Jet pressure influence on micro-abrasive waterjet trepanned hole in CFRP composite material

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KEYWORDS

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CFRP,
Delamination,
Over-Cut,
Circularity Error.

ABSTRACT

Carbon fibre reinforced polymer (CFRP) composite material is widely used in various industries such as aerospace, automobile, and defence due to its high strength-to-weight ratio and stiffness. Making holes in CFRP through conventional drilling comes with issues such as fibre pull-out, fibre breakage, delamination, and chipping. On the other hand, abrasive waterjet (AWJ) is well known for machining composite material due to its unique features such as no heat-affected zone, local erosion, minimum residual stress, etc. In this study, micro-AWJ is employed to trepan holes in the CFRP composite material, and the influence of waterjet pressure (P) on the hole diameter, over-cut, circularity error, taper angle, and damage at the hole top and bottom surface are analyzed as the pressure is a dominating parameter influencing the performance. Diametrical deviation and over-cut at top and bottom planes increase, surface damage decreases, and circularity error decreases with the increase in P.

1. Introduction

Carbon fibre reinforced polymer (CFRP) material has been used in various industries such as aerospace, automobile, and defence heavily due to its high strength-to-weight ratio and stiffness (Linganiso & Anandjiwala, 2016). The CFRP material is the most commonly and profoundly used material in aerospace to reduce aircraft weight by up to 50% (Liu et al., 2012). On the other hand, hole-making is one of the common processes in aerospace industries for the final assembly process. A 6-8 mm diameter holes are commonly required for the aircraft assembly process (Chung, 2017; Venkatesh & Sikarwar, 2018) Conventionally various type of drill bits is used for the drilling process. The common issues studied in the conventional drilling of the CFRP composite materials are delamination, uncut fibre, and hole surface damage (Hrechuk et al., 2018). The hole damage that arises due to conventional drilling can affect the mechanical property of the composite, as the hole containing high damage has lower compressive strength and fatigue life (Persson et al., 1997).

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To minimize the mentioned defects to drilling hole in composite material, abrasive waterjet (AWJ) machining has demonstrated its superiority against other methods. The AWJ is capable of trepan hole in composite materials with minimum distortion due to its advantages such as no heat affected zone, minimum residual stress, and not altering the material property of the material.

However, the aggressive jet nature of the jet may lead to delamination, over-cut, hole diametric deviation, and taper angle. During the trepanning of CFRP composite materials by AWJ, it is found that delamination increases with the waterjet pressure (P) (Phapale et al., 2016). Waterjet jet traverse speed (v_f) is the significant process parameter that affects the trepanned hole surface quality and delamination in CFRP material (Dhakal et al., 2018). Furthermore, the hole taper angle in CFRP/Ti6Al4V stacks decreases with the increase in P and increases with an increase in the v_f (Alberdi et al., 2016). With the increase in jet traverse rate, roundness error increases at the exit of the AWJ macro drilled hole in CFRP (Sambruno et al., 2019).

On the other hand, micro- AWJ can minimize the hole geometric and surface deviation as it uses a small diameter focusing nozzle and orifices, which result in narrow kerf width. The low requirement of the abrasive particles for micro-AWJ minimizes the abrasive contamination at the hole surface. Multiple studies are reported on the AWJ trepanned/drilled holes and studied delamination, hole geometry (roundness and cylindricity error), and the hole inner surface profile. However, very limited information is available regarding the micro-AWJ trepanning of the CFRP composite materials. Waterjet pressure is one of the most influential process parameters that affects the whole abrasive waterjet cutting system and controls the quality of the part produced by the AWJ.

Hence, in this study, the influence of the waterjet pressure on the micro-AWJ trepanned hole diameter, circularity error, taper angle, and the over-cut is analyzed. Furthermore, the effect of the P on the top and bottom plane of the hole surface is demonstrated.

2. Material and Experimental Setup

A hybrid 3-axis micro-abrasive waterjet machine tool (AQUAJET) was used for the trepanning trails (Fig. 1). A focusing nozzle of 300 µm diameter and an orifice diameter of 120 µm were used for realizing the 6 mm hole in 0.77 mm thick and 50 mm x 50 mm CFRP composite sheet. A garnet of mesh size 230 was used. Table 1 presents the details of the trepanning trials. A drilling head is also attached to the micro-AWJ cutting head, which can be used for hybrid operations. A drill bit of diameter 6 mm was used in the conventional drilling process. A stereomicroscope (STEMI-2000CS) and a contact type coordinate measuring machine (CMM) (ZEISS O-INSPECT) having a probe diameter of 3 mm were used for the characterization of the micro-AWJ trepanned holes. The middle plane diameter and circularity error were obtained with the help of CMM, at the middle plane, 9 points were considered at 40°, and the least square circle was fitted to obtain the diameter of the circle. A similar strategy was followed to calculate the circularity error. All the measurements repeated three times are their average were used for the analysis.

