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Original Article

Experimental investigation on the effect of dry and multi-jet cryogenic cooling on the machinability and hole accuracy of CFRP composites

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ABSTRACT

In this work, the drilling performance of carbon fibre reinforced plastic (CFRP) composites is analysed in terms of thrust force (F_n), torque (M_z), specific cutting energy (*SCE*), delamination factor (F_d), and hole quality under dry and cryogenic cooling conditions. An in-house developed multi-jet liquid nitrogen (LN_2) delivery setup is used for experimental trials. This LN_2 delivery system is retrofitted to an existing machine tool to enable the movement of jets along the axis of the spindle for better reachability of LN_2 to the cutting zone during the drilling operation. Experiments are conducted using the full factorial technique considering four levels of spindle rotational speed (*N*), four levels of feed rate (f_r), and two cutting conditions i.e., dry and cryogenic cooling. Results show increased F_n up to 35% and decreased M_z up to 24.46% using cryogenic drilling as compared to dry drilling. Moreover, SCE is reduced up to 35% using cryogenic drilling than in dry drilling. Entry F_d is decreased up to 21.55% under cryogenic drilling as compared to dry drilling. At higher *N* input and lower f_r, the exit F_d can be reduced by up to 9% using cryogenic drilling as compared with dry drilling. In terms of hole quality, cylindricity (*CYL*) decreased by up to 42.69%, lower deviation in average hole size, and decreased average surface roughness (R_a) up to 20% when using cryogenic drilling. The results show that using the multi-jet

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cryogenic cooling system provides enhanced composite machinability and sustainability for industrial use.

1. Introduction

Composite materials provide an alternative option to make lightweight components without compromising their strength [1]. Composite materials are an attractive choice for many industries since they can be custom designed and developed to provide the required properties according to application requirements [2]. Therefore, composites find their applications in structural components of aero, defence, auto, biomedical, and marine sectors and replace conventional materials such as steel and aluminium alloys at a rapid pace [3,4].

For example, Airbus has introduced four beams, a central wing box, rear pressure bulkhead and upper deck, and many other components made up of carbon-fibre reinforced plastic (CFRP) composites in its A380 aircraft. These components were previously made from aerospace-grade aluminium alloys, thereby reducing the weight by 1.5 tons [5]. Modern aircraft such as the Boeing Dreamliner and Airbus A350 have between 50 and 53% of structural components by weight made of CFRP composites [6]. Components made up of composites can be made in prerequisite shape. Hence, it requires less amount of post-processing to get into the final shape as compared to conventional alloys. However, to achieve the final shape, close tolerances, and fabrication, a large amount of machining is required [7]. Although common machining processes such as turning, drilling, and milling operations are used in the processing of these components to get them into the final shape, drilling is the most used operation to accommodate nut, bolts, and fasteners for assembly. For example, more than 100,000 holes are drilled in CFRP composites components during the making of single aircraft [8]. However, components made up of CFRP composites face a high rejection rate from the assembly line because of machining process-induced defects. These defects are caused by the difference in the mechanical properties of base and reinforcement materials.

High heat generation in the cutting zone accumulates because of the low thermal conductivity of CFRP composites that reduce machined surface quality. Owing to differences in the hardness of fibre reinforcement and epoxy matrix, problems like delamination and fibre pull out occur frequently during the machining of CFRP composites. Moreover, the abrasive fibre in the composites will increase the wear of the tool [9]. Conventional machining techniques are less efficient in processing these materials due to their anisotropy. The main challenge that arises in the drilling of CFRP composites is delamination. Delamination frequently occurs during the machining of composite materials due to their anisotropic nature [10]. Laminates tend to separate from each other when the drilling forces exceed a certain value [11]. In a drilling operation, the thrust force is a key indicator of delamination. A higher delamination factor (F_d) indicates loss of mechanical toughness and internal strength of composites materials. This may also reduce the reliability of products, which is the most important consideration in the manufacture of aerospace parts. Hence, researchers have shown a keen interest in reducing delamination during the drilling of CFRP composites [12]. To reduce the delamination problem, it is important to choose optimum input process parameters and cutting conditions. Generally, for drilling CFRP composites, it is recommended to use a low feed rate (f_r) and high spindle speed (N) [13]. Dimensional inaccuracy is another problem during the drilling of CFRP composites. This is caused by an expansion of the drill bit due to thermally induced damage [14]. The second reason for the incorrect size of the hole is the degradation of the resin is due to the high heat accumulation in the cutting area [15]. Therefore, suitable cutting conditions are required during the drilling of CFRP composites. In the drilling process of CFRP composites, dry and wet conditions are traditionally used [16]. Wet drilling is generally used to eradicate problems that are caused by high heat generation during dry drilling of CFRP composites. However, contamination caused by cutting fluids can lead to degradation of the mechanical properties of composites during wet drilling [16]. Hence, these factors need to be considered while drilling CFRP composites. Cryogenic drilling is an emerging cooling technology that can solve the above-mentioned problems encountered in the drilling of composites [17,18].

