Title	Defect evaluation of the honeycomb structures formed during the drilling process
Author(s)	Ghabezi, Pouyan; Farahani, M.; Shahmirzaloo, Ali; Ghorbani, H.; Harrison, Noel M.
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Title: Investigation of honeycomb structure defects formed in the drilling process

Article Type: Full Length Article

Keywords: Honeycomb, Delamination Factor, Uncut Fiber Factor, Drilling, Digital photography.

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Abstract

In this paper, a comprehensive experimental investigation was carried out to precisely characterize the delamination and uncut fiber in the drilling process. A digital photography procedure was developed in order to calculate the damages resulted from the drilling process. A novel method is proposed in this article bases on the image intensity to verify the obtained results. A full factorial experimental design was performed to evaluate the importance of the drilling parameters. Among other process parameters, feed rate, cutting speed and tool diameter are the principal factors responsible for the delamination damage size during the drilling. The drilling process was assessed based on two proposed factors, including the delamination and uncut fiber factors. Experimental results demonstrated that the feed rate was the paramount parameter for both delamination and uncut fiber factors. It was realized that these both factors increased by the increase in the feed rate. Additionally, by increasing the tool diameter, the delamination and uncut fiber factors have significantly increased. The effects of the cutting speed on damage factors were not linear. The minimum delamination factor and uncut fiber factor were obtained at the cutting speed of 1500 and 2500 rpm, respectively.

Novelty statement

A novel method is proposed in this article bases on the image intensity to calculate the damages resulted from the drilling process. A full factorial experimental design was performed to evaluate the importance of the drilling parameters.

Response to Reviewers

Title: Response to Reviewers

Title: Investigation of honeycomb structure defects formed in the drilling process

Dear Editor,

Thank you very much for your and the reviewer's useful and valuable comments and suggestions on the manuscript. We have modified the manuscript accordingly (in the process, we believe the paper has been significantly improved.), and detailed corrections are listed below point by point:

Responses to the comments;

Reviewer #1:

General Comments: This manuscript discusses the damage generated during drilling in honeycomb sandwich panels, based on experimental results. The goal is to find the optimal drilling conditions which minimize delamination factor (DF) and uncut fiber factor (UCFF). Since there are few comprehensive studies in the past, a certain level of originality and usefulness can be recognized in this manuscript. Therefore, its publication in IJDM can be recommended on the premise of the following minor revisions.

Response: Author is grateful to the reviewer for his positive and encouraging comments.

(1) The drilling parameters in each group seem to have the same meaning, then the expressions in each group should be unified: (feed rate or feeding rate), (cutting speed or spindle speed), (tool diameter or drill diameter or drilling diameter)

Response: Thanks for your kind consideration. All expressions in each group were unified, accordingly.

(2) A brief explanation of the effects of the following non-critical drilling parameters on the drilling damage should be given: “coolant for drilling process,” “type of materials,” and “function of the cutting tool.”

Response: Thanks for your kind comment. Presence of coolant and lubricant also affects the quality of the hole produced. The coolant and tool geometry [1,2] have directly influenced on cutting temperature and the tool wear. M. Khoran and et al. [3] have examined different types of composites on the drilling damage. They have reported drilling of balsa wood composite sandwich panel had the best quality followed by corrugated foam and PVC foam sandwich panels.

1. Bharti A, Moulick S (2013) Parametric optimization of multi response factors in micro drilling operation. Int J Sci Eng Res 4 (7):1157-1163

2. Voss R, Henerichs M, Kuster F (2016) Comparison of conventional drilling and orbital drilling in machining carbon fibre reinforced plastics (CFRP). CIRP Annals 65 (1):137-140

3. Khoran M, Ghabezi P, Frahani M, Besharati M (2015) Investigation of drilling composite sandwich structures. The International Journal of Advanced Manufacturing Technology 76 (9-12):1927-1936

(3) Describe briefly and concretely how this research result will be useful when analyzing the occurrence of drilling damage and its influence on structural strength and structural life based on continuum damage mechanics.