Table 1
Micro-AWJ trepanning parameters employed for the experimental trials.

Variable operating parameters	
Waterjet pressure (MPa)	100, 150, 200, 250, 300, 350, 400
Constant operating parameters	
Abrasive mass flow rate (g/min)	30
Standoff distance (mm)	0.6
Jet impingement angle (degree)	90
Jet traverse speed (mm/min)	15

3. Result and Discussion

3.1. Hole drilling by a conventional method

Figure 2 shows the photograph of the hole drilled in CFRP composite with the help of a 6 mm carbide drill bit by using a drilling head attached to the micro-AWJ cutting head to demonstrate the damage caused by the conventional drilling process. Fig. 2a shows fiber pull-out and uneven cutting edge at the top plane of the hole. At the bottom plane of the hole severe fiber pull-out, fiber breakage, and delamination were

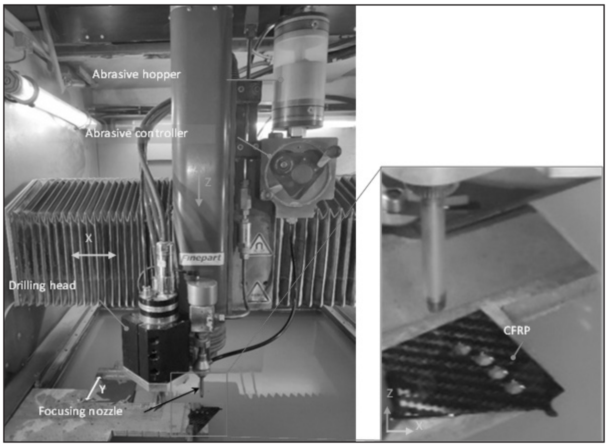

Fig. 1. Hybrid micro-abrasive waterjet experimental setup employed for trepanning.

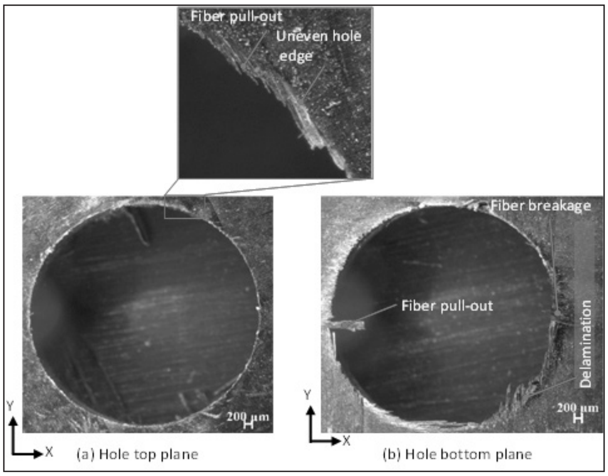

Fig. 2. Photograph of the hole drilled by the conventional drilling tool.

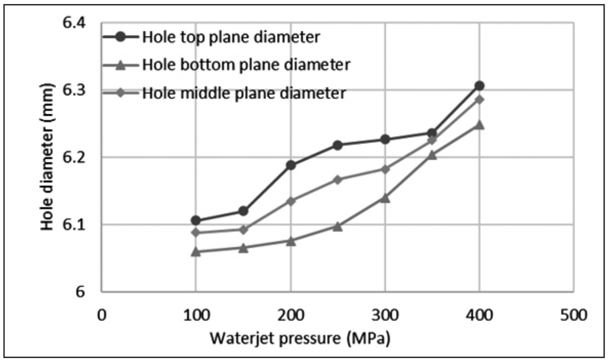

Fig. 3. Waterjet pressure influence on the micro-waterjet trepanned hole diameter.

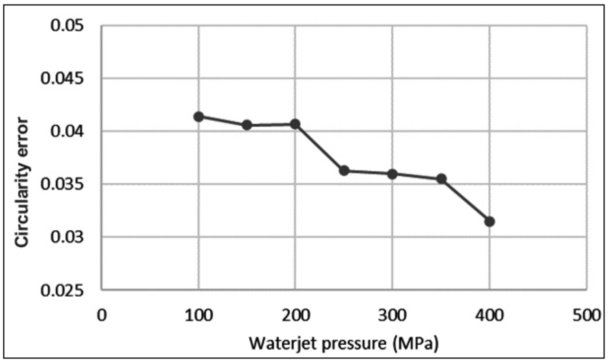

Fig. 4. Waterjet pressure influence on the circularity error of the micro-waterjet trepanned hole.

