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Effect of Support Distance on Damage of Drilled Thin CFRP Laminates

Jean François Chatelain, Imed Zaghbani, Gilbert Lebrun, Kaml Hasni

Abstract**—**Severe damages may occur during the drilling of carbon fiber reinforced plastics (CFRP). In practice, this damage is limited by adding a backup support to the drilled parts. For some aeronautical parts with curvatures, backing up parts is a demanding process. In order to simplify the operation, this research studies the effect of using a configurable setup to support parts on the resulting quality of drilled holes. The test coupons referenced in this study are twenty four-plies unidirectional laminates made of carbon fibers and epoxy resin. Different signals were measured during the drilling process for these laminates, including the thrust force, the displacement and the acceleration. The processing of these signals demonstrated that the damage is due to the combination of two main factors: the spring-back of the thin part and the thrust force. The results found were confirmed for different feeds and speeds. When the distance between supports is increased, it is observed that the spring-back increases but the thrust force decreases. The study proves the feasibility of unsupported drilling of thin CFRP laminates without creating any observable damage.

Keywords**—**CFRP, Damage, Drilling, Flexible setup.

I. INTRODUCTION

DIFFERENT techniques are utilized to limit the severe damage that can occur during the drilling of carbon fiber reinforced plastics (CFRP). These techniques include the application of variable drilling conditions, the development of special drill geometries, the preparation of pilot holes or the total support of the drilled part (back plating), with the latter being commonly used. The technique avoids reaching a critical deflection that may cause severe damage to the laminate. However, this approach presents some disadvantages which become significant with increased volume and diversification of the parts geometry. Different part geometries implies a special tooling for each part family, which leads to higher production costs and low flexibility in the use of the tooling developed. Flexible tooling systems are commercially available to overcome this problem. These systems allow different machining operations of parts, supported through multiple posts, with limited or no need for back-up. While such systems offer operational flexibility with reasonable costs, they affect the part quality of thin drilled parts. Tsao and Hocheng [1] demonstrated the negative effect of an absence of back-up on the part quality. They analytically demonstrated that back plated parts exhibit a higher threshold of thrust force while many studies have demonstrated that the thrust force is considered to be the main cause of the damage observed in holes drilled in composite materials [2]-[5]. In fact, one of the major damages that can occur during drilling is delamination at the exit surface, known as the push-down delamination. This damage is described as a circular or elliptical crack propagating in the interlaminar region of the laminate under the exerted load of the drill point and is well explained in Teti’s [4] and Lachaud [5] surveys. Right at the start of the drilling operation, the tool abrades the material and pulls it away along the flute. If this force is large enough to exceed the bonding force of the first layers of the composite material it will affect the local material integrity and result in peeling of material [6]. Afterwards, as the tool approaches the exit plane, the remaining layers cannot sustain the thrusting force of the operation. As for the peel-up at entrance, the bonding force of the remaining layers may be exceeded and the resistance to deformation vanishes (Fig. 1). The resulting delamination zone depends essentially on the cutting thrust force of the drilling operation [6], [7] while this force is depending on material properties, machining parameters and cutting tool geometry or wear [8], [9]. In particular, it has been demonstrated that the thrust force can be reduced as the exit approaches by controlling the feedrate [10]-[12].

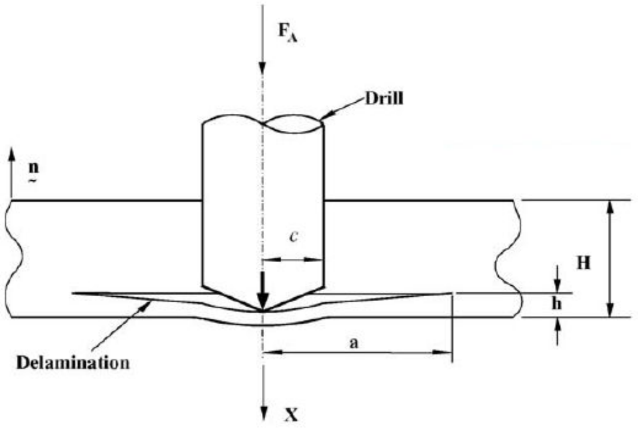

Fig. 1 Delamination zone [4]

J. F. Chatelain is with the École de technologie supérieure, Mechanical Engineering Department, 1100 Notre-Dame Street West, Montréal, Québec, Canada, H3C 1K3 (phone: 514-396-8512; fax: 514-396-8530; e-mail: jfchatelain@mec.etsmtl.ca).

