

Direct monitoring of hole damage in carbon fibre-reinforced polymer (CFRP) composites

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Abstract. Carbon fibre-reinforced polymer (CFRP) composite laminates have good specific material properties, these composites are therefore widely used by the high tech industries. Machining operations are often necessary in order to achieve dimensional requirements. However, CFRP is a difficult-to-cut material due to its non-homogenous and anisotropic features and the strong wear-effect of carbon fibres on the cutting tool. Increasing hole numbers causes the increase of cutting edge radius of the cutting tool, therefore hole damages (uncut fibres, delamination etc.) occur more often. The main objective of the present paper is to minimize uncut fibres in CFRP using direct monitoring of hole damage. Firstly, numerous orbital drilling experiments were conducted and the characteristics of uncut fibres were analysed. Secondly, the orbital drilling experiments were repeated with direct monitoring of uncut fibres and process control was applied in order to decrease the size of the burr area. Results show that hole damage decreased with the application of the used process control.

1. Introduction

Carbon fibre-reinforced plastic (CFRP) composite laminates are widely used by the aerospace, marine, sport and automobile industries due to its excellent special material properties [1]. Manufacturers aspire to laminate CFRP parts directly into the final shape, but machining is often necessary in order to remove waste parts left by the laminating process. Furthermore, to achieve dimensional requirements and to assembly parts, it is also necessary to drill holes in CFRP composites. However, CFRP is a difficult-to-cut material due to its non-homogenous and anisotropic features and the strong wear-effect of carbon fibres on the cutting tool [2].

Many researchers [3–5] investigated the influence of process parameters (feed rate, cutting speed, crew pitch of the feeding helix etc.) on hole quality parameters in CFRP in order to optimise the machining process. Sorrentino et al. [6] showed that feed rate has the most significant effect on uncut fibres during conventional drilling of CFRP. Orbital drilling (helical milling) produces less delamination and less uncut fibres than conventional drilling, according to Voss et al. [7].

Wang et al. [8] were researching the influence of cutting edge radius on the cutting-induced surface damages when machining unidirectional carbon fibre-reinforced plastic (UD-CFRP) composites. They found that if the cutting edge radius increases, the surface quality decreases significantly. If the cutting edge radius is high, the burr formation mechanisms is bending dominated. In the other hand, if the cutting edge radius is small (cutting edge is sharp), the burr formation mechanisms is crushing dominated. Ramirez et al. [9] carried out drilling experiments in UD-CFRP and analysed wear



mechanisms of the cutting tool. They showed that carbon fibres and high cutting speed significantly influence the wear of the tool radius. Furthermore, wear can be indirectly measured by monitoring the cutting force. They and [10] showed that tool wear rapidly increases with the increase of the number of holes.

The main objective of the present study is to decrease hole damage using direct monitoring and diagnostics of characteristics of uncut fibres in UD-CFRP. Numerous orbital drilling experiments were carried out with fixed parameters and the characteristics of uncut fibres were analysed. Based on these experiments and on previous researches, a decision algorithm was developed and tested with new machining experiments.

2. Experimental setup and methods

2.1. Experimental setup

Unidirectional carbon fibre-reinforced vinyl ester matrix composite laminate (of 6 mm thickness) was machined with a HSS Ø8 TIVOLY 80308810808 end mill. The helix angle of the tool is 30° and it has only one cutting edge, as can be seen in figure 1. This end mill is suggested by the tool producer to machine aluminium and plastic materials due to its sharp cutting edge (small cutting edge radius and positive rake angle).



Figure 1. TIVOLY Ø8 80308810808 end mill

Orbital drilling (helical milling) technology was used to machine holes in CFRP because it produces less delamination, fibre pull-out and uncut fibres than conventional drilling processes [5]. The machining experiments were carried out on a Kondia B640 machining centre, equipped with a Nilfisk GB733 vacuum cleaner. The CFRP specimen was fixed between two support plates in order to decrease push-down delamination. Images of the drilled holes were taken by a Dino-Lite AM4013MT digital microscope (Magnification: 10-70x; Resolution: 1.3 Megapixel; Maximum frame rate: 30 fps). The experimental setup can be seen in figure 2.

