Monitoring of Uncut Fiber in Carbon Fiber-Reinforced Polymer (CFRP) in Drilling

Anand Prakash Jaiswal[1], Hae Gu Lee[1], Hyung Wook Park[1]*

[1]*Department of Mechanical Engineering, Ulsan National Institute of Science and Technology, Republic of Korea*

Abstracts:

Carbon fiber reinforced polymer (CFRP) have better mechanical property, it is used in the specific high-tech area of part manufacturing. Drilling is an important machining concern for part assembly. Nonetheless, the uncut fiber and delamination is the big challenge in the drilling of CFRP, it is difficult to remove or optimized it. This paper identified the uncut fiber and delamination with the help of an image processing technic. First, the numerous of the experiment was done at different conditions of the machining parameters for the optimizing it for drilling. Secondary image processing was performed for the identification of the delamination and the uncut fiber. With the help of image processing count, the number of white pixels in the image and the calculate of uncut fiber area and its factor with the ideal hole of the bidirectional CFRP. The result shows that the uncut fiber is minimum on the low machining parameters and it increases when machining parameters are increases. The area factor decreases with an increase in the number of holes means tools wear increases. The area factor decreases mean uncut fiber increases.

Keywords: CFRP, Bidirectional fiber, Drilling, Digital image process, Uncut fiber, Delamination

1. Introduction:

CFRP (Carbon fiber reinforced polymer) is the present era highly used material in different kinds of prestigious industries like manufacturing of high-speed cars, shipbuilding, aerospace, shuttles industries, the component of wind turbine and many more. It has specific properties high strength with low weight, better dimensional accuracy, corrosion-free material, and better damping capacity also. Above the prestigious product manufacturing industries, they make the number of holes in a single component for assembly and fixing one part to other parts [1]. However, the machining of CFRP is quite difficult as compared to regularly used metals in terms of uncut fiber and delamination. Moreover, it difficult to predict the orientation of the uncut fiber. The drilling of CFRP material is problematic due to its specific structure of laminates, concerning the delamination is the furthermost critical damage in the CFRP drilling [2]. The phenomena of delamination occur during drilling due to the peel-up on the top layer of CFRP and the peel-out on the bottom layer of the CFRP layer of the hole. This study is focused on the bottom layer delamination that means push-out delamination [3].

Drilling and milling machining operations are highly used operations for manufacturing a product. This paper is focused on the monitoring of uncut fiber, delamination length in the drilling process. This work is providing help to understand the length of the uncut fiber and the effect of delamination in the process of drilling. Because with the naked eye it is difficult to examine the existing length of delamination [4]. Many researchers are suggested that the monitoring of the drilling operation is helpful for increase the quality of machining features (micro-cracks, delamination). It also provides help to decide the machining parameters [5].

The orbital drilling is also called the helical milling process in advanced hole manufacturing technology. A good surface quality hole can produce by the orbital drilling process as compared to the traditional drilling process. Geier et al. [1] are found that in the orbital drilling, screw and pitch of the feed were obtained in the bidirectional CFRP which has a significant reason for increasing the delamination followed by spindle speed and feed rate in the orbital drilling process. According to Wang et al. [6], the artificial neural network is the novel method to calculate the cutting force in the helical milling operation with any CFRP fiber orientation. The cutting force prediction closely correlated with the surface quality of hole surface and tool wear. Prediction with this method for online monitoring is a better solution for the machining process.

Several researchers research under this area for monitoring of drilling temperature for CFRP with the wireless sensor which is integrated with the cutting tool holder which provides help in the monitoring process of the CFRP milling [7]. Caggiano et al. [8] developed the investigating method for the recognition of a cognitive pattern in tool wear prediction. The tool wear directly affects the final finished surface. In CFRP due to tool wear another defect also comes in the picture like under-cut, push-out, and uncut fiber in some cases. The monitoring of tool wear could be a suitable method for controlling the quality of the machined surface [9].