I. Zaghbani was with the École de technologie supérieure. He is now with Pega Medical, 1111 autoroute Chomedey, Laval, Québec, Canada, H7W 5J8 (e-mail: imed.zaghbani@pegamedical.com).

G. Lebrun is with Université du Québec in Trois-Rivières, 3351 boul. Des Forges, Trois-Rivières, Québec, Canada (e-mail: gilbert.lebrun@uqtr.ca).

K. Hasni is a graduate student with the École de technologie supérieure, Mechanical Engineering Department.

Murphy et al. [13] analyzed the effect of coatings on the performance of tungsten carbide drills for the drilling of CRRP. It was found that the forces increase with tool wear and as the tool wear grows, pull-out fibers is observed similarly for all types of coatings.

Tsao et al. [14] demonstrated that the load of the drill point is mainly due to the chisel edge, while the contribution of the cutting lips in the axial thrust direction is smaller. Conversely, DiPaolo et al. [15] observed that the force exerted by the chisel edge is not the main cause of delamination cracking. In fact, they observed that the crack opens after the chisel edge exits the workpiece. Based on this contradiction and on the observation that the thrust force during supported drilling is greater than during unsupported drilling, Capello [16] shown that the delamination depends on the thrust force for the supported condition. For the unsupported drilling, the author concluded that the main causes of delamination are the elastic inflection of the workpiece under the drill point load and the spring-back movement that occurs as the chisel edge exits the workpiece.

Although it is known that the spring-back of the drilled part has a significant influence on the damage level, the issue has not been thoroughly investigated. Most studies have focused on the effect of the cutting parameters, such as feed, speed and tool geometry, while neglecting the importance of the spring-back effect. In fact, this problem is of great concern when the drilled part is unsupported. The support distance can lead to a high spring-back, which could generate a chaotic damage to the part.

In the present experimental study, the effect of the support distance was examined using a configurable setup. Different drilling parameters were tested, and their influence on the damage investigated to experimentally retrieve the optimal support distance that can reduce the resulting damage. In what follows, the details of the experimental methodology are presented followed by an analysis and discussion regarding the results found.

II. METHODOLOGY

The CFRP laminates for conducting drilling tests were prepared in a controlled aeronautical environment using carbon-epoxy unidirectional pre-impregnated material. Stacks of 24 plies were autoclave-cured to give composite plates with a fiber volume content of 64% and final thickness average of 3.5mm. The symmetric stacking sequence of the plies $[(90^\circ,-45^\circ,45^\circ,0^\circ,45^\circ,-45^\circ,45^\circ,-45^\circ,0^\circ,-45^\circ,45^\circ,90^\circ)]_s$ was such as to provide a laminate with in-plane quasi-isotropic properties. The molded plates were inspected prior to any drilling with the C-scan technique to verify the absence of any major processing internal defects. Once inspected, the laminates were drilled on all four corners for tightening on a drilling fixture, as shown in Fig. 2. The CFRP laminate (#4) was screwed at a controlled torque (5N.m) on the four mobile supports (#1). These end threaded supports were attached to an aluminum plate (#2) comprising different positioning holes for the mobile supports. Three different distances between the supports were tested (50.8, 101.6 and 152.4 mm). The aluminum plate was fixed on a Kistler 9255B three-axis table dynamometer. The charge amplifiers of type Kistler 5010 generate five output signals that are transmitted to a data acquisition card (type DT-9836) set to a sampling frequency of 48 kHz/channel, for a total recording time of eight seconds. A laser displacement accelerometer (#5) was installed under the thin CFRP plate. This Keyence sensor type IL-030 sensor was positioned at a 15mm distance relative to the center of the CFRP laminate. The sampling frequency of the sensor was set at 3 kHz, the maximum permitted for this model. Finally, an accelerometer (#6) was positioned on the thin CFRP plate to record the acceleration of the drilled part with a sampling frequency of 40 kHz.

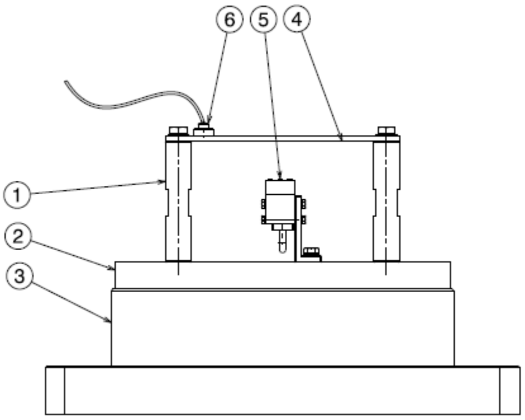

Fig. 2 Experimental setup for drilling CFRP laminate

Prior to the unsupported drilling tests, back-plated CFRP test coupons were drilled to serve as reference tests for estimating the observable damage. All drilling tests were realized under dry conditions using the same tool geometry. The selected tool was a coated drill tool with standard cutting geometry and diameter of 4.08mm. A detailed analysis of the results obtained is presented in the following section.