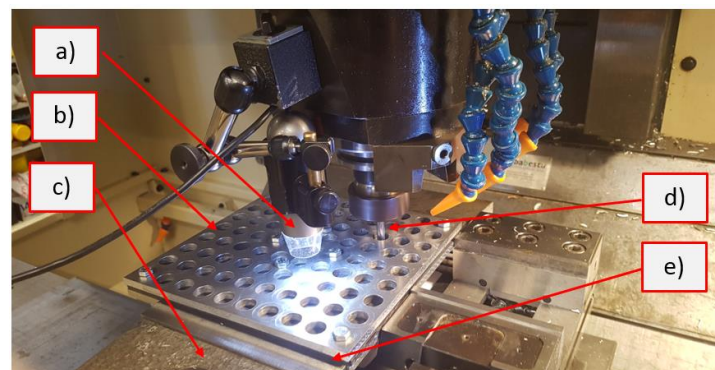


Figure 2. Experimental setup: (a) digital microscope (b) support plate (c) fixture (d) end mill and (e) UD-CFRP plate

2.2. Digital image processing

Digital image processing (DIP) was used in this study in order to analyse characteristics of uncut fibres. A unique LED light-source was located under the CFRP specimen and it lighted the hole from underneath, as can be seen in figure 3(c). With this lighting solution it was possible to increase the contrast of images of the holes. The workpiece became a shadow and the background became highlighted, so the shape of the hole became sharper, as can be seen in figure 3(a). The taken images

were then segmented using a colour histogram (figure 3(b)). The white pixels of the image were then summed and compared with the sum of the white pixels of an image with a nominal hole on it.

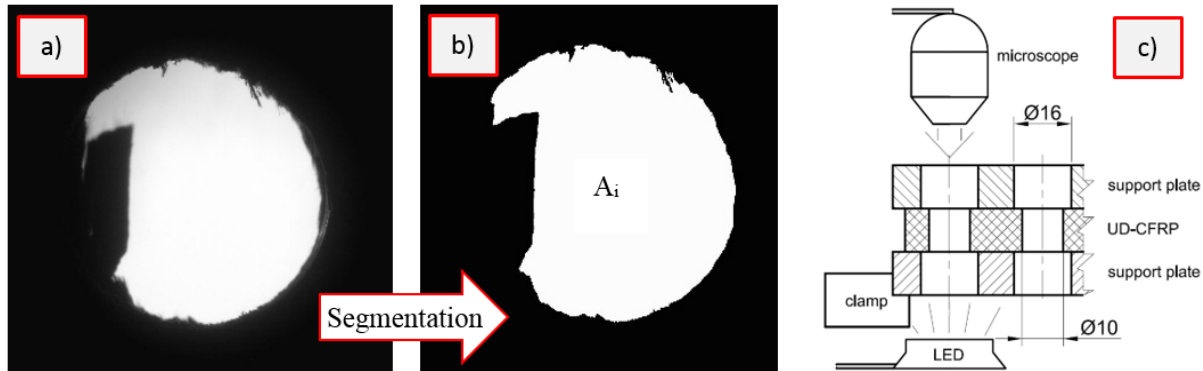


Figure 3. Digital image processing (a) image taken by the digital microscope (b) segmented image using colour histogram (c) measurement setup

In this study, the uncut fibres are characterised by the area factor (α), expressed by Eq. (1).

$$\alpha = \frac{1}{n} \sum_{i=1}^n \frac{A_i}{A_0} \quad (1)$$

where n is the number of holes in one evaluation, A_i is the number of white pixels on the analysed image and A_0 is the number of white pixels on an image of a damage-free hole. If the fibres are cut properly (the hole is damage-free) the ratio of A_i/A_0 is 1. The deviation of the results of DIP of CFRP holes is usually high, using the average of n ratios is therefore necessary.

2.3. Monitoring and diagnostics

The flowchart of the monitored orbital drilling process can be seen in figure 5. Input parameters are the following: A_0 is the number of the white pixels on an image of a damage-free hole, $\alpha_1=0.9$ and $\alpha_2=0.8$ are the critical values of the area factor, h is the screw pitch of the feeding helix, z is the drilling depth, and I is the variation interval of the parameters, as can be seen in figure 4. Based on previous research [5] the influence of h on hole-damage was the most significant, therefore this parameter is used as the first factor of the diagnostics process. With the second factor (z), it is possible to control deeper the cutting tool, so a wear-free helical flute can cut the fibres, which was not used before.