In the literature, many researchers have tried to improve the drilling performance of CFRP composites by using dry, wet, and cryogenic conditions. However, the influence of using a cryogenic environment during the drilling of CFRP composites is only studied by a handful of studies [17,19]. The application of cryogenic fluid can effectively remove heat from the cutting region [20,21]. It was previously reported that cryogenic fluid in the cutting area can reduce the difference in the hardness between resin and reinforcement materials and ultimately improve the drilling performance [22]. El-Sonbaty et al. [23] explored the drilling of fibre-reinforced composites using various combinations of inputs such as different drill bit sizes, cutting speed (v_c), f_r, fibre-volume fraction ratios. They examined the effects of different combinations of inputs on thrust force, torque, and surface finish. They reported that thrust force and surface finish were significantly affected by variation in v_c. Drill diameters were also turned out to be important input process parameters in deciding the surface finish. Khashaba et al. [24] examined the drilling of glass fibre-reinforced epoxy (GFRE) composites using different drills diameters and cutting environments. Using selected combinations of input process parameters and cutting conditions, they did not find a significant reduction in delamination. Khairusshima et al. [25] reported improvement in the drilling performance of CFRP composites in terms of delamination when drilling was performed under a chilled air environment (−10 °C). They also reported an improvement in tool life under this working condition. Watzke et al. [26] suggested a cryogenic environment in the cutting zone can improve machinability performance as it reduces the difference between the ductility of resin matrix and fibre. Due to this, material become less anisotropic under a cryogenic environment. Numerous problems related to the machining of fibre reinforced plastic (FRP) composites such as delamination and deformation of the matrix due to thermal softening, and tearing of fibres can be eliminated using cryogenic machining techniques. Xia et al. [22] examined the surface integrity of CFRP composites when it was machined under a cryogenic environment. Authors reported that the cryogenic environment during drilling has led to increased delamination and thrust force. Moreover, the use of cryogenic drilling techniques can reduce tool wear, rounding of cutting edges and improve hole quality.

Kumaran et al. [27] compared rotary ultrasonic-assisted dry and cryogenic techniques for drilling of woven CFRP composites. The surface finish of the drilled hole is improved under cryogenic drilling owing to brittle fracture of fibres as revealed in SEM images. Drilling performance was also improved under the cryogenic environment than in dry conditions. Geng et al. [28] compared rotary ultrasonic elliptical drilling and grinding drilling of CFRP composites. Authors recommended rotary ultrasonic elliptical drilling over grinding drilling for reduced cutting zone temperature and adhesion of chips. Basmaci et al. [17] recommended that using small diameter drills for CFRP composites drilling, there is design flexibility. Drilling was performed on a workpiece in submerged conditions under cryogenic fluid. An increase in thrust force was observed for drilling cryogenic conditions as compared to wet conditions. However, the use of low-temperature drilling results in an improved surface finish of the drilling. Morkavuk et al. [29] found that compared with dry drilling, the cutting force in cryogenic drilling of CFRP composites increases due to the increase in the tensile strength. They also reported improved surface finish and reduced delamination when drilling was performed under a cryogenic environment.

Joshi et al. [11] proposed a force based model to predict delamination under dry and cryogenic drilling conditions. They found that cryogenic drilling is suitable for improving surface finish and extending tool life. Impero et al. [19] reported that cryogenic drilling improves productivity compared with wet drilling of CFRP/Ti. They reported improved productivity using higher levels of process parameters under cryogenic drilling as compared to wet drilling. Geier et al. [30] examined the unidirectional CFRP composites when it was drilled from different orientations. They reported that the feed force was increased by a factor of three when drilling perpendicular to the fibre orientation. They also concluded that v_c was the most important factor in determining the drilling performance of CFRP composites. Kumar and Gururaja [20] studied the drilling of CFRP composites in terms of damage to work material due to process-induced stresses, temperature, and forces. Authors have reported significantly reduction in workpiece and cutting tool temperatures, surface roughness and higher surface integrity using cryogenic drilling than in dry drilling. Improved responses were attributed to change in fibre fracture mode using cryogenic drilling. In another investigation, Kumar et al. [31] reported reduction in torque, damage at the metal-composites interface, burr formation, and surface roughness using cryogenic drilling than in dry drilling of Ti/CFRP/Ti hybrid composites laminates. Although, a single jet non-movable cryogenic delivery setup was used in that investigation.

Many researchers have investigated the machinability of CFRP composites under different cutting conditions in terms of thrust force and delamination. However, in most previous studies, authors have used a single jet of liquid nitrogen (LN_2) for cryogenic drilling. In this study, a novel multi-jet LN_2 setup is used for the first time to enable cryogenic drilling conditions. The goal of this paper is to examine the impact of the multi-jet cryogenic delivery system on the drilling performance of CFRP composites. It is believed that this delivery setup could increase the accessibility of LN_2 to the cutting zone to maximize cooling efficiency during drilling. In this research, different performance indicators such as thrust force (F_n), torque (M_z), specific cutting energy (SCE), F_d, and hole quality are measured and analysed. Hole quality was measured in terms of cylindricity (CYL), average hole diameter, and average surface roughness (R_a). In literature, responses such as F_n, M_z, and F_d are widely investigated and discussed [7,31]. However, the influence of cutting conditions on SCE and hole quality during CFRP drilling remain underexplored. Investigation of these responses can highlight the sustainable benefit of cryogenic drilling of CFRP composites. All the results are compared with the performance obtained for drilling under dry condition.

2. Experimental plan and procedure

2.1. Experimental setup

For experiments, a 3-axis MacPower CNC vertical machining centre (Model Eco 500) was used. The machine has a maximum N of 8000 rpm. This machine was retrofitted with a multi-jet cryogen delivery setup that enables the LN_2 spray-on cutting tool and workpiece from four different directions as shown in Figs. 1 and 2.

This delivery setup is a modified version of the delivery setup used in the authors' previous study [32]. In the previous delivery setup, a single jet of LN_2 was directed at the cutting tool during cryogenic drilling of CFRP composites (Refer to Fig. 1). To improve cooling efficiency and better reachability of LN_2 to the cutting zone, four jets of LN_2 are used in this system. These four jets are well directed to the cutting tool. The fixture is also designed in such a way that the cryogen delivery setup can move along the spindle in the axial direction. To enable axial movement of jets, the fixture was directly mounted on to spindle head (refer to Fig. 2).