Response: Thanks for your kind consideration. Honeycomb design provides an excellent combination of strength and efficiency and simultaneously reduces the weight of the component. Drilling is the most common and economically adopted machining process among all hole-making processes. Nevertheless, the defects and damages often occurred during the drilling process including delamination, micro-cracking, etc. have limited the application of this practical procedure. In this research the effect of different parameters has been investigated on drilling damage and its influence on structural strength and structural life. Among other process parameters, feed rate, cutting speed and tool diameter are the principal factors responsible for the delamination damage size during the drilling. The drilling process was assessed based on two proposed factors, including the delamination and uncut fiber factors. Experimental results demonstrated that the feed rate was the paramount parameter for both delamination and uncut fiber factors. Optimum condition has been achieved for drilling honeycomb composite with the least amount of damage and independent of dimensions.

Investigation of honeycomb structure defects formed in the drilling process

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Abstract

In this paper, a comprehensive experimental investigation was carried out to precisely characterize the delamination and uncut fiber in the drilling process. A digital photography procedure was developed in order to calculate the damage resulted from the drilling process. A novel method is proposed in this article based on image intensity to verify the obtained results. A full factorial experimental design was performed to evaluate the importance of the drilling parameters. Among other process parameters, feed rate, cutting speed and tool diameter are the principal factors responsible for the delamination damage size during the drilling. The drilling process was assessed based on two proposed incurred damage factors, specifically the delamination factor and uncut fiber factor. Experimental results demonstrated that the feed rate was the paramount parameter for both delamination and uncut fiber factors. It was observed that both factors increased with an increase in the feed rate. Additionally, by increasing the tool diameter, the delamination and uncut fiber factors significantly increase. The effects of the cutting speed on damage factors were not linear. The minimum delamination factor and uncut fiber factor were obtained at the cutting speed of 1500 and 2500 rpm, respectively.

Keywords: Honeycomb, Delamination Factor, Uncut Fiber Factor, Drilling, Digital photography**.**

1. Introduction

Recent developments in composite manufacturing have conducted generally in the aerospace, marine, automotive and related industries. To date, naval vessels are generally constructed from steel, composites offer a promising weight reduction and can noticeably give rise in the increase in stealth characteristics since keeping high strength properties. In a military environment, composite materials can be exposed to a range of demanding in-service requirements. Based on the shape used in honeybee nests, the honeycomb design provides an exceptional combination of strength and efficiency, and simultaneously reduces the weight of the component. Drilling is the most common and economically adopted machining process among all hole-making processes. Nevertheless, the defects and damages often occurred during the drilling process including delamination, micro cracking and etc. have limited the application of this practical procedure. The drilling-induced delamination, which is considered as the most important concern, is found at the exit side nearby the hole's edge. This delamination may mitigate the bearing strength of joints, shortens its service life and dramatically decrease the safety of the structure [4,5]. Throughout drilling of composites, several damages are reported that can occur in the hole.

Sandwich panels were successfully designed to provide more rigidity in the structure. Generally, this feature enables the formation of a very lightweight core, such as a honeycomb lattice or a foam, sandwiched between two thin yet stiff outer panels. Here, the role of the sandwich core is to carry any shear loads and separate the two skins as far as possible. The second moment of area is a function of the cube of the depth; therefore, the bending rigidity greatly increases with this technique. Honeycomb sandwich panels are particularly sensitive to localized loads [6,7]. Accordingly, in order to limit irreparable damage to the honeycompb structure due to the loading,, holes must be drilled in a particular position within the reinforced area of the panel. Usually, the selected position is the center of the reinforced part so as to efficaciously distribute the loads. If the position of the hole is displaced from the center of the reinforced part toward the boundary, a reduced area is available for stress distribution and a resulting in a greater likelihood of damage occuring in the panel [8]. When sandwich panels are used to build primary engineering components or structures, this detrimental damage could have baleful consequences. Therefore, the holes must be carefully studied to ensure the safe operation.

