



Development of a step drill for minimization of delamination and uncut in drilling carbon fiber reinforced plastics (CFRP)

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Abstract

A step drill is developed to minimize delamination and uncut fiber in machining carbon fiber reinforced plastics (CFRP), which consists of two parts, a core part and a step part. The core part is designed to minimize the thrust force by controlling core diameter. The step part is designed to remove the delamination generated by core part without 2nd delamination, which consists of step angle. The effect of feed rate and spindle speed on the performance of drilling also investigated. To remove the uncut fibers properly, the higher rake angle of step part is applied. By measurement of thrust force, it is found that the delamination can be reduce when smaller thrust force is generated. As a result, a step drill is designed for less generation of delamination and uncut fiber for drilling T700 3K CFRP.

Keywords Drilling · Delamination · CFRP · Step drill

1 Introduction

Carbon fiber reinforced plastics (CFRPs) are attractive to high value-added industries, such as the automotive, athletics, and aerospace industries, because it has an excellent strength to weight ratio relative to other materials. Typically, CFRPs are assembled with mechanical joints (such as rivets) through drilled holes to form parts [1]. The quality of the drill hole is important, particularly in the aerospace industry, because a significant amount of drilling is required during the assembly process. However, because of the characteristics of CFRP, delamination and uncut fiber can occur during drilling [2]. CFRP is different from isotropic materials like steel, because it is made by laminating anisotropic carbon fibers. Because of the anisotropic characteristic of CFRP, there is a high probability that for a certain range of holes, delamination will occur during drilling and some fibers will remain uncut. These problems are more often observed in

unidirectional (UD) CFRP, which is made with unidirectional fiber [3, 4]. In UD-CFRP, uncut fibers occur more frequently in certain locations, according to the direction of the fibers and the cutting direction of the drill. The mechanism for generating uncut fibers is illustrated in Fig. 1a. Between 90–180° and 270–360°, the protrusion direction of the fibers in the hole is opposite to the cutting direction of the drill, so that adequate cutting force is transmitted by the cutting edge of the drill. As a result, the fibers can be cut well. However, between 0–90° and 180–270°, the protrusion direction of the fibers in the hole approximately parallel to the cutting direction of the drill. Uncut fibers are therefore generated, because the cutting edge may remove the CFRP resin more easily than the fibers, which has a higher tensile strength.

As shown in Fig. 1b, because of the characteristics of the composite, fractures occur between the fiber layers when the entry and exit portions of the CFRP are drilled, that is, in areas where there are no layers above or below the layer being drilled. Therefore, if the fracture is sufficiently large, separation occurs at the entrance and exit sites. Delamination refers to the separated layers that remain after processing. The peel-up delamination at the entrance is affected by peeling force, which is generated by machining along the direction of the flute. At the exit, push-down delamination is caused by thrust force, which is generated by the machine tools in the feed direction of the drilling [5–7].

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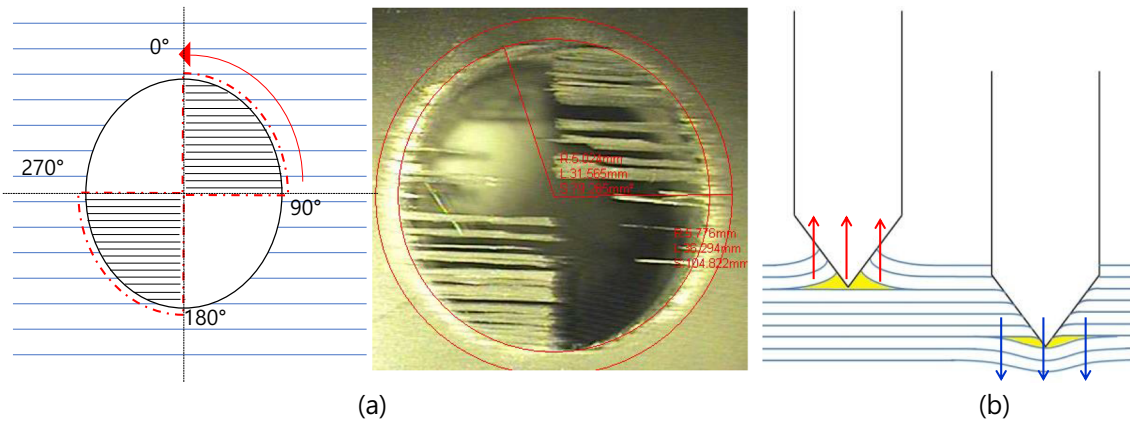


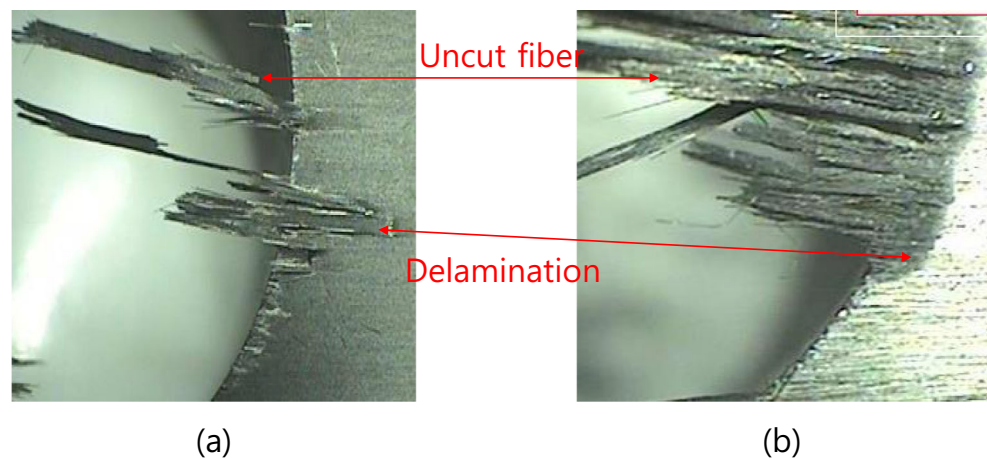
Fig. 1 **a** Schematic diagram of production mechanism of uncut fiber and actual working example. **b** Delamination

The mechanisms that generate delamination and uncut fiber are interdependent. As shown in Fig. 2a, fibers remain attached in the area of delamination. Additionally, delamination occurs when uncut fiber is generated, as shown Fig. 2b, at which the delamination is relatively small. In addition, the uncut fiber is pulled along the flute by the entrance delamination peeling force or exit delamination thrust force. Considering that more than 60% of parts are rejected as final parts in aircraft assembly [2], this is a widely acknowledged problem, and a significant amount of research attention has been paid to developing a drill shape that will suppress delamination and uncut fiber.

