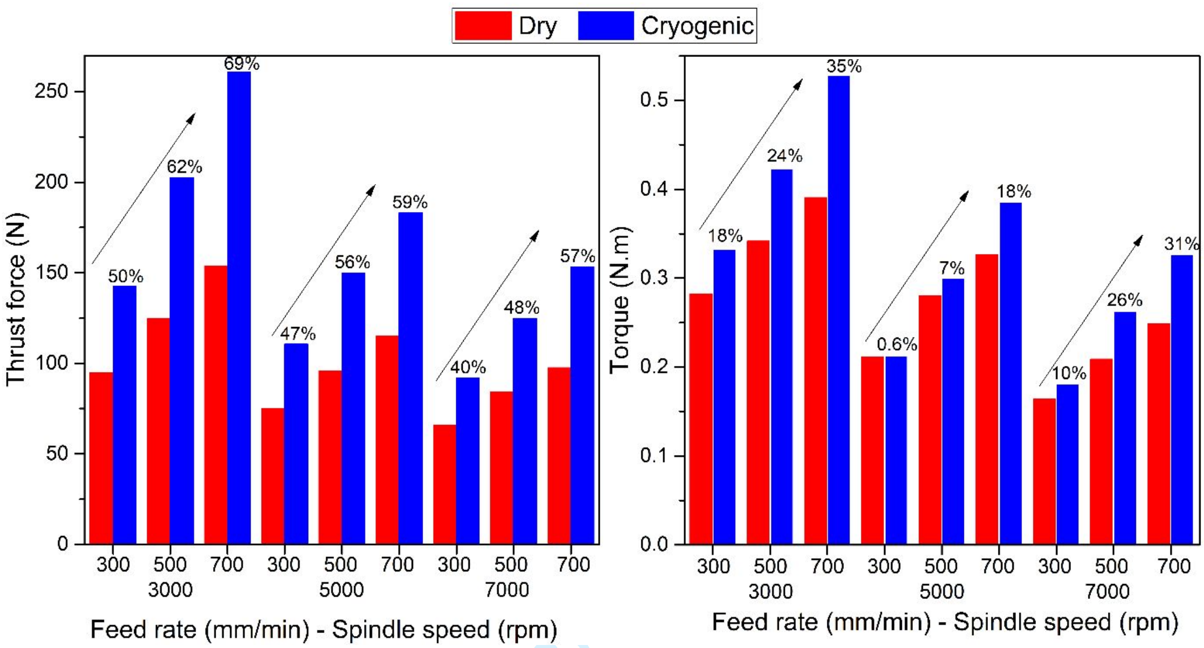

Figure 8: Average torque and thrust force under different cutting conditions

Table 4 shows part of the ANOVA analysis of cutting forces, surface roughness parameters and delamination factors at entry and exit sides. The table contains the P-value and percentage contribution for each of the analysed output parameters and the impact of cutting parameters and presence of cryogenic cooling on them. The table includes linear interaction between input parameters and their two- and three-way interactions. The percentage contribution values in red are the ones with significant contribution to the model with P-value < 0.05. It can be observed that the use of cryogenic cooling had the largest impact on thrust force with 34.41% followed by the feed rate and spindle speed, respectively. It can be also observed that the order of the importance for the controllable cutting factors when drilling GFRPs is feed rate followed by spindle speed which is in agreement with previous studies [27, 30] .

Their two-way interactions had much less impact with all of them equally contributing inferior to 5%. However, for torque, the most contributing parameter was the spindle speed with 45.22% followed by the feed rate with 36.16%. The use of cryogenic coolant had a minor contribution of 8.84% which could be because torque is more affected by increased vibrations which are directly related to the increase in the feed rate and spindle speed. The two-way interactions of both cutting parameters with the coolant were also minimal and ranged around 2%.

Table 4: ANOVA analysis of cutting forces, surface roughness parameters and delamination factors at entry and exit sides

	F_z		M_z		R_a		R_z		F_a entry		F_a exit	
Source	**P-Value**	**Contribution**	**P-Value**	**Contribution**	**P-Value**	**Contribution**	**P-Value**	**Contribution**	**P-Value**	**Contribution**	**P-Value**	**Contribution**
Model	0	98.66%	0	95.98%	0	95.98%	0	88.81%	0	95.28%	0	94.59%
Blocks	0.006	0.47%	0.039	0.84%	0.055	0.75%	0.531	0.42%	0.933	0.02%	0.602	0.16%
Linear	0	90.20%	0	90.22%	0	90.31%	0	82.30%	0	76.02%	0	81.93%
Spindle speed	0	26.97%	0	45.22%	0.425	0.21%	0.011	3.42%	0	22.48%	0	3.79%
Feed rate	0	28.83%	0	36.16%	0	6.51%	0	16.06%	0	25.17%	0	6.06%
Coolant	0	34.41%	0	8.84%	0	83.59%	0	62.82%	0	28.37%	0	72.08%
2-Way Interactions	0	7.66%	0	4.78%	0	4.71%	0.122	4.61%	0	15.03%	0	10.12%
Spindle speed*Feed rate	0	2.28%	0.385	0.51%	0.733	0.24%	0.183	2.18%	0	6.64%	0.108	1.31%
Spindle speed*Coolant	0	2.48%	0.001	1.99%	0	4.16%	0.042	2.30%	0.005	1.71%	0.156	0.62%
Feed rate*Coolant	0	2.90%	0	2.29%	0.28	0.31%	0.827	0.13%	0	6.68%	0	8.19%
3-Way Interactions	0.108	0.33%	0.888	0.13%	0.77	0.21%	0.363	1.48%	0	4.21%	0.013	2.37%
Spindle speed*Feed rate*Coolant	0.108	0.33%	0.888	0.13%	0.77	0.21%	0.363	1.48%	0	4.21%	0.013	2.37%
Error		1.34%		4.02%		4.02%		11.19%		4.72%		5.41%
Total		100.00%		100.00%		100.00%		100.00%		100.00%		100.00%

3.3 Surface roughness analysis

Figure 9 shows the average surface roughness metrics R_a and R_z for dry and cryogenic drilling conditions under different cutting parameters. The results showed that R_a and R_z tended to increase with the increase in the feed rate and decrease with the increase of spindle speed. It was also observed that R_a and R_z of the holes drilled under cryogenic conditions were much lower than their counterparts in holes drilled under dry conditions. This would imply that using cryogenic cooling bath had a positive impact on hole roughness and R_a and R_z values. Similar results have been observed when drilling metallic alloys, composites and fibre metal laminates[38, 70, 109, 110]. The reduction in $\mathrm{R_a}$ using cryogenic cooling was highest (more than 100% reduction in R_a) at $n = 7000$ rpm, this would imply that the impact of the cryogenic cooling becomes more significant at higher cutting speeds where higher drilling temperatures are more likely to be present. Similar trends were also observed for R_z. Generally, R_a and R_z ranged between 1.72 to 2.2 µm and 0.81 to 1.4 µm under dry and cryogenic drilling conditions, respectively.