2.2. Workpiece and cutting tool

A square plate of 220 × 200 × 4 mm^3 of multidirectional CFRP composites was used as a workpiece to perform drilling operations. The CFRP composites material has a fibre of high strength TC33-12K and epoxy resin. The resin content is 54%, and the hardener to resin ratio is 1:10. The CFRP workpiece was supplied by Composites Tomorrow, India and it was

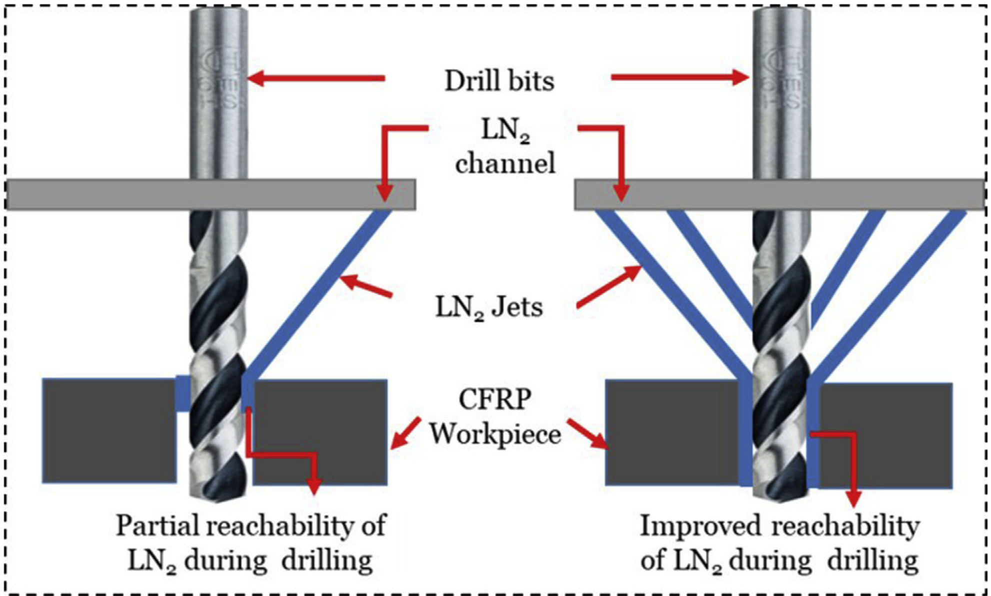

Fig. 1 – Schematic of an improved multi-jet LN_2 delivery system.

prepared using a hand layup process and then subjected to high-density compaction.

Figure 3 presents a schematic of the multi-jets LN_2 delivery nozzle used in this investigation. The drill bit is kept concentric to the grooved chamber (01). This grooved chamber receives LN_2 from its inlet (02). There are four inclined holes (04) in the top plate (03) that fits onto the grooved channel. These holes are angled towards the drill bit placed concentrically towards the tip of the drill bit, ensuring that LN_2 reaches the heating zone effectively while the machining process is conducted. The two through holes (05) are used for providing the threaded connection with a fixture used for holding the entire assembly stable and concentric with the drill bit. This vertical movement enables the direction of LN_2 at cutting edge of the drill bit. The proposed assembly is connected in such a way that it moves up and down along

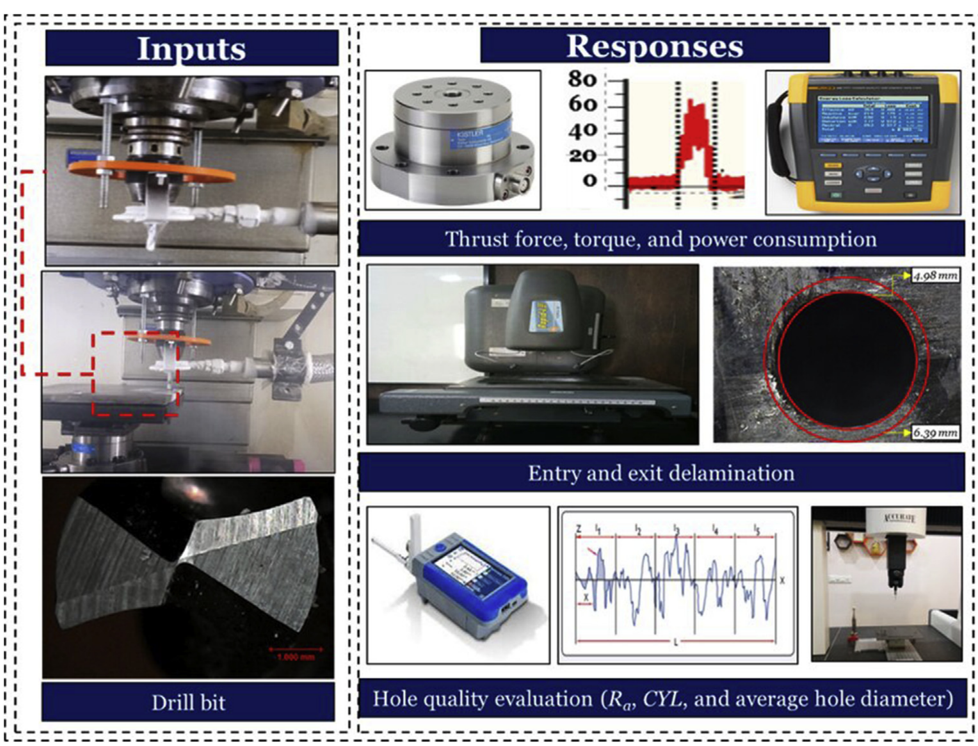

Fig. 2 – Inputs, experimental setup, and responses for this investigation.