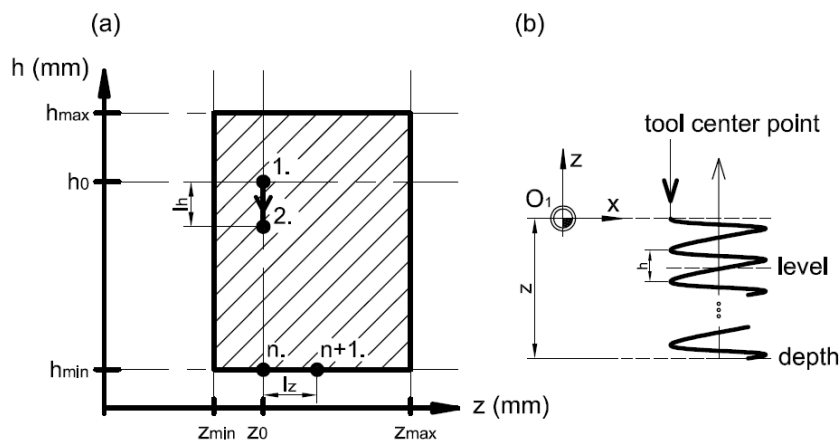


Figure 4. (a) Factor space and (b) tool patch of the monitored orbital drilling process

The explanation of theory of the method used in the tests are as follows. The first orbital drilling experiment is conducted with $h_0=3$ mm and $z_0=14$ mm parameters. In the case when good quality holes

($\alpha > \alpha_1$) were machined, h could be increased with I_h . On the other hand, if $\alpha_1 > \alpha > \alpha_2$, then process parameters should not be changed. Furthermore, if $\alpha < \alpha_2$, then h has to be decreased with I_h until $h \geq h_{min}$. If $\alpha < \alpha_2$ and $h = h_{min}$, then z is increased with I_z until $z \geq z_{max}$. If $\alpha < \alpha_2$ and $h = h_{min}$, and $z = z_{max}$, then the tool is worn and it has to be changed.

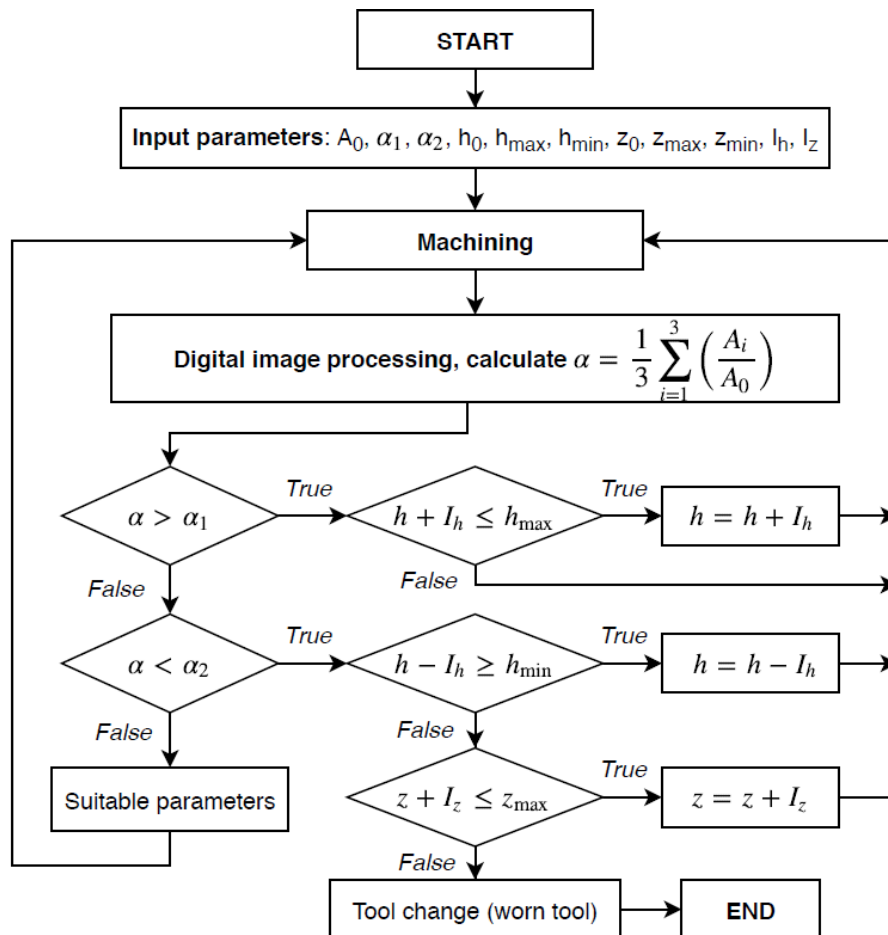


Figure 5. Flowchart of the monitored orbital drilling process

3. Results and discussion

3.1. Results of the drilling experiments when parameters were fixed

80 orbital drilling experiments were conducted with fixed process parameters: cutting speed ($v_c=150$ m/min), feed rate ($v_f=358$ mm/min), screw pitch of the feeding helix ($h=3$ mm) and climb milling without any lubricant liquid was applied. Process parameters were chosen based on previous studies [4, 5] and suggestions by tool manufacturers. Due to the high deviation of DIP of CFRP hole damages, area factor was calculated after each third drilling process from the mean value of the three drilled holes. Number of drilled holes decreases the area factor, as can be seen in figure 6. The possible reason of this is that the cutting edge radius is increased by the number of holes due to tool wear, according to [8]. Furthermore, the fibre fracture mode became bending dominated, the fibres are not cut properly.