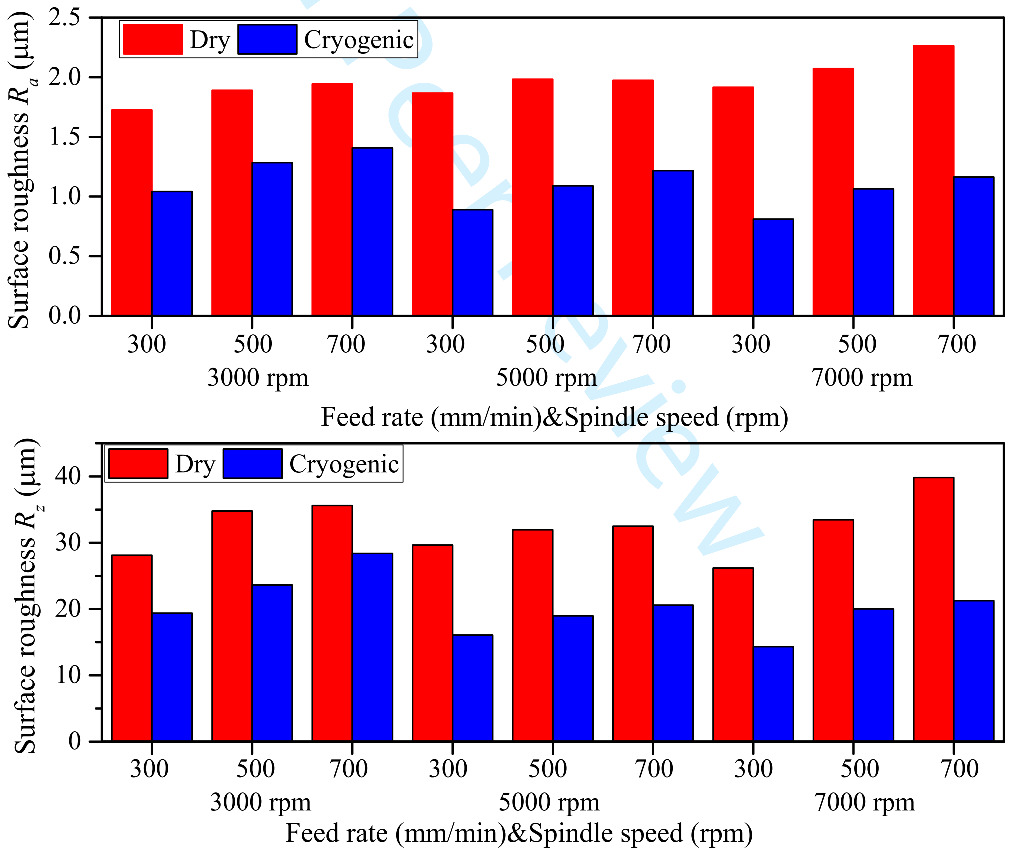

Figure 9: Average surface roughness ($\mathrm{R_a}$ and $\mathrm{R_z}$)

From the ANOVA results in Table 4, it was found that the change in spindle speed affects the surface roughness to a much lower degree than the feed rate [111]. Nevertheless, the use of cryogenic coolant had the most significant contribution with 83.59% and 62.82% for R_a and R_z, respectively. It can be also observed that the order of the importance for the controllable cutting factors when drilling GFRPs is feed rate followed by spindle speed which is in agreement with previous studies [27, 30] .

In summary, a lower feed rate and higher spindle speed produce better roughness metrics R_a and R_z. Cutting tool manufacturers reports states that the requirements of hole surface roughness R_a in composite and metallic aeronautical structures to be less than 3.2 µm and less than 1.6 µm, respectively[5, 112]. R_a results in this study are within the limits of recommended roughness values and lower than those reported in previous drilling studies of glass fibre composites under dry conditions[61, 64, 65]. Figure 10 shows several three-dimensional optical images of hole topographies drilled under dry and cryogenic conditions. The images show that using cryogenic cooling provides a smoother surface variation of peaks and valleys along with the hole depth. This in return would attribute to lower surface roughness values of R_a and R_z.

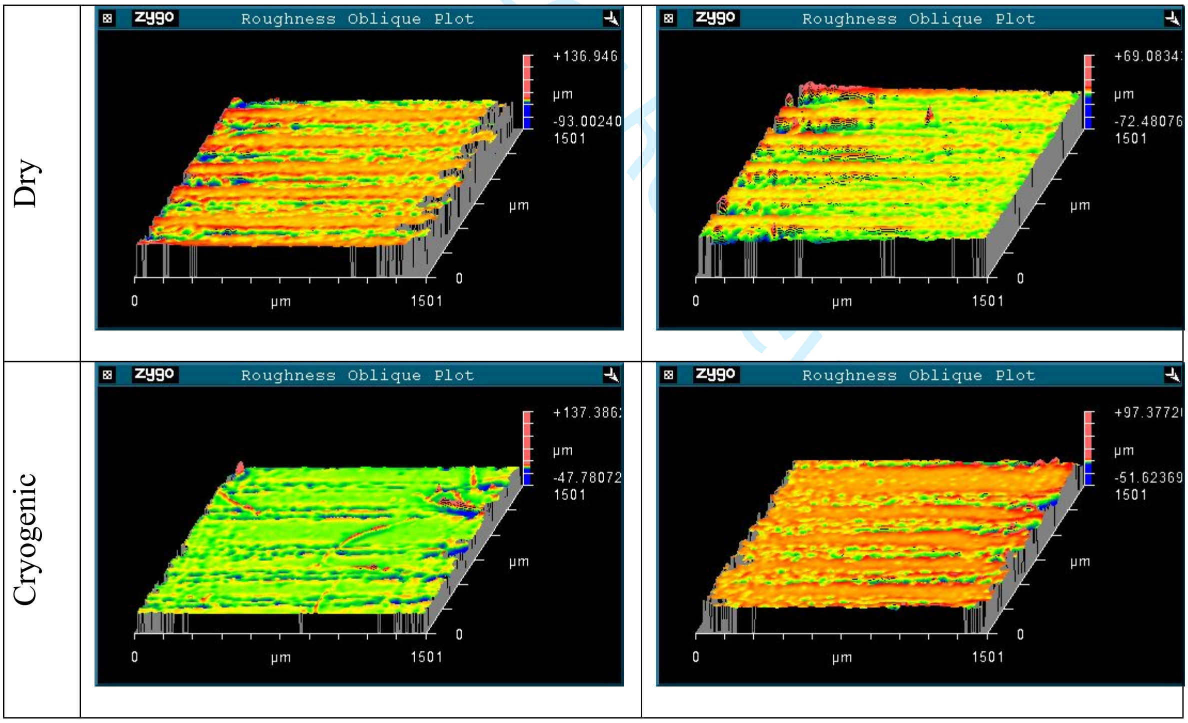

Figure 10: 3D optical microscopy showing the surface topography of holes drilled under dry and cryogenic conditions

3.4 Surface delamination analysis

Figure 11 depicts the drilling-induced delamination damage at hole exit under dry and cryogenic drilling conditions. The laminate undergoes severe cracks or decohesion between layers which cause it to split or separate into layers known as delamination[113]. The damage can be seen to propagate along the fibre direction which creates spalling regions as shown in Figure 11b. This indicates that delamination is influenced by the stacking sequence[114]. Spalling is considered as one of the major damage mechanisms which occur during drilling of composite materials [115], their size and severity becomes greater at the exit side of the hole and tends to increase with the increase of the feed rate and decrease with the increase in spindle speed. The fibre at the hole entry side was pulled upwards instead of being cut (peel-up delamination) as shown in Figure 11a.

