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Multi-scale analysis of the damage and contamination in abrasive water jet drilling of GLARE fibre metal laminates

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ABSTRACT

The goal of this study is to investigate the influence of Abrasive Water Jet (AWJ) parameters (standoff distance, water pressure and abrasive flow rate) on the machining quality (diameter, circularity, abrasive contamination, surface roughness and types of damage) during drilling of thick hybrid material viz. GLARE (Glass Laminate Aluminium Reinforced Epoxy) Fibre Metal Laminates (FML). The novelty of this work is the use of X-ray tomography and image post-processing for the quantification of abrasive contamination in function of the machining parameters. Moreover, the indicator called 'power of erosion' (E), depending on the AWJ drilling parameters chosen, has permitted to estimate a threshold below which no delamination is found. The results have shown that oversized holes (up to 6.2 mm in diameter) were produced under all cutting parameters regardless of their level. Increasing the standoff distance increased the hole size and cylindricity. The main types of damage consecutive AWJ drilling are in form of barrelling at plies level and delamination with embedded particles. For 'power of erosion' (E) values below 0.17, no delamination is found. As increasing this indicator further, delamination occurs in-between plies closer to the jet entry and more contamination is observed (up to 4 % of the total scanned surface). The surface roughness was found to be in a similar range to that reported in conventional drilling studies of GLARE (<6 μm), which suggests that AWJC could provide a similar machining performance suitable for aerospace applications.

1. Introduction

Fibre Metal Laminates (FML) are novel materials that are made by bonding thin metallic sheets and layers of composites in an alternating sequence to form a stack. FMLs were mainly developed for aerospace applications to improve fatigue and impact resistance [1,2]. GLARE is the most notable FML material which is currently used in sections of the Airbus A380 fuselage [2,3]. GLARE panels undergo edge milling and drilling operations for assembly with other structural parts in the aircraft [4]. When machining GLARE, tool wear is influenced by the abrasive glass fibres. In addition, delamination in the glass fibre layers especially lower section of the workpiece where the resistance to thrust force loading is minimal can be critical. Moreover, heat-affected zones (HAZ) occur due to the continuous rubbing between the tool and the laminate [3]. Thousands of holes are drilled in GLARE laminates which are traditionally performed using conventional twist drilling process. There has been a rapid increase on the reported studies on machining FMLs and GLARE laminates which mainly focused on hole making process. Most studies investigated the influence of the machining process and parameters on the hole quality (roughness, dimensional tolerances and delamination). Giasin et al. carried out a handful of studies on drilling in thick and thin GLARE laminates which studied the impact of cutting parameters, tool coatings [5,6], tool geometry [7], machining coolants such as cryogenic and MQL (minimum quantity lubrication) [8–10], fibre orientation and laminate thickness [11] on the hole quality and cutting forces.

Alternative non-conventional such as abrasive water jet and laser machining processes can be also used to cut FMLs such as GLARE. Non-conventional machining is employed when traditional machining methods using a cutting tool cannot be used: very hard (such as titanium and steel) and brittle (glass fibre) materials, structures too fragile or slender to clamp and resist the machining forces (such as thin metal sheets and composite layers), complex shapes such as sharp-cornered square holes [12]. Abrasive Water Jet Cutting (AWJC) uses

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pressurized water flow of up to 400 MPa in the form of a jet mixed with fine (10–150 μm) abrasive particles (70 % water/30 % abrasive particles) such as silicon carbide and glass beads. The abrasive particles remove the material by eroding the surface, micromachining, shear failure and brittle fracture of the workpiece material reaching cutting speeds of up to 900 m/s [13]. AWJC is suitable for cutting most types of materials which are sensitive to heat (concrete, ceramics, tough composites, glass, …) as well as materials that can produce hazardous fire, fumes and dust particles when cut using conventional machining processes [14–16]. The machinability of FMLs using AWJC was previously investigated in the open literature [3,17–21]. The results showed that the process is only suitable for rough edging operations and caused severe edge tapering and delamination in FMLs with thin metal sheets of 0.2 mm thick. The delamination in the laminate was strongly affected by the water pressure and was initiated by the shock wave impact of the water jet [17]. Ramulu et al. [18] found that the traverse speed can impact the material removal rate, overcut and taper damage. Similarly, there have been numerous studies reported on the use of AWJC for drilling holes in metal, composite, composite-metal stacks and to a less extent on FMLs [19,21–23]. Manoharan et al. [22] reported that hole drilling of FMLs using AWJM is possible using proper cutting parameters. However, the quality of the holes cannot be matched to those produced machined using conventional twist drilling process. Their results showed that fibre fraying was reduced when increasing the traverse speed, however, it increased the dimensional deviation and kerf taper. In addition, wavy surfaces are impossible to eliminate in the machined holes due to the action of jet energy which caused the projectile trajectory of the abrasives to deviate. The authors recommended using a 30 mm/min traverse speed for producing near-perfect hole quality [20]. Increasing the water jet pressure, flow rate and stand-off distance tended to increase the surface roughness [19,21]. Therefore, the current work presents a comprehensive preliminary study which aims to fill the gap in the literature and investigate the drilling of thick GLARE laminates (>7 mm) using AWJ.

The aim is to study the impact of cutting parameters (water pressure, abrasive flow rate and standoff distance) on the hole geometry (diameter and circularity through the plate's depth, cylindricity), surface finish delamination and contamination by abrasive particles consecutive to AWJ drilling of thick GLARE FML. Several levels of each of the AWJC parameters were used to determine their effect on the resulting damage magnitudes and failure mechanisms in the laminate. Finally, scanning electron microscopy and computerised tomography were employed to analyse the borehole condition and to further evaluate the damage mechanisms formed under different cutting regimes. X-Ray tomography also permitted to quantify the abrasive contamination in-between the plies. Moreover, the indicator called 'power of erosion' (E), depending on the AWJ drilling parameters chosen, has permitted to estimate a threshold below which no delamination is found. To the authors' knowledge, this approach to investigate the effect of the machining parameters and the contamination ratio of the GLARE material has not been proposed before.

2. Materials and method

2.1. Material

A plate made of GLARE 2B 11/10-0.4 has been selected for this investigation. This FML is composed of thin sheets (0.4064) of aluminium alloy Al2024-T3 and GFRP layers as shown in Fig. 1.a. The rolling direction of the aluminium sheets is considered as 0° as shown in Fig. 1.b. Each GFRP layer is constituted of two unidirectional prepregs of S2 glass fibres and FM94 adhesive, oriented at [90°/90°] for a thickness of 0.266 mm as shown in Fig. 1.b. The workpiece has a total thickness of 7.13 mm, for an area of 70 × 150 mm^2 and a metal volume fraction of 62.7 %.