Fibre cutting angle (angle between the vector of the cutting speed and the vector of the fibre orientation [8]) has a significant effect on surface quality of CFRP, according to Jia et al. [11]. It can be seen from the result that the middle point of the burr area (where uncut fibres were not cut properly) is located at fibre cutting angle of 130° . Furthermore, it is also clear from the results that the number of holes increases the burr area when orbital drilling CFRP.

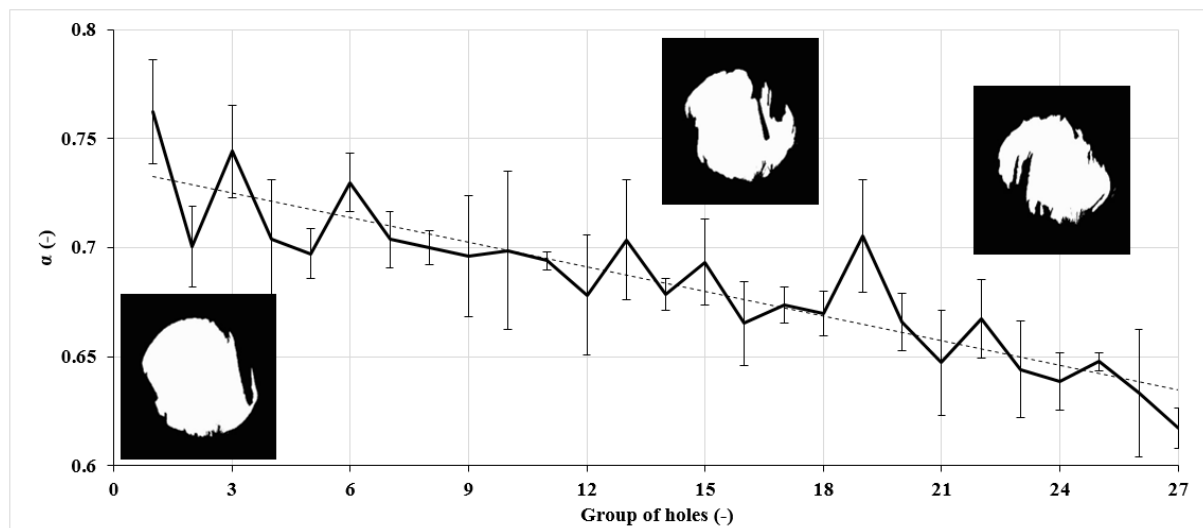


Figure 6. Group of holes vs area factor when drilling of UD-CFRP experiments were conducted with fixed parameters

3.2. Results of the monitored drilling experiments and discussion

According to the experiments described above and previous researches, it was found that the wear of the cutting edge radius is increasing rapidly with large h parameters. Furthermore, it was found that the helical flute length of the end mill is not exhausted totally. Based on these two findings, a decision algorithm was made in order to diagnose orbital drilling process, as can be seen in figure 5. Results of direct monitored orbital drilling experiments can be seen in figure 7.

Results show that in the early period of the monitored experiments (1-5 group of holes) the area factor decreased with the number of holes. However, after the fifth group of holes the area factor started to increase (the hole quality started to improve) due to optimal process parameters. As can be seen in the figure, six good quality holes (group of 8 and 9) were drilled ($\alpha > 0.8$). These better quality holes were achieved by the deeper control of the tool. However, in the case of the tenth group of holes the area factor decreased again due to worn of the helical flute length of the end mill.