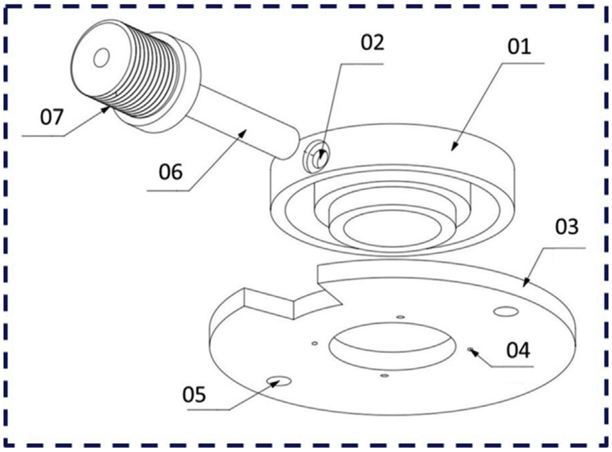

Fig. 3 – Multi-jet LN_2 delivery nozzle schematic.

with the drill bit. When drilling operation takes place, the assembly also moves down equivalent to the depth of cut. The LN_2 feeding pipe (06) is connected with the slot at the inlet of the grooved chamber (02) on one end and connected with a threaded pipe nipple (07), which would be connected with the incoming delivery line consisting of a vacuum jacketed hose.

Each lamina is formed of high strength carbon fibres in a 2 × 2 twill weave. 16 layers of were placed alternatively to obtain multi-direction CFRP composites $[0°/90°/+45°/-45°/-45°/+45°/90°/0°]_{2S}$ of the overall thickness of 4 mm. This type of composite has higher isotropy than single and dual directions composites. Uncoated tungsten carbide twist drill bits of a diameter of 5 mm with point and helix angles of 140° and 30° respectively, were used in this investigation as a cutting tool. For each new set of input process parameters, a new twist drill is used to eliminate the effect of tool wear.

2.3. *Responses measuring equipment*

For calculating F_n and M_z during the drilling of CFRP composites, a Kistler (Type-9272) piezoelectric dynamometer equipped with a data acquisition system (Type-5697A1) and a charge amplifier (Type-5070) is used. The frequency of output recording was set to be at 1 kHz. For calculation of *SCE*, Fluke three-phase power quality energy analyser (Model number: 435, series: II) is employed. It is set to record four readings of power consumed per second during experimentation. The delamination of holes is analysed using a vision measurement system that can magnify the dimensions up to 67 X. To measure the *CYL* deviation of holes, planes perpendicular to the hole axis are selected over the pan height of the hole, and the combined deviation of planes is presented as *CYL* deviation. *CYL* deviations are measured as per ISO 12180-1/2:2011 [33]. For measurements of *CYL* and average hole size, a coordinate measuring machine (*CMM*) is used. *CYL* describes the closeness of a real cylinder from a true cylinder. These measurements are made by *CMM* based on the principle of maximum inscribed circle (*MIC*). The spherical probe is used to select points with a ruby stylus. Diametric difference between the largest and smallest cylinders that can inscribe the actual cylinder gives *CYL* deviation. A Taylor Hobson Surtronic S128 surface roughness tester is used to measure the arithmetic average surface R_a of the drilled hole. A setting of evaluation length of 4 mm and a sampling length of 0.8 mm was considered for R_a measurements.

2.4. *Design of experiments*

In this work, a four-level full factorial design of experiments was used for experimental evaluation. Four levels of *N*, four levels of f_r, and two cutting conditions were considered as shown in Table 1.

Each experiment was performed thrice, and the average value of three trials was taken to analyze the responses. Depth of drill in these experiments is kept constant, i.e., 4 mm.

3. Results, analysis, and discussion

3.1. *Thrust force (F_n) and torque (M_z) evaluation*

Figure 4 presents experimental results of F_n for drilling of CFRP composites under dry and cryogenic conditions. From the results, it is observed that F_n increases with f_r, while a decrease with an increase in *N* for dry drilling of CFRP composites. Resin softening in the vicinity of the tool–workpiece interface due to a high amount of heat generation during dry drilling at higher *N* can be the reason for lesser F_n. These results are in good agreement with the previous study of CFRP drilling [11].

However, for cryogenic drilling, the decrease in F_n with *N* is lesser as compared to dry drilling. This is due to an increase in the mechanical strength of CFRP composites under a cryogenic environment [29]. Moreover, the F_n was found to be significantly increased up to 35% using cryogenic drilling than in dry drilling. This is because of the increase in strength and young's modulus of the resin material at a sub-zero temperature [22]. Impero et al. [19] reported similar observations in the drilling of CFRP composites in terms of increased F_n under cryogenic drilling conditions due to enhanced stiffness of the epoxy matrix.

In this investigation, M_z decreased up to 24.46% using cryogenic drilling than in dry drilling. The reduction in M_z could be attributed to the decrease in friction coefficient at the tool–chip interface [31,34]. Increased stiffness of fibre under cryogenic conditions help in brittle fracture of fibres rather than tearing or bending [22]. This could be a possible reason for lesser M_z obtained using cryogenic drilling than dry drilling. Furthermore, it was found that M_z decreased as *N* increased, while f_r had a comparatively higher effect on the values of M_z. It was observed that the effect of f_r on torque varied at different *N*. For example, the torque decreased with the increase of the f_r when drilling at *N* of 3000 rpm for dry and

Table 1 – Input process parameters and their levels.

