The effects of through tool cryogenic machining on the hole quality in GLARE® fibre metal laminates

Khaled Giasin, Alisha Dad, Emmanuel Brousseau, Mozammel Mia, Dabil Pimenov, Sezer Morkavuk, Ugur Koklu
Abstract

GLARE® is a composite-metal laminate currently used in the Airbus A380 fuselage due to its excellent impact and fatigue performance. GLARE® undergo extensive drilling for riveting purposes making it prone to thermal effects and increased tool wear. Therefore, using coolants becomes necessary, however, conventional coolants can lead to moisture absorption. An alternative is to use cryogenic coolants due to their positive impact on machining aerospace materials in the past. In this study, through tool cryogenic machining technology is used for machining GLARE® laminates by delivering liquid nitrogen at -196°C through the spindle allowing the coolant to be in direct and continuous contact with the cutting zone. The aim is to investigate the impact of drilling parameters and cryogenic cooling on surface roughness, hole size, circularity and hardness at hole entry and exit sides. In addition, microstructural evaluation using scanning electron microscopy. The results indicate that the cryogenic cooling improved hole surface finish and gave better hole size at the top, while it had no impact on hole circularity. The hardness was increased at the entry and exit sides of the hole compared to that observed in dry drilling tests while scanning electron microscopy revealed that burr formation was minimised.

Keywords: Cryogenic cooling; Drilling; GLARE®; Surface roughness; Hardness; Hole size; Hole Circularity.

Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMLs</td>
<td>Fiber Metal Laminates</td>
</tr>
<tr>
<td>GLARE®</td>
<td>Glass Aluminum Reinforced Epoxy</td>
</tr>
<tr>
<td>Al2024</td>
<td>Aluminum alloy 2024</td>
</tr>
<tr>
<td>LN₂</td>
<td>Liquid Nitrogen</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>HV</td>
<td>Vickers Hardness</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>CMM</td>
<td>Coordinates Measurement Machine</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>Ra</td>
<td>Arithmetic average roughness (µm)</td>
</tr>
<tr>
<td>Rz</td>
<td>Ten-point mean roughness (µm)</td>
</tr>
<tr>
<td>n</td>
<td>Spindle speed (rpm)</td>
</tr>
<tr>
<td>f</td>
<td>Feed (mm/min)</td>
</tr>
</tbody>
</table>

1. Introduction

Despite the pandemic of COVID-19, the global aerospace material sector is predicted to grow for the next seven years reaching a total of $38.08 billion by 2027, a 200% growth from 2018 figures [1]. This growth is driven by the rise in spending power and air passenger traffic and the need for replacing ageing fleets. Another key factor is the strict
regulations on aircraft fuel emissions which accounts for 12% of the CO₂ emissions from all transport sources [2]. Therefore, it is expected that there will be further demand for using lightweight and fuel-efficient materials such as composites and fibre metal laminates. However, there are limited choices of materials that can be used in an aircraft due to the complex requirements. Of those most prominent materials is a hybrid fibre metal laminate material commercially known as GLARE®. GLARE® is a multi-material made from aluminium sheets mainly Al2024-T3 alloy and thin prepregs of S2/FM94 glass fibre adhesive epoxy [3]. The material was developed in the 80-90s period and is currently installed in parts of the Airbus A380 commercial aircraft structure. GLARE® has distinctive characteristics due to its hybrid nature making it an attractive choice for use in areas of the aircraft where impact and fatigue resistance are needed such as the fuselage. Indeed, 3% of Airbus A380 weight is comprised of GLARE [4, 5]. It is well known that the best method to date for joining large aircraft structures is using riveted joints. This is mainly because aluminium alloys which make a large percentage of the overall mass of the aircraft are difficult to weld and riveting provides a stronger and more durable bond than welded joints. A commercial aircraft can have anything between 1.5 to 3 million holes within its structure [4]. The holes are drilled using a conventional machining process and poor hole quality is an issue that leads to rejection prior to assembly [6, 7]. Hybrid aerospace materials like GLARE® are susceptible to heat-affected zone (HAZ) and hole microstructural damage due to machining. In addition, the distinct mechanical and thermal properties of its constituents bring out machining problems that usually occur when drilling metals and composites alone. The studies on machining GLARE® have surged in recent years especially in the conventional machining domain. The past studies looked into the effect of cutting parameters and drill geometry on the hole quality for different types of GLARE® laminates [8, 9]. Giasin et al. investigated the effect of cutting parameters, ply orientation and tool coating on hole quality metrics (surface roughness and geometrical tolerances) [8, 10, 11]. Pawar et al. investigated the effect of tool geometry on the same metrics and found that two-flute and four-faceted drills produce holes without delamination [12]. In another study, Giasin et al. [5] reported that the type of tool coating can impact the cutting forces and hole quality. Due to the abrasive nature of S2 glass fibre layers in GLARE® laminates, several studies tested the advantages and limitations of using environmentally friendly coolants to reduce tool wear and improve hole quality [3, 13, 14]. The studies found that using cryogenics such as liquid nitrogen improved certain aspects of hole quality but considerably increased cutting forces and delamination [13, 15, 16].

Cryogenic machining is a sustainable cooling and lubrication alternative to machining using flood coolants [17]. The use of cryogenic coolants in machining aerospace materials was explored since the 1950’s mainly for machining
difficult to cut materials made from steel or titanium alloys [18, 19]. The most notable effects of using cryogenic cooling in the machining process are the ability of the cryogen to absorb the heat in the machining area and the formation of a thermal barrier between the tool-chip [20]. For example, Shokrani et al. [21] reported that using cryogenic LN$_2$ cooling in end milling of Ti–6Al–4V titanium alloy resulted in up to 39% surface roughness reduction compared to conventional dry and flood cooling milling. Pu et al. [22] reported that using LN$_2$ cooling during machining of AZ31B magnesium could significantly affect the microstructure of the machined surfaces by inducing grain refinement which is responsible for improving the corrosion resistance. Sahoo et al. [23] found that deep cryogenic treatment of cemented carbide cutting tools increased their hardness and resulted in a reduction of tool wear compared to untreated tools. The improvement in tool wear was attributed to the increased $\eta$ (eta) phase carbides formed on the surface of cryogenically treated tools. Özbek et al.[24, 25] studied the effects of cryogenic treatment of cemented carbide tool on wear behavior in machining stainless steel. They reported wear resistance of cryogenically treated tools significantly improved. Kumar et al. [26] reported that the external supply of LN$_2$ to the cutting zone when drilling FMLs resulted in increased cutting forces and hardness. However, hole quality metrics such as burr height, surface roughness, average hole size, circularity error, and perpendicularity error were significantly improved in comparison to dry drilling conditions. In another study by Shokrani et al. [27], developed a hybrid MQL (minimum quantity lubrication) and cryogenic cooling system to study its impact on the end milling of Ti-6Al-4V titanium alloy. The hybrid cooling system was compared against flood, MQL, and cryogenic cooling methods and found that the hybrid system significantly improved tool life and productivity. Khoran et al. [28] used CO$_2$ (carbon dioxide) as a cryogenic coolant in grinding PEEK thermoplastic polymers and compared its performance against cooling using chilled air. Their results show that the load on the cutting tool was reduced when using cryogenic cooling and reduced surface roughness. Amigo et al. [29] studied the effect of CO$_2$ cryogenic cooling on the cutting forces during machining of Inconel 718. They compared the results against oil emulsion and found that cryogenic cooling resulted in increased surface roughness due to less lubrication imposed by low temperatures. Varghese et al. [30, 31] studied the effect of the cryogenic soaking period of the cutting tools on their wear behavior when end milling maraging steel. They found that all treated tools regardless of the soaking period improved surface finish and reduced cutting forces. In addition, the study found that optimum soaking period -after which no further improvement in tool/workpiece quality can be achieved- to be 24 hours. Jebaraj et al. [32] found that using either LN$_2$ or CO$_2$ cryogenic cooling when machining steel alloys resulted in significant cutting temperature reduction (up to 54%) compared to conventional wet cooling.
They also found that both cryogenic coolants reduced cutting forces, chip width and surface finish. Chen et al. [33] studied the effect of using different cooling technologies on the drilling performance of β-type titanium-zirconium-niobium alloy dental implants. Their results showed that using cryogenic cooling on its own resulted in increased brittleness due to low temperatures. However, they concluded that combining cryogenic cooling with MQL showed promising improvement in oxidative wear.