III. RESULTS AND DISCUSSION

The experimental set-up described above in Fig. 1 was used to record different signals during the drilling operation. A sample of the recorded signal for the thrust force, in the case of the unsupported plate is presented in Fig. 3. The drill tip enters in contact with the laminate at an approximate time equals to 0.20 sec., then the force reach a maximum value when the tool is fully engaged in the material, just before the tip point begins its exit from the material. At this point, the force linearly decreases until the chisel edge leaves the part. At this instant, when t = 0.77 sec., a remarkable aspect in the profile is the presence of a damped sine portion, which results from a high spring-back movement of the laminate due to the full exit of the tool from the workpiece. To explain the presence of this damped sine in the force signal for the unsupported plate, the same test was repeated with a back-plated CFRP laminate. The

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signal recorded during the drilling of the back-plated thin laminate is also reported in Fig. 3. It can be seen that the cutting force signal does not present a damped sinus section. Additionally, it was observed that the vibration level of the plate during this phase was very low compared to the one obtained in the case of unsupported drilling, under the same cutting conditions. The peak value of the acceleration recorded was ±2g, while it was higher than ±50g in the case of unsupported drilling. This is an indication that back plating helps to reduce or even eliminate the spring-back effect.

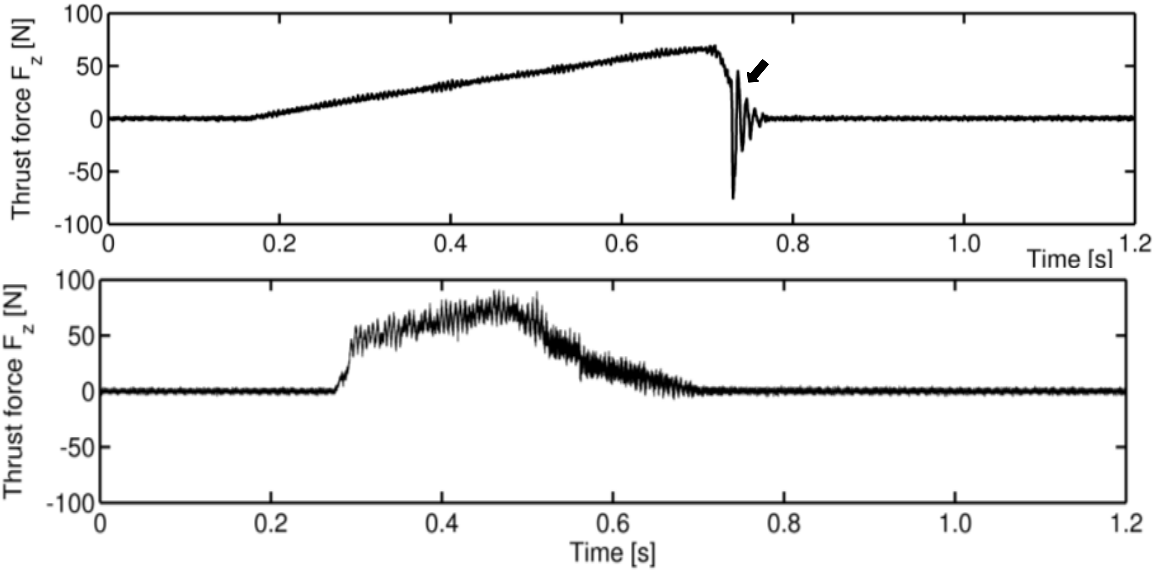

Fig. 3 Thrust force signals during drilling of CFRP laminate for unsupported plate (top) and supported plate (bottom), d=152.4 mm, f=0.075 mm/rev, and Vc= 70 m/min

The two drilling configurations generated an observable damage, as illustrated in Fig. 4. While the unsupported configuration has a maximal thrust force of only 80N, the observed damage is more severe than for the supported case for which a higher value of maximal thrust force is recorded (Fz_{max} = 90N). It can be seen that not only the spread of the damage is higher, but it is also deeper. The authors estimated that for unsupported drilling, the damage would only affect the last ply, while the damage affects the last three plies of the laminate in the case of the unsupported drilling. From these observations, it seems that the damage was due to two combined effects: the thrust force and the spring-back effect. In the case of unsupported drilling, the spring-back effect is the major cause of damage because the sudden movement of the thin laminate causes a change in the direction of the thrust force.