Many researchers have investigated delamination due to drilling. H. Hocheng and C. C Tsao [8, 9] modeled the cutting force of various types of drills, such as twist drills, saw drills, candle stick drills, and core drills; and studied the relationship between cutting force predictions and the cutting force at which delamination occurred. This information was used to calculate the critical thrust force and critical feed rate for each drill. Using various machining conditions, Feito et al. [10] compared cutting force and delamination between a brad drill, reamer drill, and step drill.

Also, Feito et al. [11] modeled the thrust forces of general drills, worn drills, and step drills and compared the predicted force values with experimental values. Additionally, they analyzed how feed rate and cutting speed affected delamination. Lin Zhang et al. [12] examined the shape of burrs, tool wear, cutting force, and lifetime by using two types of drills on CFRP and alloy stacked specimens. As a result, the crown-shaped drill showed better performance than the general shaped drill, and the best process results were obtained at the rotation speed of 4000 rpm and the feed rate of 0.04. Also, after 400 holes, the quality of the hole dropped drastically due to flank wear. Jinyang Xu et al. [13] compared cutting forces according to feed and spindle speeds of brad spur drill, dagger drill, and twist drill, and analyzed the characteristics of machined holes in each case. The critical thrust force was also calculated through the relationship between the 3D delamination factors and the thrust force, and the accuracy of the machined hole and the mode of wear were examined. Recently, various methods have been studied to improve the precision of CFRP machining such as ultrasonic-assisted drilling [14], waterjet-guided laser cutting [15], and rotary ultrasonic

Fig. 2 Relationship between delamination and uncut fiber. **a** Uncut fiber at the location of delamination. **b** Delamination with uncut fiber



machining [16] as well as the classical drilling process. However, these methods require the installation of new equipment by the additional investment. Compared with these methods, the new step drill can minimize the delamination efficiently.

Ko et al. [17] developed a burr-minimizing drill through experiments with a standard carbide drill, chamfer drill, round drill, and step drill. The researchers observed that the step drill produced the smallest thrust force and minimized burr formation in the exit stage. Therefore, a step drill with a different design could potentially minimize delamination. Considering that the most important cause of delamination is the thrust force generated during drilling, we designed a step drill that will produce minimal thrust force when drilling CFRP.

2 Design of step drill and cutting mechanism

During previous work on minimizing burr formation when drilling metal, many types of drills have been manufactured and assessed. Step drills with optimized geometries have been demonstrated to minimize burr production during drilling. By understanding delamination and burr formation are formed by the thrust force at the exit stage of drilling, we become to know that they are formed through similar basic mechanisms. This observation guided us to use the step drill to minimize delamination, considering the effects of thrust force and machinability during drilling. As shown in Fig. 3, the step drill for CFRP was divided into two parts: a core part with a smaller diameter, D_2 , and a step part, which may remove the material remaining after core-part drilling and can be specified with step angle, θ_1 . As shown

in Fig. 3c, the rake angle of step part can be defined at the cross section to the drill axes at a specified location. Figure 4 shows the delamination mechanism for the step drill. The core part, with smaller diameter D_2 (see Table 1), produces a small hole with delamination and uncut fiber. The delamination area decreases with decreasing diameter and is expected to be located within the final hole area, where material will be removed by the step part of drill. Step-part drilling is expected to remove the delamination and uncut fiber generated by core-part drilling. The thrust force in step-part drilling must be kept small, so that less delamination is generated. Instead, step-part drilling is expected to remove the delamination generated by core-part drilling. If the thrust force increases above a certain level, additional delamination will be generated during step-part drilling. To ensure that this does not occur, the step angle, θ_1 , will be controlled to a sufficiently low value. However, as the step angle becomes small, it becomes very difficult to machine due to the increased friction between step drill and specimen in the feed direction. Therefore, an optimum step angle must be identified experimentally.

In summary, the two most important factors in the design of a step drill for CFRP are the diameter of the core part and the step angle. If the core diameter is too large, then delamination by the core part will increase above what the step part can remove. However, if the core diameter is too small, then the step part must perform significant machining, producing secondary delamination and severe wear on the step part of the drill. To balance these tradeoffs and design an appropriate drill, experimental analyses are conducted.

While the step part can minimize delamination, it can also reduce the number of uncut fibers. However, the small