Different kinds of the study were done on the effect of delamination and uncut fiber due to the mechanical and structural property of the lamination of the CFRP which gives a negative effect on CFRP drilling and milling. The drilling results show a substantial drop in static strength and fatigue strength. Moreover, it is supposed that a large number of feed rates are the main cause of the delamination, and due to its result provide higher feed force. Nonetheless, many more researchers are obtaining the optimum property of machining, to reduce the delamination and uncut fiber also [10].

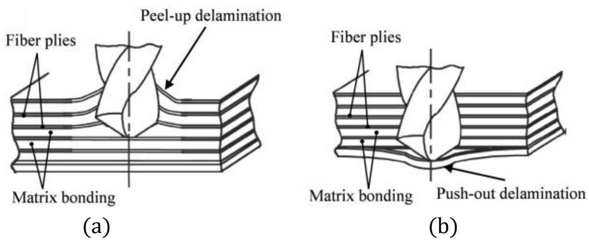

Fig.1. Delamination in drilling (a) peel-up delamination and (b) push-out delamination [11].

The author of this paper is focused to introduce a new digital method for clear visualization of uncut fiber and delamination. This monitoring method provides help in the industrial environment for understanding the defect. The experimental results and its validation method are the main objectives to present this work. For monitoring, digital diagnosis methods are used which is called digital image processing. The digital image investigation characterized the uncut fiber and its length. It also considered the delamination area and its length which, experimentally validate.

2. Digital image characterization of uncut fibers in drilling operation

In the machining of the CFRP different kinds of defects were generated. After the drilling operation, the quality of the drill hole was scrutinized by the two-dimensional digital image processing (DIP) of the microscopic image. Image processing characterizes the uncut fiber and its delamination on the last layer (bottom layer) of the CFRP drilled hole. The original image of drilled hole was taken from the exit side (Bottom side) of the hole. In the image processing, the original image was converted into the binary image for applying the other image processing technic which is done by the self-generating python code.

Figure 2 shows the image processing of uncut fiber and delamination in the 3mm through-hole. Fig. 2 (a) is the original image of the drill hole which shows the delamination and uncut fiber in the CFRP drilling, the image was taken by the microscope on 50X zoom and 1000µm scale size. Fig. 2(b) shows the contour of the uncut fiber which identified the uncut fiber length and direction of the uncut fiber. Figure 2(c) identified the area of uncut fiber with the help of uncut fiber contour. The contour was generated by the source image which is fig. 2(a). The source-coloured image is converted into a binary-coloured image and then contour by the OpenCV library in python [12]. Figure 2(d) provides the help to study uncut fiber by binary scale image it identified the uncut fiber and its length. The optimum parameters are used for the calculation of the area uncut fiber. The average area factor (A_c) of uncut fiber is expressed in equation (1). Figure 2(e) identified the uncut fiber and delamination also, both were occurred on the bottom layer surface in the case of the drilling due to machining condition and property of the CFRP. Figure 2(f) shows only the delamination that occurred on the CFRP drilling. It identified the delamination affected length on the biaxial CFRP sheet due to drilling in terms of the diametrical difference between the maximum and nominal diameter. The maximum diameter indicates the maximum delamination affected region nearby the drilling hole.

$$A_c = \frac{1}{n} \sum_{i=1}^{n} \frac{Ai}{Ao} \quad \ldots\ldots\ldots\ldots (1)$$

Where n is the number of evaluating holes, A_i and A_o are the number of white pixels in the evaluating image with the uncut fiber and evaluating image without uncut fiber (error-free) respectively.