Nondestructive testing of composite components to evaluate the drilling-induced delamination is substantially necessary in the aviation industry. For this purpose, ultrasonic testing has been commonly used [9]. Due to the usage of coupling agents, ultrasonic waves hurt from diffraction and affect blind detecting parts near the edge of the drilling hole. However in practice, the low resolution typically associated with portable ultrasonic detector

Commented [HN1]: Do you mean steath as in radar stealth

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Commented [HN3]: need to rewrite this sentence, not clear what you mean limit the ability for on-site inspection at the edge of drilled holes. Hence, it is suggested that X-ray tomography may be more suited to detecting drilling-induced delamination in composite components [10,9]. However, this method is requires a larger investment in inspection infrastructure and can be limited in terms of specimen size and shape. As a further alternative, visual optical inspection is the most common nondestructive inspection method, but is limited to examination of the external delamination [11,10,9]. Hence, a single effective detection method for drilling-induced delamination in composite components has yet to emerge.

The delamination at the drill entry and exit sides were analyzed by several researchers [12-19]. Koenig et al. [20] showed that the thrust force as the principal reason for the delamination is not significant until it reaches a critical level. Cheng et al. [21] improved the linking between the tool geometry and hole quality. The damage or delamination is not the chisel edge but is due to the cutting lips concluded by Paolo et al. [22]. Jain et al. [23] have predicted critical thrust force that could be the limiting factor for small damages in the drilling of composites. On the other hand, digital photography was exploited to measure the damage of the hole by Zhang et al. [24]. Davim et al. [11] findings indicated the promising potential for digital image acquisition in evaluating the damage after drilling composites.

Bosco et al. [25] investigated the machining of glass fiber reinforced polymer (GFRP) armor steel sandwich with varying properties. Ghabezi and Farahani have investigated the fracture mode I and II in composite laminate samples and adhesive joints [A, B, C]. Shanmugam et al. [26] performed experimental works to minimize the delamination during drilling. M. Khoran et al. [27] found the optimum machining condition to create a hole in the different types of composites sandwich panels with minimum delamination factor (DF) and uncut fiber factor (UCFF).

Sun et al.[28] presented a new application of the laser ultrasonic technique for the recognition of drilling-induced delamination in CFRP composite laminate. A laser ultrasonic system was constructed and experiments were performed to discover the drilling delamination, based on the propagation characteristics of ultrasonic waves. They depicted that the laser ultrasonic method can be a possible and effective technique for detecting the drilling-induced delamination.

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According to the literature, limited studies can be found dealing with the comprehensive study of the drilling of honeycomb structure. Due to the unique characteristics of honeycomb structure and considering many applications of the drilling process, a method for the inspection of drilled holes in reinforced honeycomb sandwich panels is proposed in the current study. The aim of this study is finding the best and optimum drilling condition to make a hole in composite sandwich panels by honeycomb core with minimum DF and UCFF.

2. Experimental procedure

After million years of evolution in the nature, honeycomb has become one of the most stable structures. Based on the shape used in honeybee nests, the honeycomb design provides a superior combination of both strength and efficiency, while drastically diminishing the weight of the component. Honeycombs utilize far less materials than a solid panel, but still provide exceptional strength, making the structure a highly economical option for a plentiful number of applications. Honeycombs are available in a wide range of standard and custom shapes and sizes. A honeycomb sandwich panel with a length (L) of 240 mm, width (b) of 40 mm and thickness (h_c) of 12 mm was used for the current experimental study. The thickness of both the top and bottom face sheets of the panel is 1 mm. Internal angles core are 120°, cell sheet thickness, $t_c = 0.4mm,$ and cell edge length, d= 4mm. The geometrical dimensions of honeycomb sandwich panel are shown in Fig. 1. The considered sandwich panel consists of two composite skins, which are identical to six layers of bidirectional (0/90) E-glass fabrics with the surface density of 200 g/m^2. A specific unsaturated polyester resin suitable for VARTM process was used in this study with the viscosity of 100 to 120 MP mixed with 0.01 % cobalt naphthenate, as accelerator, and 1.25 % methyl ethyl ketone peroxide, as initiator. The core structure is made from aramid fibers (ECA) folded and glued together forming a hexagonal cell.

