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Experimental Investigations Towards Hole Accuracy in Micro-drilling of Carbon Fibre Reinforced Polymer Material

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Nowadays, Carbon Fibre Reinforced Polymer (CFRP) materials are extensively used as substitutes for metal parts in aircraft and automotive components since they are lighter in weight. However, micro drilling CFRP materials during the assembly process poses various challenges such as low hole accuracy and delamination. Hence, an experiment has been executed to investigate the influence of micro drilling parameters towards hole accuracy. The spindle speed and feed rate are the machining parameters that have been considered in this experiment. Three different optimum parameters have been obtained from previous experiments, involving the spindle speed combinations of 8,000, 10,762 and 11,017 min^{-1} with a feed rate of 0.01 mm/rev. A drill bit with a diameter of 0.9 mm is used to drill approximately 300 holes. It has been revealed that the combination of the spindle speed of 11,017 min^{-1} and feed rate of 0.01 mm/rev produce high hole accuracy at the 2nd hole compared to the 300th hole due to the presence of uncut fibres at the 300th hole which have reduced the hole area. Hence, outcome of this research could provide the benefit to the industries in term of manufacturing time and materials expenditure.

Keywords: CFRP, Delamination, Hole Accuracy, Micro-drill, Uncut Fibre

1 Introduction

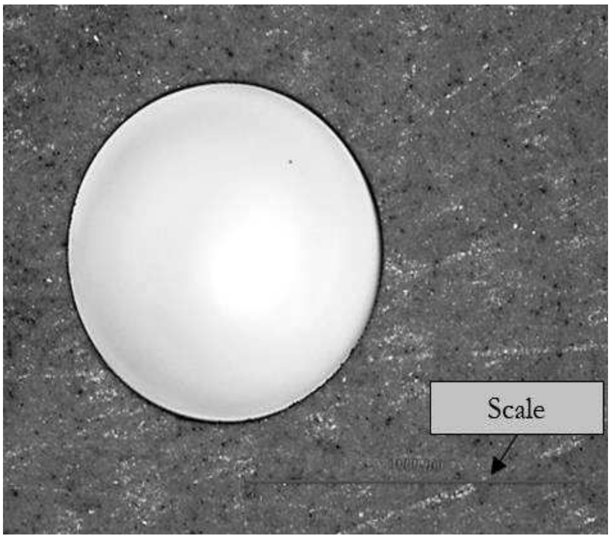
In airframe structural applications, carbon fibre reinforced plastics (CFRP) are commonly used for their excellent material composition; they are corrosion resistant, lightweight and possess high material strength [1], [2]. Besides, CFRP material also provided benefit to sports optics as it has high stiffness and thermally stable [3]. Over time, a few machines have been developed to perform drilling processes such as laser beam machining, ultrasonic machining, electro discharge machining (EDM) and electrochemical machining (ECM)[4], [5]. In this research, the CNC router machine is used to examine the fundamental elements of the micro drilling process on the CFRP material in dry condition to avoid contamination on CFRP material.

Several researchers have previously defined the range of micro-drilling diameter [6]–[9]. For instance, the diameters of 1 μm to 1 mm were described as micro drilling diameters [8]. Hence, drilling process with diameter below than 1 mm can be defined as micro drilling. However, there were particular defects occurred when drilling CFRP material such as delamination and uncut fiber [10], [11]. In addition, the material is hard to drill due to the high structural stiffness of carbon fiber and low thermal conductivity of polymer [12], [13]. Therefore, the hole accuracy and diameter will be affected by this kind of defect.