2.2. Abrasive water jet machine and drilling parameters

The 6 mm in diameter normal drilling operations were performed with AWJ machine 'Flow Mach 4c' (Flow International Corporation), equipped with Paser 4 nozzle and Hyplex pump. 120 mesh garnet sand provided by Wuxi Ding Long Minerals Co. Ltd. (China) was chosen as the abrasive medium included in the water jet. As the aim of this study is to analyse the influence of the AWJ drilling parameters on the geometrical and surface characteristics of the holes, three levels of water pressure (P), two different standoff distances (SoD) and three abrasive flow rates (AFR) have been selected (cf. Table 1). The drilling conditions have been selected based on a literature review [17,19,21] and preliminary tests. Indeed, the main parameters influencing the machining quality in AWJ process are the water pressure, the abrasive mass flow rate and the

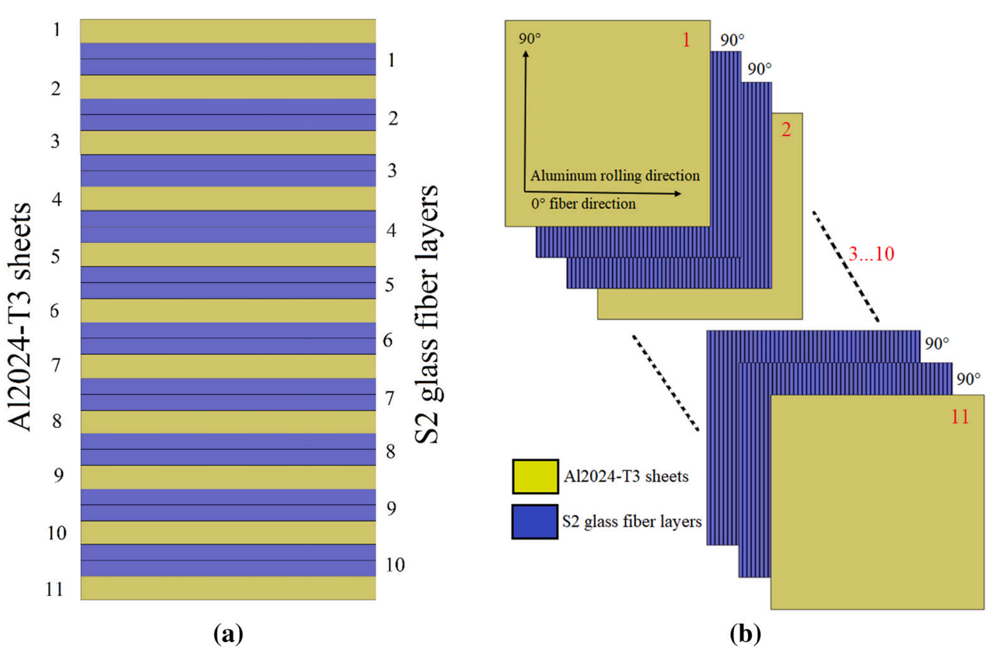

Fig. 1. GLARE workpiece details (a) side view (b) constituents order.

Table 1
Abrasive water jet variable parameters.

Levels	1	2	3
Pressure (MPa)	124	218	304
Standoff distance (mm)	2.5	5	–
Flow rate (g/min)	180	360	540

standoff distance. Moreover, the sets of parameters were selected during the preliminary study to assure through cutting while having a limited yet existing delamination. The hole size was chosen in this study is common for creating fasteners holes in aerospace structures. Moreover, the common hole size drilled in Airbus A380 structures range between 4.8 and 6.4 mm [11,24,25].

The other machining parameters were set (cf. Table 2). The traverse speed value has been chosen according to the literature review. Indeed, from the work of Manoharan et al. [22] investigating hole drilling in FMLs using AWJM, a traverse speed of 30 mm/min is recommended for producing near-perfect hole quality (low delamination forces induced). However, as the thickness of the FML is greater in the present study, it was decided to reduce this value to 20 mm/min.

The GLARE plate was mounted on a wooden plank fixed to the machining table to avoid movement induced by the water swirl formed during the drilling process. In addition, the cutting path strategy is chosen so the jet entrance and exit both occur at the centre of the holes, with circular approaches from its centre to its border (cf. Fig. 2). For each of the 18 sets of parameters, three holes have been cut in order to study the repeatability of the process.

2.3. Characterisation methods

2.3.1. Hole geometry

Geometric parameters of the holes, viz. diameters and circularities, mean diameters and cylindricities, have been obtained using Global Performance 5.7.5 Coordinate Measuring Machine (CMM) from Hexagon DEA. The CMM is equipped with a touch probe stylus (20 mm long) with a ruby ball tip having 2 mm in diameter. For each hole, five circles distributed along the hole's axis (0.8 mm, 2.4 mm, 4.0 mm, 5.6 mm and 7.0 mm below the jet entry surface respectively) have been probed "continuously" (400 points) to extract the mean diameter and circularity.

2.3.2. Surface quality and defects

Surface quality inside each hole, parallel to the axis, has been quantified using *Surftest* surface roughness tester from Mitutoyo. The stylus, with a tip radius of 2 µm, moved along the internal surface of the holes a distance of 4 mm from around 400 µm from the jet entrance side of each hole to the jet exit side. This distance corresponds to 56 % of the hole depth. Mean arithmetic roughness (R_a) has been extracted from the profiles thanks to the software provided by Mitutoyo, with a 2.5 mm cut-off length Gaussian filter. For each hole, four measurements were made at jet entry/exit (referred to as 0°) and at respectively 90°, 180° and 270° from this position as shown in Fig. 2.

After the drilling and the geometrical and surface characterisation operations, the plate is cut by AWJC process to obtain small pieces of FML (12 × 12 mm^2) centred around each hole. A small GLARE specimen

Table 2
Abrasive water jet set parameters.

Parameter	Value
Focusing tube diameter	1.016 mm
Focusing tube length	76 mm
Orifice diameter	0.3302 mm
Type of abrasive	Garnet sand
Abrasive size	#120
Traverse speed	20 mm/min

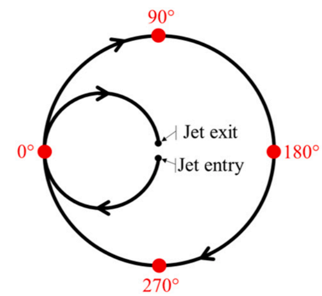

Fig. 2. Cutting path strategy used in this study. The four orientations correspond to the roughness measurements.

of each set of drilling parameters is placed into a Nikon XT H 225 X-ray machine CT scan machine at 10 cm from the X-ray source under a voltage of 225 kV and a current of 2000 mA. With this selection of parameters, the average voxel size is 18 µm. The scanned samples were then processed to generate the 3D volume of the specimens using Volume Graphics VG Studios Max version 2.0 and myVGL 3.5.2 software. In addition, a second specimen of each set of machining parameters was examined using Scanning Electron Microscopy (SEM) with a secondary electron sensor to identify the defects induced by AWJ drilling (nature, size).

3. Results and discussion

3.1. Holes geometrical analysis

Fig. 3 sums up the main effects of the studied drilling parameters on the cylindricity and mean diameter of the holes. The cylindrical shape of the holes mainly depends on the standoff distance. By using a higher standoff distance, both the mean diameter and the cylindricity of the holes increase. This is because the jet expands as the mix of water and abrasive particles exit the nozzle. It can be noticed that as the standoff distance is small (i.e., 2.5 mm), the mean hole diameter is very close to 6 mm, which is the target value. This observation confirms the recommendations of Hashish's work [26], which advises a standoff distance between 2 and 5 mm when machining with AWJC technique to avoid the loss of jet focus. For the two other cutting parameters, viz. the water pressure and the abrasive flow rate, their influence is not significant on both the mean diameter and the cylindricity of the holes given the mean standard deviations of the measurements (0.012 mm and 0.014 mm respectively).