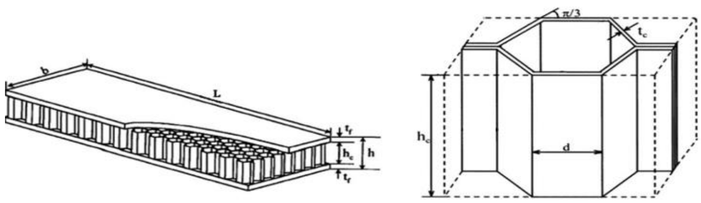

Fig. 1. Geometrical parameters of honeycomb sandwich panel.

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The drilling process was carried out on honeycomb specimens, using a twist drill bit made of high-speed steel manufactured according to the standard of DIN 338A 118° point angle, and the drill geometry has been adapted to honeycomb drilling. A universal milling machine

DECKEL FP4M with 4- kW spindle power, cutting speed from 50 to 2500 rpm and feed rate of 8–630 mm/min (x/y/z), have been used for the experiments.

Drilling parameters such as a coolant for drilling process, and tool geometry have a little impact on the drilling damage. Presence of coolant and lubricant also affects the quality of the hole produced. The coolant and tool geometry [1,2] have directly influenced on cutting temperature and the tool wear. Effective parameters of the drilling process are tool diameter, cutting speed, feed rate, coolant of drilling process, material type and cutting tool features. Among them, the most critical parameters are tool diameter, cutting speed and feed rate. The considered tools diameters in this study were 4, 7 and 9 mm, because this range is the most common diameters used in composite mechanical connections. The range of cutting speeds and feed rate considered as the widest available range of the employed drill machine. Cutting speeds of 500, 1600, and 2500 rpm at typical feed rate of 50, 200, and 400 mm/min, without using a coolant during the drilling process have been employed for the experiments. Digital photographs of the hole entry and the exit were taken, and the images were subsequently processed through CAD CAM software to evaluate delaminated/damaged areas around the entry/exit hole. Digital photography technique was effectively used by means of a Canon Powershot SX540 HS camera with 20-MP resolution and the auto-focus ability. The typical drilled holes are presented in Fig. 2. It is recognized that there is a delamination which occurs on the periphery of the holes, as well as uncut fibers embeds into the drilled holes.

Fig. 2. Drilled holes with different diameter in sandwich composite sample.

2.1. Delamination and uncut fiber factors determination

There are diverse modes of damage in the drilling process of composite materials including matrix cracking, fiber pull-out, uncut fiber and matrix, fiber breakage, and delamination. Fig. 3 describes the defect formation during the drilling process in the honeycomb sandwich panel. Close to the hole exit, delamination damage is formed because of separating the uncut layer (the bottom layers as shown in Fig. 3) from the rest of the laminate. This damage is considered as an important weakening factor in the structure.

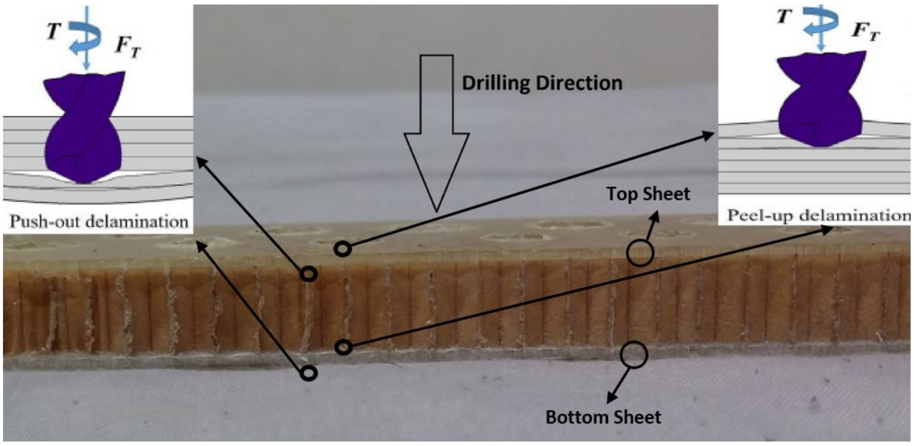

Fig.3. Drilling induced delamination mechanisms in a honeycomb sandwich panel.