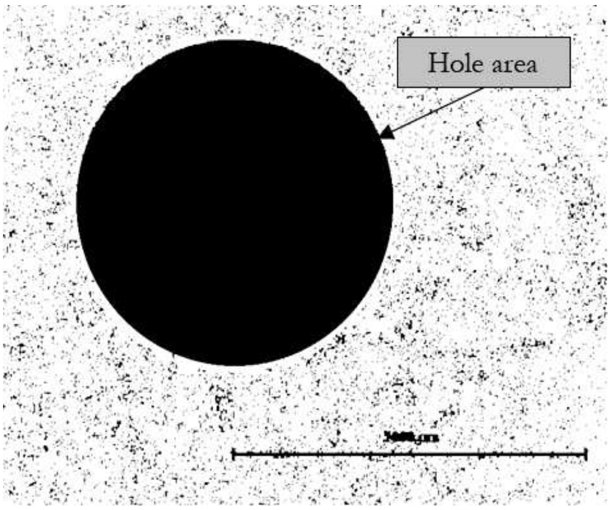
Since the diameter of the drill bit is micro in size, the probability of tool breakage to occur during the drilling process is higher. Prior to tool breakage, the issue of tool wear is also common for drill bits with more than 1 mm diameter. Besides, ANOVA revealed that the feed rate and tool geometry as the greatest significant parameters towards delamination and thrust force and cutting speed is insignificant parameter [10], [14]. To overcome this problem, tool wear observation is a vital approach to identify the start of tool wear, alerting users in advance before their workpiece gets damaged [15]–[17].

By applying optimum machining parameters for the spindle speed and feed rate, good quality holes can be achieved [18]–[20]. Research found that with increase of feed rate with same cutting speed, the surface intergrity of material improved [21]-[22]. Hence, the selection of machine parameter is vital to obtain optimum machining performance towards material behaviour. The circularity of drilled hole is influenced by machining spindle speed and feed rates [23]. The hole accuracy is critical as it is related to product safety during the assembly process. For example, low hole accuracy can lead to loosened bolts and nut joints due to the presence of gaps between the hole and bolt or the rivet joint [24]. Industries such as electronics, automotive, medical, aerospace and sports equipment are common users of the CFRP material [25].

Figure 1 presents an image of a hole on the CFRP composite panel fibre using a microscope and Image J software with 100 times magnification. It is compulsory to have the scale on the image captured using microscope (Figure 1a) as the scale is required when setting the actual scale in Image J software so that the value measured reflects the actual value.



(a)



(b)

Fig. 1 *Image of micro-drill hole area with 100 times magnification under (a) Microscope Nikon ECLIPSE LV100 and (b) Image J*

2 Methodology

This experiment analysed the output of drilled hole accuracy on the CFRP material. This section provides an explanation on the machine and equipment used for the micro-drilling process and hole accuracy evaluation.

2.1 Micro-drilling Process

The laminated CFRP composite with a dimension of 184 mm x 86 mm x 3.8 mm was the workpiece of this experiment, as shown in Figure 2. The panel is made of 26 unidirectional pre-impregnated plies with stacking sequence of [45/135/902/0/90/0/90/0/135/452/135] s. It contained 57.42% nominal volume of fibre based on the carbon fibre of AS4, and the resin was epoxy. Figure 3 illustrates the cross-sectional view of the CFRP panel. Next, the tool employed was the HSS carbide twist micro drill bit with 0.9 mm diameter and 3 mm shank diameter. It is 10 mm in length and consists of 4 flutes. Figure 4 presents the image of the micro drill bit and its dimensions.