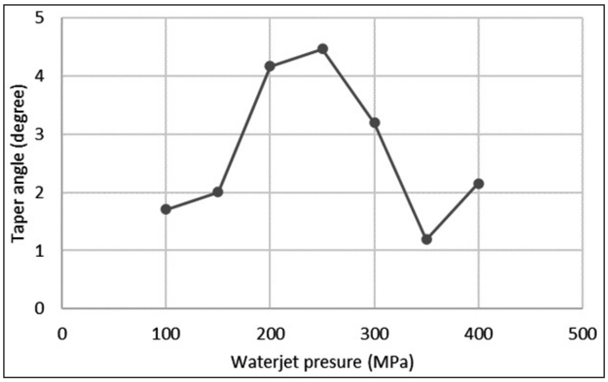

Fig. 5. Waterjet pressure influence on the taper angle of the micro-waterjet trepanned hole.

observed (Fig. 2b). Fiber pulls out and the uneven edge deteriorates the hole dimensions such as diametrical deviation, circularity error, and the taper angle. To rectify the above mention issues, special cutting tools or secondary operations are required in addition to the extra manufacturing cost.

3.2. Waterjet pressure influence on hole diameter

Figure 3 shows the influence of the waterjet pressure on the micro-AWJ trepanned hole diameter at the top, middle, and bottom planes. The hole diameter converges from top to bottom. It can be explained as the jet interact with the material; it starts losing its eroding capability resulting in a smaller diameter at the hole bottom plane. With the increase in waterjet pressure hole diameter increases for both the top, middle, and bottom plane, this can be attributed to the increased jet energy with the increase in *P*. The difference between top, middle, and bottom diameter were highest at 250 MPa, which can be explained as follows: at lower waterjet pressure due to lower energy of the jet, the outer portion of the jet plume do not have enough energy to erode the material hence, the difference in top and bottom diameter is less. At middle pressure at the top plane, the jet plume outer portion also has enough energy to take part in the erosion of the material; however, as it enters into the material, the jet do not have enough energy to maintain its eroding capability resulting in a high difference in top and bottom diameter. Furthermore, as waterjet pressure keep increasing, overcoming the loss of the jet energy due to the material interaction leads to reduce in the dimeter difference between the top and bottom plane.

3.3. Waterjet pressure influences on circularity error of the hole

Figure 4 shows the influence of the waterjet pressure on the circularity error of the AWJ trepanned hole. With the increase in the *P*, the circularity error of the hole decreases it can be attributed to the increase in jet energy with the increase in the *P*. Low-energy jet pull out the fibers during the trepanning process however, higher energy jets cut through the fibers efficiently without creating the uneven surface leads to minimizing the circularity error.

3.4. Waterjet pressure influences on taper angle of the hole

Figure 5 shows the influence of the waterjet pressure on the taper angle of the hole. At first, from the *P* from 100 MPa to 250 MPa, the taper angle increased as, at lower pressure, the jet loses its eroding capability significantly as it enters into the material, leading to a higher diametrical difference between the top- and bottom-hole diameter. As pressure increases, jet energy increases, compensating the energy loss of the jet during penetration of the material resulting in a low diametrical deviation between top- and bottom-hole diameter. At very high pressure, again taper angle increases it can be explained as a very high energy jet even the outer region of the jet start participating in material removal, leading to a large diameter hole at the top plane of the hole, leading to the higher diametrical deviation between the top and bottom plane hole diameter.

3.5. Waterjet pressure influences over-cut

Figure 6 shows the schematic of the trepanning tool path and the over-cut. Jet started from point 1 to avoid the damage caused by the jet impact. Jet travels from point 1 to 2 linearly and at point 2 starts following the trepanning path. At point 2, when the jet tends to enter into the circular path, it changes its direction, which causes a significant reduction in jet traverse speed, and due to the aggressive nature of the jet, it removes more material at point 2. Furthermore, the jet followed path 3 and returned to point 4 after completing the 360^{o} rotation and stopped at point 5.