All the holes were oversized, the hole size at the entry was greater than that measured at the hole exit due to reduction in cutting energy with depth. The difference in hole size at entry and exit decreased with the increase of the water jet pressure. On average, the hole oversize ranged between 81 and 170 µm at the entry and between 1 and 206 µm at the exit. This also indicates that the hole size at the exit can vary significantly under different cutting parameters. In aerospace structures, holes size should be slightly undersized and close to their nominal diameter to ensure adequate rivet-joint performance [24]. A significantly over/undersized hole requires further machining to bring the holes to the right tolerances. Looking into the literature on conventional drilling of GLARE laminates, it is evident that the hole size is influenced by drilling parameters and presence/absence of coolant. In a conventional study on drilling 6 mm holes in GLARE 2B 11/4-0.4 laminates, Giasin et al. [9] reported that holes are likely to be oversized when using coolants, the oversize is higher when using cryogenic coolants such as liquid nitrogen compared to minimum quantity lubrication. Meanwhile, holes tended to be undersized especially near the hole exit under conventional dry drilling conditions since temperature effects are more significant. Similar results were reported by Hoekstra et al. [27] when drilling flax/epoxy laminates using conventional and abrasive water jet

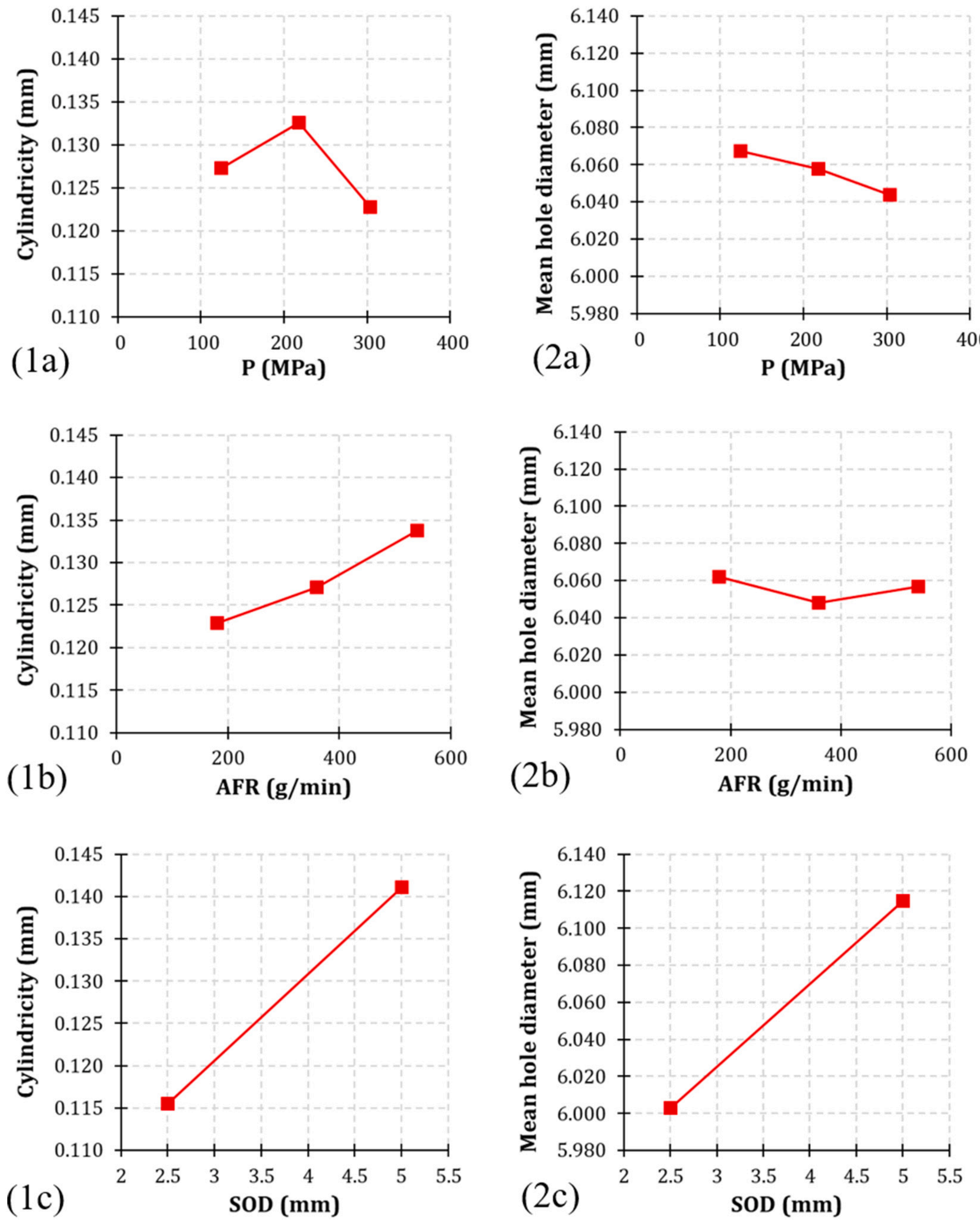

Fig. 3. Influence of the studied machining parameters – pressure (a), abrasive flow rate (b) and standoff distance (c) – on the cylindricity (1) and mean diameter (2) of the holes.

drilling methods. The aerospace industry recommendation is to produce holes with 0 to +30 μm of their nominal diameter to comply with a H9 tolerance [24,28]. Cutting tool manufacturers recommend hole size tolerances in aeronautical materials to be between ±20 μm but can be relaxed to ±40 μm due to difficulties in achieving tight tolerances with conventional cutting tools [24,29]. The range in hole size reported in this study is outside the recommended range for aerospace structures. To overcome this problem when machining GLARE using AWJC, it is recommended to drill holes using a smaller diameter to account for the oversize issue. This would require an optimisation process to achieve an optimum/desirable hole size with minimal hole size deviation throughout the hole depth such that tolerance limit can be maintained. It was also observed that the hole size in GFRP layers was always greater than that for Al2024-T3 sheets [30]. This is a characteristic of AWJC of FMLs which caused by the build-up of high pressure due to slow penetration of the abrasive water jet in the metal layers.

To further analyse the effect of each drilling parameter on the hole geometry, five circles have been probed by CMM throughout the depth of each hole (cf. Fig. 3). As seen in Fig. 4, the effect of each parameter on the measured diameter of the circles is similar to the one observed on the mean diameter of the holes. Moreover, these additional measurements permit to distinguish of different shapes of the holes, depending on the machining parameters used. Indeed, as shown from Fig. 4-2a, increasing the jet pressure altered the general shape of the hole from classical V-shape ($P = 124$ MPa) to barrel shape ($P = 304$ MPa). This variation of the hole shape can be explained by the fact that as the jet goes deeper within the material, its energy decreases and it is guided by the wall of the hole. Therefore, the reduction of the jet energy led to the diminution of the erosion at the bottom of the plate. In fact, this can explain why the size of the hole is reduced from the entry to the exit. However, the increase in