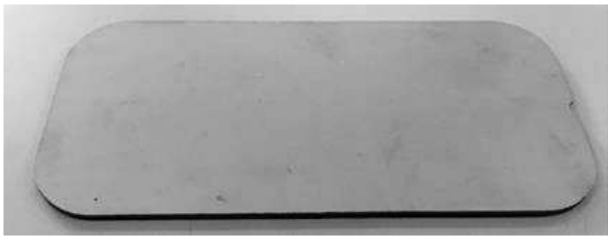


Fig. 2 *Laminated CFRP composite*

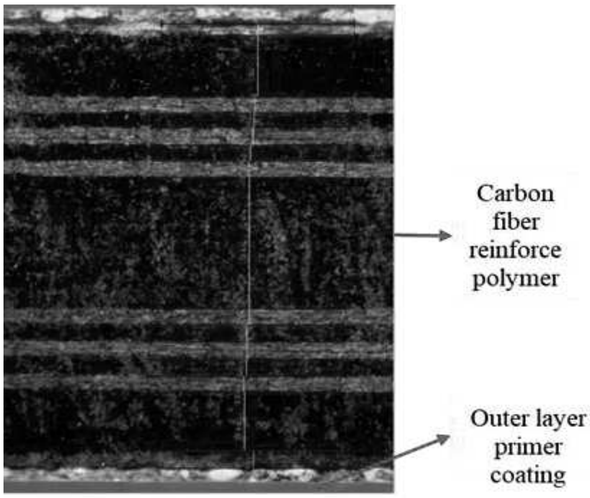


Fig. 3 *Cross-sectional view of the laminated CFRP composite panel*

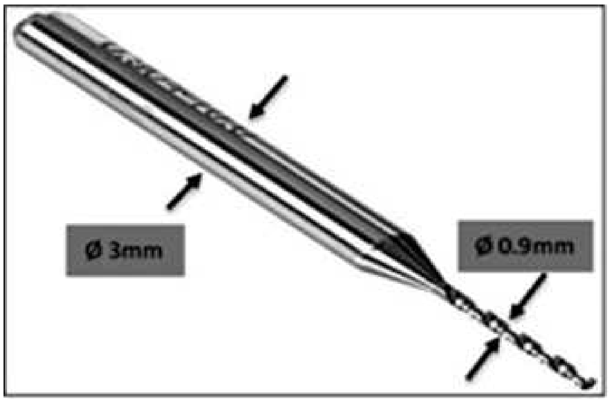


Fig. 4 *Dimensional Image of drill bit*

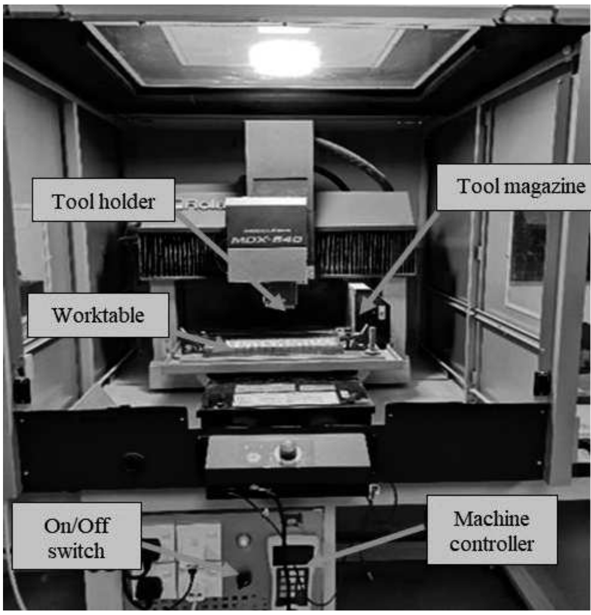


Fig. 5 *CNC Router MODELAPRO11 MDX-540*

Figure 5 portrays the overall setup of the 3-axis CNC Router MODELAPRO11 MDX-540 machine for the micro drilling process of the CFRP material. The feasible range of the spindle speed for this machine is from 400 to 12,000 min^{-1} . The dynamometer was installed on the worktable to capture the thrust force value along the drilling process. In order to avoid damage of the dynamometer, the holding fixture held the CFRP panel to ensure there is a gap between the bottom part of the workpiece and the dynamometer during the machining process. Next, the drilling process was conducted using the optimum parameter obtained from a previous study, as shown in Table 1.

Tab. 1 *Optimum parameter for micro-drilling process*

Parameter	1	2	3
Spindle Speed (min^{-1})	8,000	10,762	11,017
Cutting Feed Rate (mm/rev)	0.01	0.01	0.01
Hole Diameter (mm)	0.9	0.9	0.9

2.2 Hole Accuracy Measurement

To obtain the accuracy of holes, a selected number of drilled holes were evaluated: hole numbers 2, 60, 120, 180, 240, and 300. The images of the holes, with 100 times magnification, were captured using Nikon ECLIPSE LV100 microscope with the Solution DT software, as displayed in Figure 6. Next, the Image J software was employed to measure the hole accuracy, as shown in Figure 7.