Delamination is one of the most important defects which has two general types: peel up and push out. In fact, for both of them there are two modes of delamination damage; one is the fiber damage around the hole; and the other mode is the existing uncut fiber that appears inside the hole. So, in this paper, these two factors, delamination factor (DF) and uncut fiber factor (UCFF), are taken into account and are characterized as follows. With these equations, the drilling induced defects are measured independent of the hole geometry.

$$\mathrm{UCFF} = A_i/P_{Hole} = A_i/2\pi R \tag{1}$$

$$\mathrm{DF} = A_0/P_{Hole} = A_0/2\pi R \tag{2}$$

Where, P_{Hole} is the perimeter of the drill hole (mm), A_0 is the area between the hole circle and outer border of the delamination zone (mm^2), and A_i is the area between the hole circle and inner damage zone. These two areas are presented in Fig. 4. There is a delamination which occurs on the periphery of the drilled hole shown in Fig. 4 .The scheme of measurement of A_0 and A_i is also presented in Fig. 4. As can be seen, details of the methodology used by the authors for determining UCFF and DF for a typical drilled hole where the damaged area was mapped and measured using image processing software, are presented.

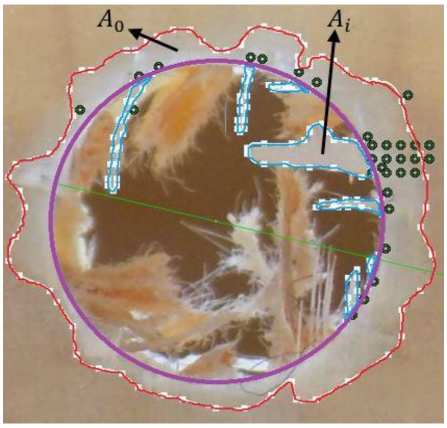

Fig. 4. Different sections for the calculation of damage factors.

A new method is presented in this article for measuring DF and UCFF based on the image intensity. Each pixel's brightness is represented by a single 8-bit number, whose range is from 0 (black) to 255 (white) in monochrome images [29,30]. DF and UCFF areas have their own light intensity as shown in Fig. 5. In this way, the damaged zones are separated and measured.

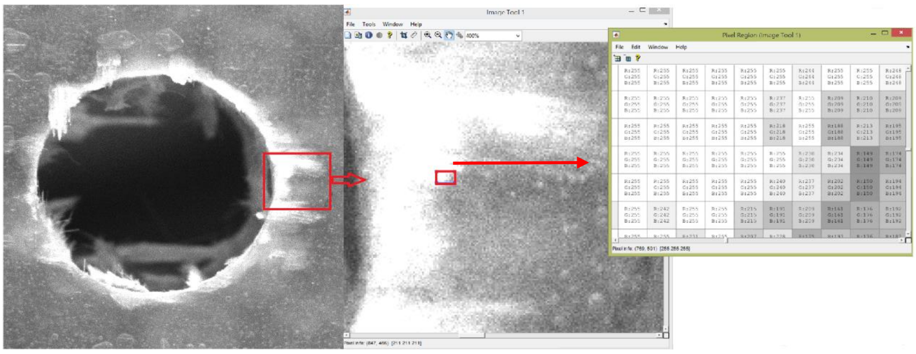

Fig. 5. The possible range of the pixel values dependent on the image light intensity.

3. Results and discussion

In the drilling of sandwich composite panels, delamination and uncut fiber damages happened on the surrounding and inner part of the drilled holes, respectively. These two damages were formed through the thrust force during the drilling on the faces of the panel. These defects are known as critical problems in the drilled hole which can negatively affect the mechanical joint strength. They could increase stress concentration which in turn decreases the strength of the composite structure. This research was conducted to find the optimal drilling process parameters in order to reach the desirable hole quality. Thus, it is necessary to precisely investigate the effect of main parameters such as cutting speed, feed rate and tool diameter. The machinability of composite sandwich panels made of glass/polyester with a honeycomb core were studied for the drilling at different cutting conditions. The obtained result of experimental works are used to investigate the effect of drilling parameters (cutting speed, feed rate and tool diameter) on DF and UCFF. The results of the uncut fiber factor (UCFF) and delamination factor (DF) for different machining condition is presented in Table 1.