However, cryogenic machining became more prominent with the advancement in machining centre technologies that allowed the incorporation of cryogenic coolants into the machining process. At the early stages of using cryogenic technology, the workpiece material and cutting tool were either pre-cooled [34, 35], coolant was indirectly delivered to the cutting tool [36-38], or sprayed externally using a nozzle that is directed towards the cutting zone or the cutting tool [39-41]. However, these techniques require large amounts of cryogenic coolant which is neither feasible economically nor for large-scale production operations. In addition, previous methods can lead to undesired cooling effects or overcooling. There have been attempts in the past to deliver cryogenic coolant through the coolant holes in the cutting tool to perform a variety of machining processes [42-44]. However, in this case, the cutting tool was fixed such as in turning processes [38], or was made fixed to avoid tool breakage due to extremely low temperatures to perform the drilling process [45]. Other studies were successful in delivering LN₂ through the tool coolant holes by developing a rotary liquid nitrogen applicator to be used in milling operations [42, 43, 46]. However, delivering cryogenic coolants through rotary cutting tools can be challenging due to premature tool breakage caused by increased brittleness of the cutting tool.

Newly developed technologies allowed delivering LN₂ through the spindle and the cutting tool [17, 47]. The new technology helps to reduce the amount of fluid used and making the cryogenic machining process more sustainable and better performing than other traditional cooling processes such as conventional flooding. Indeed, previous studies reported that the economic and environmental impacts of the cryogenic machining implementation for the manufacturer are significant, for example, a comparison study between flood cooling and through tool cryogenic machining showed that using the later method can reduce the overall machining costs by 26.2% and 22.8% reduction in energy costs [47]. The study was based on considering the costs incurred by labour, material, cutting tool, coolant and its disposal, energy, capital costs and material recycling.
The current experimental work is focused on studying the effects of delivering cryogenic coolants through the cutting tool to reduce the amount of coolant used and optimise the target area to cool [17]. This will help the current and past experimental research to better understand the impact of using cryogenics on machining GLARE® to facilitate this technology for improving the performance of FMLs in aerospace applications. The aim here is to improve the hole to make FMLs such as GLARE® an even more attractive choice than metals or composites. Machining GLARE® using through tool cryogenic cooling technology is novel since no previous studies were reported on the subject, while only a few studies investigated the impact of externally applying LN2 on GLARE® laminates by Giasin et al. [48, 49]. In addition, it could pave the path towards sustainable machining of aerospace materials if proved successful in improving certain hole quality aspects. Therefore, this study aims to carry out a comparison between dry and through tool cryogenic drilling of a GLARE® laminate. The study investigates how the combination of cutting parameters and the use of cryogenic coolant can influence certain hole quality characteristics like surface roughness \( (R_a \text{ and } R_z) \), hole geometrical tolerances (hole size and circularity at entry and exit sides) and micro-hardness near the edge of the hole at 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 of all possible combinations of three factors (spindle speed, feed rate and dry or cryogenic coolant) at different levels. To support the findings of this study, Analysis of Variance (ANOVA) statistical method was used to evaluate the percentage contribution of cryogenic coolant, cutting parameters, the interaction between cutting parameters and cryogenic coolant on the measured hole metrics.

2. Materials and methods

2.1 Workpiece and cutting tool

The workpiece is made up of eleven aluminium sheets (Al2024-T3) and ten S2/FM94 preregs as shown in Figure 1.a. GLARE® workpiece of 150 mm x 210 mm x 7.06 mm thick was used in the drilling studies as shown in Figure 1.b. Each aluminium sheet was 0.4 mm thick while each S2/FM94 prepreg was made from two plies oriented at 90°/90° and 0.133 mm thickness. The chemical composition by weight percentage of Al2024-T3 alloy and S2 glass fibre are given in Table 1. The fibres are manufactured as a prepreg including the FM94 adhesive system (Cytec®) from Cytec, U.K [3]. The distance between the centre of the holes was kept constant at 15 mm vertically and horizontally as shown in Figure 1.b.
Figure 1: GLARE® 2B 11/10-0.4 laminate showing (a) stacking sequence of the laminate (b) front view with hole array setup

Table 1: Chemical composition by weight percentage of Al2024-T3 alloy and S2 glass fibre [50, 51]

<table>
<thead>
<tr>
<th></th>
<th>Al2024-T3</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al</td>
<td>Cr</td>
<td>Cu</td>
<td>Fe</td>
<td>Mg</td>
<td>Mn</td>
<td>Other, each</td>
<td>Other, total</td>
<td>Si</td>
<td>Ti</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max 0.05</td>
<td>Max 0.15</td>
<td>Max</td>
</tr>
<tr>
<td>90.7-94.7</td>
<td>Max</td>
<td>0.1</td>
<td>4.9</td>
<td>0.5</td>
<td>1.8</td>
<td>0.3-0.9</td>
<td>Max 0.05</td>
<td>Max 0.15</td>
<td>Max</td>
<td>Max</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>S2 glass fibre</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
<td>Al₂O₃</td>
<td>CaO</td>
<td>MgO</td>
<td>Na₂O +K₂O</td>
<td>Fe₂O₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>64-66</td>
<td>24-25</td>
<td>0-0.18</td>
<td>9.5-10.2</td>
<td>0-0.2</td>
<td>0-0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A 5/16-inch (7.9375 mm) Star SU BlueZone™ CTS-0048RD solid carbide drill was used in the study which was supplied by Fullerton. The drill has an h7 tolerance and is covered with FC20 coating and has ½ inch shank diameter and two internal passages and a front radial vent for delivering LN₂ to the cutting edges. FC20 coating is a single component polymer modified fairing coat. The coating is crack-free and has a shrinkage compensating feature, which can be applied as thin surface coats that significantly lowers operating cutting temperatures compared to other coatings. These two unique characteristics make it an excellent choice for machining a variety of materials and to have
excellent performance at very low (cryogenic) temperatures. Only one drilling tool was used to drill 36 holes for each set of tests (i.e. dry and cryogenic).

2.2 Cutting parameters

The cutting parameters analysed in the current study are spindle speed \((n)\) and feed rate \((f)\) as they have a direct influence on hole quality [52]. The choice of cutting parameters that would give optimum hole quality may vary with material and tool geometry; the past literature on drilling composites and FMLs recommend a low feed rate and a high spindle speed [53]. However, for the drilling of Al2024-T3 alloy, the best hole quality is achieved using a high spindle speed and feed rate [54].

Drilling tests have been conducted using a full experimental design with a three-level system model of cutting parameters. Besides, two drilling strategies (with and without cooling) and one cutting tool type (i.e. fixed coating, size and geometry) as shown in Table 2. Each test run produced a set of nine holes, which was repeated three additional times to confirm repeatability. Therefore, all values reported in this study represent the mean values of the four runs. The full factorial model with three factors (i.e. cutting parameters and presence/absence of cooling) was carried out for both dry and cryogenic cooling tests, thus requiring a total number of 72 holes (36 holes for dry tests and 36 holes for cryogenic tests). The collected data was analysed using a statistical approach and Minitab® software. The factorial analysis was carried out using P-value < 0.05 indicating that the effect of the statistical model in terms of its input parameters on the analysed hole metrics are significant at 95% confidence level [5].