Figure 7 shows the waterjet pressure influence on the over-cut at the top and bottom plane of the hole. Over-cut depth is less at the bottom than at the top plane; it can be attributed to jet energy loss. over-cut depth increases with the increase in waterjet pressure in both cases, it can be explained as jet energy increases with an increase in waterjet pressure resulting in high over-cut. The difference between the top and bottom plane over-cut depth is higher at the lower *P* however, it decreases with the increase in the waterjet pressure, it can be explained as, at lower *P,* the jet energy difference at the bottom plane is noticeable even for lower thickness material, however, as waterjet pressure increases this difference gets diminished with the increase in *P*.

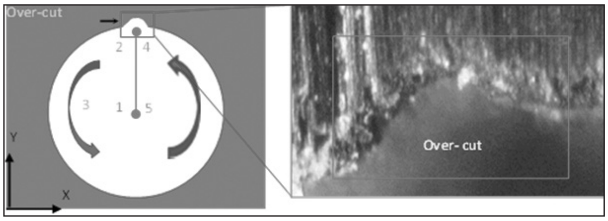

Fig. 6. Schematic of the hole trepanning jet path and photograph of the over-cut location of the hole.

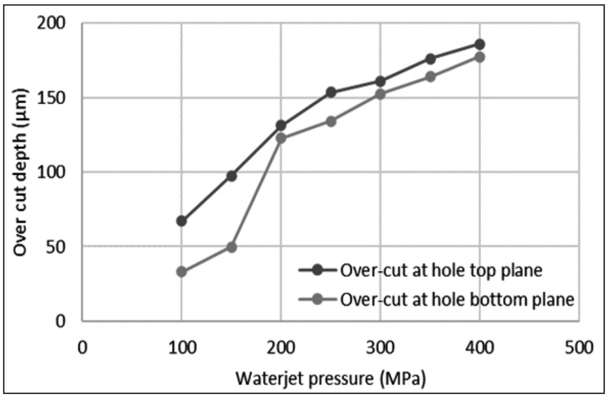

Fig. 7. Waterjet pressure influence on the over-cut depth.

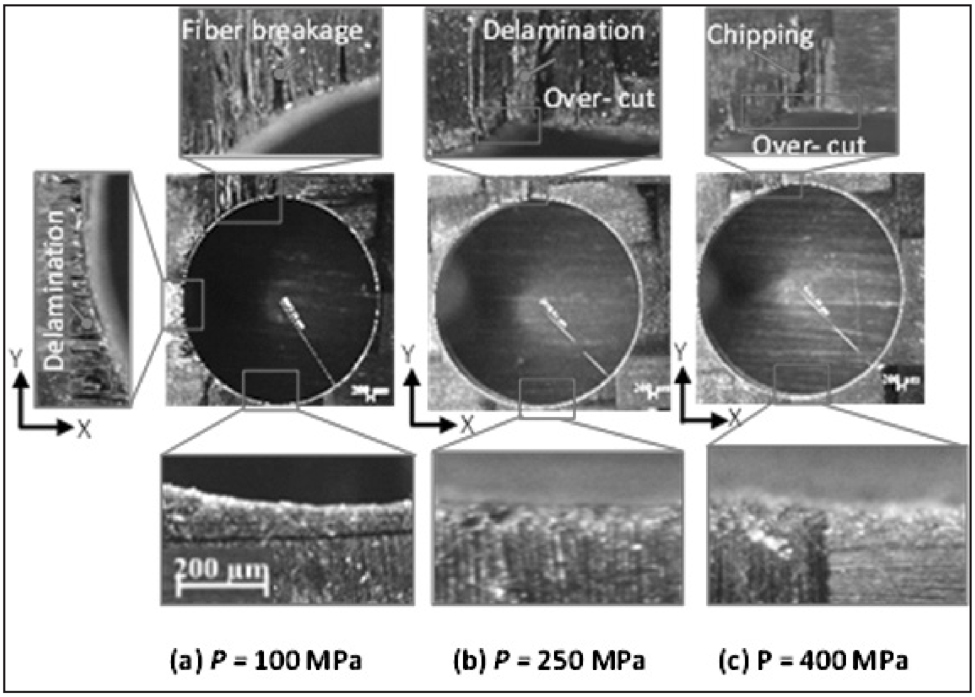

Fig. 8. Photograph of the micro-waterjet trepanned hole top plane at various waterjet pressure.