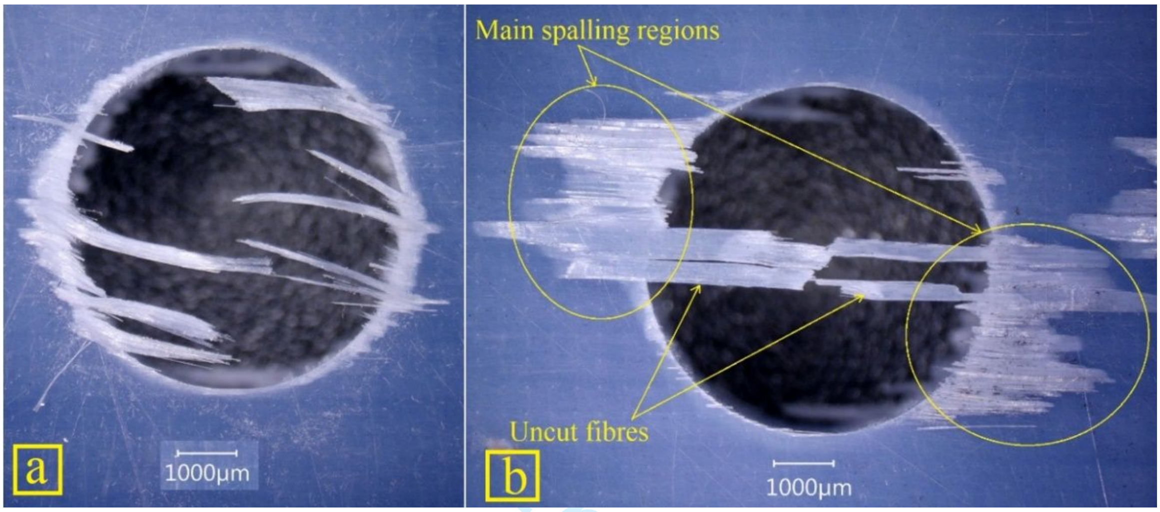

Figure 11: Drilling induced delamination damage at hole exit at 3000 rpm and 300 mm/min under a) dry and b) cryogenic drilling conditions

Figure 12 shows the delamination factor (F_a) at different cutting parameters for dry and cryogenic drilling conditions. Delamination at hole exit side was greater than at the entry side which is well-known phenomenon since delamination is more likely to occur at the interfaces near the hole exit side when the thrust force exceeds a critical value which induces delamination. Therefore, a common strategy to avoid introducing delamination is to reduce the thrust force (by reducing the feed rate). Also, delamination factor under cryogenic condition was always greater than that under dry condition which could be attributed to the higher thrust force as shown previously in Figure 8. It is well known that the mechanical properties of polymer materials depend on frequencies of molecular excitation through the relaxation time, which depends on temperature[81]. Therefore, exposing the glass fibre samples to sub-zero temperatures during the drilling temperature might have introduced cracks and delaminated areas possibly by misfit strains at the interfaces, because of the differential coefficient of expansion between the fibre and polymer matrix[81].

The results also showed the delamination factor increased with the increase of the feed rate while the spindle speed showed a somewhat variable effect. Previous studies on delamination in composites reported that the feed rate was the most influential factor and suggested using low feed rates to reduce delamination around the hole and cutting tool with small web thickness (chisel edge) [116, 117]. However, in this study, it appears that both drilling parameters had an influence on delamination. This was evident by the results of the ANOVA analysis which showed that both cutting parameters had similar contribution as shown previously in Table 4. It was also observed that the presence of cryogenic coolant had the largest impact on delamination at entry and exit sides of the hole with 28.37% and 72.08%, respectively. The results also showed that the interaction between the feed rate and the coolant and the three-way interaction between all the input parameters had minor contribution ranging from 2.37% to 8.19%. Delamination decreased as the spindle speed increased within the tested feed rate range, probably due to an increased cutting temperature with spindle speed; this leads to enhanced softening of the matrix and less delamination [113]. In addition, under dry conditions, the delamination at the exit was less affected by the cutting parameters compared to delamination in holes drilled under cryogenic cooling.

The thrust force induced during cutting as well as the nature of the interface between layers of the composite define the machinability of composite materials which directly affects the drilling-induced delamination. Many studies reported a reduction in exit delamination by using a back-up plate[118-120] or by using a pre hole or by using a step drill. Perhaps using a support plate at the bottom part of the workpiece is an appropriate method to control drilling-induced delamination when using cryogenic cooling, which will be investigated in a future study.

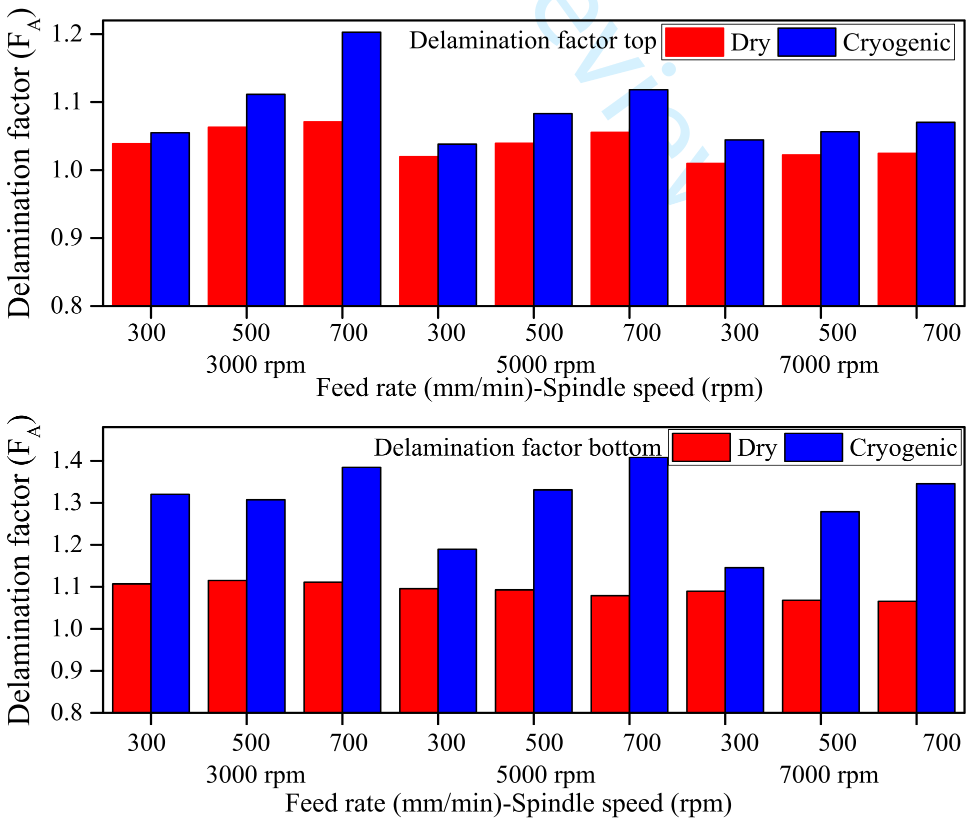

Figure 12: Delamination factor at (a) Hole entry (b) Hole exit.

3.5. Surface texturing analysis using SEM

Scanning electron microscopy (SEM) was employed to inspect the surface texture of drilled holes under dry and cryogenic conditions at fibres scale. In fact, the inspection of the SEM images illustrated in the Figure 13 did not show any signs of cracks or separation of layers in all holes drilled under dry and cryogenic conditions. However, the entry and exit edges of the holes were damaged which could be due to the interaction of the drill with the workpiece. The severity of damages was more pronounced when dry machining is considered compared to cryogenic drilling case. In addition, it can be noticed that, the damage recorded at the hole exit in both cases (dry and cryogenic) are superior to those observed at the hole entry. This could be due to the fact that, the parameters responsible of the generation of these damage are not the same. For the SEM images it can also mentioned that, no clear indication of whether cryogenic cooling provided a better surface condition throughout the hole depth since similar damage forms were observed in both conditions. However, it was previously reported that cryogenic conditioning causes differential contraction which may increase the deboning resistance caused by temperature rise which weakens the adhesive bonding strength[106]. The impact of cryogenic conditioning during drilling process will be investigated in a future study.