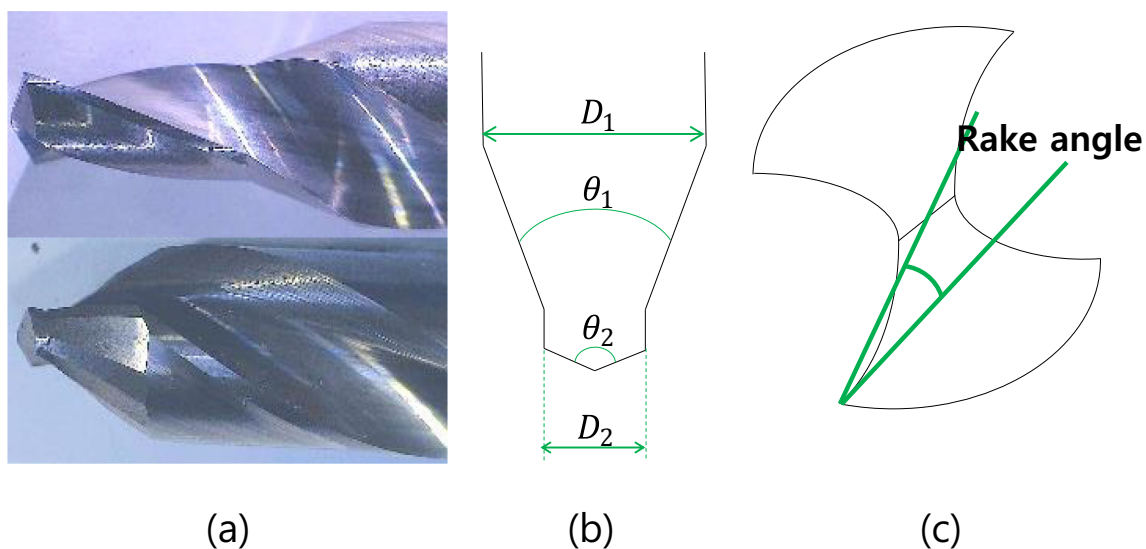


Fig. 3 a Step drills used for experiment. Long core drill is designed for easy measurement of cutting force for comparison with prediction forces. b Configuration of step drill. c Cross section of step drill

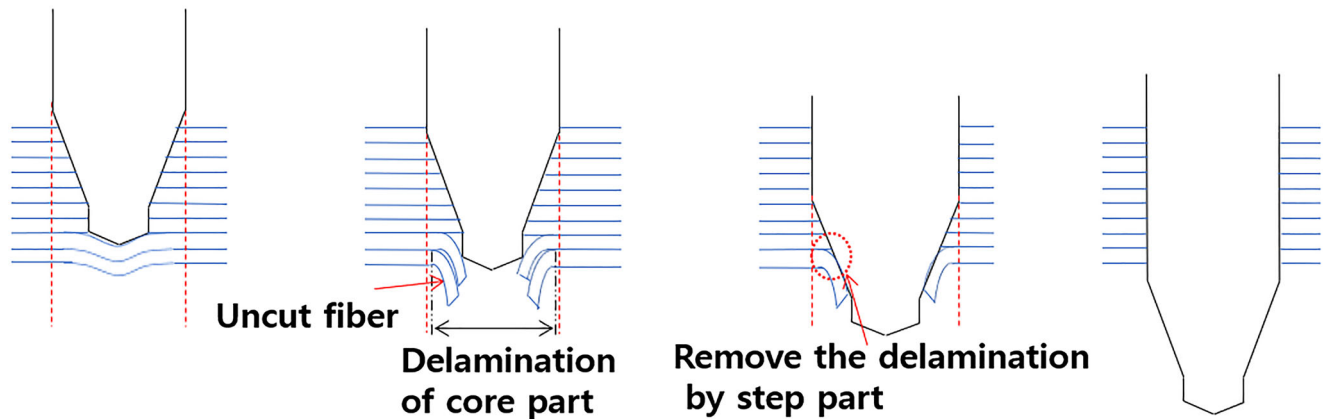


Fig. 4 Mechanism of minimization of delamination in drilling CFRP

step angles that are suitable for reducing delamination are also likely to produce uncut fiber, because of decreased machinability. For a given step angle (e.g., an angle designed to minimize delamination), the removal of uncut fiber can be enhanced by designing the edge of the step part to be sharper, giving it better machinability. A larger rake angle can reduce uncut fiber. The sharper step-part edge may more easily remove the fibers, even when the cutting direction is parallel to the protrusion direction of the fiber, as in Fig. 1a. Of course, the wear problems caused by sharper edges may be also handled more later. In addition, small step angles can increase the overall length of the drill, which will increase the processing time required for drilling. Therefore, when designing the length of the step drill, it is important to optimize the core diameter, step angle, and rake angle, according to the specific characteristics of the CFRP.

3 Experiment

As the drilling specimen, 10-mm thick UD-CFRP(T700 3K) is used. UD-CFRP tends to exhibit more delamination than woven CFRP in which fibers are interwoven at 90° angles. Because it is anisotropic and has higher strength, UD-CFRP is widely used in the aerospace industry. An

uncoated carbide drill was used to drilling a 10-mm hole. As shown in Fig. 3a, the drill has a core part and a step part. The core part has a diameter of D_2 , which is less than 10 mm, and a standard point angle of 140°. The step part has a step angle of θ_1 . All drills are 10 mm in diameter with a helix angle of 25.4°. In this study, various drills are fabricated, by adjusting the diameter of the core part and the step angle. The rake angle was varied as 14.2° and 28.4°, and the effects of rake angle on uncut fiber removal were analyzed. The parameters of each drill are shown in Table 1.

The optimal geometry was determined from cutting performance experiments, by measuring the delamination and uncut fiber generated by each drill. Additionally, the optimal cutting conditions were determined by comparing the cutting performance for various combinations of feed rate and spindle speed. Spindle speed was varied as 1000, 2000, and 3000 rpm, and feed rate was varied as 150, 300, 450, and 600 mm/min. Cutting performance was analyzed by measuring the delamination factor, D_f , and the area ratio of uncut fiber, R_{uf} . The delamination factor is defined as $D_f = D_{max}/D$, as shown in Fig. 5a, where D_{max} is the maximum diameter of the circle which includes maximum delamination and “ D ” is the diameter of hole. The area ratio of uncut fibers is defined as, $R_{uf} = A_{uf}/A$, where A_{uf} is the area of the uncut fiber and A is the area of the hole. A_{uf}