<table>
<thead>
<tr>
<th>Input Factor</th>
<th>Low level</th>
<th>Medium level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle speed (rpm)</td>
<td>2268</td>
<td>4535</td>
<td>6803</td>
</tr>
<tr>
<td>Feed rate (mm/min)</td>
<td>226.8</td>
<td>453.5</td>
<td>680.3</td>
</tr>
<tr>
<td>Cooling</td>
<td>No (Dry)</td>
<td>Cryogenic LN(_2) delivered through the tool coolant holes</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Experimental machine setup and procedure

The drilling tests were carried out on a Doosan NHP 6300 Horizontal Machining Centre (HMC) as shown in Figure 2. The machine has an operational spindle speed of up to 16,000 rpm. The workpiece was mounted using a Kurt 8” vice w/10” o fixture opening vertically and mounted on a tombstone. Clamp-on plate sides were used while no “full” back-plate support was used to reveal the free break-out condition.
2.4 Cryogenic system setup

The cryogenic delivery system was developed by 5ME LLC and is currently commercialized for industrial use. The system is made from a user-friendly cryogenic kit similar to that shown in Figure 2, which is capable of delivering LN$_2$ through the spindle through to the cutting edges via thermally insulated fluid passages [17, 47]. The cooling strategy of the system is to cool the cutting tool and the workpiece simultaneously and during the whole machining process. The cooling of the cutting edges is achieved through internal channels in the tool, while the workpiece is cooled by cryogenic heat transfer which occurs due to convection and conduction. Conductive cooling of the workpiece occurs due to the continuous contact with the cryogenically cooled cutting tool, while convection cooling occurs due to the forced convective boiling heat transfer from the subcooled LN$_2$. The functions and details of the cryogenic system components are discussed in detail in a previous study by Lu et al. [17]. Additional information about the 5ME’s cryogenic machining system is given in Table 3.

Table 3: Technical information about 5ME’s cryogenic machining system [55]
<table>
<thead>
<tr>
<th>Coolant medium</th>
<th>Liquid Nitrogen (LN₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System output</td>
<td>Mix of liquid Nitrogen and Nitrogen gas (LN₂/N₂)</td>
</tr>
<tr>
<td>Machining operations</td>
<td>Drilling, Milling, Turning, Reaming and Boring</td>
</tr>
<tr>
<td>Targeted materials</td>
<td>CGI, Titanium, Aluminium, Composites, Hardened/Stainless steel alloys and Inconel</td>
</tr>
<tr>
<td>Temperature of LN₂</td>
<td>-321 °F/-196 °C</td>
</tr>
<tr>
<td>Flow rate</td>
<td>0.25-1 Litre/min (Fixed at 0.25 Litre/min for this study)</td>
</tr>
<tr>
<td>System pressure</td>
<td>2 bars (Self-pressurizing)</td>
</tr>
<tr>
<td>Feed lines</td>
<td>Vacuum Jacketed tube</td>
</tr>
<tr>
<td>Coolant delivery</td>
<td>Through spindle</td>
</tr>
</tbody>
</table>

2.5 Surface roughness, hardness, hole size and circularity measurements

A Mitutoyo Surftest SJ-210 portable profilometer was used to measure the arithmetic $R_a$ and $R_z$. Four measurements were taken around the perimeter of each at angles of (0°, 90°, 180°, 270°) by rotating the workpiece. The average values of the four measurements represent the mean value for $R_a$ and $R_z$ values which is reported in the results and discussion section. A Duroline-M hardness tester was used to measure the hardness around the hole edges at entry and exit sides. For each hole drilled using the same cutting parameters, the hardness was measured five times for each hole condition around its edge roughly at locations corresponding to (0°, 90°, 180°, 270°) at entry and exit sides (180 total measurements). A 1 kgf load and 10 seconds dwell time was applied for all measurements as it gave a well-defined pyramid shape and allowed ease of measurement. The hardness measured around the hole edges was taken at least 3-4 indentation widths away from the hole edge as shown in Figure 3.a. Hole size and circularity at entry and exit sides were measured using a Sheffield Cordax-D8 Coordinate Measurement Machine (CMM) [10, 11]. The GLARE® sample was placed on the CMM bed as shown in Figure 3.b and the measurement at entry was taken at 1 mm beneath the top surface of the workpiece, while the measurement at the exit was taken at 6 mm below the upper surface of the workpiece.
3. Results and Discussion

3.1 Analysis of micro-hardness at hole edges

Figure 4 shows the average micro-hardness measured around the hole edge for the upper and lower aluminium sheets. This figure depicts a comparison of the measured hardness values at the entry and exit sides for the dry and cryogenic drilling tests. The nominal Vickers hardness of Al2024-T3 is 137 HV [4]. The average hardness in the present study was found to range between 134 HV and 142 HV. For dry drilling conditions, the hardness measured at the hole entry was always generally lower than that measured at the exit side, this shows that the hardness increases with depth. For cryogenic drilling conditions, the hardness measured at the hole entry was higher for spindle speeds of 2268 and 4535 rpm and lower thereafter. Moreover, the difference between the hardness at entry and exit sides for cryogenic tests were less than those observed in their counterparts under dry drilling conditions. The overall hardness under cryogenic conditions ranged between 134 and 143 HV, while for dry drilling conditions, the hardness values ranged between 125 and 137 HV.
Looking back at Figure 4, under dry condition the hardness at the entry side decreased with the increase of the feed rate under all spindle speeds which could be due to the increase in chip removal rate from the hole meaning that more heat is being removed at higher cutting parameters (greater partition of the overall heat) and as a result, less plastic deformation occurs and hardness is decreased. This is mainly due to the fact that strain hardening during plastic deformation decreases with increasing temperature [56]. In addition, previous work showed that as temperature increases in Al2024, the ductility increases and the strength of the material decreases due to the dynamic recovery and recrystallization which occur at high temperatures and reduce the room temperature restrictions on grain mobility [57]. Indeed, Rotella et al. [58, 59] found that applying LN₂ encourages the formation of small grain size after dynamic recrystallization during the machining process, which results in higher hardness at the surface of the material. However, this effect can be concluded in the current study, perhaps because the delivery method of LN₂ through the cutting tool vents prevents direct contact of the coolant with the machined surface and thus making any significant effect on the hole microstructure.

Similarly, at the exit side, the hardness in dry tests decreased with the increase of the feed rate when drilling at a spindle speed of 2268 and rather increased thereafter at spindle speeds of 4535 and 6803 rpm which could indicate that higher cutting parameters lead to significant temperature rise in the workpiece and cutting tool due to

```
<table>
<thead>
<tr>
<th>Feed rate (mm/min)</th>
<th>Spindle speed (rpm)</th>
<th>Max hardness (nominal)</th>
<th>Minimum hardness (nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>226.8</td>
<td>2268</td>
<td>146</td>
<td>110</td>
</tr>
<tr>
<td>453.5</td>
<td>4535</td>
<td>144</td>
<td>112</td>
</tr>
<tr>
<td>680.3</td>
<td>6803</td>
<td>142</td>
<td>114</td>
</tr>
</tbody>
</table>
```

Figure 4: Average micro-hardness around the hole edge entry and exit side of the holes
increased frictinal loads [60]. In addition, the hardness at the exit side was higher than at the entry, this could be explained by the fact that there is a significant strain hardening which occurs when temperatures in Al2024 alloy reach up to 150 °C when machining at higher cutting temperatures [56]. However, since the temperatures were not measured, this can be only a speculation and measuring the machining temperatures at the tool-workpiece interface is required to confirm such a claim. For cryogenic drilling, the hardness at entry increased with the increase of the feed rate when drilling at a spindle speed of 2268 rpm, then somewhat decreased thereafter at spindle speeds of 4535 and 6803 rpm. This could indicate that the cryogenic cooling provides beneficial effects when drilling at low spindle speeds but its effectiveness in removing heat away from the cutting zone becomes less efficient with the increase in cutting parameters. For cryogenic tests, the hardness at the exit side generally increased with the increase of the feed rate under all spindle speeds. Therefore, it is argued that no firm conclusion may be made from the direct observation in terms of what is the impact of LN2 cooling on the hardness of the holes at entry and exit sides. Instead, one can use data in Figure 4 to analyse the relative reduction or increase in the hardness between the entry and the exit regions of the hole at a certain value of feed and speed. It can be also argued that the hardness in holes drilled cryogenic conditions were within the range of the nominal hardness of the workpiece measured nominal hardness. This indicates that using through tool cryogenic cooling does not alter the hardness around the hole edge, which can be considered as a beneficial effect over dry drilling tests which reduced the hardness at entry and exit locations by 5-10 Vickers below the minimum observed average microhardness.