Generally, the fibre-matrix tended to stretch and overlap which could be due to rise in drilling temperatures due to poor thermal conductivity of the material and the action of the feed force due to the drill motion on the borehole walls. SEM images showed small segments of broken fibres which were forced into the laminate and adhered to the hole surface which could occurred during the subsequent removal of glass fibre layers. This phenomenon was more present in holes machined at highest spindle speeds and feed rates. Smearing was present when drilling is conducted at high spindle speed and feed rates. This could be due the rise in cutting temperatures at the drill-workpiece interface which caused smearing of the matrix and fibres on the borehole walls.

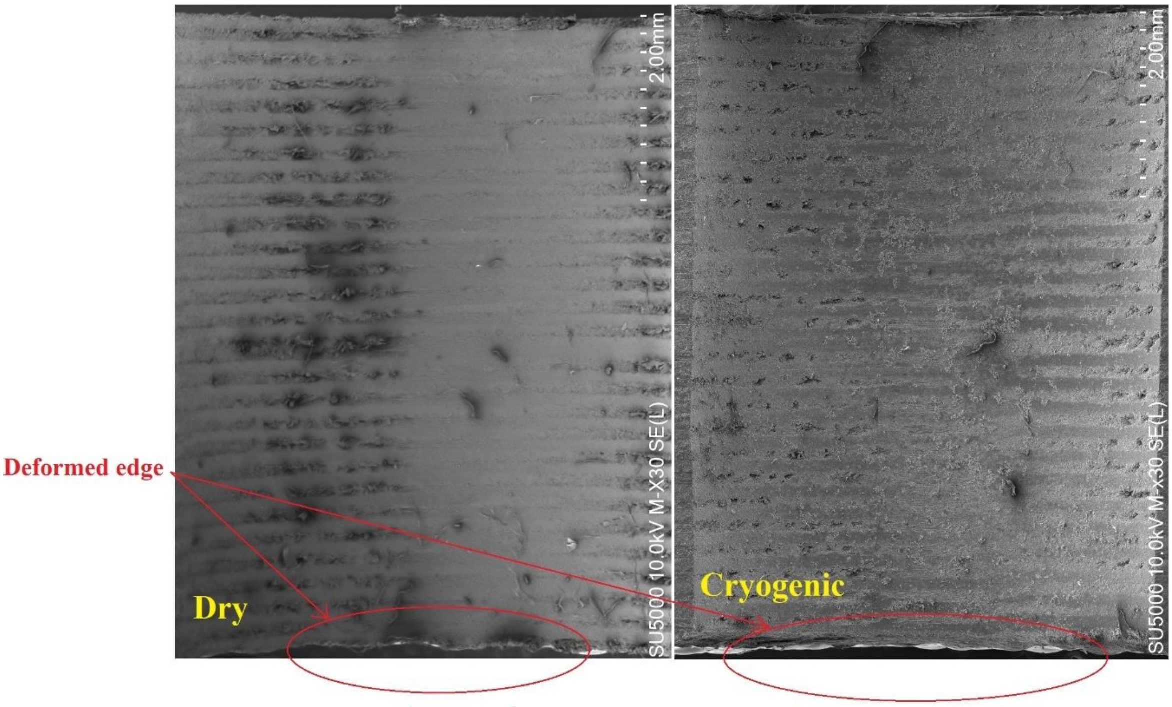

Figure:13 SEM of holes cross-sections under dry and cryogenic conditions when machining is conducted with feed rate of 300 mm/min and spindle speed of 7000 rpm.

SEM images shows that fibres were partially embedded into the matrix after being cut which could be due to the entrapment of broken fibres between the tool and the borehole wall forcing them into the matrix as shown in Figure14 a and Figure 14 c. Fibre rupture (fracture) and fibre pull-out were observed in different regions around the borehole as shown in Figure14 b. Fibre rupture occur due to excessive rubbing on the drill surface causing them to stretch along with the drill rotational motion until they break (split) from the fibre-matrix system. Some of the fibres were cut perpendicular to their direction due to the compressive action of the drill edges onto the surface causing micro-buckling of fibres (compressive failure of 0°)[42]. Usually, the least damage on fibre by cutting tools occurs when the fibres are at 0° relative to the cutting edge[121]. Those fibres are subjected to shearing from the supporting epoxy matrix and form smooth socket surfaces which are known as 'Cusps' as shown in Figure 14 d. The inter laminar shear stress at the fibre-matrix interface increase with fibre orientation up to 90° which in return decreases the size of the formed discontinuous chip[5, 84]. The resulting machined surface is irregular and fibres protrude out of the surface in various lengths as shown in Figure 14 d due to the elastic recovery of the fibres after the progression of the cutting tool away from the machined surface and the continuous stretching-induced fractures of the fibres, the protruded fibres are the cause of flank wear[5, 42, 122].