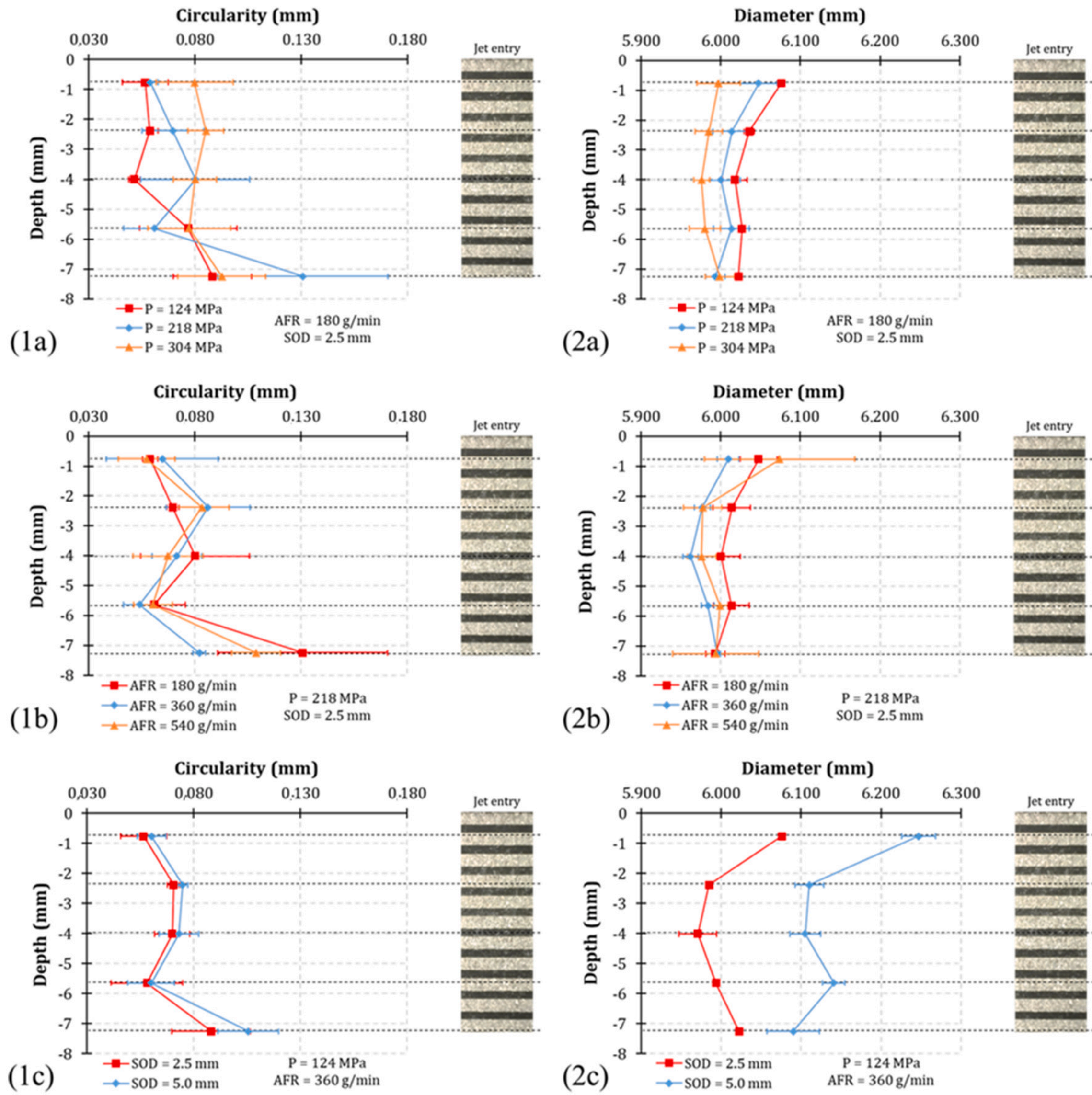

Fig. 4. Influence of the studied machining parameters – water pressure (a), abrasive flow rate (b) and standoff distance (c) – on the circularity (1) and diameter (2) of different circles probed along the holes.

pressure leads to an increase in available energy for the erosion and air volume flow rate [31]. Likewise, the same evolution in shape is observed when increasing the abrasive mass flow rate (cf. Fig. 4-2b). The abrasive-mass flow rate can influence the abrasive particles acceleration process. Increasing the number of particles causes the granulometry of the abrasive grits to become wider (fragmentation of the grits due to the more numerous collisions in the mixing chamber), which induces a less consistent erosion through the depth of the plate. In addition, increasing the abrasive mass flow rate can decrease (almost linearly) the velocity of the abrasive-particle [32].

Finally, increasing the standoff distance increases the mean diameter of the holes as already explained in the previous section. However, it also changes the general shape of the hole, reducing the barrel shape, but reducing the reproducibility of the drilling operation, as shown from the greater standard deviations (cf. Fig. 4-2c). This last observation can be explained by the aspect of the walls of the hole. Indeed, as seen from Fig. 5, the wall of the hole drilled with a standoff distance of 5 mm is way more undulated than the one drilled at SoD = 2.5 mm. These undulations are periodic and correspond to the changes in material within the GLARE plate, from aluminium to GFRP or vice versa. The analysis of the circularities shows that there is no significant effect of the drilling parameters on this feature. However, it can be noticed that the circularity is almost constant within the depth of the hole except when reaching its exit. Indeed, as the mean circularity is around 80 μm for the four first circles, it increases to almost 130 μm for the bottom-most circle. These changes in shape along the depth and perimeter of the hole might influence its surface quality.

At a constituent level, the CT scans revealed that a V-shaped taper was observed in the uppermost aluminium sheet. This type of taper is characterized by slightly more material removal at the top of the cut where the jet stream first cuts through the workpiece. This type of taper is common when cutting thicker materials and can also occur in multilateral stacks in which the outer layer is harder than the following layer which is the case in the GLARE laminate. The CT scans of the holes also revealed two unique taper patterns: convex barrelling taper in the aluminium sheets and concave barrelling taper (pocketing) in the GFRP layers. This is attributed to the mechanical properties of GLARE constituents and the associated micro-cutting mechanisms. The modulus of elasticity of Al2024-T3 is 72.2 GPa which is about 30 % greater than that of the S2/FM 94 epoxy is 54–55 GPa [33–36], and therefore can exhibit higher ductility. Moreover, the UTS (ultimate strain) of Al2024-T3 is 19 %, whereas the UTS of the glass/FM 94 epoxy prepreg is 3.5 %–4.7 % in