During machining, when cooling is fast enough, it will lead to higher strength. However, rapid cooling will lead to the formation of undesirable residual stresses [61]. Ambrosy et al. [62] previously reported that external cryogenic cooling using LN2 increased plastic deformation within the workpiece surface layer. This in return resulted in a significant increase in hardness due to work hardening. Generally, the hardness should increase with residual stress present at the surface since the surface has to tolerate the applied load during the hardness testing. However, tensile and compressive stresses can form on the surface which could affect the hardness differently. For example, if compressive stress is applied to a material that is under tensile residual stress, the compressive stress needed to cause yielding or plastic deformation to deform the metal -as is the case in hardness measurement- must be increased [63]. Indeed, Paul et al. [40] reported that during the machining process, the working material is plastically deformed by the cooler sublayers, leading to tensile residual stress on cooling. In the case of LN2, the low temperatures due to cooling would further increase tensile residual stresses around the hole edges and therefore higher hardness is
expected. Morkavuk et al. [32] and Basmaci et al.[64] stated that tensile strength and elastic modulus of the fibre reinforced plastics which are exposed to LN$_2$ improved. Zhang et al. [65] reported that during milling of aluminium-lithium alloys, the compressive residual stresses under LN$_2$ cooling are significantly less than that under dry cutting conditions but tensile residual stresses were not mentioned. However, in other studies [66, 67], it was reported that cryogenic machining produced less tensile stresses on the surfaces of Inconel alloy and an increase in the compressive residual stress of AZ31B Magnesium alloy. Therefore, it is speculated that in the current work, the surface around the holes drilled using LN$_2$ produced higher tensile residual stresses than those formed in holes under dry drilling conditions. However, this claim needs to be confirmed with further analysis of residual stresses and their effect on the hardness near the hole edges, therefore, an additional study is needed.

Comparing the current work to the only other available work on drilling GLARE® laminates under external cryogenic LN$_2$ jet cooling, it can be said that the current hardness data does not follow a direct trend similar to that observed in the previous studies, mainly because different parameters magnitudes were used in the past studies [4, 48]. However, it is evident from the current and past studies that supplying LN$_2$ externally in large volumes leads to a significant increase in workpiece hardness. This phenomenon is not present when supplying LN$_2$ through the cutting tool vents as is the case in the current study, this can be said to be another benefit of using internal cryogenic cooling.

In the previous study by Giasin et al. [48], it was found that the hardness increases significantly by up to 9.35% when using LN$_2$ in comparison with the dry condition. This was observed to be higher at the entry where the cryogenic coolant was in direct contact with the upper surface of the workpiece as shown in Table 4. However, in the current study, the variation in hardness among dry and cryogenic tests was greater. This means that the cooling effect of the through tool cryogenic cooling remains equally effective throughout the hole thickness in contrast to that observed when LN$_2$ is supplied externally. Therefore, it can be concluded that the method by which LN$_2$ is applied to the cutting zone can significantly impact the hardness of the hole, especially when drilling at a wide range of cutting parameters.

**Table 4: Dry Vs Cryogenic Vickers microhardness range from the current and past literature on drilling GLARE® 2B 11/10 laminates**

<table>
<thead>
<tr>
<th>Drilling condition</th>
<th>Dry (HV)</th>
<th>Cryogenic (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current study (Entry)</td>
<td>125-130</td>
<td>128-137</td>
</tr>
<tr>
<td>Current study (Exit)</td>
<td>134-143</td>
<td>132.5-139</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>Previous study (Entry) [48]</td>
<td>139-144</td>
<td>148-152</td>
</tr>
<tr>
<td>Previous study (Exit) [48]</td>
<td>139-142</td>
<td>146-150</td>
</tr>
</tbody>
</table>

ANOVA table was generated from the full factorial design implemented in the current study as shown in Table 5. The table shows the most important parts of the ANOVA data which are the P-value and percentage contribution for each of the studied hole outputs. A P-value of fewer than 0.05 means that the input parameter or the interaction of the parameters is significant. From Table 5, the most significant parameters on hardness at the entrance and exit are the presence/absence of coolant with 33.55% and 8.71% at entry and exit, respectively. There was a noticeable contribution of the spindle speed at the exit side of the hole with 7.22% and the linear interaction between the spindle speed and the presence/absence of coolant with 10.78% at the exit. The regression coefficient R-squared obtained from the ANOVA analysis of the hardness data at entry and exit sides were very low as evident by the large error in the analysis. However, even if low R-squared values are observed, the independent variables are statistically significant, and it is valid to draw important conclusions about the relationships between the input and output variables. The low R-squared values would imply that other variables have a significant influence on the outputs but were not evaluated in the current statistical model or that quadratic terms need to be added to improve the model.

3.2 Surface roughness analysis ($R_a$ and $R_z$)

It was not possible to measure the surface roughness metrics ($R_a$ and $R_z$) of the GLARE constituents (glass fibre layers and aluminium sheets) individually using the 2D surface profilometer due to their small thicknesses. Therefore, the average surface roughness values reported here are calculated from measuring the surface roughness of all S2 glass fibre layers and aluminium sheets along with the hole depth. Figure 5 shows a typical roughness profile observed in holes machined in GLARE® laminates. The roughness of the aluminium sheet was always lower than that of the glass fibre layers. The material property differences between GLARE® constituents can result in significant discrepancies in the types and mechanisms of damages experienced by the aluminium sheets and glass fibre layers. When the drill cuts through glass fiber layers, powdery chips are formed due to the brittle nature of glass fiber. The machined surfaces of glass fibre layers appear rough and fuzzy. When cutting through aluminum sheets, the material is plastically deformed, and the chips are removed by the cutting edges and travel up the drill flutes. This variation in surface roughness is also attributed to the fuzzy and fibrous nature of machined glass fibre surfaces and the influence of ply.
orientation on the roughness measurement process [68]. The roughness profile observed in the aluminum sheets appears to be regular and smooth (i.e. lower difference between peaks and valleys of the roughness profile). It should be also pointed out that the surface roughness measurement technique used here is highly influenced by the surface condition of the machined glass fiber layers due to different types of damage and morphologies (i.e. porosities, the fuzziness of the fibers, fiber pull-outs and crushed bundles of fibers). It is likely for the stylus of the roughness tester to get entangled by the protruding fibers for example which can lead to some errors in the results of the measurements.

A more realistic and robust evaluation of roughness metrics in GLARE® laminates is to measure the roughness metrics of the glass fiber layers and the aluminum sheets individually. However, this process is time-consuming and therefore, an additional study is needed.

Figure 5: Typical profile of average surface roughness $R_a$ in GLARE® laminates [5]

Figure 6 shows the average surface roughness $R_a$ for dry and cryogenic drilling tests. The values of average surface roughness $R_a$ were less than 1.3 µm in all drilled holes regardless of the cutting parameters used. Previous work reported on surface roughness by Giasin et al. [48] on drilling GLARE® 2B 11/10-0.4 showed that $R_a$ values observed at 0.1 mm/rev under external cryogenic cooling were significantly higher than those reported in the current study under 0.1 mm/rev. Therefore, it can be said that through tool cryogenic cooling is more efficient in reducing the surface roughness than external cryogenic cooling. However, it should be noted that different tool coating and geometry were used in the two studies which could also have contributed to this phenomenon.
Figure 6: average surface roughness $R_a$ for dry and cryogenic conditions under different cutting parameters