It was hypothesized that the damage occurs during the damped sinus stage, which implies that if this stage is eliminated, it should be possible to reduce the damage. To that end, the first step was to find the minimal support distance beyond which the spring-back occurs. For that, the extreme feed of 0.075mm/rev, was tested. After various trials, it was possible to experimentally find the distance that can significantly reduce the spring-back. Fig. 5 shows that the displacement recorded under the CFRP plate decreases with smaller support distances, reaching its lowest value at a distance of 50.8mm. For a support distance higher than 50.8 mm, the spring will occur. However, we can see that in spite of the “absence” of a spring-back, the damage occurred and remained more significant than the damage occurring under supported drilling (Fig. 6).

The second step was to find the cutting parameters (feed and speed) under which no observable damage can take place. It was possible to significantly reduce the observable damage in the case of unsupported drilling by modifying the feed and speed. To obtain these results, the feed was reduced to a third of the feed at which there is no spring-back in the case of unsupported drilling. The feed value of 0.025mm/rev was tested with cutting speeds of 30m/min, 50m/min and 70m/min and no significant difference in quality of parts was observed. Thus, increasing the cutting speed does not have any negative effect on the part quality; however, higher cutting speeds can improve productivity, as the operation can be realized faster.

The effect of the cutting speed on the observable damage is more obvious in the case of supported drilling, where the observable damage was relatively higher than in unsupported drilling. This is due to two main reasons: firstly, the absence of a dynamic effect at the selected distance between supports, and secondly, the low “relative feed” at which the drilling operation is executed, in the case of unsupported drilling. In fact, for the unsupported configuration the relative feed is the programmed feed minus the speed of the plate due to its displacement. In the case of supported drilling, the damage observed was most probably due to a higher thrust force, which was beyond the force threshold.

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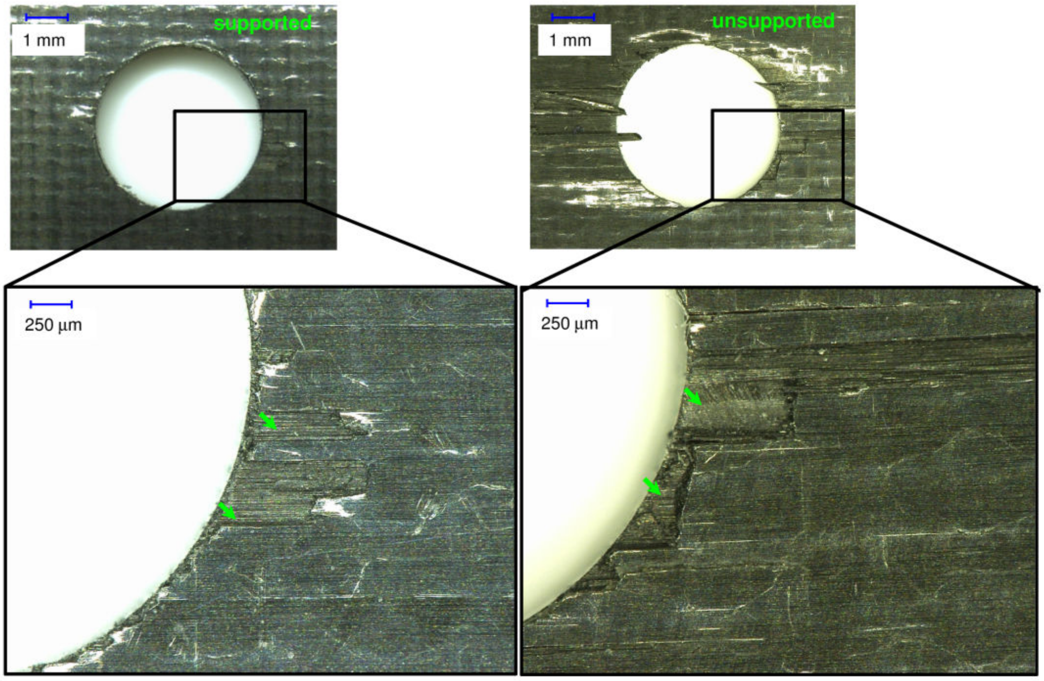