Table 1 Geometry of the drill used in the experiment

| Number | Species | $\theta_1(^{\circ})$ | $D_1(\text{mm})$ | $\theta_2(^{\circ})$ | $D_2(\text{mm})$ | Rake angle($^{\circ}$) |
|--------|----------------|----------------------|------------------|----------------------|------------------|--------------------------|
| 1 | Standard drill | – | 10 | 140 | – | 14.2 |
| 2 | Step drill | 40 | 10 | 140 | 7 | 14.2 |
| 3 | Step drill | 40 | 10 | 140 | 6 | 14.2 |
| 4 | Step drill | 40 | 10 | 140 | 5 | 14.2 |
| 5 | Step drill | 40 | 10 | 140 | 4 | 14.2 |
| 6 | Step drill | 20 | 10 | 140 | 4 | 14.2 |
| 7 | Step drill | 60 | 10 | 140 | 4 | 14.2 |
| 9 | Step drill | 60 | 10 | 140 | 4 | 25.4 |

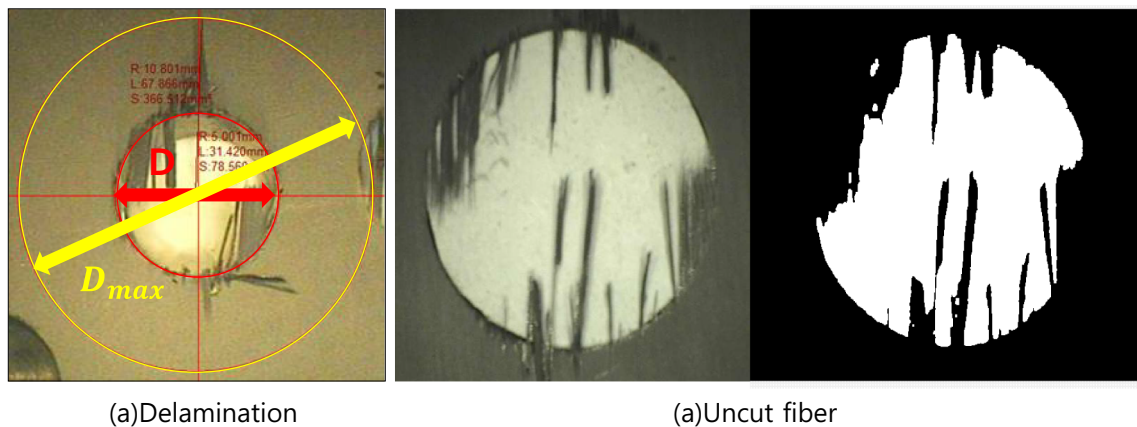


Fig. 5 a Observation of delamination and definition. b Image of uncut fiber and image processed picture

and A will be measured by the number of pixels for each image which can be obtained by image processing as shown in Fig. 5b.

4 Experimental analysis for minimizing delamination and uncut fiber

4.1 Effects of diameter of core part

To understand how CFRP cutting performance is affected by core diameter, we prepared drills with core diameters of 4, 5, 6, and 7 mm, all of which had 140° point angles. The geometry of the step part was kept constant, with a step angle of 40° and diameter of 10 mm. For comparison, experiments using a standard drill 10 mm in diameter without a step part are also conducted. With respect to the cutting conditions, a spindle speed of 3000 rpm and a feed rate of 450 mm/min are used. Figures 6 and 7a show the change in delamination factor, D_f , and uncut ratio, R_{uf} , for each drill. It can be seen that the step drill reduced delamination relative to the standard drill. As the core diameter increases, the delamination factor increases, as does the uncut ratio. When core diameter of 4 mm showed lower delamination factor D_f , by 0.5 and lower uncut fiber ratio R_{uf} by 10% compared with the drill with larger core diameter 7 mm.

Smaller thrust force at smaller core diameter causes smaller delamination compared with the large diameter [5]. And the smaller delamination is analyzed to be removed easily from the step part. These results are similar to those of Xinyi Qiu [18]. The delamination generated by core drilling is then removed by step drilling. As a result, a drill with a smaller core diameter generated less delamination. Additionally, the uncut ratio increases as core diameter increases, because less delamination produces a lower amount of uncut fibers for the same cutting conditions.

4.2 Effects of step angle

To analyze how changes in step angle affected drilling performance, drills with core diameters of 4 mm and step angles of 20° , 40° , and 60° are experimented with a spindle speed of 3000 rpm and a feed rate of 300 mm/min. Figures 7b and 8 show the smallest D_f value at 40° . The D_f value increased substantially for a step angle of 20° . It was expected that smaller thrust forces will cause less delamination. However, when drilling with a step angle of 20° , loud noises and high due to the severe friction created by the very small step angle were observed. The very low machinability at a step angle of 20° induced significant delamination and left many fibers uncut, as shown in Fig. 8. Drilling with a step angle of 60° increased the thrust

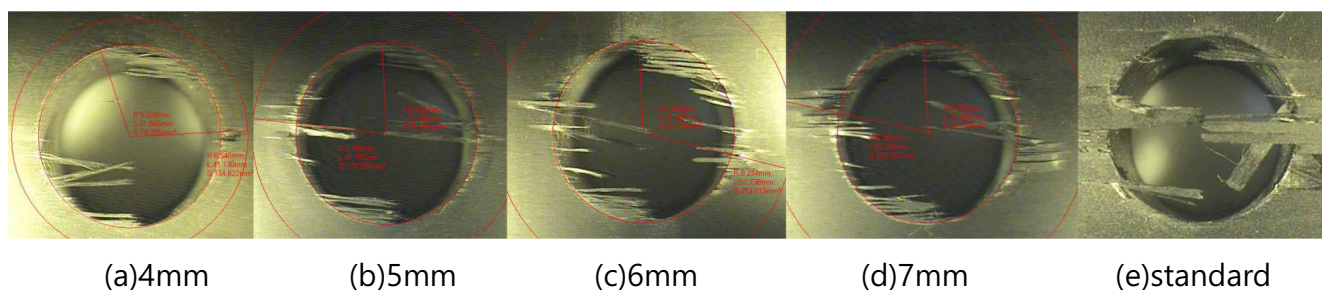


Fig. 6 a–e Observation of delamination and uncut fiber on the exit surface in drilling with different diameter of core part (diameter 10 mm, step angle 40° , point angle 140° , rake angle 14.2° , rpm 3000, 450 mm/min)