For dry drilling tests, $R_a$ increased with the rise in the feed rate and the highest $R_a$ was observed in the holes machined at 680.3 mm/min, which agrees with the results reported by Giasin et al [4]. For holes drilled under dry conditions, the largest increase in $R_a$ occurred at 2268 rpm, rising by 27.9% with the increase in the feed rate from 226.8 to 680.3 mm/min. The maximum $R_a$ value obtained for dry holes was 1.44 µm, occurring on the first run at $n = 4535$ rpm and $f = 680.3$ mm/min. For cryogenic drilling tests, $R_a$ increased with the rise in the feed rate when machined at spindle speeds of 2268 and 4535 rpm. However, at a spindle speed of 6803 rpm, $R_a$ was found to decrease when increasing the feed rate. This is contrary to expectations and what is observed in holes machined under dry conditions. At higher feed rates and spindle speeds, the cutting temperatures are higher and therefore, play a bigger role in the final hole quality. Similar trends were observed in previous work on cryogenic machining of metals which stated that there is a certain combination of feed rate and spindle speed at which cryogenic cooling shows optimum performance [69]. In addition, it is possible that using LN₂ significantly lowers the effect of high machining temperatures and further improve surface finish. This could be also attributed to the formation of a hydrodynamic film which provides a lubrication effect and lowers friction coefficients [70]. A more detailed explaining of the lubrication effects due to LN₂ cooling is provided in the following paragraphs. Similarly, the maximum $R_a$ of 1.24 µm observed under cryogenic conditions occurred on the second run at $n = 4535$ rpm and $f = 680.3$ mm/min. Although the maximum $R_a$ occurred for both drilling conditions under the same feed rate of 680.3 mm/min, the maximum $R_a$ for the dry hole occurred at
the lowest spindle speed of 2268 rpm. In addition, FC20 coating have high hardness and elasticity, low friction, and high oxidation resistance. Therefore, the reduction in surface roughness at higher feed rates could be also attributed to coating performance and drill geometry. However, this needs to be validated in a separate study by comparing the effect of tool geometry and coating on the surface hole surface roughness. Zitoune el al [52] previously reported that the value of the depth of cut depends on feed rate and diameter of drill when drilling CFRP/Al2024 stacks. They found that the effect of the drill diameter and the feed rate affect chip breakability due to the increase in cross sectional area of chip. They concluded that increasing the feed rate facilitates chip breaking which is critical for improving surface finish during drilling of Al2024. This was also reported by Batzer et al. [71] which found that larger chips result in higher surface-roughness. It could be also that the increased hardening of sliding chips and high oxidation resistance of the FC20 coating tends to reduce the stickiness of the chips on the cutting tool [4] and thus, improving the hole surface roughness. However, since the chips were not collected in this study, this remains an assumption which should be investigated in a separate study by analysing the chips at different cutting parameters. Therefore, a firm conclusion can be drawn from observing the results of surface roughness that there appears to be a trade-off between improved chip breakability versus hydrodynamic lubrication effect on surface roughness.

It was observed that except for holes drilled at a feed rate of \( f = 226.8, 453.5 \text{ mm/min} \) and spindle speeds of 2268, 4535 (i.e. 0.1 mm/rev), \( R_a \) in holes drilled using cryogenic coolant were lower than their counterparts drilled under dry conditions. The reduction in surface roughness when using tool cryogenic cooling ranged between 2.14% and 25.95%. The reduction in surface roughness due to cryogenic cooling in comparison to dry machining was found to increase with the increase of the cutting parameters. During the drilling process, the heat is generated at the cutting zone of the laminate and the molecules realign as the part cools. The previous study indicated that when the machined surface heats the molecules realigns and as the part cools down there is a chance for better alignment due to cryogenic cooling which results in a better surface finish [72]. Moreover, when the drill cuts through the laminate constituents, if the cutting temperature is high then the layers will be too rubbery and cause significant internal burrs which would increase the surface roughness. However, the low temperature induced by LN\(_2\) provides a non-ductile zone at which the metal and glass fibre layers behave in a brittle manner and cracks when machined. This is speculated to result in a better surface finish.
GLARE® laminate consists of three constituents (the aluminium sheets, the fibres and the matrix in the glass fibre layers). During machining, and due to the difference in the coefficients of thermal expansion of the laminate constituents, the surface finish can be highly influenced by the different levels of expansion/contraction of the laminate constituents relative to each other. It is possible that the LN$_2$ cooling reduces the severity of dimensional change due to cutting temperature effects (relaxation or contraction of the laminate constituents). This in return would result in fewer distortions at the interface between aluminium sheets and glass fibre layers and result in a better surface finish. It is also possible that cryogenic machining helps in moderating the frictional characteristics at the tool–chip interface, reduce adhesions between interacting surfaces and modifying the properties of the workpiece and the cutting tool material [70], hence, improving the machinability of the material [73]. Additionally, compressive stresses that form due to the difference between thermal-expansion coefficients of fibre/matrix in the laminate provided a better bonding of fibres, and thus cleaner shear fractures are obtained rather than bending and tearing, which could also explain the improvement in surface finish under cryogenic machining [74].

This could be also attributed to the lubrication effect of LN$_2$ and is explained by the work of Hong et al. [70] who looked into the effect of LN$_2$ to better understand the lubrication mechanisms involved. In their work, LN$_2$ was supplied at five different cooling strategies between two materials all of which were metals. They found that LN$_2$ lubrication generates hydrodynamic film which yields very low friction coefficients. In addition to the LN$_2$ cooling effect, the formed hydrodynamic film generates the same lubricating effect regardless of the material pair in contact. The hydrodynamic film thickness was found to degrade with greater pressure (load) which tended to squeeze the lubricating film out such as the case with drilling at higher feed rates at a constant spindle speed. Another explanation could be that surface roughness was reduced due to improved chip breakability due to the increase in microhardness of the laminate [75].

The results also show that the efficiency of cryogenic coolant in lowering the surface roughness becomes more significant when drilling at higher spindle speeds. This improvement could be due to a reduction in machining temperatures at the chip-tool interface and its consequent impact on improving surface finish. Using LN$_2$ cryogenic cooling reduces the variation in surface texture, allowing for a greater degree of accuracy in the drilling process. This is critical in industries such as in the aerospace sector where holes with strict tolerances are required for fastener
installation. An $R_a$ of (3.2 µm for composites and 1.6 µm for metals) or lower is required based on aerospace guidelines and cutting tool manufacturers [76].

Figure 7 shows the ten-point mean roughness ($R_z$) for the dry and cryogenic conditions under different cutting parameters. $R_z$ in holes drilled using cryogenic coolant was lower than their counterparts drilled under dry conditions. The reduction in $R_z$ ranged between 13.29% and as high as 33.94% when drilling at $n = 6803$ rpm. $R_z$ increases for both drilling conditions at high spindle speeds and high feed rates. High spindle speeds during the drilling of GLARE® reduces hole quality due to the low thermal conductivity of the prepreg which reduces the ability of the laminate to dissipate heat away from the cutting zone [77]. There is rather a greater variation in $R_z$ for the dry holes, which ranges from 8.65 – 10.82 µm compared to 7.41 – 8.31 µm in cryogenic tests. This suggests the use of LN$_2$ as a coolant can assist in controlling the surface roughness. The clear disparity between the two methods highlights the advantages of LN$_2$ on the hole surface finish in GLARE® laminates.

![Average ten point roughness $R_z$ (µm)](chart)

**Figure 7:** Ten-point roughness for dry and cryogenic conditions

The ANOVA analysis of surface roughness parameters ($R_a$ and $R_z$) is given in Table 5. It can be observed that the use of cryogenic cooling has the largest impact with 39.97% and 50.98% for $R_a$ and $R_z$, respectively. The contribution of the feed rate and the spindle speed on $R_a$ and $R_z$ which ranged is diminished when using LN$_2$ and is between 2.12% to 6.43% and 4.23% and 5.51% for spindle speed and feed rate, respectively. The regression coefficient
R² for \( R_a \) and \( R_z \) were found to be around 71.41% and 75.11% which indicates that the experimental data is somewhat satisfactory.

### 3.3 Hole size and circularity

Figure 8 shows the average hole size for holes drilled under dry and cryogenic conditions at top and bottom locations. The results show that the hole size at the top was always greater than at the bottom for both dry and cryogenic tests which is in agreement with the previously reported studies on drilling GLARE® laminates [49]. This indicates that hole size tends to decrease with depth due to the relaxation of the lamina [49, 78].

It was also observed that in both tests, the hole size was always greater than the drill nominal diameter. It should be noted that the drills used for cryogenic and dry tests were produced with the same tolerance (h7 drill tolerance) and were taken from the same batch. For this reason, it is possible to carry out direct observation from Figure 8 with regard to which drilling conditions produced the largest hole oversize. Moreover, data in Figure 8 can be used to compare the relative change in the hole diameter along the hole depth at measured locations for dry and cryogenic tests.