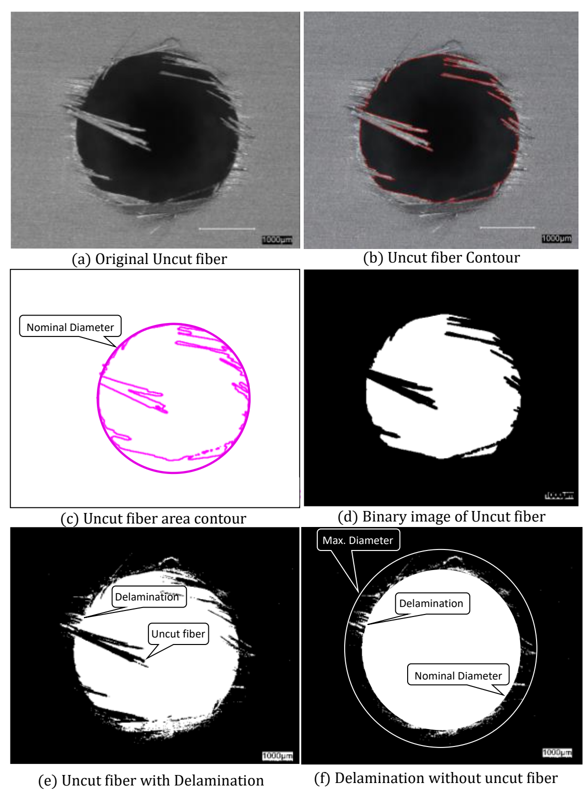

Fig. 2. Digital image characterization of uncut fiber

3. Experimental setup

The bidirectional CFRP drilling experiments were performed on diamond tool Cutting 'DONGBU LIGHTEC/FA-402DSN' CNC machine at dry conditions. The machining was performed on the eight different feed rates 20, 40, 60, 80,100,120,140, and 160 mm/min with four kinds of rotational spindle speed 3000, 5000, 7000, and 9000 RPM with two repetitions. The machining center was used a water-cooled spindle with an air tool holder. For the experiment 'Kennametal' tools were used, which is a high-Performing 3XD drill dia carbide titanium nitride coating tool. The diameter of the tool was 3 mm with a rake angle 30^0 and a point angle 140^0. The through-holes were generated on a 3 mm bidirectional CFRP composite plate. The 100x100mm bidirectional CFRP sheet has 10 numbers of layers with the sequence of 90°, 0°, 90°, 0°…. For the support of drilling used a specific aluminum jig which is shown in fig.3, that provided the support in the drilling operation. KEYENCE VHX-7100 digital microscope was used for the image evaluation. Thirty-two experiments were designed in this experimental study. For each set, two experiments were performed. The experimental results were reaching the goal to evaluate the uncut fiber and delamination by digital image processing.

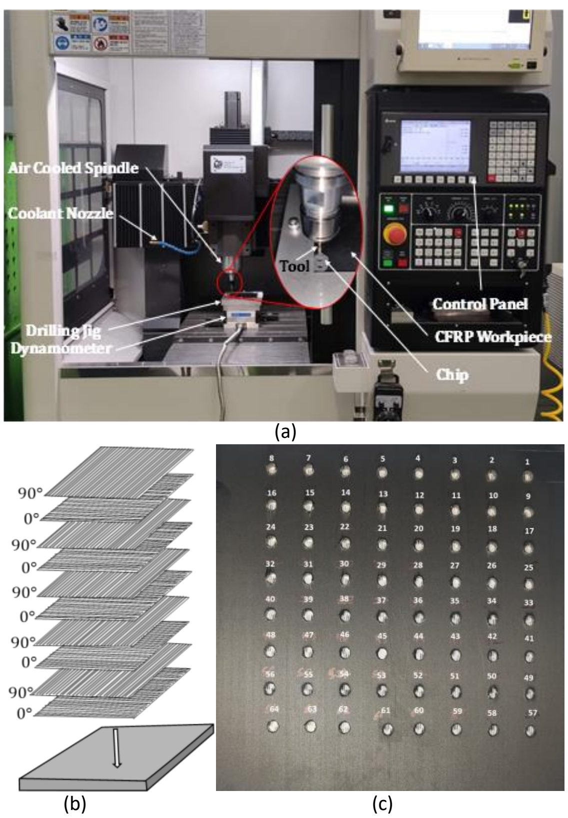

Fig. 3. (a) Machine Experimental setup, (b) Schematic of Multilayer composite fiber (c) CFRP sheet after drilling with uncut fiber (Bottom view)