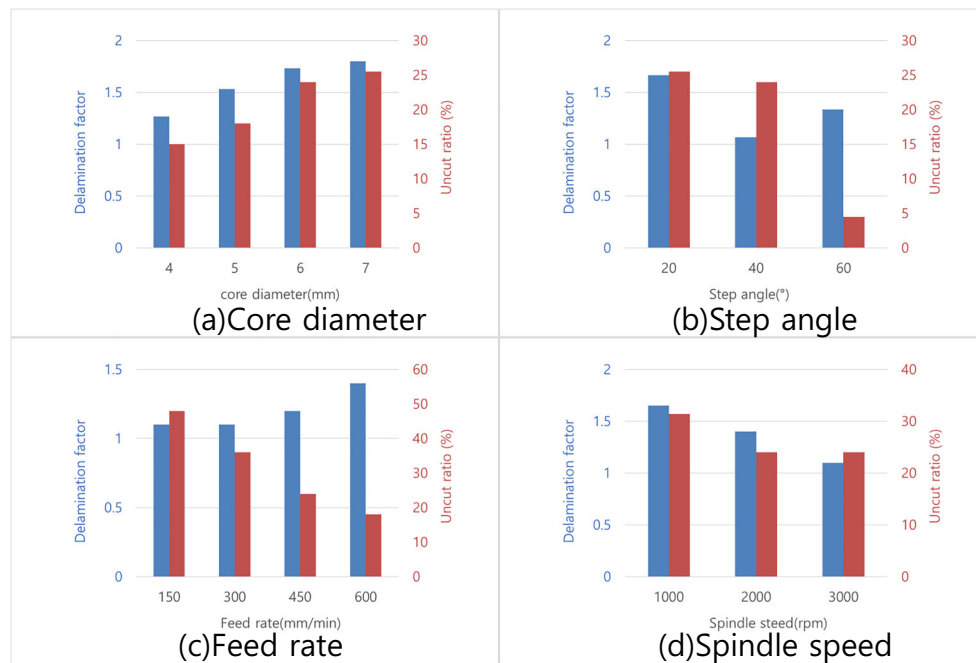


Fig. 7 Delamination factor and uncut ratio in drilling with different geometry and cutting conditions with same point angle of 140° of core part, rake angle 14.2° , and diameter 10 mm. **a** Different diameter of core part (step angle 40° , rpm 3000, feed rate 450 mm/min).

b Different step angle (core diameter 4 mm, rpm 3000, feed rate 300 mm/min). **c** Different feed rate (core diameter 4 mm, step angle 40° , rpm 3000). **d** Different rpm (core diameter 4 mm, step angle 40° , feed rate 300 mm/min)

force at the step portion, causing more delamination. However, uncut fibers decreased because of the machinability improvements. From these results, it can be observed that delamination is dependent on thrust force and machinability and that uncut fibers are well removed in cases where machinability is better.

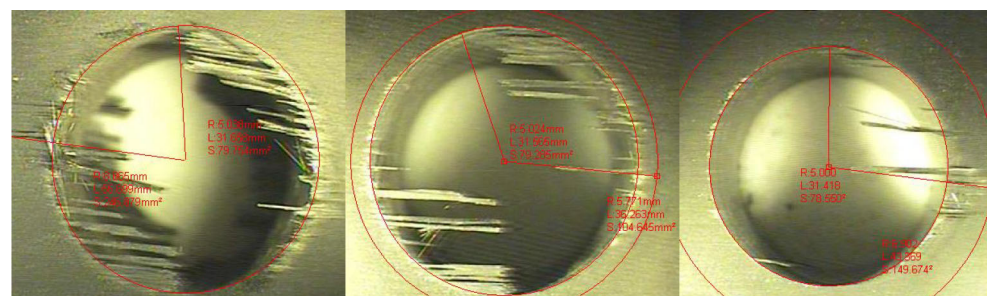
4.3 Effects of feed rate and spindle speed

It is investigated how different feed rates affected drilling performance, maintaining the drill geometry constant with a core diameter of 4 mm, point angle 140° , and step angle of 40° . Four different feed rates (150, 300, 450, 600 mm/min) were applied for a constant spindle speed of 3000 rpm. It is clearly observed that drilling with a larger feed rate

produced more delamination but fewer uncut fibers. The case of feed rate of 150 mm/rev showed lower delamination factor D_f , by 0.4 and larger uncut fiber ratio R_{uf} by 30% compared with the case of larger feed rate 600 mm/rev. It is well understood that higher feed rates produce larger thrust forces, which produce more delamination [3]. For the core part of the drill, the most delamination was produced at a feed rate of 600 mm/min. The delamination that remained after step-part drilling at this feed rate is shown in Fig. 9d. However, larger feed rates produced better machinability of uncut fibers. Very low feed rates can be expected to push the last layer of CFRP very slowly like rubbing, which will produce large amounts of uncut fibers.

To investigate the effects of changes in spindle speed, speeds of 1000, 2000, and 3000 rpm are applied, maintaining

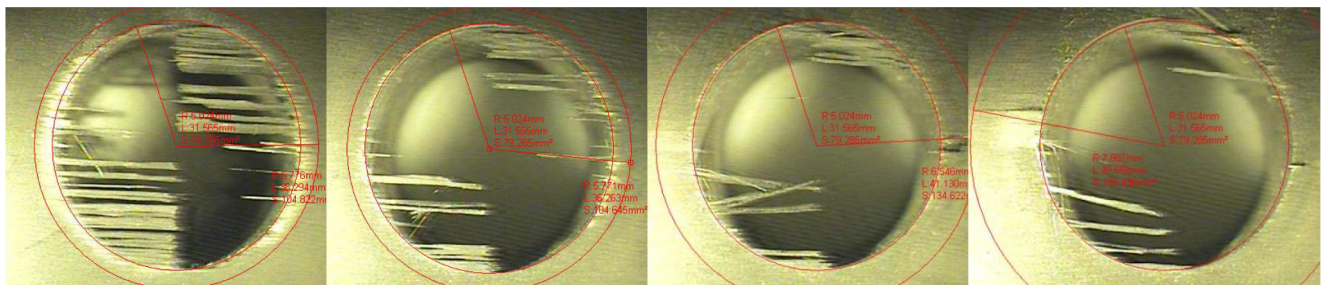
Fig. 8 a–c Observation of delamination and uncut fiber in drilling with different step angle (core diameter 4 mm, point angle 140° , rake angle 14.2° , rpm 3000, 300 mm/min)