Table 1. Uncut fiber and delamination damage factors in different drilling conditions

UCFF	DF	Feed rate F (mm/min)	Cutting speed V (rpm)	Tool diameter D (mm)
0.096	0.7236	50	500	4
0.147	1.007	200	500	4
0.18	2.075	400	500	4
0.126	0.6503	50	1600	4
0.264	0.7531	200	1600	4
0.399	1.0106	400	1600	4
0.075	0.6822	50	2500	4
0.081	0.8621	200	2500	4
0.09	1.207	400	2500	4
0.147	1.035	50	500	7
0.175	1.1938	200	500	7
0.252	1.821	400	500	7
0.266	0.963	50	1600	7
0.336	1.0737	200	1600	7
0.448	1.2953	400	1600	7
0.133	1.0145	50	2500	7
0.1561	1.1683	200	2500	7
0.1918	1.3466	400	2500	7
0.198	1.3269	50	500	9
0.243	1.503	200	500	9
0.324	2.251	400	500	9
0.2367	0.945	50	1600	9
0.3537	1.144	200	1600	9
0.3555	1.238	400	1600	9
0.189	0.9723	50	2500	9
0.225	1.2059	200	2500	9
0.279	1.3192	400	2500	9

Fig. 6 and Fig. 7 illustrate the effect of the tool diameter on DF and UCFF for honeycomb sandwich panel samples. It can be clearly inferred that the increase in the tool diameter can result in a trivial increase in both the delamination and uncut fiber factors, generally. By the increase in the tool diameter, the tool load and contact load between the tool and composite panel increase which thereby culminates in an increase in the damage on the sandwich panel.

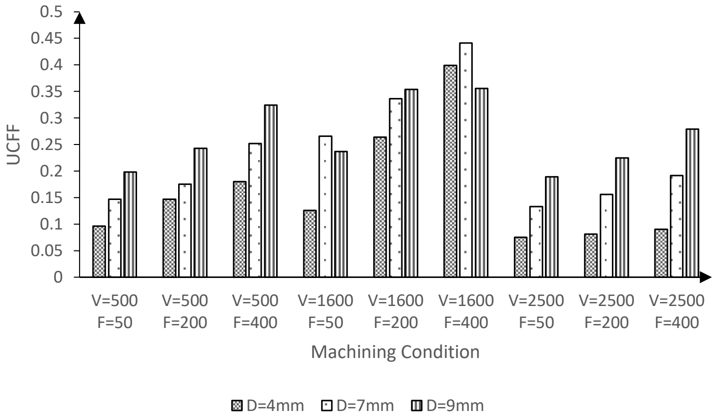

Fig. 6. Effect of the tool diameter on UCFF in a honeycomb structure.

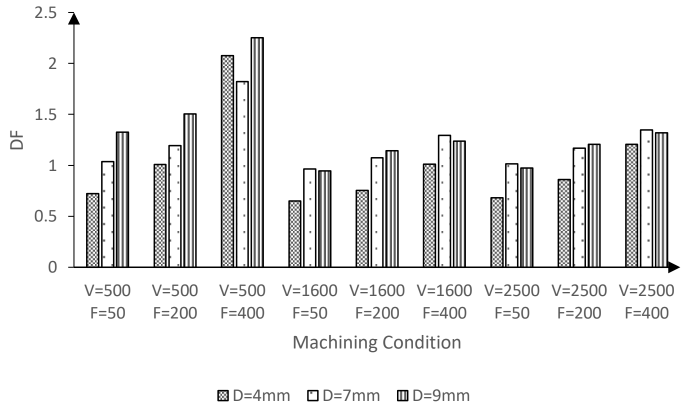

Fig. 7. Effect of the tool diameter on DF in a honeycomb structure.