Inputs	Level 1	Level 2	Level 3	Level 4
N (rpm)	2500	3000	3500	4000
f_r (mm/rev)	0.02	0.04	0.08	0.16
Cutting conditions	Dry	Cryogenic		

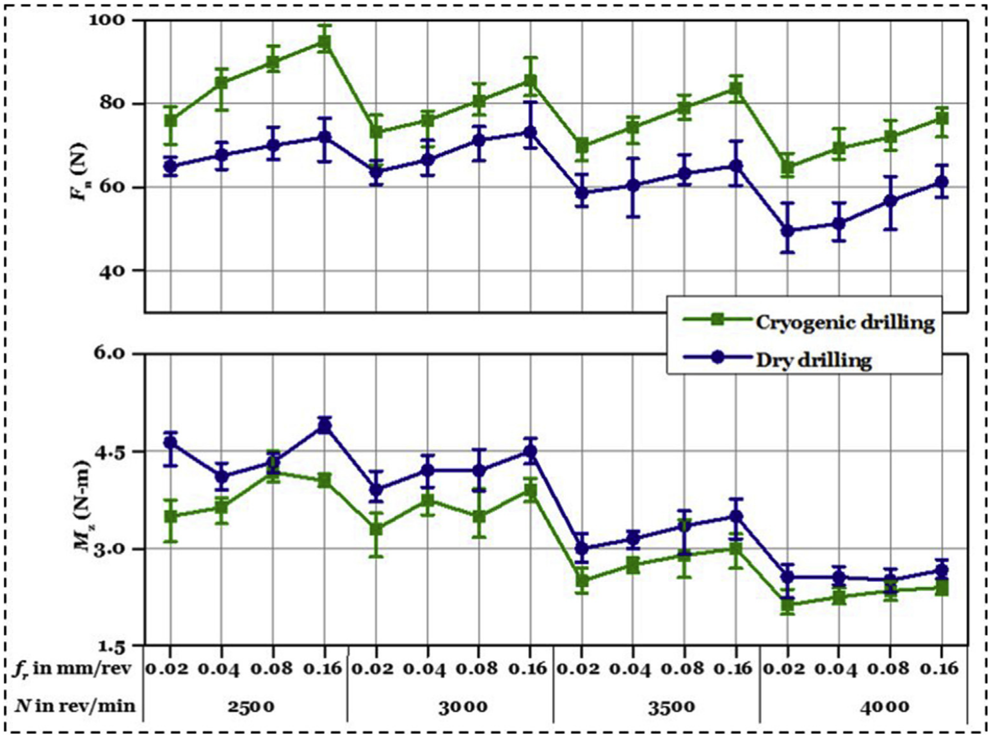

Fig. 4 – Variation in F_n and M_z using dry and cryogenic drilling.

cryogenic drilling tests. However, increasing the *N* to 3500 rpm showed an opposite trend where torque increased with the increase in the feed rate. Drilling at a higher *N* of 4000 rpm shows that the effect of increasing feed rate on torque becomes less significant which could be due to increased softening in the composite due to higher cutting temperatures [35].

3.2. SCE *evaluation*

SCE consumption is also examined for drilling under dry and cryogenic conditions. SCE is calculated using Equation (1). Where $P_{cutting}$ represents power consumption during the drilling operation. P_{idle} represents power consumption by machine tool in idle condition running at a specific set of parameters when not cutting material. *MRR* represent the material removal rate. For this work, the different combinations of v_c and f_r are considered. Figure 5 display the experimental results of SCE under dry and cryogenic drilling condition. Results depict that SCE decrease with an increase in f_r.

$$SCE = \frac{P_{cutting} - P_{idle}}{MRR} \quad (1)$$

This is due to the lesser time required to drill the hole at high f_r. Dry drilling consumed more SCE than cryogenic drilling at most of the combinations of process parameters. SCE consumed using cryogenic drilling decreased up to 35% as compared to dry drilling. This is due to cryogenic conditions during drilling enabling better heat dissipation that helps in lowering friction at cutting interfaces and that resulted in lesser SCE consumption using cryogenic drilling than in dry drilling at most of the process parameters [36].

Kumar and Gururaja [20] also highlighted the friction behaviour of the cutting interface under cryogenic conditions during the machining of CFRP composites. Moreover, it can also be due to lesser heat induces less wear to the drilling tool under cryogenic conditions than in dry conditions [17]. This is also related to the fact that the M_z values obtained using cryogenic drilling are lower than those obtained using dry drilling.

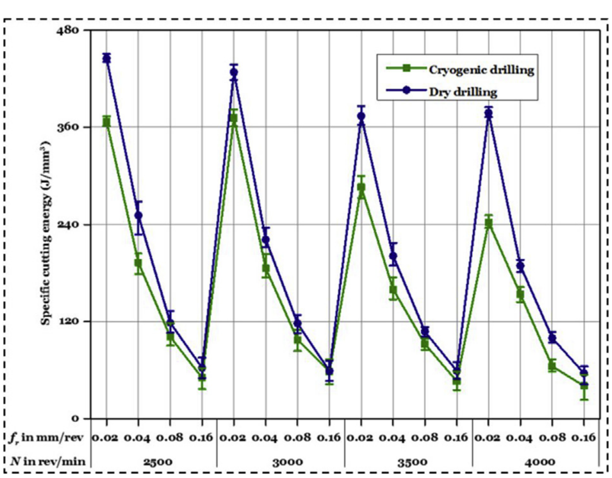

Fig. 5 – Variation in SCE using dry and cryogenic drilling.

3.3. *Delamination evaluation*

During the drilling of CFRP composites, laminates can be affected due to process-induced thermo-mechanical stresses.

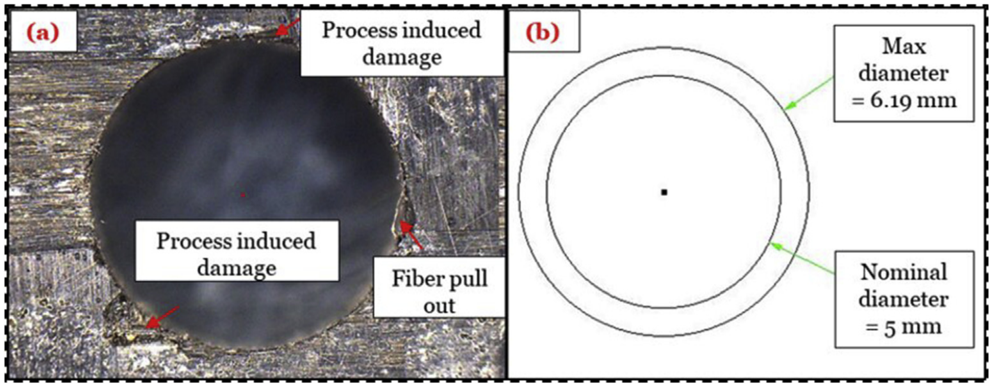

Fig. 6 – Damage measurement (a) image of a hole (b) maximum and nominal diameters calculation.