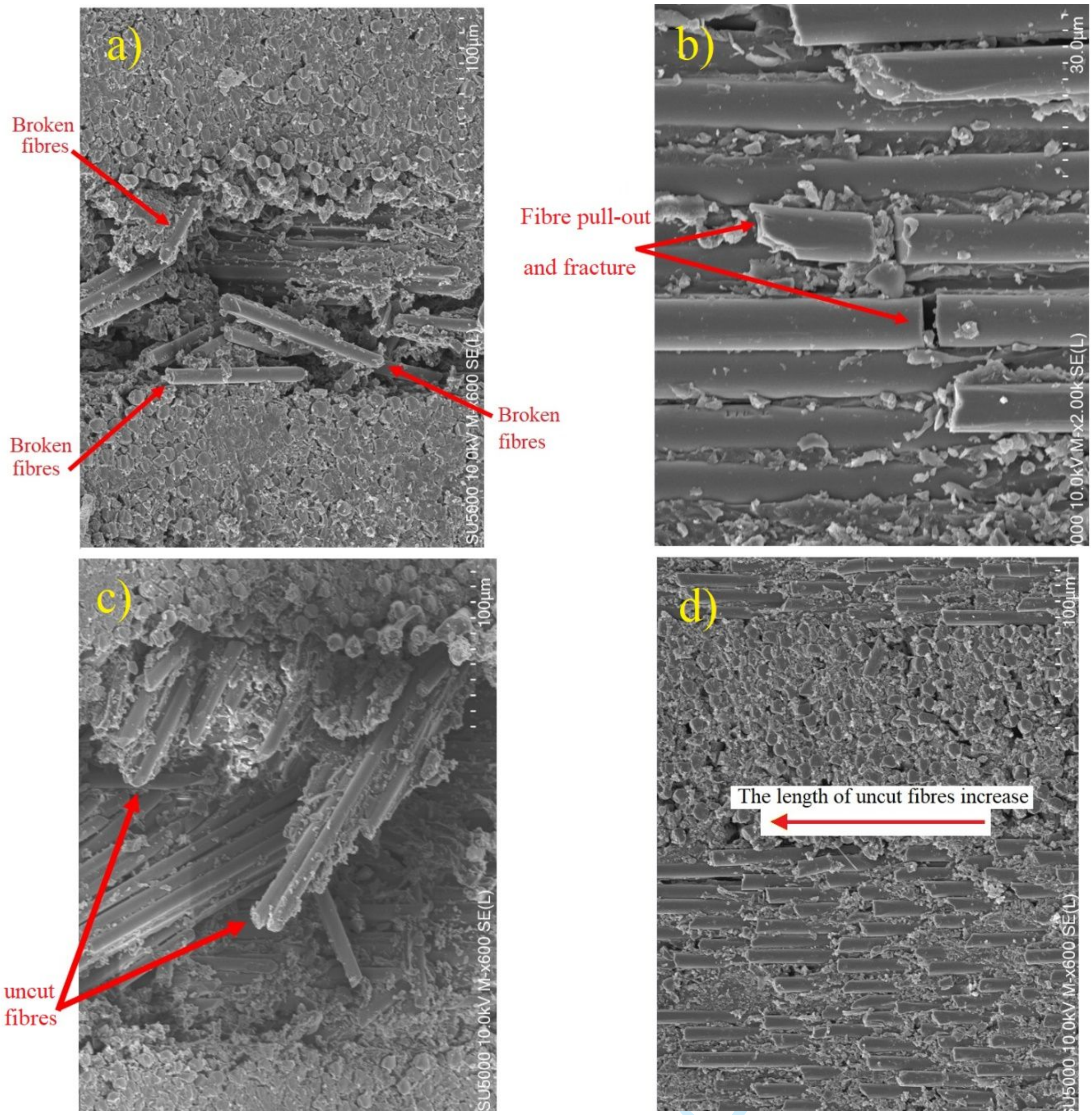

Figure:14 SEM images of holes cross-sections under dry conditions a) Broken fibres (5000 rpm and 500 mm/min) b) fibre pull-out and fractured fibres (3000 rpm and 300 mm/min) c) uncut fibres (7000 rpm and 500 mm/min) d) fibre length around the hole (3000 rpm and 300 mm/min)

It was also observed that plies with 0° fibres were protruding more than plies with 90° orientation as shown in Figure 15 a. This could be due to the difference in their thermal expansion coefficients. The thermal expansion coefficients of the workpiece can influence the hole quality due to the transverse isotropy of the glass fibre epoxy[90]. As shown earlier in Table 2, the thermal expansion coefficient of S2 glass in fibre and transverse directions (α1, α2) are $6.1 \cdot 10^{-6}$ 1/ºC and $26.2 \cdot 10^{-6}$ 1/ºC, respectively[87]. The large mismatch in thermal expansion coefficients in cross configurations causes the laminate plies to stretch and shrink at different rates [5]. The 0° fibres expand along their longitudinal direction while the 90° fibres contract in the transverse direction causing geometric mismatch and increased residual stresses in the hole which also promotes for debonding of the fibres from the matrix[5, 121].

Not all fibres are cut and removed by the cutting edges of the drill, some fibres that escape the cutting process undergo bending when the composite layers peels and slides along the rake face of the drill causing them to bend like a cantilever beam[42]. The progression of the drill into the laminate and the continuous peeling and bending of the fibre/matrix without fracturing. This in return produces small segmented (discontinuous) chips which flatten upon separation and attain their original shape as shown in Figure15 b.

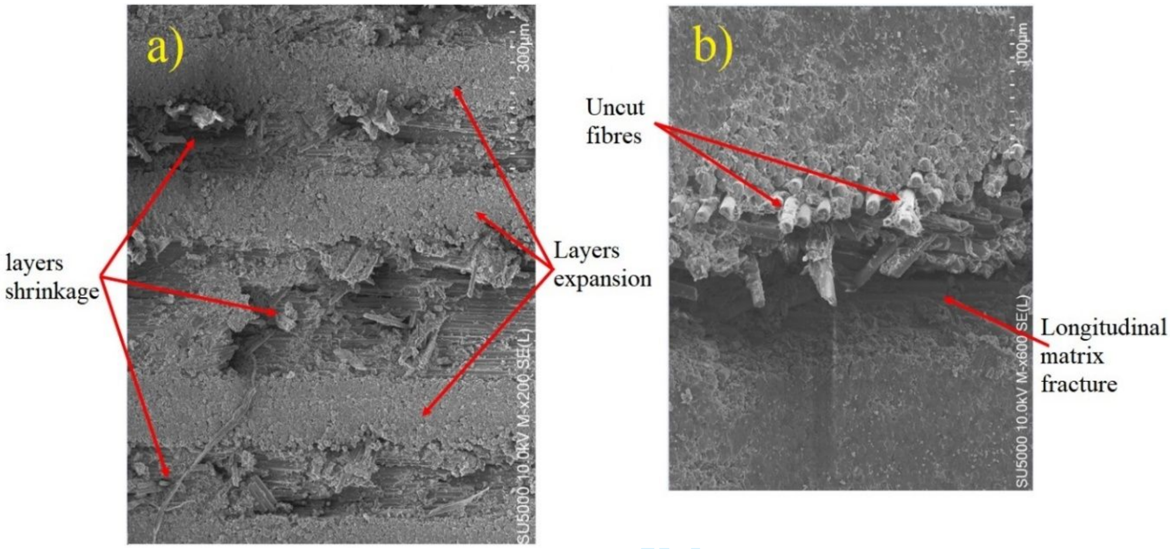

Figure 15: SEM images of holes cross-sections a) shrinkage and expansion of composite layers (dry 7000 rpm and 700 mm/min) b) uncut fibres and longitudinal matrix fracture (dry 5000 rpm and 300 mm/min)

4. Conclusions

The machinability of S2/FM94 glass fibre adhesive epoxy was investigated through a conventional twist drilling process under dry and cryogenic drilling conditions. The aim was to evaluate the impact of using cryogenic liquid nitrogen cooling bath on the cutting forces, surface roughness, post-machining hardness and delamination factor at entry and exit sides. The specific aim was to study the suitability of liquid nitrogen coolant for drilling aerospace-grade composite materials. The results from cryogenic cooling tests were compared with results from conventional drilling tests using the same drilling parameters, drill geometry and coating. The study was driven by the fact that the impact of cryogenic coolants was previously tested for cutting different metallic and composite materials but never on S2 glass fibre composites. The investigation of environmentally friendly cooling process is an important issue when it comes to drilling aeronautical materials due to limited reported studies in the open literature. Based on the findings of the study, it can be concluded that:

- The post-machining hardness, cutting forces and delamination factor at entry and exit sides of holes drilled under cryogenic conditions were always greater than those obtained under dry conditions.
- Surface roughness metrics R_a and R_z were reduced when using cryogenic cooling. ANOVA analysis shows that coolant contribution on those metrics was approximately 83.59% and 62.82%, respectively.
- The presence of cryogenic cooling had a significant impact on delamination factor at hole exit side with 72.08% contribution. The spindle speed, feed rate and coolant had a somewhat equal impact on delamination factor at hole entry side.
- Apart from the clear effect of cryogenic cooling on cutting forces and analysed hole quality metrics, the feed rate is the dominant parameter, which affects the thrust force, surface roughness metrics and delamination factor in drilling GFRP composites.
- Despite showing a positive impact on surface roughness, it was observed that cryogenic cooling did not improve the other analysed hole metrics which indicates that additional adjustments are necessary when using cryogenic coolants to limit its negative impact on hole metrics. A recommended procedure would be to use a backup plate to reduce cutting forces and exit delamination which will be investigated in a future study.