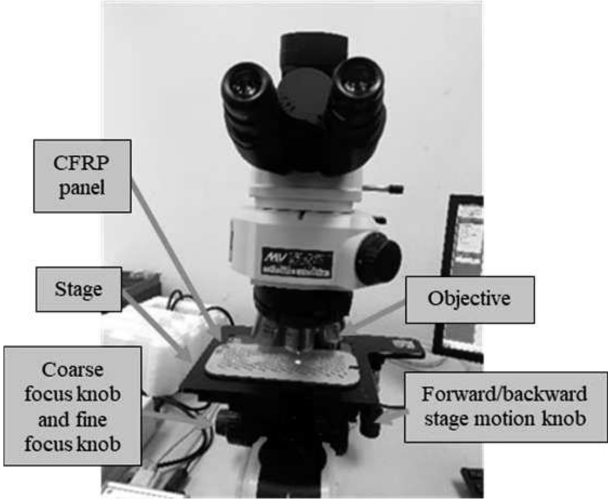


Fig. 6 *Nikon ECLIPSE LV100 microscope*

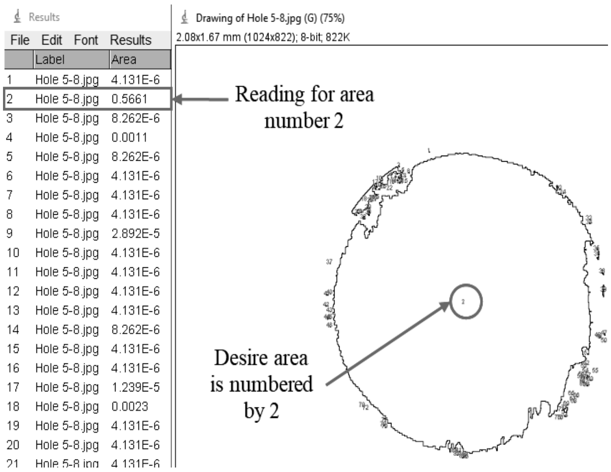


Fig. 7 *Measuring hole area by using Image J software*

Equation 1 was applied to measure the nominal value of the hole area with a diameter of 0.9 mm. The actual hole area calculated using the Image J software was then divided by the nominal value of the hole area to obtain the percentage of hole accuracy.

$$\text{Total area of holes} = \pi r^2, \tag{1}$$

Where:
r...radius of hole

3 Results and Discussion

3.1 Experimental Results of Entry Hole Accuracy

Hole number 1 was selected to be measured at the beginning of the micro-drill test. However, after the evaluation process, an error for hole number 1 was caused by machining factors. Therefore, hole number 2 was selected as the replacement. Figure 8 shows a comparison of hole accuracy results for the 3 parameters.