Delamination is one of the most common phenomena in the drilling of CFRP composites. When the fibre is subjected to sudden stress due to the insertion of the drill bit, delamination may occur on the entrance side of the workpiece, or it can occur at the exit side when fibres go into a stress cycle when the drill exits from the workpiece. Moreover, the delamination phenomenon also depends on input process parameters and cutting conditions. Damage of the workpiece at the entry and exit of the drill is evaluated in terms of F_d as shown in Fig. 6.

The delamination is assessed in terms of an established dimensionless term which is known as the delamination factor (F_d) as presented in Equation (2). It is defined as the ratio of the largest circle diameter (D_{max}) covering damage to the nominal diameter (D) of the drilled hole. Damage around the drilled hole is due to the separation of adjacent piles because the drilling force can result in premature failure of the material.

$$F_d = \frac{D_{max}}{D} \tag{2}$$

The entry surface defects in the multidirectional CFRP for various f_r, N and cutting conditions are presented in Fig. 7. It is observed that F_d for the entry side was higher using dry drilling than in cryogenic drilling as shown in Fig. 9. This phenomenon can be attributed to the fact that the sub-zero temperature during drilling promotes a brittle mode of fracture of fibres and hence results in lesser fibre pull out and peel up phenomena occurring as compared to dry drilling [37]. Due to the shearing of fibres along the hole, the rubbing of chips is lesser under cryogenic conditions than in the case of dry machining [11]. However, for cryogenic drilling environments, an increase in F_d value with the increase of the f_r due to the increase in F_n. As workpiece resistance to delamination also decreases due to thermal softening of the laminate. But, as compared to dry drilling, the values of the F_d reduced up to 21.55% under cryogenic drilling, which could be attributed to the improved cooling that leads to efficient heat removal from the cutting zone [38].

However, F_d at the exit was higher under both conditions as compared to entry F_d as shown in Fig. 8. This is mainly due to the reduced thickness of the workpiece with depth and therefore the last few layers in the composite cannot withstand the thrust force action which causes increased delamination at the exit.

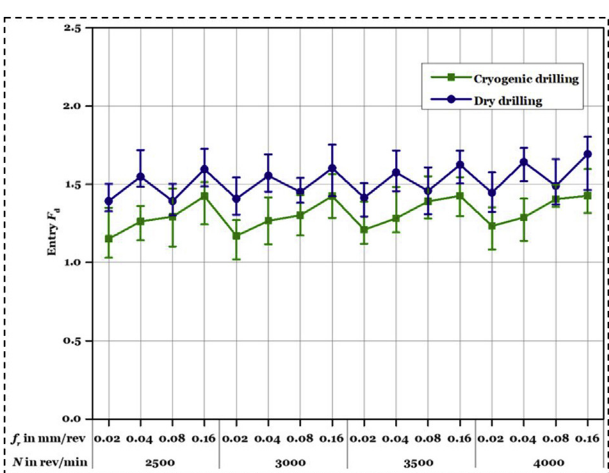

Fig. 7 – Variation in entry F_d using dry and cryogenic drilling.

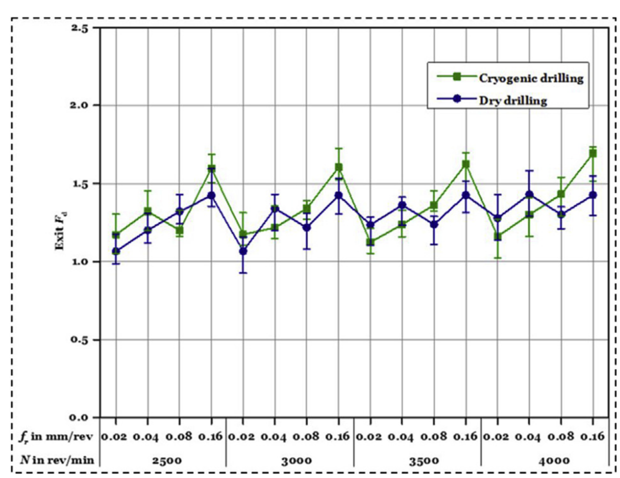

Fig. 8 – Variation in exit F_d using dry and cryogenic drilling.