References

1. Airbus. *Airbus annual report 2018*. 2018.
2. Research S. What is the future of Aerospace Composites Market? Know Covid Impact on Size, Share & Forecasts, https://medium.com/@stratviewresearch/what-is-the-future-of-aerospace-composites-market-know-covid-impact-on-size-share-forecasts-f87ee1facc82 (2020, accessed 19/07/2020 2020).
3. Markets Ra. Global Composites Market to Exhibit a Negative CAGR of 4.4% Between 2019 & 2021 due to the Halt of Manufacturing Operations Worldwide Amid COVID-19, https://www.prnewswire.com/news-releases/global-composites-market-to-exhibit-a-negative-cagr-of-4-4-between-2019--2021-due-to-the-halt-of-manufacturing-operations-worldwide-amid-covid-19--301065134.html (2020, accessed 19/07 2020).
4. Cadorin N and Zitoune R. Wear signature on hole defects as a function of cutting tool material for drilling 3D interlock composite. *Wear* 2015; 332: 742-751.
5. Giasin K. *Machining Fibre Metal Laminates and Al2024-T3 aluminium alloy*. University of Sheffield, 2017.
6. Tenek LT and Argyris J. *Finite element analysis for composite structures*. Springer Science & Business Media, 2013.
7. Balasubramanian M. *Composite materials and processing*. CRC press, 2013.
8. Jones RM. *Mechanics of composite materials*. CRC press, 2014.
9. Elhajjar R, La Saponara V and Muliana A. *Smart Composites: Mechanics and Design*. CRC Press, 2013.
10. Chawla KK. *Composite materials: science and engineering*. Springer Science & Business Media, 2012.
11. Giurgiutiu V. *Structural health monitoring of aerospace composites*. Academic Press, 2015.
12. Bajpai PK and Singh I. Drilling behavior of sisal fiber-reinforced polypropylene composite laminates. *Journal of Reinforced Plastics and Composites* 2013; 32: 1569-1576.
13. Mouritz AP. *Introduction to aerospace materials*. Elsevier, 2012.
14. Giasin K and Ayvar-Soberanis S. An Investigation of burrs, chip formation, hole size, circularity and delamination during drilling operation of GLARE using ANOVA. *Composite Structures* 2017; 159: 745-760.

15. Hocheng H. *Machining technology for composite materials : principles and practice*. Cambridge, UK; Philadelphia, PA: Woodhead Pub., 2012.
16. Giasin K, Ayvar-Soberanis S and Hodzic A. An experimental study on drilling of unidirectional GLARE fibre metal laminates. *Composite Structures* 2015; 133: 794-808.
17. Kaplan P. *Big Wings: The Largest Aeroplanes Ever Built*. Pen and Sword, 2005.
18. Giasin K. The effect of drilling parameters, cooling technology, and fiber orientation on hole perpendicularity error in fiber metal laminates. *The International Journal of Advanced Manufacturing Technology* 2018; 97: 4081-4099.
19. Saleem M, Zitoune R, El Sawi I, et al. Role of the surface quality on the mechanical behavior of CFRP bolted composite joints. *International Journal of Fatigue* 2015; 80: 246-256.
20. Saleem M, Toubal L, Zitoune R, et al. Investigating the effect of machining processes on the mechanical behavior of composite plates with circular holes. *Composites Part A: Applied Science and Manufacturing* 2013; 55: 169-177.
21. Zitoune R, Crouzeix L, Collombet F, et al. Behaviour of composite plates with drilled and moulded hole under tensile load. *Composite Structures* 2011; 93: 2384-2391.
22. Gunnink J, Vlot A, Alderliesten R, et al. Towards technology readiness of fibre metal laminates. In: *International Congress of Aeronautical Sciences, 22 nd, Harrogate, United Kingdom* 2000.
23. Sinke J. Manufacturing of GLARE parts and structures. *Applied composite materials* 2003; 10: 293-305.
24. Vlot A, Vogelesang L and De Vries T. Towards application of fibre metal laminates in large aircraft. *Aircraft Engineering and Aerospace Technology* 1999; 71: 558-570.
25. Hartman D, Greenwood ME and Miller DM. High strength glass fibers. *Moving Forward With 50 Years of Leadership in Advanced Materials* 1994; 39: 521-533.
26. Aamir M, Tolouei-Rad M, Giasin K, et al. Recent advances in drilling of carbon fiber–reinforced polymers for aerospace applications: a review. *The International Journal of Advanced Manufacturing Technology* 2019; 105: 2289-2308.
27. Palanikumar K, Prakash S and Shanmugam K. Evaluation of delamination in drilling GFRP composites. *Materials Manufacturing Processes* 2008; 23: 858-864.
28. Kilickap E. Optimization of cutting parameters on delamination based on Taguchi method during drilling of GFRP composite. *Expert systems with applications* 2010; 37: 6116-6122.
29. Mohan N, Kulkarni S and Ramachandra A. Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials. *Journal of Materials Processing Technology* 2007; 186: 265-271.
30. Palanikumar K. Experimental investigation and optimisation in drilling of GFRP composites. *Measurement* 2011; 44: 2138-2148.
31. Davim JP, Reis P and Antonio CC. Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up. *Composites Science Technology* 2004; 64: 289-297.
32. Kilickap E. Investigation into the effect of drilling parameters on delamination in drilling GFRP. *Journal of Reinforced Plastics and Composites* 2010; 29: 3498-3503.
33. Giasin K, Gorey G, Byrne C, et al. Effect of machining parameters and cutting tool coating on hole quality in dry drilling of fibre metal laminates. *Composite Structures* 2019.
34. Giasin K, Hawxwell J, Sinke J, et al. The effect of cutting tool coating on the form and dimensional errors of machined holes in GLARE® fibre metal laminates. 2020: 1-16.
35. Janakiraman A, Pemmasani S, Sheth S, et al. Experimental Investigation and Parametric Optimization on Hole Quality Assessment During Drilling of CFRP/GFRP/Al Stacks. 2020; 101: 291-302.
36. Giasin K, Ayvar-Soberanis S and Hodzic A. The effects of minimum quantity lubrication and cryogenic liquid nitrogen cooling on drilled hole quality in GLARE fibre metal laminates. *Materials & Design* 2016; 89: 996-1006.
37. Giasin K and Ayvar-Soberanis S. Evaluation of Workpiece Temperature during Drilling of GLARE Fiber Metal Laminates Using Infrared Techniques: Effect of Cutting Parameters, Fiber Orientation and Spray Mist Application. *Materials* 2016; 9: 622.
38. Giasin K, Ayvar-Soberanis S and Hodzic A. Evaluation of cryogenic cooling and minimum quantity lubrication effects on machining GLARE laminates using design of experiments. *Journal of Cleaner Production* 2016; 135: 533-548. DOI: http://dx.doi.org/10.1016/j.jclepro.2016.06.098.
39. Arul S, Vijayaraghavan L, Malhotra S, et al. Influence of tool material on dynamics of drilling of GFRP composites. *The International Journal of Advanced Manufacturing Technology* 2006; 29: 655-662.
40. Vlot A and Gunnink JW. *Fibre metal laminates: an introduction*. Springer, 2001.
41. J.F.W.Coesel. *Drilling Of Fibre-Metal Laminates*. Master Thesis, Delft University of Technology, 1994.
42. Sheikh-Ahmad JY. *Machining of polymer composites*. Springer, 2009.