Effects of feed rate and cutting speed on both delamination and uncut fiber factors are indicated in Fig. 8 and Fig. 9. As shown in Fig. 8, it was observed that by increasing the feed rate, both DF and UCFF increases. The delamination gradually increases at higher feed rates.

It can be concluded that by increasing the feed rate, the drilling time decreases and the transverse vibration of the tool increases, while the delamination in the drilling of laminate composites decreases by increasing the feed rate [31].

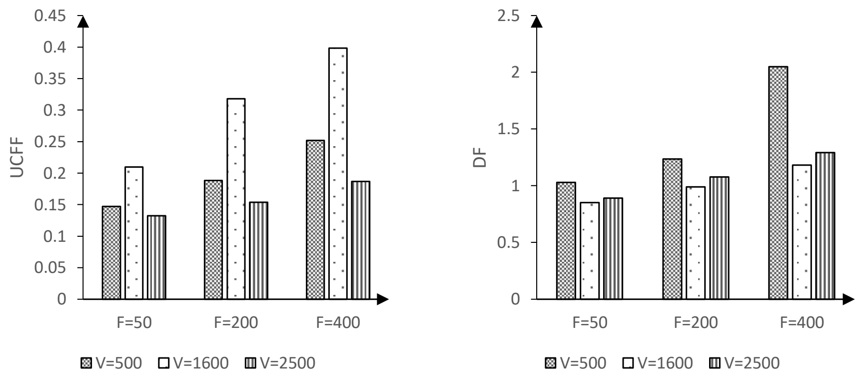

Fig. 8. Effects of feed rate on damage factors.

According to the obtained results, it can be derived that there is an optimum drilling velocity (V=1600) for DF. However, the 1600 rpm cutting speed corresponds to a maxmimum UCFF. Due to the softening of the matrix phase by increasing the cutting speed, the material removal would be easier and consequently the DF decreases.

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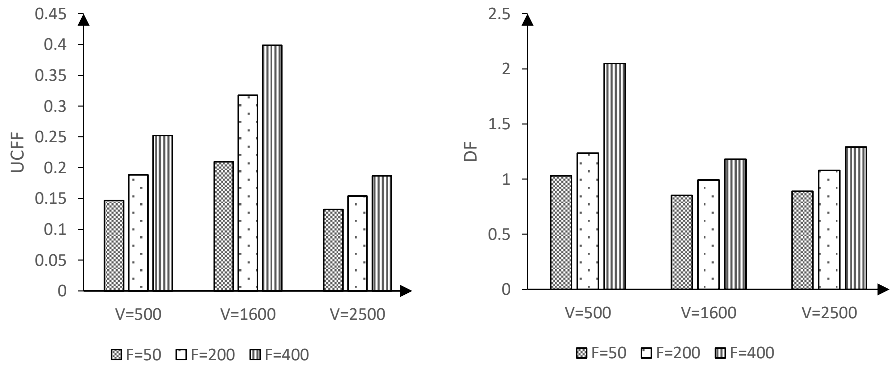

Fig. 9. Effects of cutting speed on damage factors.

The mean effect of cutting speed, tool diameter, and feed rate on the hole quality is shown in Fig. 10, Fig. 11 and Fig. 12, respectively. The mean values of DF and UCFF at different cutting speeds and feed rates as a function of the tool diameter were presented in

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Fig. 10. Based on attained experimental results, both UCFF and DF increases by raising the tool diameter (for a constant cutting speed). Kilickap [32] reported that feed rate and cutting speed were the most vital factors that influence the delamination in a composite laminate. They reported that the minimum delamination was obtained at lower cutting speeds and feed rates.

Commented [HN8]: am i correct in this?

Nevertheless, as shown in Fig. 11, for honeycomb structures there is an optimum point for cutting speed (1600 rpm) which led to a minimum DF. On the other side, UCFF is maximum in the cutting speed of 1600 rpm, as demonstrated in Fig. 12, and both UCFF and DF are evidently seen that increase by increasing the feed rate. Analogous results were reported by Kilickap et al. for the drilling induced delamination in composite laminates [32].