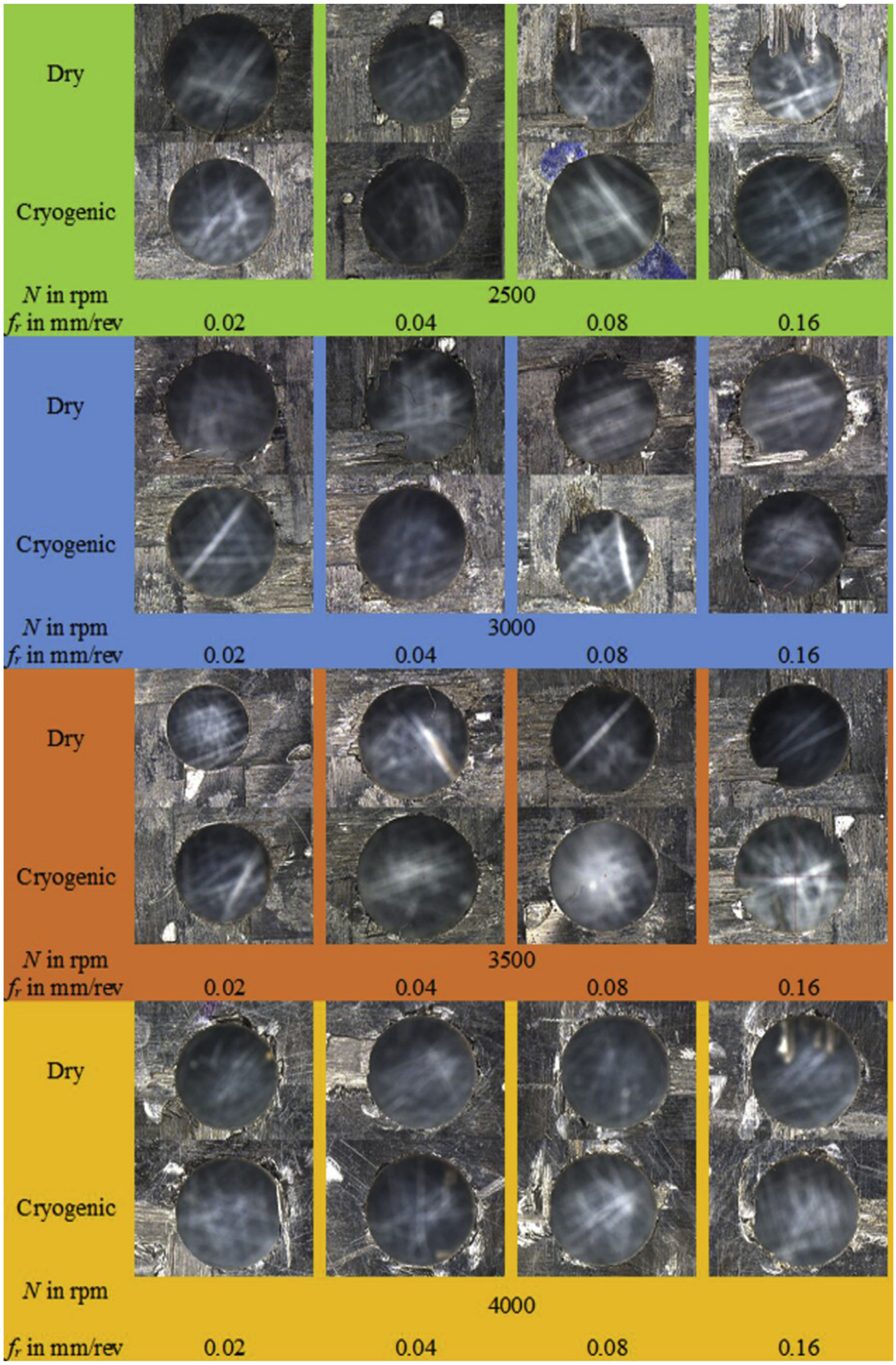

Fig. 9 – Observation of the entry surface at various combinations of N, f_r, and cutting conditions.

However, when drilling under low-temperature conditions, compared with dry conditions, it is found that the outlet F_d can be reduced by as much as 9% under the combination of higher N and lower f_r. This is because of the strong proportionality between the F_n and the F_d. High F_n cause problems for the last few exit piles as it tends to increase the delamination. As it promotes fibre pull out and severe process-induced damage to the workpiece [39]. As compared

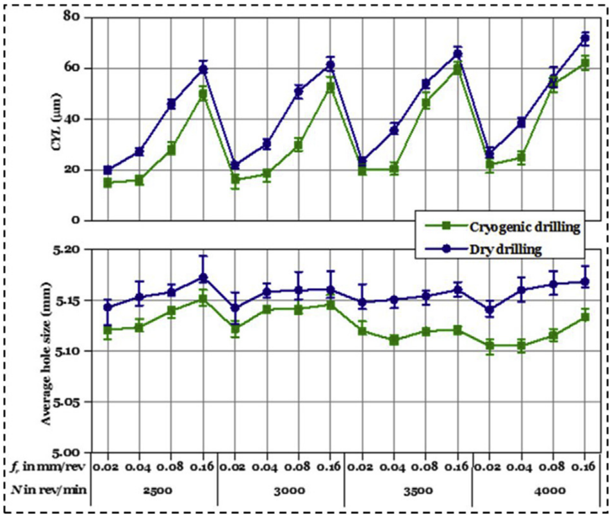

Fig. 10 – Variation in CYL and average hole size using dry and cryogenic drilling.

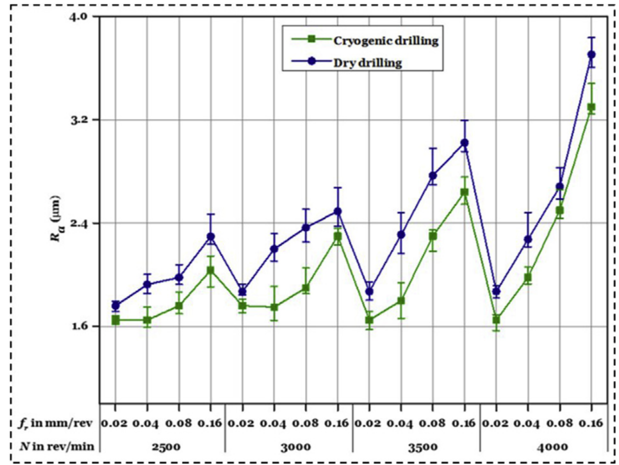

Fig. 11 – Variation in R_a using dry and cryogenic drilling.

to the results obtained using a mono-jet LN_2 delivery system for drilling of CFRP composites, the multi-jet system proved to be more efficient to get reduced exit f_d.

3.4. Hole quality evaluation

3.4.1. Hole size and cylindricity analysis

Figure 10 presents the CYL of drilled holes measured at different N and f_r under dry and cryogenic conditions. The results show that CYL mainly depends on f_r. Under dry and cryogenic drilling conditions, low CYL deviation values can be achieved at high N and low f_r. Moreover, an increase in CYL deviation is observed with an increase in f_r, this is due to an increase in F_n as f_r increases for both drilling conditions. CYL deviations are observed to be decreased under all combinations of inputs using cryogenic drilling in place of dry drilling of CFRP composites.