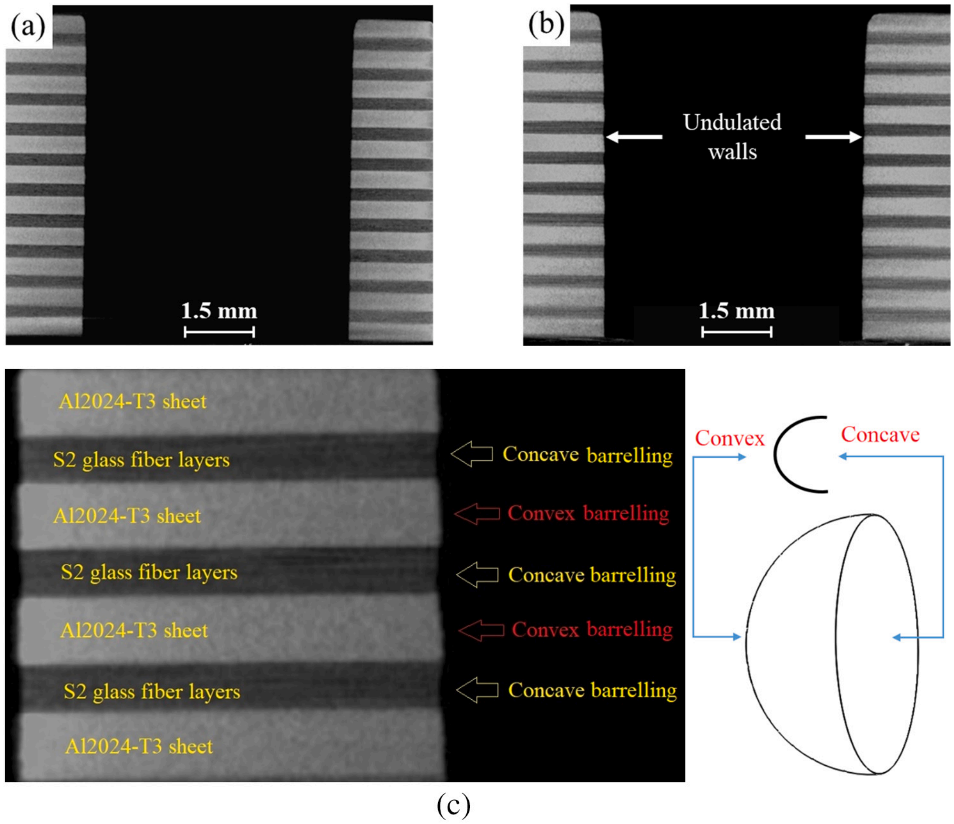

Fig. 5. CT scans of holes drilled by AWJ with P = 124 MPa, AFR = 360 g/min, (a) SoD = 2.5 mm and (b) SoD = 5.0 mm (c) Convex and concave barrelling phenomenon in aluminium sheets and glass fibre layers.

fibre direction and 0.6 in the normal direction to the fibres [10]. The variation in the mechanical properties of the laminate constituents causes the jet stream to remove more material from the "weaker" GFRP layers than that from the aluminium sheets and therefore, the formation of pockets in GFRP layers. It was also observed that pockets formed in GFRP layers diminish in the lower GFRP layers of the laminate due to the loss of kinetic energy. The literature regarding solid-particle erosion is extensive. The cutting mechanisms by solid particle erosion include 1) cutting by penetration of the cutting edge and plastic deformation to failure, 2) fatigue (cyclic failure), 3) non cyclic brittle fracture and 4) loss of fluid state, all of which occur simultaneously in AWJC [31]. In the context of these four mechanisms, the material removal (erosion) of ductile-behaving materials such as Al2024-T3 is a function of the material flow stress and hardness according to several micro-cutting models [31]. The cutting mechanism in ductile materials includes plastic deformation and ductile shearing [31,37]. For GFRP layers, the micro-cutting mechanism is governed by the brittle properties of the fibres [31].

3.2. Surface quality

3.2.1. Hole surface finish analysis

Fig. 6 shows the influence of the three process parameters studied in this work (viz. the water pressure, the abrasive flow rate, and the standoff distance) on the surface quality of the holes, defined by the surface roughness R_a (mean arithmetic). As explained in Section 2.2, four measurements have been made around the holes, 0° direction corresponding to the entry and exit of the jet (cf. Fig. 2). As this region is subjected to the effect of the abrasive water jet twice, smaller values of R_a have been registered. The recorded values are of the same order of level as those recorded when drilling is conducted with the conventional process [38]. This order of level of roughness can be explained by the fact that during the second pass of the jet, the abrasive particles glide along the hole's wall, smoothening the surface. In addition, as each particle within the jet acts as a single cutting edge, the removed depth is thin. It is important to notice that, for a given water pressure (cf. Fig. 6a) or abrasive flow rate (cf. Fig. 6b), the values of Ra are similar whatever the measuring direction. Moreover, the high standard deviations of R_a calculated thanks to the profiles obtained by varying the water pressure or the abrasive does not permit to conclude on the influence of this process parameter on the surface quality of the holes. When the average R_a of the hole is considered in Fig. 6a, it can be seen that when water pressure increases, the surface roughness becomes higher. The collision of abrasive particles against the hole walls becomes more aggressive in the violent environment of the highly pressurized jet due to the increased effects caused by the water ingress and wedging, in addition to embedment of abrasive particles in the inter-laminar spaces of the GLARE laminate [39]. There is a vast literature which reports on the effects of AWJC parameters when drilling composite and metallic materials. A study on AWJC of aluminium alloys reported that increasing the water pressure can affect surface roughness either ways depending on the used traverse speed [40]. Same was reported when using AWJC for cutting polymer matrix composites [41]. Another study on AWJC of aluminium alloys found that increasing the water jet pressure up to 400 MPa decreases the surface finish [42]. While another study reported that the surface finish was improved when increasing the water pressure. Another study on AWJC of aluminium alloys found that increasing the water jet pressure up to 400 MPa decreases the surface finish due to reduced jet flaration which reduces the waviness pattern on the surface [43]. Other authors claim that increasing water jet pressure could initially improve surface finish but increasing it further have a negative impact caused by the higher and irregular cutting energy in the jet zone [44,45].

No noticeable influence of the jet pressure on the wall's profile of the

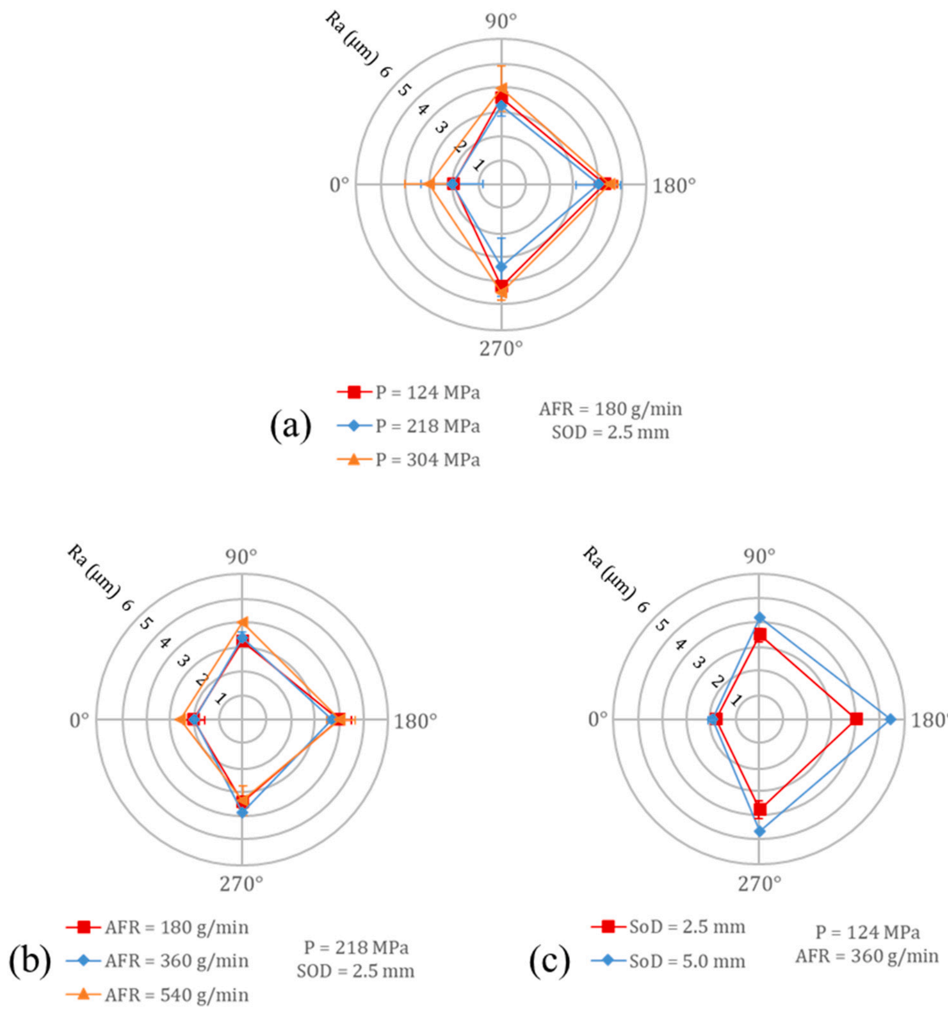

Fig. 6. Influence of the studied machining parameters – pressure (a), abrasive flow rate (b) and standoff distance (c) – on the mean arithmetic surface roughness (Ra) of the holes in four directions. 0° corresponds to both the jet entry and exit.