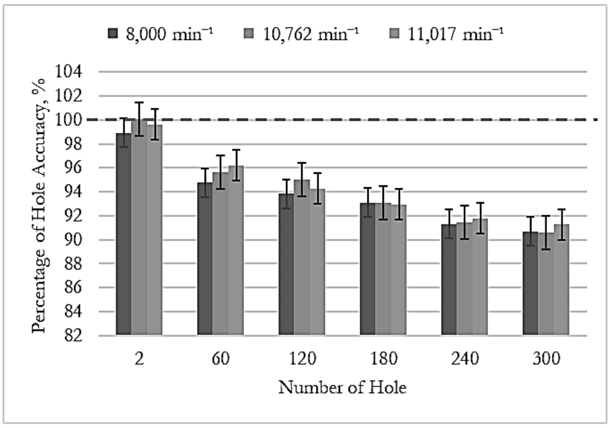
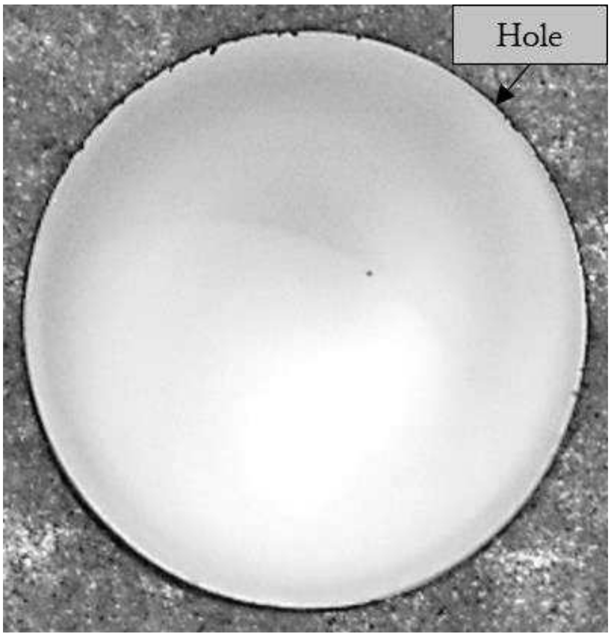
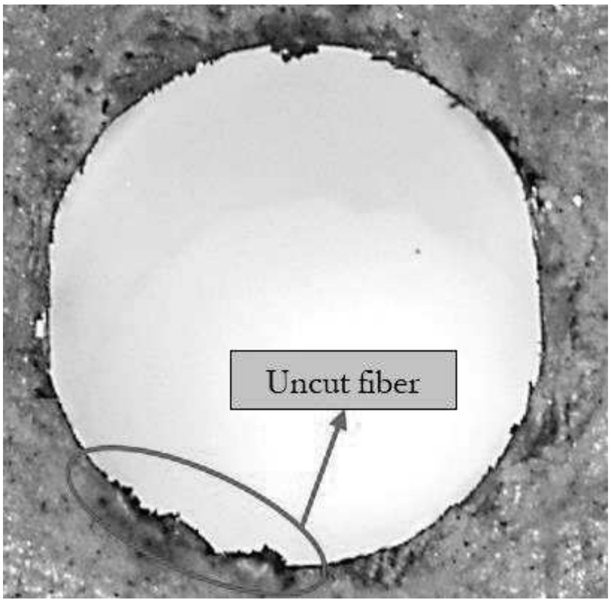


Fig. 8 *Comparison of entry hole accuracy results*



(a)



(b)

Fig. 9 *Image of (a) 2nd entry hole and (b) 300th entry hole*

Based on Figure 8, the spindle speed of 10,762 min^{-1} for the hole position number 2 achieved the highest percentage of hole accuracy (100.07%). The area was higher than the nominal area; in other words, the hole was overcut by 0.07%. However, an acceptable tolerance of 99.11% to 100.89% was present. The lowest entry hole accuracy for the same parameter was 90.59% for the 300th hole. At the 60th hole, Parameter 3 displayed the highest hole accuracy of 96.2%, however, the outcome was not within the tolerance range (i.e., the hole was undersized).

Overall, the results indicate that the hole accuracy decreased as the number of holes increased. Only two holes fell between the acceptable tolerance range: the 2nd hole for both Parameter 2 and Parameter 3. This was due to the formation of uncut fibres and delamination on the area of the holes. When the drill bit had cut the CFRP, the carbon dust left on the face of the drill bit had disturbed the cutting process. Other than that, the tool began to wear out, leading to an inconsistent cutting rate along the CFRP structure . Figure 9 presents the image comparison of hole area between the 2nd and 300th hole under a microscope with 100 times magnification. Uncut fibre and delamination captured at the 300th hole have contributed to lower hole accuracy.

3.2 Experimental Results of Exit Hole Accuracy

According to Figure 10, the highest hole accuracy was obtained from Parameter 3 for hole number 2, with a 99.71% of hole accuracy. Parameter 2 captured an oversized hole with a 100.91% of hole accuracy. The result is similar with the entry hole outcome where Parameter 2 contributed to an oversized hole at position 2. Parameter 1 produced an undersized hole with a 98.76% of hole accuracy. At the 60th hole, Parameter 3 captured a higher hole area compared to Parameter 2 and Parameter 1. This trend continued until the 300th hole, excluding the 240th hole where Parameter 2 produced a slightly larger hole area compared to Parameter 3.