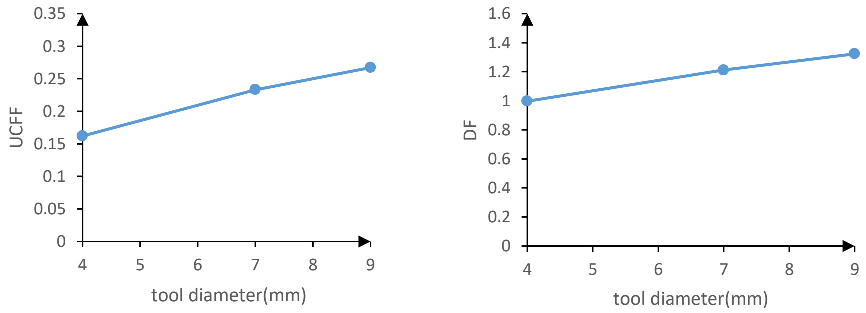

Fig. 10. Mean values of UCFF and DF versus tool diameter for a honeycomb structure.

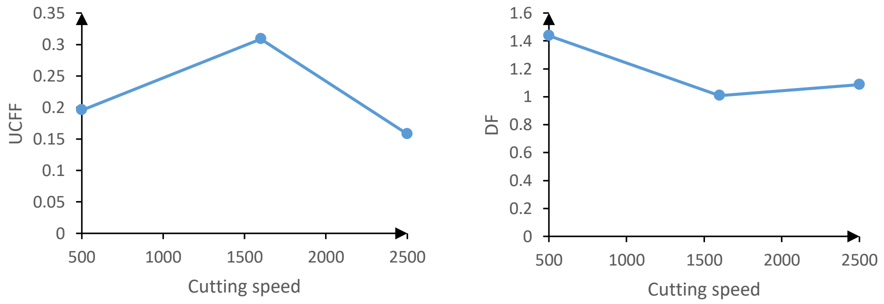

Fig. 11. Mean values of UCFF and DF versus cutting speed for a honeycomb structure.

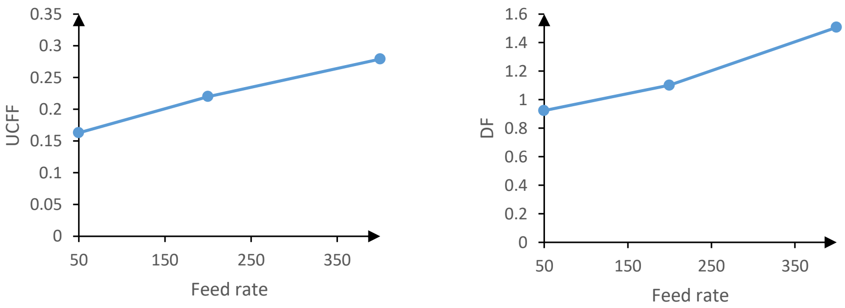

Fig. 12. Mean values of UCFF and DF versus the feed rate for a honeycomb structure.

4. Conclusion

In the present study, the damages induced by drilling process were thoroughly characterized by optical analysis. The two factors of delamination and uncut fiber were defined in order to quantify the hole damages. Furthermore, digital photography was used to assess the drilling induced damages, and also an image processing technique based on the image intensity was employed to measure the area of damage. Besides, UCFF and DF have been measured for different drilling conditions (various cutting speeds, feed rates and tool diameters). According to the experimental observations, the following conclusion were drawn:

- The DF and UCFF increase by increasing the feed rate.
- Feed rate is the parameter that has the greatest influence on the DF, followed by cutting speed and tool diameter, respectively.
- Feed rate is the parameter that has the most effect on the UCFF, followed by tool diameter and cutting speed, respectively.
- For honeycomb structures, by the increase in the tool diameter both DF and UCFF increased.
- By increasing the cutting speed from 500 to 1600 rpm, the DF was reduced significantly. No noticeable changes was observed in DF by further increase in the cutting speed.
- The UCFF is maximum for the cutting speed of 1600 rpm.
- This optical method may serve as a potential rapid NDT inspection tool within a composite manufacturing and assembly industrial setting.

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