43. Mohamed SB, Ab Rashid R, Muhamad M, et al. *Down Milling Trimming Process Optimization for Carbon Fiber-Reinforced Plastic*. Springer, 2019.
44. Jahanmir S, Ramulu M and Koshy P. *Machining of ceramics and composites*. Marcel Dekker, 1999.
45. Brockhoff T and Walter A. Fluid minimization in cutting and grinding. *Abrasives Magazine* 1998: 38-42.
46. Shaikh V. *Effects of Minimum Quantity Lubrication in Drilling 1018 Steel*. University of North Texas, 2008.
47. Benedicto E, Carou D and Rubio E. Technical, economic and environmental review of the lubrication/cooling systems used in machining processes. *Procedia engineering* 2017; 184: 99-116.
48. Khashaba U. Delamination in drilling GFR-thermoset composites. In: *International Conference on Aerospace Sciences and Aviation Technology* 2003, pp.461-481. The Military Technical College.
49. Singh I and Bhatnagar N. Drilling of uni-directional glass fiber reinforced plastic (UD-GFRP) composite laminates. *The International Journal of Advanced Manufacturing Technology* 2006; 27: 870-876.
50. Işık B and Ekici E. Experimental investigations of damage analysis in drilling of woven glass fiber-reinforced plastic composites. *The International Journal of Advanced Manufacturing Technology* 2010; 49: 861-869.
51. Ranganathan S, Senthilvelan T and Gopalakannan S. Multiple performance optimization in drilling of GFRP composites using grey analysis. In: *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM-2012)* 2012, pp.12-18. IEEE.
52. Singh I, Bhatnagar N and Viswanath P. Drilling of uni-directional glass fiber reinforced plastics: experimental and finite element study. *Materials & Design* 2008; 29: 546-553.
53. Khashaba U, El-Sonbaty I, Selmy A, et al. Drilling analysis of woven glass fiber-reinforced/epoxy composites. *Journal of composite materials* 2012.
54. Latha B, Senthilkumar V and Palanikumar K. Influence of drill geometry on thrust force in drilling GFRP composites. *Journal of reinforced plastics and composites* 2011; 30: 463-472.
55. Mehbudi P, Baghlani V, Akbari J, et al. Applying ultrasonic vibration to decrease drilling-induced delamination in GFRP laminates. *Procedia Cirp* 2013; 6: 577-582.
56. Ramkumar J, Aravindan S, Malhotra S, et al. An enhancement of the machining performance of GFRP by oscillatory assisted drilling. *The International Journal of Advanced Manufacturing Technology* 2004; 23: 240-244.
57. Lin S-C and Shen J-M. Drilling unidirectional glass fiber-reinforced composite materials at high speed. *Journal of composite materials* 1999; 33: 827-851.
58. Nagarajan V, Sundaram S, Thyagarajan K, et al. Measuring Delamination Severity of Glass Fiber-Reinforced Epoxy Composites During Drilling Process. *Experimental Techniques* 2012.
59. Zitoune R, Collombet F and Lopez GH. Experimental and analytical study of the influence of HexFit® glass fibre composite manufacturing process on delamination during drilling. *International Journal of Machining and Machinability of Materials* 2008; 3: 326-342.
60. Palanikumar K, Rubio JC, Abrao A, et al. Influence of drill point angle in high speed drilling of glass fiber reinforced plastics. *Journal of composite materials* 2008; 42: 2585-2597.
61. Khashaba U, El-Sonbaty I, Selmy A, et al. Machinability analysis in drilling woven GFR/epoxy composites: Part I–Effect of machining parameters. *Composites Part A: Applied Science and Manufacturing* 2010; 41: 391-400.
62. Khashaba U, El-Sonbaty I, Selmy A, et al. Machinability analysis in drilling woven GFR/epoxy composites: Part II–Effect of drill wear. 2010; 41: 1130-1137.
63. Ramesh B and Elayaperumal A. Optimization of process parameter levels during drilling high fiber volume fraction nonlaminated GFRP polymeric composites. *International Journal of Science and Engineering Applications* 2012; 1: 120-126.
64. Krishnaraj V. Effects of drill points on glass fibre reinforced plastic composite while drilling at high spindle speed. In: *Proceedings of the World Congress on Engineering* 2008, pp.2-4.
65. Sarma P, Karunamoorthy L and Palanikumar K. Surface roughness parameters evaluation in machining GFRP composites by PCD tool using digital image processing. *Journal of Reinforced Plastics and Composites* 2009; 28: 1567-1585.
66. Corrêa HL, Rodrigues RV and da Costa DD. Machining process of glass-fiber-reinforced polyamide 6.6 Composite: pathways to improve the drilling of recycled polymers. *Engineering Research Express* 2020; 2: 015037.
67. Latha B and Senthilkumar V. Fuzzy rule based modeling of drilling parameters for delamination in drilling GFRP composites. *Journal of Reinforced Plastics Composites* 2009; 28: 951-964.
68. Palanikumar K. Modeling and analysis of delamination factor and surface roughness in drilling GFRP composites. *Materials Manufacturing Processes* 2010; 25: 1059-1067.

69. Baraheni M and Amini S. Feasibility study of delamination in rotary ultrasonic-assisted drilling of glass fiber reinforced plastics. *J Journal of Reinforced Plastics Composites* 2018; 37: 3-12.
70. Morkavuk S, Köklü U, Bağcı M, et al. Cryogenic machining of carbon fiber reinforced plastic (CFRP) composites and the effects of cryogenic treatment on tensile properties: A comparative study. *Composites Part B: Engineering* 2018; 147: 1-11.
71. Pušavec F, Stoić A and Kopač J. The role of cryogenics in machining processes. *Tehnički vjesnik* 2009; 16: 3-10.
72. Yildiz Y and Nalbant M. A review of cryogenic cooling in machining processes. *International Journal of Machine Tools and Manufacture* 2008; 48: 947-964.
73. Bhattacharyya D and Horrigan D. A study of hole drilling in Kevlar composites. *Composites Science and Technology* 1998; 58: 267-283.
74. Stewart HA. Cryogenic treatment of tungsten carbide reduces tool wear when machining medium density fiberboard. *Forest products journal* 2004; 54: 53-56.
75. Gisip J, Gazo R and Stewart HA. Effects of cryogenic treatment and refrigerated air on tool wear when machining medium density fiberboard. *Journal of Materials Processing Technology* 2009; 209: 5117-5122. DOI: http://dx.doi.org/10.1016/j.jmatprotec.2009.02.010.
76. Singh V, Ghosh S and Rao PV. Grindability Improvement of Composite Ceramic with Cryogenic Coolant. In: *Proceedings of the World Congress on Engineering* 2010.
77. Xia T, Kaynak Y, Arvin C, et al. Cryogenic cooling-induced process performance and surface integrity in drilling CFRP composite material. *The International Journal of Advanced Manufacturing Technology* 2015: 1-12.
78. Kumaran ST, Ko TJ, Li C, et al. Rotary ultrasonic machining of woven CFRP composite in a cryogenic environment. *Journal of Alloys and Compounds* 2017; 698: 984-993.
79. Ekici E and Motorcu AR. Evaluation of drilling Al/SiC composites with cryogenically treated HSS drills. *The International Journal of Advanced Manufacturing Technology* 2014; 74: 1495-1505.
80. Koklu U and Morkavuk S. Cryogenic drilling of carbon fiber-reinforced composite (CFRP). *Surface Review and Letters (SRL)* 2019; 26: 1-11.
81. Ray BC. Adhesion of glass/epoxy composites influenced by thermal and cryogenic environments. *Journal of Applied Polymer Science* 2006; 102: 1943-1949.
82. Nagaraj A, Uysal A and Jawahir I. An Investigation of Process Performance when Drilling Carbon Fiber Reinforced Polymer (CFRP) Composite under Dry, Cryogenic and MQL Environments. *Procedia Manufacturing* 2020; 43: 551-558.
83. Xia T. Investigation of drilling performance in cryogenic drilling on CFRP composite laminates. 2014.
84. Giasin K and Ayvar-Soberanis S. Microstructural investigation of drilling induced damage in fibre metal laminates constituents. *Composites Part A: Applied Science and Manufacturing* 2017; 97: 166-178.
85. O'Higgins MR, Padhi G and McCarthy M. A study of damage initiation and growth in composite bolted joints. In: *National Symposium of The Irish Research Council for Science, Engineering and Technology* 2005, p.287.
86. Seo H. *Damage Tolerance and Durability of GLARE Laminates*. ProQuest, 2008.
87. De Vries TJ. Blunt and sharp notch behaviour of Glare laminates. 2001.
88. Mohit G, Frank A, Michael F, et al. Predicting Bearing Strength of Fiber Metal Laminates Via Progressive Failure Analysis. *52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. American Institute of Aeronautics and Astronautics, 2011.
89. Yaghoubi AS and Liaw B. Damage Assessments of Ballistic Impact Behaviors of GLARE 5 (3/2) Beams with Various Stacking Sequences. *Dynamic Behavior of Materials, Volume 1*. Springer, 2013, pp.503-512.
90. Hagenbeek M. *Characterisation of fibre metal laminates under thermomechanical loadings*. TU Delft, Delft University of Technology, 2005.
91. Tyczynski P, Lemanczyk J and Ostrowski R. Drilling of CFRP, GFRP, glare type composites. *Aircraft Engineering and Aerospace Technology* 2014; 86: 312-322.
92. Giasin K, Hodzic A, Phadnis V, et al. Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study. *The International Journal of Advanced Manufacturing Technology* 2016; 87: 2041-2061.
93. Zitoune R, Krishnaraj V and Collombet F. Study of drilling of composite material and aluminium stack. *Composite Structures* 2010; 92: 1246-1255.
94. Phadnis VA, Makhdum F, Roy A, et al. Drilling in carbon/epoxy composites: Experimental investigations and finite element implementation. *Composites Part A: Applied Science and Manufacturing* 2013; 47: 41-51.