(a) 20°

(b) 40°

(c) 60°



(a)150mm/min (b) 300mm/min (c) 450mm/min (d)150mm/min

Fig. 9 a–d Observation of delamination and uncut fiber in drilling with different feed rate (core diameter 4 mm, point angle 140°, step angle 40°, rake angle 14.2°, rpm 3000)

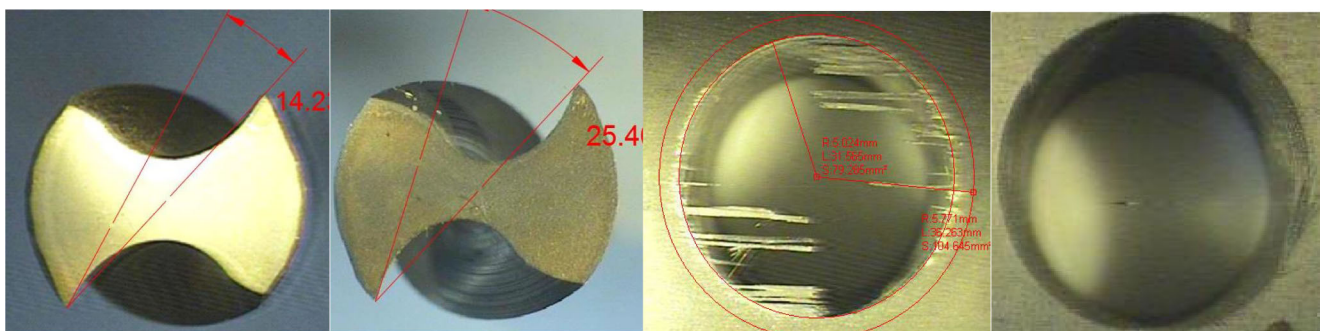
the feed rate constant at 300 mm/min, and using a step drill with a core diameter of 4 mm, point angle of 140°, and step angle of 40°. Using a larger spindle speed with the same feed rate means that the feed per rotation is reduced, which leads to reductions in thrust force. As a result, delamination is expected to decrease, as shown in Fig. 7d. The occurrence of uncut fibers also tended to decrease, but this effect was less pronounced than was observed for feed rate. In the experiment, according to the change of spindle speed and feed rate, it was proved that increasing the feed per rotation increased delamination. The effect of feed rate and spindle speed on CFRP using step drill is similar to that of Xinyi Qiu [18]. However, in practice, even high spindle speeds induced decreases in delamination and uncut fiber, there are limitations associated with very fast tool wear, which must be handles for the development of grade and coating later.

From our experiment comparing how changes of different variables could be used to minimize delamination and uncut fiber, we determined that the core diameter should be 4 mm, as is clearly shown in Figs. 6 and 7a. The step angle is selected as 40° from Figs. 7b and 8 to minimize

delamination. Even uncut fibers are not clearly removed, the drilling conditions (such as feed rate and spindle speed) can be adjusted according to the type of CFRP. For materials T700 and 3K, a spindle speed of 3000 rpm and feed rate of 300 mm/min are recommended. However, in this experiment, even when delamination was minimized $D_f=1.1542$, uncut fibers problems remained serious, with $R_{uf}=23.7\%$. This is shown in Fig. 7b. To solve this problem, an additional drill geometry factor was considered: the rake angle of the step drill. Higher rake angles of step part may increase machinability, which is expected to improve the removal of uncut fibers.

4.4 Analysis of rake angle for minimizing uncut ratio

As demonstrated in previous experiments, the step drill had a great effect on minimization of delamination. However, it was found that uncut fibers could not be completely removed by changing the drill core diameter and step angle or by changing the cutting conditions. Additionally, we observed that the removal of uncut fibers is strongly correlated with machinability during drilling, which can be



(a)14.2° (b)25.4° (c)14.2° (d)25.4°

Fig. 10 a, b Sectional shape of step drill with the change of rake angle. **c, d** Observation of delamination and uncut fiber according to the change of rake angle (core diameter 4 mm, point angle 140°, step angle 40°, feed rate 300 mm/min, rpm 3000)

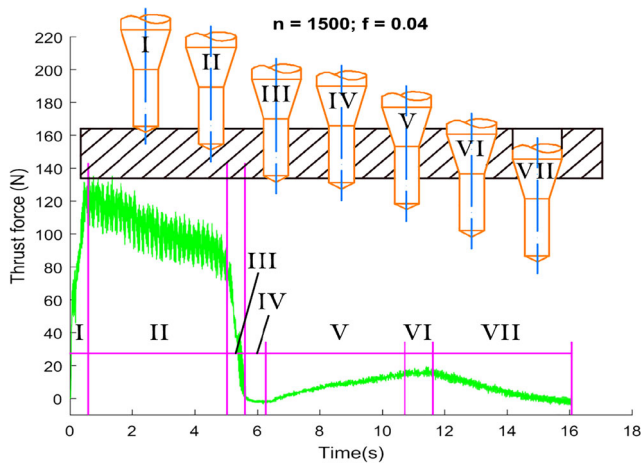


Fig. 11 Cutting force measurement according to the drilling processes by step drill

improved by increasing the step angle and feed rate, as shown in Figs. 8 and 9. From this sense, as one of the geometrical factors that can be handled by design, the change of rake angle of step part is expected to improve the machinability for removing the uncut fibers. Using the optimized step drill geometry determined in the previous experiment (core diameter of 4 mm, step angle of 40° , and rake angle of 14.2°), the rake angle from 14.2° to 25.4° , expecting improvements in machinability, as of step part is changed shown in Fig. 10. As can be seen in the figure, because of the manufacturing process, the actual rake angles were 14.2° and 25.4° . Using the same step drill geometry and cutting conditions, we successfully minimized delamination and uncut fiber. As shown in Fig. 10d, $D_f=1$ and $R_{uf} \cong 0\%$, which was the best result. We had not expected delamination to disappear when the uncut fibers were removed completely. This is because the delamination in Fig. 10c is caused by uncut fibers generation, as

depicted in Fig. 3b. Therefore, the delamination also disappeared when the uncut fibers were removed as a result of the rake angle being increased from 14.2° to 25.4° .