**Figure 8: Average hole size at top and bottom for cryogenic and dry drilling tests**
Giasin et al. [49] previously reported that the deviation of the hole size from the drill nominal diameter -when using external LN$_2$ cooling- was always greater than that under dry conditions using same cutting parameters at top and bottom locations. However, in this study, the hole deviation at the top using cryogenic cooling was always lower than that for holes drilled under dry conditions by up to 39% in some cases. In addition, the hole deviation at the bottom using cryogenic cooling was close to that observed in holes drilled under dry conditions. This indicates that through tool cryogenic cooling provides less hole deviation from the drill nominal size than applying cryogenic coolant externally [4, 49]. This could be attributed to lesser deviations caused by machining temperatures when using cryogenic cooling. Indeed, Dix et al. [79] reported that delivering LN$_2$ through the tool can significantly reduce its temperature by up 50-53% within the drill itself when compared to dry drilling. Also, Xia et al.[45] emphasised that the reason for oversized holes probably is due to the thermal expansion of the matrix from increased cutting temperatures in dry machining. In any machining process, the heat generated in the cutting zone can be removed by two primary transfer modes: convective and conductive cooling. In convective cooling, heat exchange occurs due to the temperature difference between the cutting zone and the surroundings (i.e. ambient air or a cooling fluid such as oil, water or cryogenic gases). For conductive cooling, the heat transfer occurs due to the physical contact between the workpiece and cutting tool. The temperature difference between the cutting zone and the back end of the cutting tool acts as a heat sink which removes the heat. When using conventional coolants, this effect is negligible but when using cryogenic coolants this can significantly reduce the bulk tool temperature and therefore, the difference in temperature between the cutting edges and the body of the cutting tool is high.

Moreover, previous work of Giasin et al. [4, 49] reported that hole size at the bottom under dry conditions was below the drill nominal diameter when a TiAlN coated tool was used which did not occur in the current study when using FC20 coated tools. This could also indicate the tool coating can influence the hole size which requires an additional study. Moreover, the geometry of the drill used in the current study has a strong influence on the temperature distribution as it was optimized for cryogenic machining applications. The drills used in the study have thermally highly stressed cutting edge. In addition, the favourable position of the coolant channels within the drill itself provides better cooling as they radiate LN$_2$ to the side of the drill away from the cutting zone.

For holes drilled under dry conditions, the deviation of the hole size from the drill nominal diameter at top ranged between 21.73 µm and 24.92 µm, and between 10.96 µm and 26.86 µm at the bottom. The variation in hole
size from top to bottom did not exceed more than 12.46 μm. Similarly, for cryogenic drilling conditions, the deviation of the hole size from the drill nominal diameter at top ranged between 17.92 μm and 21.28 μm, and between 12.74 μm and 17.07 μm at the bottom. The variation in hole size from top to bottom for holes under cryogenic conditions did not exceed 7.76 μm. This means that using through tool cryogenic coolant can produce holes that have lower size deviation throughout its thickness.

For dry drilling tests, the largest increase in hole size from the drill nominal diameter occurred at \( n = 4535 \) rpm and \( f = 680.3 \) mm/min, due to the increase in drill vibration at higher spindle speeds [80]. The hole size drilled at \( n = 2268 \) rpm and \( f = 680.3 \) mm/min were closest to the drill nominal diameter. For cryogenic drilling tests, the largest and smallest increase in hole size occurred at \( n = 4535 \) rpm and \( f = 226.8 \) mm/min and at \( n = 6803 \) rpm and \( f = 680.3 \) mm/min, respectively. Another observation from the data reported in Figure 8 is that in general, it can be said that the hole size on the top for dry and cryogenic conditions increased with the increase of spindle speed. Whereas at the bottom, it decreased with the increase of the spindle speed when drilling at constant feed rate similar to a previous study [81]. Thus, different phenomena, related to the increase in spindle speed, occur at the entrance and exit of the holes [81]. For the bottom region, the continuous rubbing of the drill and evacuated hot chips increase the temperature at the cutting zone leading to thermal shrinkage [81, 82]. This does not occur at the top part of the hole as the more dominant influence in this region is the drill vibration [81].

Finally, for the spindle speed/feed rate combinations that result in 0.1 mm/rev feed rate (i.e. 226.8/2268, 453.5/4535 and 680.3/6803 ((mm/min)/rpm), the results indicate that hole size at top and bottom tended to increase with the reduction of drilling time. The aerospace industry requires producing holes that meet certain hole tolerances and standards such they need to be close to the nominal diameter or it will degrade the rivet structure performance, especially under cyclic loading [4, 81]. A machined hole that is out of tolerance would require a post-machining process such as reaming to bring the hole to the desired tolerance. In the current study, hole size variation ranged between (-1.94 μm to +26.86 μm) which falls in the upper range of H9 hole tolerance (0 to +30 μm). H9 hole tolerance is one of the most recommended and used tolerance by aerospace manufacturers [4, 81, 83]. In addition, industrial reports of drill manufacturers indicate that hole tolerances in aerospace components could vary between ±20 μm and can be even stretched to ±40 μm [4, 81, 84]. Therefore, it is safe to say that the range of the hole size reported here is within the allowable limits and would only reaming process is needed to enlarge the undersized holes [81].
The ANOVA analysis provided in Table 5 shows that only the coolant had an impact on the hole size at the top (56.38 %) followed by the linear interaction between presence/absence of coolant with the feed rate (6.32 %). For hole size at the bottom, the feed rate had the highest impact (20.92 %) followed by the spindle speed (8.05 %), while the presence-absence of coolant did not have any impact. However, it was found that the linear interaction between the three parameters had a significant impact on the hole size at the bottom (35% in total). For hole size at the bottom, the ANOVA results indicate that all three input parameters had a significant influence on the hole size. However, the most significant contribution is from the interaction between the cutting parameters with 13.93 %.

Figure 9 shows the average hole circularity under the dry and cryogenic conditions at different drilling parameters. For dry drilling tests, the average hole circularity on the top was between 8.19 and 20.54 µm, while at the bottom location, it was between 19.44 and 30.37 µm. In the current study, a larger drill diameter and different cutting parameters were used compared to all previous studies on GLARE® laminates. Nevertheless, the results reported here are in agreement with the circularity range reported in previous literature (between 3-34 µm) [4, 81]. Results show that the hole circularity will increase with depth due to the gradual increase in thermal load while cutting through the material and the non-isotropic nature of the coefficient of thermal expansion of the glass fibre layers [4, 49, 81, 85].

Figure 9: Average hole circularity at top and bottom for cryogenic and dry drilling tests
For cryogenic drilling tests, the average hole circularity on the top and the bottom were better than that observed in dry tests as it ranged between 8.23 and 16.83 µm, while at the bottom, it was between 14.87 and 23.38 µm. This can be attributed to the cryogenic cooling effect which limits thermal distortions that might impact the hole circularity. For dry and cryogenic drilling tests, the largest variation in hole circularity between top and bottom occurred when drilling at \( n = 6803 \) rpm, \( f = 453.5 \) mm/min, while the least hole circularity variation was achieved at \( n = 2268 \) rpm, \( f = 226.8 \) mm/min. For the spindle speed/feed rate combinations that result in 0.1 mm/rev feed rate, the results showed that the hole circularity at the top tended to decrease when using higher cutting parameters for dry and cryogenic conditions. However, at the bottom, the hole circularity tended to increase with the reduction of drilling time which indicates that drilling holes faster will be at the expense of increased hole circularity.