95. Giasin K. The effect of drilling parameters, cooling technology, and fiber orientation on hole perpendicularity error in fiber metal laminates. *The International Journal of Advanced Manufacturing Technology* 2018.
96. Giasin K, Hodzic A, Phadnis V, et al. Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study. *The International Journal of Advanced Manufacturing Technology* 2016: 1-21. journal article. DOI: 10.1007/s00170-016-8563-y.
97. Basmaci G, Yoruk AS, Koklu U, et al. Impact of cryogenic condition and drill diameter on drilling performance of CFRP. *Applied Sciences* 2017; 7: 667.
98. Zitoune R, Krishnaraj V, Almabouacif BS, et al. Influence of machining parameters and new nano-coated tool on drilling performance of CFRP/Aluminium sandwich. *Composites Part B: Engineering* 2012; 43: 1480-1488.
99. Abrão AM, Faria PE, Rubio JCC, et al. Drilling of fiber reinforced plastics: A review. *Journal of Materials Processing Technology* 2007; 186: 1-7. DOI: 10.1016/j.jmatprotec.2006.11.146.
100. Srivatsan T. *Processing and Fabrication of Advanced Materials, XVII: Part 8: Polymer-based composites and nano composites: Volume Two*. IK International Pvt Ltd, 2009.
101. Capello E. Workpiece damping and its effect on delamination damage in drilling thin composite laminates. *Journal of Materials Processing Technology* 2004; 148: 186-195.
102. Isbilir O and Ghassemieh E. Delamination and wear in drilling of carbon-fiber reinforced plastic composites using multilayer TiAlN/TiN PVD-coated tungsten carbide tools. *Journal of Reinforced Plastics and Composites* 2012; 31: 717-727.
103. Dini G. On-Line Prediction of Delamination in Drilling of GFRP by Using a Neural Network Approach. *Machining Science and Technology* 2003; 7: 295-314. DOI: 10.1081/mst-120025280.
104. Giasin K, Ayvar-Soberanis S, French T, et al. 3D finite element modelling of cutting forces in drilling fibre metal laminates and experimental hole quality analysis. *Applied Composite Materials* 2017; 24: 113-137.
105. Lundberg M, Saarimäki J, Moverare JJ, et al. Surface integrity and fatigue behaviour of electric discharged machined and milled austenitic stainless steel. *Materials Characterization* 2017; 124: 215-222.
106. Ray B. Effects of thermal and cryogenic conditionings on mechanical behavior of thermally shocked glass fiber-epoxy composites. *Journal of Reinforced Plastics Composites*

2005; 24: 713-717.
107. Koklu U and Coban H. Effect of dipped cryogenic approach on thrust force, temperature, tool wear and chip formation in drilling of AZ31 magnesium alloy. *Journal of Materials Research and Technology* 2020.
108. El-Sonbaty I, Khashaba UA and Machaly T. Factors affecting the machinability of GFR/epoxy composites. *Composite Structures* 2004; 63: 329-338.
109. Ahmed LS and Kumar MP. Cryogenic drilling of Ti–6Al–4V alloy under liquid nitrogen cooling. *Materials and manufacturing processes* 2016; 31: 951-959.
110. Uçak N and Çiçek A. The effects of cutting conditions on cutting temperature and hole quality in drilling of Inconel 718 using solid carbide drills. *Journal of Manufacturing Processes* 2018; 31: 662-673.
111. Chashhin N, Pashkov A, Ivanov Y, et al. Roughness of holes in metal and polymer composite bags. In: *IOP Conference Series: Materials Science and Engineering* 2019, p.012089. IOP Publishing.
112. coromant S. Machining carbon fibre materials. *Sandvik coromant user's guide - composite solutions* 2010.
113. Babu J, Basavarajappa S, Blass D, et al. *Machinability of fibre-reinforced plastics*. Walter de Gruyter GmbH & Co KG, 2015.
114. Lucas JP. Delamination fracture: effect of fiber orientation on fracture of a continuous fiber composite laminate. *Engineering fracture mechanics* 1992; 42: 543-561.
115. Panchagnula KK and Palaniyandi K. Drilling on fiber reinforced polymer/nanopolymer composite laminates: a review. *Journal of materials research and technology* 2018; 7: 180-189.
116. Naveen P, Yasaswi M and Prasad R. Experimental investigation of drilling parameters on composite materials. *Journal of Mechanical and Civil Engineering* 2012; 2: 30-37.
117. Tsao C and Hocheng H. Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials. *International Journal of Machine Tools and Manufacture* 2005; 45: 125-130.
118. Ho-Cheng H and Dharan C. Delamination during drilling in composite laminates. *Journal of Engineering for Industry(Transactions of the ASME)* 1990; 112: 236-239.
119. Tsao C and Hocheng H. Effects of exit back-up on delamination in drilling composite materials using a saw drill and a core drill. *International Journal of Machine Tools and Manufacture* 2005; 45: 1261-1270.
120. Astakhov VP, Patel S and Woon KS. *Drilling Technology: Fundamentals and Recent Advances*. Walter de Gruyter GmbH & Co KG, 2018.
121. KHAN ZM. *A study of the drilling of advanced carbon fibre composites*. University of Salford, University of Salford, 1991.

122. Bhudwannachai P. *Performance evaluation and analysis of the use of CO2 cooling for conventional drilling of carbon fibre reinforced plastics*. University of Warwick, 2014.