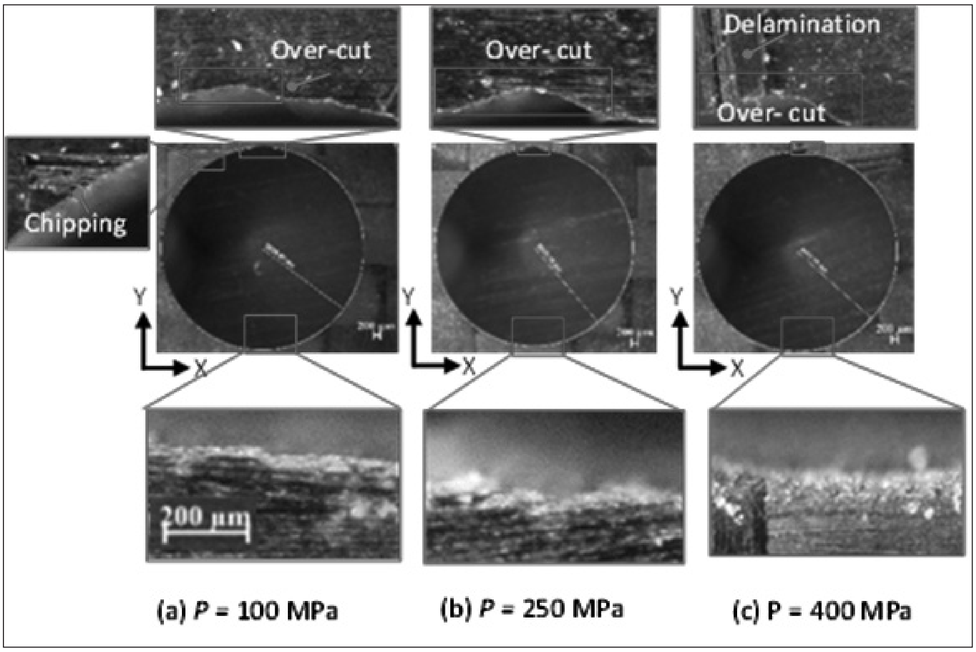

Fig. 9. Photograph of the micro-waterjet trepanned hole bottom plane at various waterjet pressure.

3.6. Waterjet pressure influence on hole top plane

Figure 8 shows the micro-AWJ trepanned hole top plane surface at various waterjet pressures. At lower *P*, over-cut was the minimum. However, damages around the edge were maximum. Delamination and fibre breakage were observed at lower *P* (Fig. 5a). It can be explained as a lower energy jet finding it difficult to penetrate through the material hence, try to escape towards the radial direction causing delamination and the fibre breakage around the hole edges. As the *P* increased, the depth of the over-cut increased, however, the damage around the hole edges decreased significantly as high energy jet cut through the material efficiently (Fig. 5b). Chipping was observed near to over-cut location at higher *P*, as the material may get chipped off due to the radial higher energy jet.

3.7. Waterjet pressure influence on hole bottom plane

Figure 9 shows the bottom plane of the hole trepanned by micro-AWJ at various waterjet pressures. Over-cut was observed at all the *P*, however, its depth increased with the increase in *P*. Fibre pull-out and breakage were not observed at the bottom edge of the hole. At the lower *P* edge, chipping was observed at the near-to-over-cut location (Fig. 6a). Damage-free bottom edge of the hole was observed at the medium *P*. Delamination was observed at the higher *P* near the over-cut location, it can be attributed to the high-energy radial jet that penetrates through the layer of the composite material.

4. Conclusions

The waterjet pressure influence on the hole diameter and top and bottom plane surface characteristics realised by the micro-abrasive waterjet trepanning in the CFRP composite material were analyzed. The following conclusion can be drawn:

- Diametrical deviation increases, and circularity error decreases with the increase in the *P*.
- Surface damage at the top and bottom planes decreased. Surface damage at the top and bottom plane of the hole gets minimized with the increase in *P*.
- Taper angle of the hole first increases with the increase in *P* and then decreases beyond the critical *P*.
- Over-cut depth increases with the increase in the *P*.

Hence, it can be concluded that the medium *P* is suitable for the trepanning of the CFRP composite material as diametric deviation, and the surface damage was in the acceptable range, however, optimum *P* needs to be identified, and other process parameters (v_f and m_a) influence need to be analyzed for realizing accurate holes with desired surface quality.

Although the quality of the trepanned hole is increased considerably relative to the holes trepanned by solid cutting tools, the final hole quality can be maintained for high precision applications by the specially designed hybrid machine tool (Fig. 1) at IIT Madras, India that has both micro-AWJ cutting head integrated with high-speed drilling spindle.

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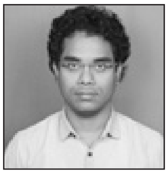

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