Fig. 4 Microscopic observation of the damage for supported (left) and unsupported cases (right), f=0.075 mm/rev, Vc=70 m/min

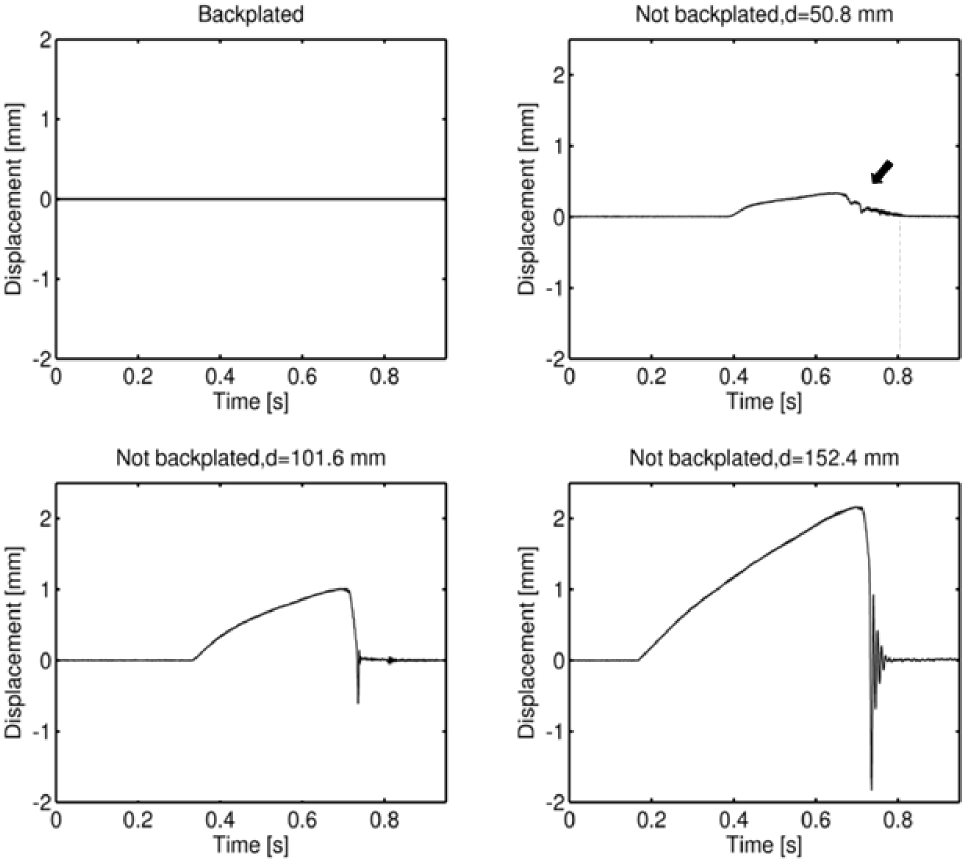

Fig. 5 Thin plate displacement in the case of supported and unsupported drilling, feed=0.075mm/rev, Vc =70m/min

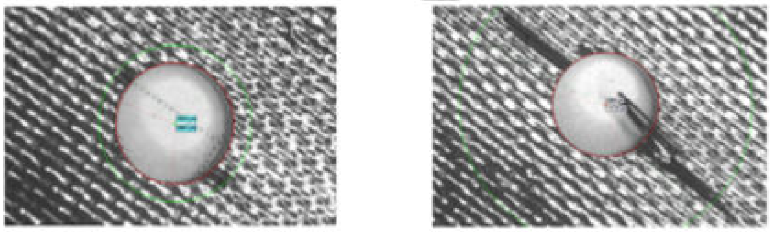

Fig. 6 Damage for supported (left) and unsupported drilling (right), d=50.8mm, feed=0.075mm/rev, Vc =70m/min

IV. CONCLUSION

In the case of unsupported drilling, the observable damage on drilled holes in thin CFRP laminates is due to the combined effects of the exerted thrust force and spring-back of the composite plate. While the former can only be reduced, the latter can be suppressed by selecting an adequate distance between supports. In the present study, the adequate distance was retrieved through an experimental approach, and once done; the cutting parameters were optimized to reduce the observable damage. Using high cutting speeds and a low feed, it was possible to completely eliminate the observable damage. It was seen that at optimal conditions, unsupported drilling can generate holes that are relatively better than those obtained in supported drilling. This experimental study proves the feasibility of unsupported drilling of thin CFRP laminates without creating any observable damage. However, the development of a theoretical background is necessary to generalize the proposed approach to other part geometries, fiber orientations and fiber volume contents.

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