4. Results and discussion

The experimental study was performed on the two variable parameters feed rate and the spindle speed. According to the reference article, selecting the drilling parameters based on them for the bidirectional CFRP. The selected feed rate starts from a low value of 20 mm/min to a high value of 160 mm/min and tool rotation speed starts from 3000 RPM to 9000 RPM. The operation was performed without lubrication. The average area factor of uncut fiber was calculated by digital image processing after taking the digital microscopic image. For the calculation of the uncut fiber average area factor, uses the same diameter ideal or reference drill hole image.

The uncut fiber in the CFRP drilling was generated due to the lack of support from the last layer. In the CFRP drilling, at the time of cutting bottom layer of the CFRP sheet were provide the base support to the adjacent layer. Moreover, on the layer it does not have an adjacent layer, on the last layer bending is occur due to the point load which, creates uncut fiber. One more impotent reason for uncut fiber is the fiber angle and the tool geometry which provide help in the cutting. The delamination is occurred due to the sub-optimized machining parameters, the distance gap between two consequent holes, and the sticking bound between the two adjacent layers.

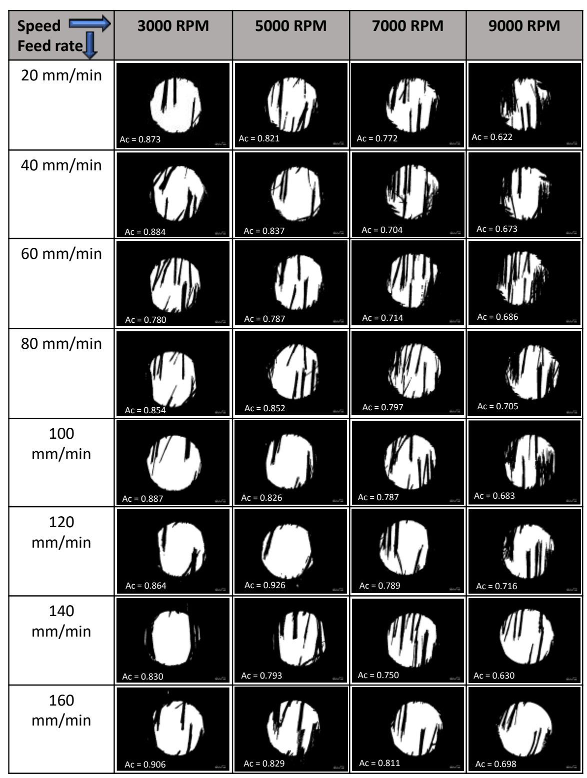

Fig. 4. Drill hole binary image on different machining conditions

Figure 4 shows the results of the two same types of repeated parameter sets of experimental results in which the selected one is shown. The average area factor can be $0 < A_c \leq 1$, 1 is possible only in case of a perfect hole without any error and the 0 is for the worst case. According to the observation of fig. 4 shows that the combination of the low feed and low speed generates less area factor as compared to the other conditions, it also generates a miner length of delamination. Feed rate 20 to 40 mm/min and up to 5000 RPM rotational speed shows the optimum area factor which means minimum uncut fibers.

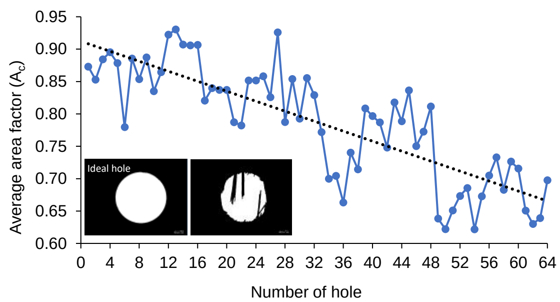

Fig. 5. Average area factor

Figure. 5 shows that the average area factor of uncut fiber which indicates the trend line that is decreasing gradually with the increase of the number of holes. It significantly shows that when tool wears increases then uncut fiber also increases.

