Defect evaluation of the honeycomb structures formed during 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 imaging 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 r/min, respectively.

Keywords
Honeycomb, delamination factor, uncut fiber factor, drilling, digital imaging

Introduction
Recent developments in composite manufacturing have happened generally in the aerospace, marine, automotive, and related industries (Hajideh et al., 2018). While, previously naval vessels

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were 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 (Tabasi et al., 2016). 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 (Enami et al., 2018). 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, microcracking, 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 (Kavad et al., 2014; Koenig et al., 1985). 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 (Bozhevolnaya et al., 2003; Smith and Banerjee, 2012). Accordingly, in order to limit irreparable damage to the honeycomb 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 resulting in a greater likelihood of damage occurring in the panel (Iarve et al., 2006). 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 (Tsao and Hocheng, 2005). 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 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 (Davim et al., 2007; Khashaba, 2004). However, this method 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 it is limited to examination of the external delamination (Davim et al., 2007; Khashaba, 2004; Wern et al., 1993). 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 was analyzed by several researchers (Chowdhury et al., 2018; Okabe et al., 2018; Voyiadjis and Kattan, 2019; Wern et al., 1993; Xu et al., 2018; Zhang et al., 2017; Zhou et al., 2017; Zou et al., 2018). König and Grass (1989) showed that the thrust force as the principal reason for the delamination is not significant until it reaches a critical level. Hocheng and Puw (1992) improved the linking between the tool geometry and hole quality. The damage or delamination is not the chisel edge but it is due to the cutting lips concluded by DiPaolo et al. (1993). Jain and Yang (1993) have predicted that critical thrust force 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. (2001). Davim et al.’s (2007) findings indicated the promising potential for digital image acquisition in evaluating the damage after drilling composites.

Bosco et al. (2013) investigated the machining of glass fiber reinforced polymer armor steel sandwich with varying properties. Ghabezi and Farahani (2017, 2018a, 2018b) have investigated the fracture modes I and II in composite laminate samples and adhesive joints. Shanmugam et al. (2008) performed experimental works to minimize the delamination during drilling. M Khoran et al. (2015) 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 and Zhou (2014) 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 (Heidarpour et al., 2018).

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.

**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 = 0.4 mm, and cell edge length, d = 4 mm. The geometrical dimensions of honeycomb sandwich panel are shown in Figure 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/m². 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 (Ghabezi et al., 2015). The core structure is made from aramid fibers (ECA) folded and glued together forming a hexagonal cell.

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 (Mohammadzadeh Jamalian et al., 2016). A universal milling machine DECKEL FP4M with 4-kW spindle power, cutting speed from 50 to 2500 r/min, and feed rate of 8–630 mm/min (x/y/z) has 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 (Bharti and Moulick, 2013; Voss et al., 2016) 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 tool diameters in this study were 4, 7, and 9 mm because these are 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 r/min 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 the 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 Figure 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.

**Delamination and UCFFs 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. Figure 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 Figure 3) from the rest of the laminate. This damage is considered as an important weakening factor in the structure.

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, DF and UCFF, are taken into account and are characterized as follows. With these equations, the drilling-induced defects are measured independent of the hole geometry

\[
UCFF = \frac{A_i}{P_{Hole}} = \frac{A_i}{2\pi R}
\]

\[
DF = \frac{A_0}{P_{Hole}} = \frac{A_0}{2\pi R}
\]
where $P_{\text{Hole}}$ 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 Figure 4. There is a delamination which occurs on the periphery of the drilled hole shown in Figure 4. The scheme of measurement of $A_0$ and $A_i$ is also presented in Figure 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.

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 (Rahmatabadi et al., 2019a, 2019b). DF and UCFF areas have their own light intensity as shown in Figure 5. In this way, the damaged zones are separated and measured.

**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 was studied for the drilling at different cutting conditions. The obtained result of experimental works is used to investigate the effect of drilling parameters (cutting speed, feed rate, and tool diameter) on DF and UCFF. The results of the UCFF and DF for different machining conditions are presented in Table 1.

**Figure 4.** Different sections for the calculation of damage factors.

**Figure 5.** The possible range of the pixel values dependent on the image light intensity.
Figures 6 and 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 UCFFs, 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.

Effects of feed rate and cutting speed on both delamination and UCFFs are indicated in Figures 8 and 9. As shown in Figure 8, it was observed that by increasing the feed rate, both DF and UCFF increase. 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 (Sardinas et al., 2006).

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

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

UCFF: uncut fiber factor; DF: delamination factor.
According to the obtained results, it can be derived that there is an optimum drilling velocity (V=1600) for DF. However, the 1600 r/min cutting speed corresponds to a maximum 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.

The mean effect of cutting speed, tool diameter, and feed rate on the hole quality is shown in Figures 10 to 12, respectively. The mean values of DF and UCFF at different cutting speeds and feed rates as a function of the tool diameter are presented in Figure 10. Based on the attained experimental results, both UCFF and DF increase by raising the tool diameter (for a constant cutting speed). Kilickap (2010) 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.
Figure 8. Effects of feed rate on damage factors.

Figure 9. Effects of cutting speed on damage factors.

Figure 10. Mean values of UCFF and DF versus tool diameter for a honeycomb structure.
Nevertheless, as shown in Figure 11, for honeycomb structures there is an optimum point for cutting speed (1600 r/min) which led to a minimum DF. On the other side, UCFF is maximum in the cutting speed of 1600 r/min, as demonstrated in Figure 12, and both UCFF and DF are evidently seen that increase by increasing the feed rate. Analogous results were reported by Kilickap (2010) for the drilling-induced delamination in composite laminates.

**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 conclusions 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 r/min, the DF was reduced significantly. No noticeable changes were observed in the DF by further increase in the cutting speed.

The UCFF is maximum for the cutting speed of 1600 r/min.

This optical method may serve as a potential rapid Non Destructive Testing (NDT) inspection tool within a composite manufacturing and assembly industrial setting.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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References