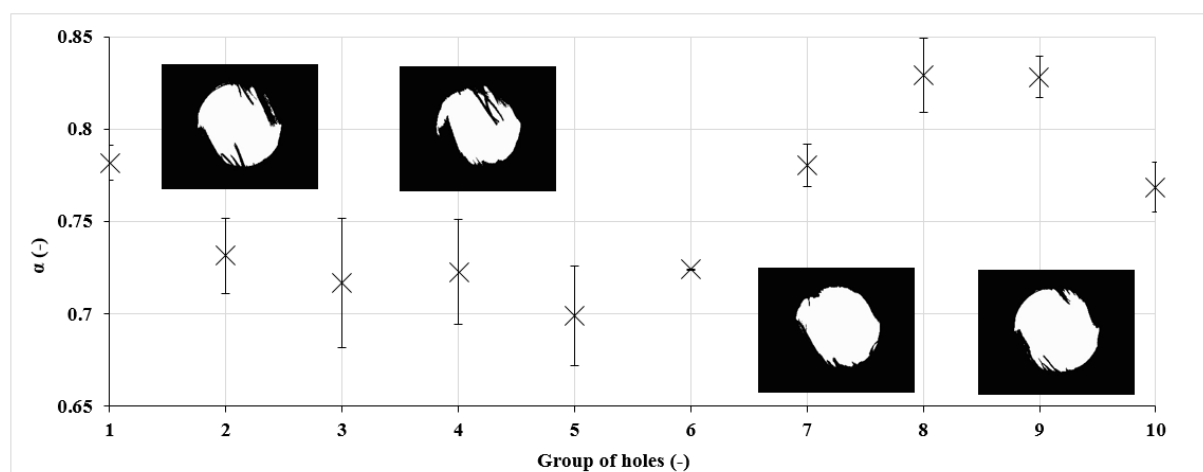


Figure 7. Group of holes vs area factor when monitored drilling of UD-CFRP experiments were conducted

The results of the original and the repeated orbital drilling experiments can be seen on figure 8. It can be seen from the diagram that the monitored drilling process could provide better quality holes

than the original one. However, the machining time of the monitored experiments are longer due to longer cutting tool path. Based on the deviation of the area factor the size of the groups of holes (it was $n=3$ in this study) can be changed in order to optimise the monitoring process. However, in the future, the algorithm has to be optimised based on the present study in order to minimise the number of holes, where $\alpha < 0.8$.

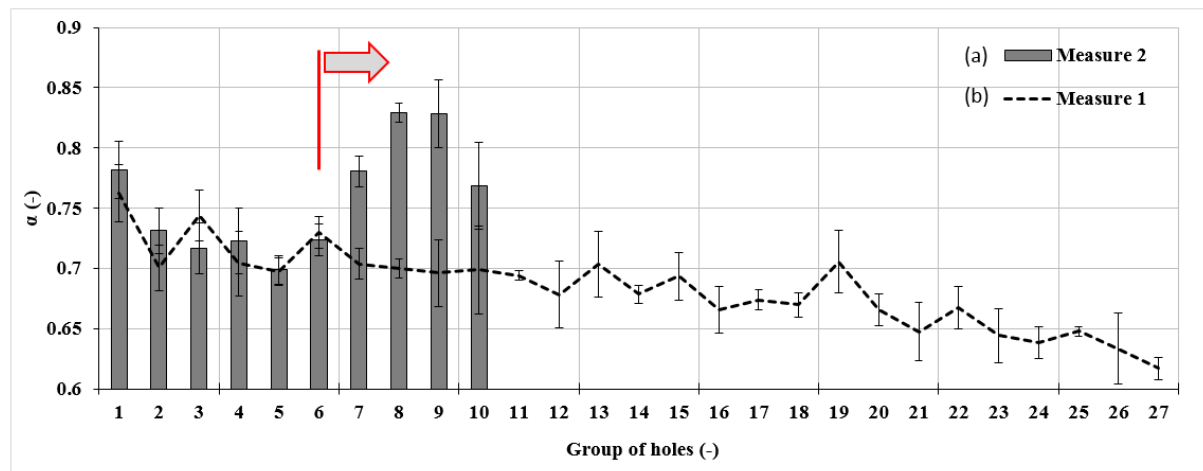


Figure 8. Group of holes vs area factor when (a) drilling of UD-CFRP experiments with fixed parameters and when (b) monitored drilling of UD-CFRP experiments were conducted

4. Conclusions

In the present study, numerous orbital drilling experiments were conducted and the characteristics of uncut fibres were analysed in UD-CFRP. Secondly, the orbital drilling experiments were repeated with direct monitoring of uncut fibres and process control was applied. According to the present study, the following conclusions can be drawn:

- A decision algorithm was developed in order to diagnose orbital drilling process.
- Number of orbital drilled holes decreases the area factor due to tool wear. Furthermore, number of holes increases the burr area too, when orbital drilling UD-CFRP.
- Monitored orbital drilling process could provide better quality holes than the conventional one. However, the machining time of the monitored experiments are longer due to longer cutting tool path.

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