5 Analysis on the cutting forces in drilling with step drill

Understanding the cutting forces in drilling CFRP would suggest proper way for the design of new tool geometry and reasonable cutting parameters. The analysis on the thrust force will give a good clue for optimum design of drill geometry as well as optimum cutting parameters in order to achieve the least delamination occurrence.

Figure 11 shows the thrust force data obtained through drilling process for CFRP by step drill which is designed in this study. It is obvious that the thrust force at step part is much smaller than that by the core part, because the step part does not contain the chisel edge as the core part, which is explored as the main region contributing to the thrust force. By using the special design of step drill with long step length between core part and step part as in Fig. 3a, cutting forces from two cutting lips of each part can be measured separately. The drilling stages can be described as follows. At stage I, there is a sharp increase of thrust force because the tip of the core part starts cutting into the specimen. The force at this stage is induced by the chisel edge area and the cutting lip of core part of drill. At stage II, when the core part had entered completely the specimen, the thrust force should be constant, but it decreases slightly. The reduction in thrust force while increasing the drilling depth can be explained by the elastic deformation of the remained uncut part of the specimen, which is continued until the cutting lips arrive to the last layer of CFRP. Also, by the heat generation during the cutting process and the low thermal conductivity of epoxy matrix, the accumulated heat will induce the rise of temperature and the decrease of

Fig. 12 Comparison of the measured thrust forces and prediction by force model according to the change of **a** diameter of core part (step angle of 40° , feed rate 450 mm/min, 3000 rpm) and **b** feed rate (core diameter 4 mm, step angle 40° , 3000 rpm)

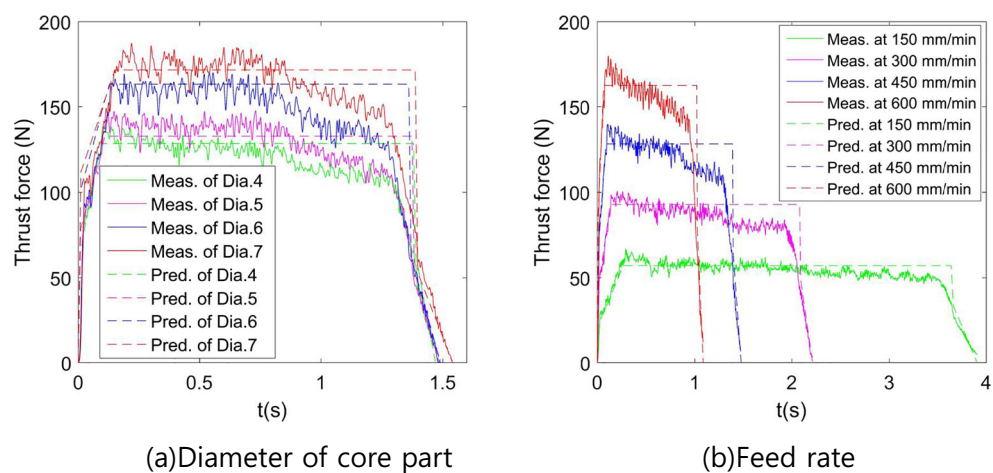
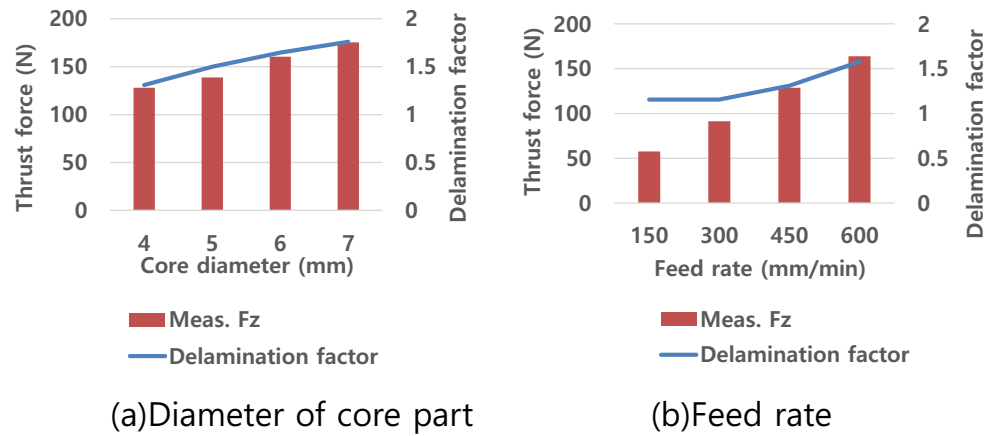


Fig. 13 Comparison of measurement and prediction of thrust forces and delamination factor according to the change of **a** diameter of core part (step angle of 40°, feed rate 450 mm/min, 3000 rpm) and **b** feed rate (core diameter 4 mm, step angle 40°, 3000 rpm)