holes (cf. Fig. 7a). However, an interesting feature can be found when a pressure of 304 MPa was used. Indeed, an important delamination appeared between the glass plies and the aluminium layer, close to the exit side of the hole. As seen from Fig. 7b, more rugged walls are observed as going deeper within the GLARE plate, especially for high AFR values. This can be linked to the available energy provided by the jet pressure to the abrasive particles. Indeed, a given jet pressure corresponds to the amount of energy available within the jet. This energy is distributed to the abrasive particles, which have a greater part as they are fewer. This, combined with the decrease in energy as the particles penetrate deeper within the workpiece or are bouncing along the wall of the holes, can explain the poorer quality of the holes when machining with a high AFR value. In addition, the higher number of collisions and cuts made by abrasive particles per unit of time due to the rise of AFR increases their chances of hitting non-desirable regions around the hole walls. Moreover, the change from one material to the other is highlighted by high peaks and valleys. As for pressure, the standoff distance seems to have no clear effect on the roughness profile of the walls of the holes (cf. Fig. 7c). Indeed, within the range of tested standoff distances, the jet is focused hence the fluctuations within it are similar. This is coherent with the work of Hashish 36 which recommends keeping the SoD between 2 and 5 mm.

There are limited studies in the open literature on hole surface roughness in FMLs machined using AWJC process. In summary, the analysis of hole roughness metrics R_a under different cutting parameters ranged between 3 and 6 µm. Previous study by Giasin et al. [10] reported that hole surface roughness in GLARE 2B 11/10-0.4 laminates under conventional drilling ranged between 1 and 3 µm under dry conditions, around 1.4–2 µm under cryogenic conditions and around 1.1–2.3 µm under minimum quantity lubrication. This clearly indicates that hole surface roughness is higher using AWJC process compared to conventional drilling and are similar to those reported when AWJC of aluminium alloys and lower than those reported in AWJC of composites [43,46,47]. In conventional drilling, the cutting tool is rigid and has precise geometry, the material is removed as the chisel edge advances into the workpiece and material is removed by the cutting edges such that the machined surface is formed by a combined action of cutting and rubbing. Some cutting tool manufacturer [48] indicates that R_a in holes machined using conventional drilling of aerospace composite metal stacks should be lower than 3.2 µm in composites and lower than 1.6 µm in metals [24]. The overall R_a results reported in this study for the holes machined in the laminate are within the range of surface roughness values which were reported in previous studies on conventional drilling of GLARE® laminates [11,24]. However, in recent works on the relationship between surface quality consecutive to AWJ machining and mechanical behaviour, it was clearly mentioned that the Ra criterion might not be a suitable indicator to describe the machining quality and the mechanical performances of the composite structures. In fact, a new parameter called 'crater volume' has been proposed and better correlate to the mechanical performances of monolithic and bonded structures (compressive strength, tensile strength, endurance limit) [49–52].

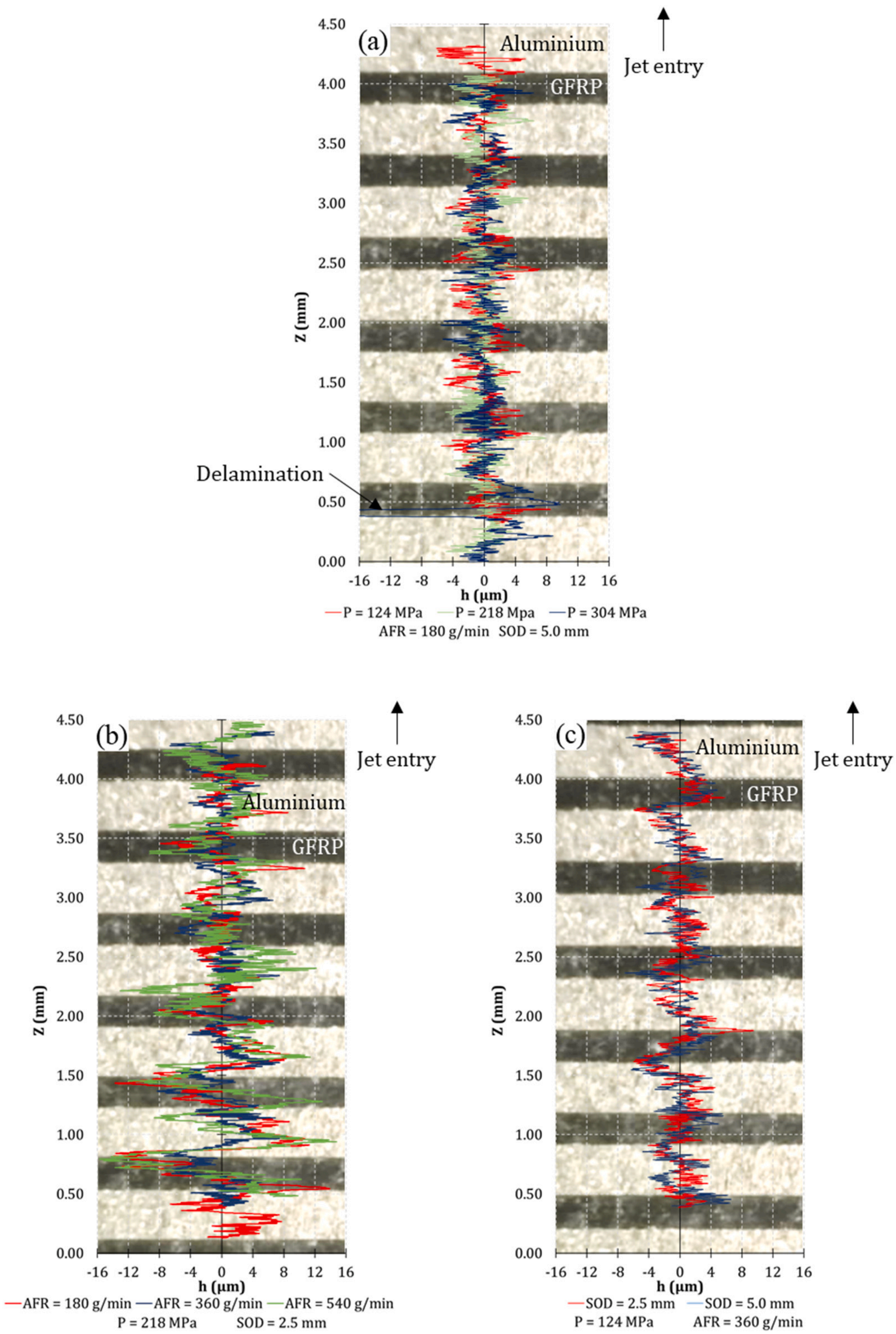

Fig. 7. Evolution of the profiles measured by the surface roughness tester in 90° direction as a function of (a) the jet pressure, (b) the abrasive flow rate and (c) the standoff distance.