The ANOVA analysis provided in Table 5 shows that the hole circularity at the top was mainly influenced by the spindle speed (57.49 %) followed by a minor impact by the feed rate (3.39 %). For hole circularity at the bottom, the presence/absence of coolant and the linear interaction between the cutting parameters with 14.13 % and 14.19 %, respectively. The feed rate and the linear interaction between the feed rate and the coolant had less impact with 6.32 % and 8.6 %, respectively. The interaction between the three parameters was rather significant with 9.85 % thus which further supports an earlier comment on the results of Figure 9. However, it was found that the linear interaction between the three parameters had a significant impact on the hole circularity at the bottom (35% in total). For the bottom region, the ANOVA results suggest that all three input parameters had a significant contribution to hole circularity. However, the main contribution is seen from the interaction between cutting parameters as stated earlier.
<table>
<thead>
<tr>
<th>Source</th>
<th>Hardness at entry</th>
<th>Hardness at exit</th>
<th>$R_a$</th>
<th>$R_z$</th>
<th>Hole size Top</th>
<th>Hole size Bottom</th>
<th>Hole circularity top</th>
<th>Hole circularity bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-Value</td>
<td>Contribution</td>
<td>P-Value</td>
<td>Contribution</td>
<td>P-Value</td>
<td>Contribution</td>
<td>P-Value</td>
<td>Contribution</td>
</tr>
<tr>
<td>Model</td>
<td>0</td>
<td>61.32%</td>
<td>0.004</td>
<td>42.08%</td>
<td>0.000</td>
<td>71.41%</td>
<td>0.000</td>
<td>75.11%</td>
</tr>
<tr>
<td>Blocks</td>
<td>0.26</td>
<td>3.07%</td>
<td>0.417</td>
<td>3.39%</td>
<td>0.513</td>
<td>1.30%</td>
<td>0.439</td>
<td>1.35%</td>
</tr>
<tr>
<td>Linear</td>
<td>0</td>
<td>37.17%</td>
<td>0.002</td>
<td>17.78%</td>
<td>0.000</td>
<td>46.32%</td>
<td>0.000</td>
<td>62.92%</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>0.237</td>
<td>1.67%</td>
<td>0.018</td>
<td>7.22%</td>
<td>0.061</td>
<td>2.12%</td>
<td>0.003</td>
<td>6.43%</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.188</td>
<td>1.95%</td>
<td>0.344</td>
<td>1.85%</td>
<td>0.030</td>
<td>4.23%</td>
<td>0.006</td>
<td>5.15%</td>
</tr>
<tr>
<td>Coolant</td>
<td>0</td>
<td>33.55%</td>
<td>0.002</td>
<td>8.71%</td>
<td>0.000</td>
<td>39.97%</td>
<td>0.000</td>
<td>50.98%</td>
</tr>
<tr>
<td>2-Way Interactions</td>
<td>0</td>
<td>18.81%</td>
<td>0.011</td>
<td>18.74%</td>
<td>0.001</td>
<td>17.98%</td>
<td>0.139</td>
<td>6.38%</td>
</tr>
<tr>
<td>Spindle speed*Feed rate</td>
<td>0.565</td>
<td>1.69%</td>
<td>0.256</td>
<td>4.64%</td>
<td>0.000</td>
<td>13.65%</td>
<td>0.086</td>
<td>4.22%</td>
</tr>
<tr>
<td>Spindle speed*Coolant</td>
<td>0</td>
<td>16.62%</td>
<td>0.003</td>
<td>10.78%</td>
<td>0.425</td>
<td>0.97%</td>
<td>0.140</td>
<td>2.0%</td>
</tr>
<tr>
<td>Feed rate*Coolant</td>
<td>0.646</td>
<td>0.50%</td>
<td>0.15</td>
<td>3.32%</td>
<td>0.059</td>
<td>3.36%</td>
<td>0.850</td>
<td>0.16%</td>
</tr>
<tr>
<td>3-Way Interactions</td>
<td>0.416</td>
<td>2.26%</td>
<td>0.638</td>
<td>2.17%</td>
<td>0.048</td>
<td>5.80%</td>
<td>0.073</td>
<td>4.46%</td>
</tr>
<tr>
<td>Spindle speed<em>Feed rate</em>Coolant</td>
<td>0.416</td>
<td>2.26%</td>
<td>0.638</td>
<td>2.17%</td>
<td>0.048</td>
<td>5.80%</td>
<td>0.073</td>
<td>4.46%</td>
</tr>
<tr>
<td>Error</td>
<td>-</td>
<td>38.68%</td>
<td>-</td>
<td>57.92%</td>
<td>-</td>
<td>28.59%</td>
<td>-</td>
<td>24.89%</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>100.00%</td>
<td>-</td>
<td>100.00%</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Values in red colour show the significant parameters and their interactions for each of the analysed hole quality metrics.
3.4 Tool condition and Surface damage analysis using SEM

Figure 10 shows optical microscopic images of the pre and post conditions of the drills used in the dry and cryogenic tests (at 50x magnification). The microscopic analysis shows that very limited tool wear was present for both tools used for dry and cryogenic tests. Post-test drills are shown in Figure 10.c and Figure 10.d, shown at 100x magnification. The measured flank wear was around 20 µm, however, in the drill used for dry tests showed a relatively larger worn area along the cutting edges compared to that observed in the drill used in cryogenic tests. This indicates that using through tool cryogenic cooling can increase tool life, increase productivity, and reduce costs associated with replacing worn tools and interruption of drilling production. Through tool cryogenic cooling was claimed to be more efficient than LN$_2$ sprays in terms of a stronger and much more stable cooling effect on the cutting tools [74]. In addition, longer tool life can be achieved because of the maintenance of the hardness and strength of the tool material, and the reduction of chemical reactivity of the workpiece since there is no contact between the cryogen and workpiece and so there are no changes in properties of the workpiece [74]. The reduced tool wear under cryogenic conditions is possibly due to a consequence of enhanced fibre cutting and a reduction in tool temperature [13]. However, it should be noted that for foreseeing higher tool life for the cryogenic cooling system than for dry cutting, longer duration tool-life tests are necessary to confirm the tendency which could be carried out in a future study. Although tool wear observed on the cutting tools was minimal, it remains significant from hole size chart perspective where range of variation was found to be ~ 0.02 mm. This means that tool wear might have some influence on the hole size variation under dry and cryogenic conditions. However, as stated earlier, longer duration tool-life tests are necessary to confirm the effect of tool wear on hole size with number of drilled holes.
Figure 10: Optical microscopy of drills a) Pre-test drill edge showing part of the drill, b) Pre-test drill full front view, c) Post-test drill cutting edge in cryogenic tests, d) Post-test drill cutting edge in dry tests

Figure 11 shows the condition of the holes under dry and cryogenic tests. Charted feeds marks were observed on the exit sides for both tests regardless of the cutting parameters. In addition, several burr caps were formed in both tests which formed from the drilling through the aluminium sheets. The region at which burr caps separate from the edge of the hole showed significant burr formation compared to other regions around the hole edge [86]. The uncut portion of the aluminium sheets around the hole edge undergoes rapid stretching and thinning followed by fracture and formation of small burrs around the hole edge [4, 86, 87]. Burrs were formed in all holes, indicating that it is not caused by tool wear. For dry tests, some burr caps detach from the workpiece, while some burr caps tended to clog inside the hole or partially remain attached inside the hole or at the exit as shown in Figure 11.a. This formation of burr caps was also observed in previous studies on drilling GLARE® [8, 48]. The presence of burr caps in the holes means that each hole needs to be inspected individually and burr caps to be removed manually which adds extra costs and increased time for inspection. For holes drilled under cryogenic conditions, all the burr caps tended to completely separate from the hole as shown in Figure 11.b. This is mainly attributed to the pressure of the cryogenic coolant which reduces the elongation and therefore ductility of the chips causing the chips and burr caps to break in a brittle manner. Moreover, the pressure of the cryogenic coolant blows away the burr caps that are partially attached to the
edge of the hole. Therefore, it can be said that using through tool cryogenic coolant produces clean-cut holes which do not require any further cleaning or post machining leading to cuts in costs and reduce inspection time.

Figure 11: Exit side of holes a) dry tests b) cryogenic tests

Table 6, Table 7 and Table 8 show the state of the hole exit under SEM for dry and cryogenic cooling tests. Although burr formation was not measured, SEM images showed that the size of the burr at the hole exit was always greater than that at the entry similar to previous studies [11, 86]. Entry burrs are formed due to the tearing process characterized by bending and shearing or lateral extrusion [4, 88]. Exit burr, on the other hand, occurs due to plastic deformation of the aluminium sheets in front of the chisel edge without cutting them [4, 89]. SEM images and visual inspection also showed that the burr size was greater in holes drilled under dry conditions. The damage around the hole edge was most noticeable when drilling at high spindle speeds and feed rates for dry and cryogenic tests. The previous study on using external cryogenic cooling showed that it tended to cause a significant increase in burr size compared to burrs formed under dry tests which were attributed to excessive cooling [49]. This means that through tool cryogenic cooling provides an excellent alternative to dry and external cryogenic cooling in terms of reducing burr formation. Generally, the burr size at the hole entry was small, which means that the hole can be considered burr-free at the entrance and therefore does not require deburring [49].
<table>
<thead>
<tr>
<th>Feed rate (mm/min)</th>
<th>Dry</th>
<th>Cryogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>226.8</td>
<td>Entry</td>
<td>Exit</td>
</tr>
<tr>
<td>2268</td>
<td>Entry</td>
<td>Exit</td>
</tr>
<tr>
<td>4535</td>
<td>Entry</td>
<td>Exit</td>
</tr>
<tr>
<td>6803</td>
<td>Entry</td>
<td>Exit</td>
</tr>
</tbody>
</table>