5. Conclusions

In this study, the bidirectional CFRP drilling experiment was conducted and image monitoring was done by the image processing technic. The image processing technic generates a contour of the drill hole identified the affected area of the uncut fiber and it also can identify the delamination length. According to the above study, the subsequent conclusion can be drawn:

- With the use of image processing easily investigate the delamination area.
- The low speed and low feed rate give minimum uncut fiber and the delamination also.
- Regarding the time of machining, the error increased concerning the tool wear.

6. References

[1] N. Geier, G. Póka, and C. Pereszlai, "Monitoring of orbital drilling process in CFRP based on digital image processing of characteristics of uncut fibres," *Procedia CIRP*, vol. 85, no. ii, pp. 162–167, 2020.

[2] F. Lissek, J. Tegas, and M. Kaufeld, "Damage quantification for the machining of CFRP: An introduction about characteristic values considering shape and orientation of drilling-induced delamination," *Procedia Eng.*, vol. 149, no. June, pp. 2–16, 2016.

[3] J. Xu *et al.*, "Damage quantification for the machining of CFRP: An introduction about characteristic values considering shape and orientation of drilling-induced delamination," *Int. Conf. Innov. Technol. IN-TECH 2019*, vol. 201, no. June, pp. 2–16, 2018.

[4] C. Pereszlai, N. Geier, D. I. Poór, B. Z. Balázs, and G. Póka, "Drilling fibre reinforced polymer composites (CFRP and GFRP): An analysis of the cutting force of the tilted helical milling process," *Compos. Struct.*, vol. 262, no. December 2020, p. 113646, 2021.

[5] S. A. Ashrafi, P. W. Miller, K. M. Wandro, and D. Kim, "Characterization and effects of fiber pull-outs in hole quality of carbon fiber reinforced plastics composite," *Materials (Basel).*, vol. 9, no. 10, pp. 1–12, 2016.

[6] S. Swan, M. S. Bin Abdullah, D. Kim, D. Nguyen, and P. Kwon, "Tool wear of advanced coated tools in drilling of CFRP," *J. Manuf. Sci. Eng. Trans. ASME*, vol. 140, no. 11, 2018.

[7] M. Zimmermann, L. Heberger, F. Schneider, C. Effgen, and J. C. Aurich, "Investigation of Chip Formation and Workpiece Load When Machining Carbon-fiber-reinforced-polymer (CFRP)," *Procedia Manuf.*, vol. 6, pp. 124–131, 2016.

[8] A. Caggiano, P. Centobelli, L. Nele, and R. Teti, "Multiple Sensor Monitoring in Drilling of CFRP/CFRP Stacks for Cognitive Tool Wear Prediction and Product Quality Assessment," *Procedia CIRP*, vol. 62, pp. 3–8, 2017.

[9] C. Ramirez, G. Poulachon, F. Rossi, and R. M'Saoubi, "Tool wear monitoring and hole surface quality during CFRP drilling," *Procedia CIRP*, vol. 13, pp. 163–168, 2014.

[10] N. Poor, D., Geier, N., Pereszlai, C., & Forintos, "a Pilot Experimental Research on Drilling of Cfrp Under Tensile Stress," *Int. Conf. Innov. Technol. IN-TECH 2019*, vol. 1, pp. 126–129, 2019.

[11] J. Xu, C. Li, S. Mi, Q. An, and M. Chen, "Study of drilling-induced defects for CFRP composites using new criteria," *Compos. Struct.*, vol. 201, no. March, pp. 1076–1087, 2018.

[12] S. O. Bochkarev, I. B. Litus, and N. S. Kravchenko, "Irregular objects. Shape detection and characteristic sizes," *CEUR Workshop Proc.*, vol. 1814, no. 2, pp. 28–35, 2017.