3.2.2. *Defects induced by AWJ drilling*

The SEM pictures of the holes' wall permit observing the different kinds of defects induced by the AWJ drilling operation. First, small flat surfaces are found in aluminium (cf. Fig. 8a) corresponding to micro-cutting marks induced by the impact of the particles. Moreover, embedded abrasive particles are observed as well as micro craters (cf. Fig. 8b). These craters might be the footprint of embedded particles which were removed by the jet during the cutting operation, as observed by Sourd et al. [53] in the case of AWJ milling of titanium alloy Ti6Al4V. Two types of defects are also noticed in the GFRP plies: unevenly cut fibres (cf. Fig. 8b, c) and delamination occurring at the interface with the aluminium plies (cf. Fig. 8c and d). Though the delamination starts at the interface between the GFRP plies and the aluminium layer, it deflects in the GFRP ply. A closer look highlights the presence of abrasive

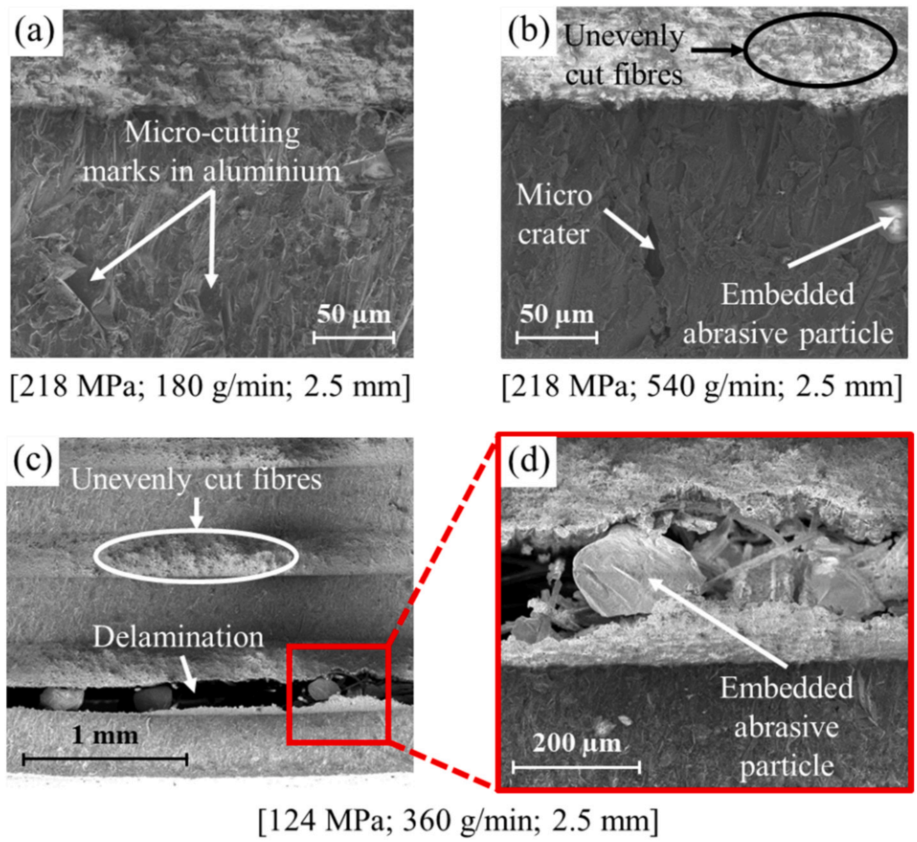

Fig. 8. SEM pictures showing the defects induced by AWJ drilling on GLARE with: (a) micro-cutting marks, (b) micro-craters and embedded particles in aluminium, (c, d) unevenly cut fibres in GFRP and delamination with embedded abrasive particles at the interface.

particles inside the delaminated zone. The X-Ray analysis of the holes permits a better understanding of the delamination scenario. Indeed, due to the loss of kinetic energy of the jet when passing from one material to the other, changes in taper can be observed when cutting a multi-layered multi-material plate [54,55]. When the two consecutive materials being machined have different mechanical properties, the loss of kinetic energy result in transverse machining at the interface [19], and a defect known as hydro-distortion, generated by the convergence followed by the divergence of the jet, appears. This is the case when cutting a GLARE laminate as seen from Fig. 8c. This defect, combined with the wedge effect of water, promotes delamination initiation. Once the delamination is initiated, the abrasives can enter the crack and are pushed further by water, propagating the delamination (cf. Fig. 8b and c). The different mechanical properties of GLARE laminate constituents cause the water jet to machine transversely which results in what Pahuja et al. [23] described as a "in a geometrically varying profile". This phenomenon was also reported to be a direct effect from hydraulic pressure, a low pressure tends to produce irregular cut between dissimilar materials [19,56].

3.2.3. Defects quantification

For further analysis, the position of delamination, as well as the contamination ratio of each hole, has been characterized. As the hydro-distortions are generated by the erosion, a parameter called "power of erosion" (E) has been introduced in order to compare all the machining conditions under a single indicator. The erosion rate increases with an increase in the water pressure (P) and a decrease in the standoff distance (SoD) or the abrasive flow rate (AFR), E can be written as:

$$E = \frac{\frac{P}{P_{max}}}{\frac{AFR}{AFR_{min}} \times \frac{SoD}{SoD_{min}}} \quad (1)$$

where $P_{max} = 304$ MPa, $AFR_{min} = 180$ g/min and $SoD_{min} = 2.5$ mm.

It has to be noted that the purpose of this parameter is only to associate an indicator to a given set of parameters (P, SoD, AFR) and to rank them from the least severe to the harsher machining conditions within the intervals tested. It can be seen from Fig. 10 that the appearance of delamination within the holes can be related to the "power of erosion" E. Actually, two zones are distinguished. For $E < 0.17$ none of the holes delaminated (Zone 1). For $E > 0.17$ (Zone 2), the great majority of the holes present at least a delaminated ply. Two particular cases appear, one with no delamination despite being in Zone 2, the other one presenting an important over-erosion in a GFRP lay-up but no delamination.

For all the holes presenting delamination, both the position of this defect within the GLARE plate and the contamination by abrasive particles are plotted as a function of the "power of erosion" (cf. Fig. 11). It can be seen that as the power of erosion increases the delamination occurs closer to the jet entry within the GLARE plate. For example, the first interface between the aluminium layer and the GFRP plies delaminates for $E = 0.17$, whereas this is the sixth for $E = 0.67$. This observation is in agreement with conventional machining. Therefore, when drilling is conducted with a cutting tool, the position in the thickness of the delaminated zone is strongly influenced by the feed rate [57,58]. Indeed, when drilling is conducted with a high feed rate, the delamination occurs close to the first plies located at the hole entry.