Table 6: SEM images of hole edge at entry and exit side for dry and cryogenic drilling tests.
Table 7: SEM images of hole edge at entry and exit side for dry and cryogenic drilling tests

<table>
<thead>
<tr>
<th>Feed rate (mm/min)</th>
<th>Spindle speed (rpm)</th>
<th>Entry</th>
<th>Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>453.5</td>
<td>2268</td>
<td><img src="image1" alt="SEM image 1" /></td>
<td><img src="image2" alt="SEM image 2" /></td>
</tr>
<tr>
<td></td>
<td>4535</td>
<td><img src="image3" alt="SEM image 3" /></td>
<td><img src="image4" alt="SEM image 4" /></td>
</tr>
<tr>
<td></td>
<td>6803</td>
<td><img src="image5" alt="SEM image 5" /></td>
<td><img src="image6" alt="SEM image 6" /></td>
</tr>
</tbody>
</table>
Table 8: SEM images of hole edge at entry and exit side for dry and cryogenic drilling tests

<table>
<thead>
<tr>
<th>Spindle speed (rpm)</th>
<th>Feed rate (mm/min)</th>
<th>Dry</th>
<th>Cryogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2268</td>
<td>680.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4535</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6803</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SEM images show that the damage forms on the hole bore that was found in the current study were similar to those reported on previous studies on drilling GLARE® laminates under different cooling and machining conditions [4, 90]. Damage forms such as fibre pull-out, broken fibres, bent and uncut fibres as shown in Figure 12. Moreover, feed marks were seen to happen on all the aluminium sheets and were more visible when drilling at higher feed rates which could be attributed to excessive feed force as it was also found in previous studies [4, 90]. At higher feed rates, the machined surfaces of aluminium sheets show signs of the intense flow of material in the plane of the surface which tends to produce poorer surface finish than that obtained at lower feed rates [4,
Powdery glass fibre dust is seen to be scattered all over the borehole surface especially for holes drilled under dry condition. Some the broken glass fibres and dust cannot escape the hole and remain intact on the surfaces of machined glass fibre layers. Some of the machined glass fibre layers appear to be eroded which could be caused by the evacuated metallic chips spiralling up the flutes. No delamination (separation within the glass fibre plies or at the interface of the aluminium sheets and glass fibre layers) was seen to occur. This could be attributed to the stacking nature of GLARE® where a glass fibre layer is always stacked between two aluminium sheets and thus providing a form of support to peel up and push out delamination similar to what is observed when drilling composite metal stacks [91]. The back-up provided by the aluminium sheets limits the bending of the uncut glass fibre layer above it and prevent the propagation of any existing cracks or delamination when machining composite metal stacks [90]. The thicker the aluminium plate is, the less likely the applied load induces local bending in aluminium plate and therefore, preventing delamination in the composite part of the hole. In addition, some fibres were uncut due to bending and were left protruding outwards as shown in Figure 12.

An improvement in hole quality observed in the current study in both cryogenic and dry drilling tests compared to that reported from previous studies on dry drilling of GLARE® is the absence of micro-sized gaps [4, 90]. These micro gaps exist at the interface between the metallic and composite layers which can sometimes be filled with waste material or allow the formation of interlayer burrs. This could be due to tool design and coating which improved chip breakability in this study. However, for holes drilled under dry condition, there was relatively more accumulation of powdery chips on the borehole walls and presence of different forms of damage than that found in holes drilled under cryogenic conditions as it can be seen from Figure 12. This could be related to the ability of LN₂ to more effective removal of heat from the cutting zone thus preventing the deformation and adhesion of metallic chips or glass fibre powder to the borehole surface [90].
2268 rpm, 680.3 mm/min

Dry

Cryogenic

Al 2024 sheet
S2-FM94 prepreg
Al 2024-T3 sheet
S2-FM94 prepreg
Al 2024 sheet
S2-FM94 prepreg
Al 2024 sheet
S2-FM94 prepreg

Smooth cutting
Figure 12: SEM images of hole drilled under dry and cryogenic conditions, $n = 2268$ rpm and $f = 680.3$ mm/min (1: Uncut fibres and fibre protrusions, 2: Pitting due to fibre pull-out, 3: Fibre bending 4: Matrix crack, 5: Debonding, 6: Al 2024 and powdery S2-FM94 chips, 7: Broken fibre, 8: Fibre pull-out, 9: Resin debris).

4. Conclusions

The current paper investigates the applicability of through tool cryogenic cooling using liquid nitrogen on the hole quality when drilling GLARE® fibre metal laminates. The investigation compares several hole quality parameters including (microhardness, surface roughness metrics: $R_a$ and $R_z$, hole size and hole circularity) from two sets of drilling experiments. The first set of experiments is drilled without the aid of any coolants (dry conditions), while the other set was drilled by continuously supplying liquid nitrogen (LN$_2$) cooling through the cutting tool. The aim was to provide an equal comparison to highlight the effects of using liquid nitrogen as an environmentally friendly coolant and its impact on the machining of fibre metal laminates. The study also employed ANOVA statistical technique to highlight the contribution of the cutting parameters (spindle speed, feed rate) and the presence or absence of cryogenic coolant on the analysed hole quality parameters. The followings can be concluded:

- Holes machined using LN$_2$ through tool cooling had higher microhardness of the upper and lower aluminium sheets around the holes compared to that from dry drilling. The reason for higher hardness values may be attributed to increasing in Young modulus and tensile strength due to the increase in elastic stiffness at low temperatures. The microhardness of the holes was below the nominal hardness of Al2024-T3 (137 HV) in both dry and cryogenic drilling tests.

- LN$_2$ through tool cooling approach provide lower surface roughness metrics $R_a$ and $R_z$ relatively by changing the material structure from ductile to brittle and preventing thermally induced damages on the borehole surface. This indicates that cryogenic coolants help reducing surface roughness, especially when drilling at higher cutting parameters.

- The hole size was always greater than the nominal diameter of the drill regardless of whether cryogenic coolant was used or not. But, in cryogenic machining, the deviation from the nominal diameter is less than those observed under dry conditions in addition to this the average hole circularity on the top and the bottom were better than that observed in dry tests. These phenomena may be attributed to the thermal distortions in dry machining due to cutting temperatures.

- From the ANOVA results, it was found that the hole size at the top was mainly influenced by the presence-absence of coolant with 56.38 % contribution while for hole size at the bottom did not have any impact. This is related to the continuous rubbing of the drill in the bottom region, and evacuated hot chips.
increase the temperature at the cutting zone leading to thermal shrinkage. This circumstance does not occur at the top part of the hole.

- Optical microscopy of tool condition post drilling tests showed that the flank wear of the tool used for cryogenic tests was smaller than that observed in the tool used for dry drilling tests. The formation of less flank wear in cryogenic machining could be associated with a lower temperature increase in the cutting zone.
- SEM analysis showed that the burr size was relatively smaller in holes drilled under cryogenic conditions and several forms of damage that are common in metal and composite were present in holes drilled under both conditions.
- Beyond the effects of cryogenic cooling on drilling GLARE® laminates, the use of liquid nitrogen as a coolant is environmentally friendly and reduces the need for post-machining clean-up or coolant disposal.

Acknowledgements

The authors would like to thank Dr Peter J. Kortbeek from DELFT University and the Fibre-Metal Laminate Centre of Competence (FMLC) for the provision of GLARE® sample. The authors acknowledge the support of experimental work by 5ME cryogenics and Fullerton Tools for providing the cutting tools for the drilling experiments.

Data availability

The raw experimental data reported in this work will be available upon request.

5. References

4. Giasin, K., Machining Fibre Metal Laminates and Al2024-T3 aluminium alloy. 2017, University of Sheffield.


50. AGY, High Strength Glass Fibers. 2006.
73. Hong, S.Y. and Z. Zhao, *Thermal aspects, material considerations and cooling strategies in cryogenic machining*. Clean Products Processes