It has decreased up to 42.69% for drilling under cryogenic conditions than in dry conditions. It can be due to lesser heat-induced damage of drill bit due to improved cooling under cryogenic conditions than in dry conditions. High temperatures are generated during dry drilling, which will cause the resin to soften, the fibre will be easily pulled out, and cause delamination. Figure 10 presents the variation in average hole size obtained after dry and cryogenic drilling of CFRP composites. Results show that the average hole diameter for a hole drilled under dry drilling has a higher deviation than in cryogenic drilling. The average hole size for dry drilling (5.14–5.17 mm) is higher than for cryogenic drilling (5.10–5.15 mm). While the nominal diameter of the drill bit is 5 mm. It means more precise holes obtained using cryogenic drilling as compared to dry drilling. Shrinkage of the drilled hole in composites is a common phenomenon due to the relaxation of the lamina [40]. The average hole size depends on the thermal expansion coefficient of the workpiece material. In the case of composites, resin and fibre have different thermal expansion coefficients, due to this, additional compressive stresses generate which leads to the improved bounding of fibres [38,41]. Giasin et al. [42] also reported the significant influence of the thermal expansion coefficient of workpiece material on hole size. Dry drilling resulted in oversized holes mainly due to poor chip evacuation and expansion of resin when it is exposed to the high-temperature zone during a drilling process in absence of coolant. Similar results of average hole diameter were reported in the literature [22]. Moreover, it can also be due to lesser heat-induced wear to the cutting tool under cryogenic conditions than in dry conditions.

3.4.2. Surface roughness analysis

R_a value also indicates the quality of the drilled hole. During the drilling of CFRP composites, lesser de-bonding of laminates, lesser fibre pull out, and shear fracture will produce a smoother surface. In this study, R_a of the holes is measured

Table 2 – Performance comparison for dry and cryogenic drilling.

Performance attributes	Results using cryogenic drilling as compared to dry drilling	Comparison with previous studies
F_n	Increased by 35%	In well agreement with [20,22,32]
M_j	Decreased by 24.46%	In good agreement with [19,20]
SCE	Decreased by 35%	Not reported in the literature
Entry F_d	Decreased by 21.55%	Improved due to modified cryogenic delivery setup as compared to [22]
Exit F_d	Decreased by 9% at higher N and lower f_r	Improved due to modified cryogenic delivery setup as compared to [22]
CYL	Decreased by 42.69%	In good agreement with [32]
Average hole diameter	Lesser deviation from the nominal diameter	In good agreement with [20,22]
R_a	Decreased by 20%	In good agreement with [20,32]

which is drilled at various N, f_r, and cutting conditions. Figure 11 shows the result of R_a obtained under different combinations of input process parameters. Analysis of these results shows that cryogenic drilling consistently produces better hole quality in terms of surface finish as compared to dry drilling. R_a values reduced up to 20% using cryogenic drilling than in dry drilling. Moreover, a combination of low f_r and high N is found to be suitable to obtain lower R_a values. A cryogenic condition during drilling of CFRP composites causes its ductile to brittle transition that results in direct shear fracture of fibre during drilling [17,38]. This phenomenon reduces fibre pull out and promotes isotropy of CFRP composites that result in improved surface finish. The second reason for the reduction in R_a can be due to lesser heat-induced damage of cutting edge using cryogenic drilling, unlike dry drilling.

Xia et al. [17] reported a similar observation on improved hole quality using cryogenic drilling due to lessening in rounding of the cutting edge of a drill bit. Thermo-mechanical loading due to high temperature and mechanical loading results in increased delamination in the drilling zone. Table 2 presents a comparison between dry and cryogenic drilling performance. Results obtained in this research are also compared with works reported in the literature.

4. Conclusions

In this work, the drilling performance of CFRP composites is analysed at different input process parameters and cutting conditions. An in-house developed multi-jet liquid nitrogen delivery setup is used to produce cryogenic condition during the drilling process. Machinability is analysed concerning thrust force, torque, specific cutting energy, delamination, and hole quality. Hole quality is assessed concerning average hole size, cylindricity, and average surface roughness. The following conclusions are drawn from this study:

- Multi-jet cryogenic drilling of CFRP composites results in increased thrust force up to 35% when compared to dry conditions. Feed rate has a higher impact on thrust force. Higher thrust force was obtained at a higher level of feed rate. This phenomenon can be attributed to an increase in the mechanical properties of CFRP composites under the effect of a cryogenic environment. In the case of dry drilling, the thrust force tends to decrease due to the thermal softening of the resin. Moreover, torque is found to be decreased up to 24.46% using cryogenic drilling. This can be due to an increase in isotropy of composites under cryogenic conditions.
- Multi-jet cryogenic drilling of CFRP composites also results in reduced specific cutting energy up to 35% using cryogenic drilling than in dry drilling. As it is also correlated with torque. Moreover, the cutting force and torque tends to increase with an increase in the feed rate but are reduced at higher spindle rotational speed.
- Multi-jet cryogenic drilling of CFRP composites results in reduced delamination at entry by 21.55% and by 9% at the exit as compared to dry drilling. The hole quality improved under cryogenic conditions in terms of reduced cylindricity (up to 42.69%), average hole size, and average surface roughness (up to 42.69%). Superior hole quality is obtained using cryogenic drilling due to reduced torque and lesser heat-induced damage to the cutting tool.

Performance obtained using multi-jet liquid nitrogen delivery setup for drilling of CFRP composites is superior to dry drilling and previously used mono-jet cryogenic drilling. This setup can be used for producing quality holes in critical components used in the aerospace industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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