As illustrated previously in Fig. 9 the delaminated zone is polluted by abrasive grits. The contamination rate is influenced by the power of erosion (cf. Fig. 11b). In fact, when the power of erosion varies from 0.17 to 0.5 a clear augmentation of the contamination rate is noticed (no grits found for E = 0.17 and 0.18, against 4 % of the total surface polluted for E = 0.5). However, when E = 0.67 a slight decrease of the contamination is recorded. Moreover, two peculiar cases (represented in Fig. 11 by

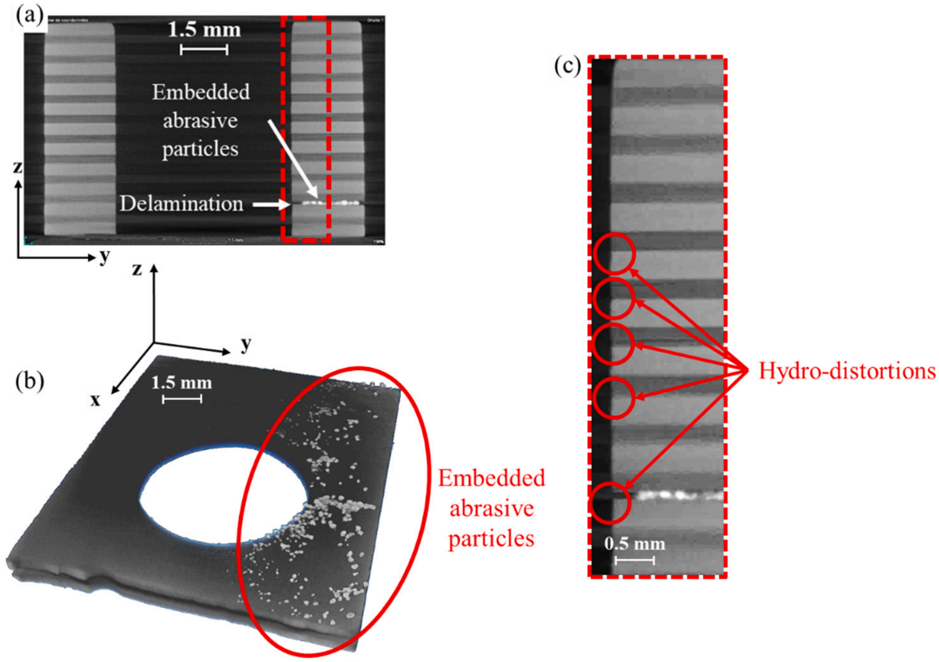

Fig. 9. Tomography pictures showing delamination (a), grit contamination (b) and hydro-distortions through the thickness of the GLARE plate (c) induced by AWJ drilling.

squares and triangles) can be observed. In the case of E = 0.50 (squares), two consecutive interfaces were delaminated by the AWJ drilling operation. In the case of E = 1, the whole last aluminium layer has delaminated, so it was not possible to quantify the induced contamination.

4. Conclusions

The goal of this work was to study the influence of the AWJ machining parameters on the geometrical features and the integrity of holes. In this context, a full factorial experimental design has been followed by varying three parameters viz. the water pressure, the standoff distance, and the abrasive flow rate. After drilling, the holes have been characterized geometrically (diameter, cylindricity, roughness…). A focus was made on the integrity of the GLARE plate, both in terms of delamination and abrasive contamination. Based on the results of this investigation, the following conclusions can be drawn:

- The water pressure and the standoff distance are the two most important tested parameters on the hole's geometry. Drilling with a high-water pressure permits to reach the target diameter as well as a more cylindrical hole. Moreover, using a standoff distance of 5 mm reduces the barrel shape of the hole but generates wavier walls due to the change in material within the GLARE laminate.
- There is no noticeable influence of the drilling parameters on the surface roughness of the holes' walls. The maximum measured roughness is below 6 μm, which is similar to the values reported in conventional drilling of GLARE. This means that AWJ is a suitable drilling process for aerospace applications. The SEM observations of the walls of the holes highlight different types of defects induced by AWJ drilling, mainly in the form of unevenly cut-glass fibres, delamination and abrasive embedment.
- Both the position of the delaminated plies within the thickness of the GLARE plate and the contamination by abrasive particles are influenced by the machining parameters used for hole drilling. Based on the proposed criterion named the power of erosion (E), it is evident that, when machining is conducted with small values of E (<0.17), the machining quality can be considered as good (no delamination). However, when drilling is performed for higher values of E (>0.17), the delamination occurs between layers of GLARE. The harsher the machining conditions, the higher are located the delaminated plies and the more contaminated is the zone between them.

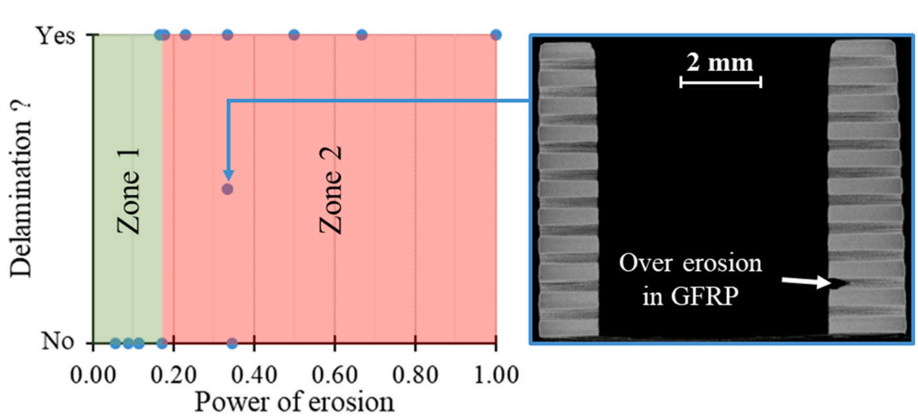

Fig. 10. Delamination with respect to the “power of erosion” of the AWJ drilling operation.

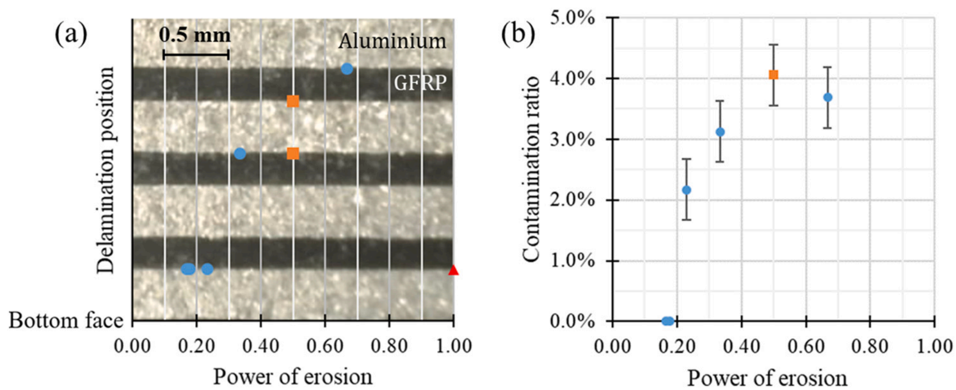

Fig. 11. Position of the delaminated plies (a) and contamination ratio (b) as a function of the “power of erosion”.

- Drilling with high water pressures and high AFR will permit to obtain the best holes both in terms of geometry and surface quality. This is due to the reduced part of jet energy allocated to the water droplets, which permits to cut more efficiently the workpiece by the high speed abrasive particles and decreases the hammer pressure responsible for delamination.

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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