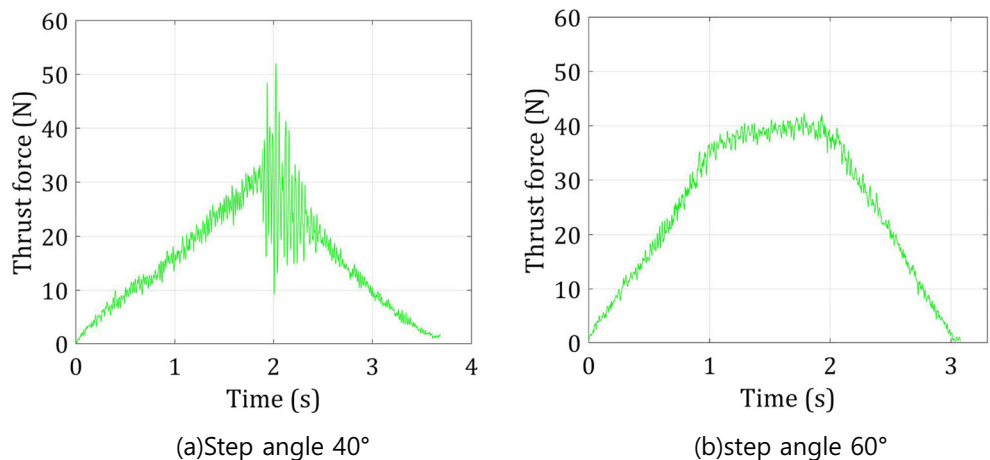
the mechanical strength of the specimen, which leads to a decrease of the thrust force. Then the drill starts going out of the specimen at stage III leading to a rapid drop of thrust force. Stage IV shows the non-cutting at intermediate length between the cutting lips of core part and step part. At stage V, the step part enters to the specimen, and the thrust force increases until the drill was completely in the specimen as at stage VI, where the force remains almost constant. At stage VII, when the step part was coming out of the specimen, the thrust force gradually decreases to zero.

It is well observed that the thrust force at the step part is much smaller than that at the core part, which means that most generation of delamination is decided by the core part. The step part may have two kinds of role: the first one is to remove the delamination generated at core part with second generation of delamination. The second important role of step part is to remove uncut fibers properly. Figure 12 shows the measurement of the thrust forces in drilling with only core part of different core diameter and feed rate, which covers the stage I, II, and III in Fig. 11. These experiments are accomplished with the same point angle of core part of 140°, step angle 40°, rake angle of 14.2°, and spindle speed of 3000 rpm. From Fig. 13,

it is well proved that the core part with larger diameter and larger feed rate produces larger thrust force, which induces the larger delamination proportionally as shown. It can be observed that the tendency of the delamination factor is very well coincident to the change of the thrust forces, which will be used for the optimum design of the step drill for minimization of delamination. Even it shows some difference of the trend when feed rate is low like 150 and 300 mm/min, generally the trend of delamination factor is well matched with that of feed rate. The increase of delamination can be attributed to the increase of feed rate, particularly at first part of core part. The thrust force increases according to the increase of feed rate, then it induces more delamination as shown in Fig. 13 [3].

Figure 14 shows the measured thrust forces when drilling with step part of two different step angles, 40° and 60° with the same conditions as core diameter of 4mm, rake angle 25.4°, and feed rate 300 mm/min and 3000 rpm. The drilling result is shown in Fig. 10d when step angle is 40°. To observe the behavior of the step part easily, only the thrust forces by the step part are described, which covers the stage V, VI, and VII in Fig. 11. The step drill is designed with long step length to separate the force observation

Fig. 14 **a, b** Observation of thrust forces in drilling with step part with different step angle (core diameter 4 mm, rake angle 25.4°, feed rate 300 mm/min, 3000 rpm)



between core part and step part. In both cases, delamination factor and the area ratio of uncut fiber are measured as $D_f=1$ and $R_{uf} \cong 0\%$, which means perfect delamination and uncut fiber removing were performed. However, observing the noise from the thrust force signal in Fig. 14a, some interference in removing the fibers can be estimated due to the friction between fibers and cutting edge when step angle is 40° .

Comparatively, there is a clean force signal can be observed when drilling with step angle of 60° , even the thrust force is little bit higher than the case of step angle of 40° . As a conclusion for the design of the step drill with 10-mm diameter for machining CFRP, T700 3k, the diameter of core part of 4mm, step angle of step part 40° , and rake angle of 25.4° are suggested specifically with feed rate of 300 mm/min and spindle speed of 3000 rpm. Of course, even these designs are given specifically for T700 3k CFRP for minimum of delamination and uncut fiber, the methodology can be applied in a similar way for other materials.

6 Conclusions

In this paper, a step drill is suggested to suppress delamination and uncut, which is a problem in CFRP machining. It was found that the step drill has the potential of suppressing the generation of delamination and uncut fiber during CFRP processing as a result of previous work. The core diameter, step angle, rake angle, spindle speed, and feed rate of the step drill greatly influence the machining quality of CFRP.

By understanding the mechanism of the generation of delamination and uncut fiber, a step drill is designed by deciding proper core diameter, step angle, and rake angle. It became possible by separating the functions of each parameter. To minimize delamination in drilling, the thrust force generated in drilling is managed to be minimized. For this, the diameter of the core part is decided as 4 mm for 10-mm hole drilling with a drill of 140° point angle. Using proper step angle, the step part can remove the delamination generated during the drilling by core part without 2nd delamination. One more important role of step part is to remove the uncut fibers properly. For the improved machinability of the step part, higher rake angle of step part is implemented. As the feed rate increases, the thrust force increases, which results in the increase of the delamination but decrease of the uncut ratio.

Through the observation that the smaller thrust force induces smaller delamination, it becomes more efficient to design the step drill for the minimization of delamination and uncut fiber, which must have been obtained through experiment before. As the results of this experiment, the step drill performed drilling with free of delamination and uncut

fiber at a feed rate of 0.1 mm/rev. This is an advantage of the new step drill that it can perform drilling with a relatively high feed rate among existing results. The high feed rate will greatly improve the productivity. In addition, simulations for predicting the thrust force of a step drill have been developed, and the behavior of the thrust force according to machining conditions can be predicted without experiments. This result may suggest the possibility of the optimization of design of new step drill for drilling various CFRP.

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