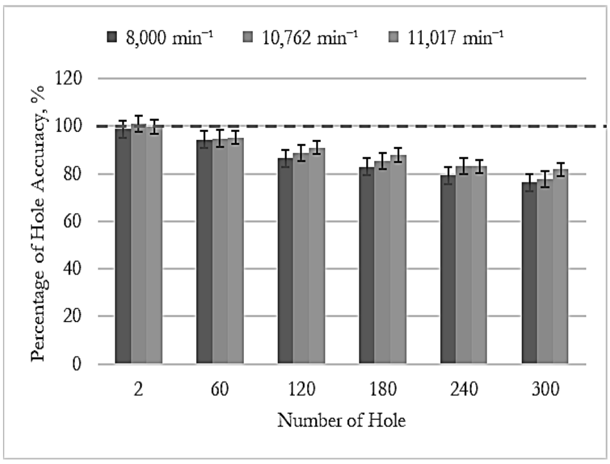
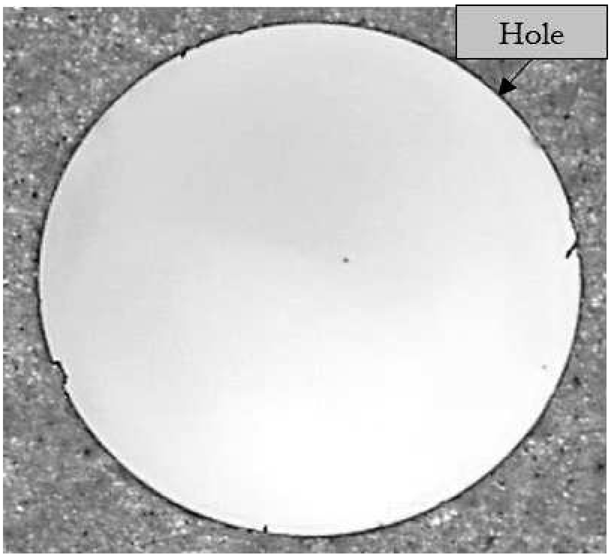
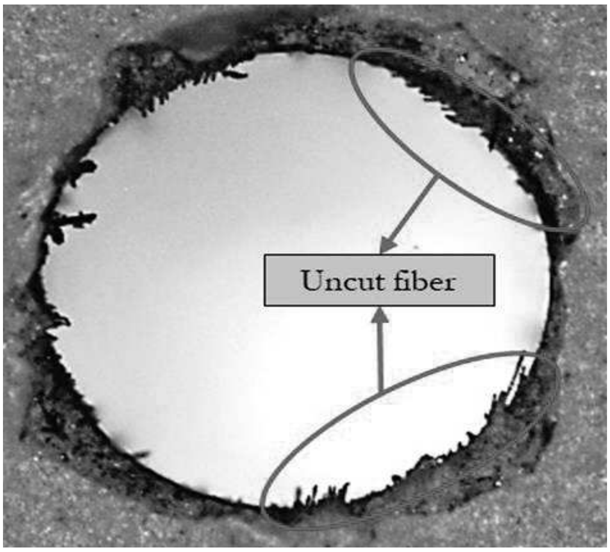


Fig. 10 *Comparison of exit hole accuracy results*

However, Parameter 1 always provided the lowest hole accuracy. The lower spindle speed produced higher thrust force. Higher thrust will expedite tool wear and increase the risk of uncut fibres and delamination [26]. Figure 11 presents a comparison of the exit hole image at the 2nd and 300th holes where the condition of the 300th exit hole was extremely poor due to delamination and uncut fibres.



(a)



(b)

Fig. 11 *Image of (a) 2nd exit hole and (b) 300th exit hole*

4 Conclusions

To conclude, by referring to previously studied parameters, the results from the experiment were compared. It was found that Parameter 2 with the spindle speed of 10,762 min^{-1} always produces oversized holes at the 2nd hole of both the entry and exit holes. However, from the 60th to the 300th hole, Parameter 3 achieved the highest hole accuracy with the spindle speed of 11,017 min^{-1} compared to other parameters. This trend continued until the 300th hole, excluding the 240th hole. Parameter 1 exhibited the lowest hole accuracy at both the entry and exit holes for all hole positions. It can be concluded that Parameter 3 is the best parameter to achieve higher hole accuracy and minimise the defect of uncut fibres and delamination on the area of the hole.

Acknowledgement

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