Drilling of Carbon Fibre Reinforced Laminates – a Comparative Analysis of Five Different Drills on Thrust Force, Roughness and Delamination

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Abstract. The distinguishing characteristics of carbon fibre reinforced laminates, like low weight, high strength or stiffness, had resulted in the increase of their use during the last decades. Although parts are normally produced to “near-net” shape, machining operations like drilling are still needed. In result of composites non-homogeneity, this operation can lead to delamination, considered the most serious kind of damage as it can reduce the load carrying capacity of the joint. A proper choice of tool and cutting parameters can reduce delamination substantially. In this work, the results obtained with five different tool geometries are compared. Conclusions show that the choice of adequate drill geometry can reduce the thrust forces and consequently, the delamination damage.

Introduction

The use of composite laminates, like carbon fibre reinforced polymers, in complex structures has increased significantly for the last decades. Reasons for this can be found in some unique properties like low weight, high strength and stiffness. Nevertheless, there are still some issues when considering the use of composite laminates. Some of these issues are cost-related, but considerations about machining also lead to some difficulties and lack of acceptance for the implementation of these materials.

One of the main machining operations needed for parts assembly in structures is drilling, when it is necessary to join different parts. Generally, drilling can be carried out using conventional machinery, with adaptations. However, this operation is likely to cause several damages in the laminates, namely in the region around the drilled hole, being delamination the most serious as it causes a loss of mechanical and fatigue strength around the drilled hole area [1]. Normally, two kinds of delamination are identified: “peel-up” delamination and “push-out” delamination. Other damages are likely to occur, like fibre torn-out or thermal degradation of the matrix [2].

The main mechanism responsible for delamination is the indentation effect caused by the quasi-stationary drill chisel edge, acting over the uncut plies of the laminate. These plies tend to be pushed away from the plate, causing the separation of two adjacent plies of the laminate [3]. If the thrust force exerted by the drill exceeds the interlaminar fracture toughness of the plies, delamination will take place [4]. The referred delamination is known as “push-out” delamination. It can be found at the drill exit side of the laminate, and is difficult to avoid.

Besides “push-out” delamination, another type can also be identified when drilling laminate composites, the “peel-up” delamination. This delamination is a consequence of the drill entrance in the upper plies of the laminate. As the drill moves forward it tends to pull the abraded material along the flute and the material spirals up [4]. Usually, the adoption of low feed rates can avoid this outcome.
The former type of delamination is considered as the most serious kind of damage. So, several approaches had been presented in the last years in order to reduce it. Generally, it is accepted that delamination can be reduced with an adequate combination of feed rate, cutting speed and drill geometry. A comprehensive review of the steps towards delamination free drilling can be found in [4]. According to Piquet et al. [5], a drill designed for composite laminates machining should have a small rake angle to prevent peel-up, raised number of cutting edges to increase the contact length between the tool and the part and minimum chisel edge to diminish the indentation effect. Dharan and Won [6] suggested that feed should be controlled to prevent delamination in two of the drilling phases: when drill tip makes contact with the plate and when drill approaches breakthrough. Won and Dharan [7] established the contribution of chisel edge length to total thrust force at different speeds. Chisel edge contribution to total feed rate varies from 60% to 85%, depending on feed rate. Tsao and Hocheng [8] compared several drill geometries in order to establish mathematical models to predict the critical thrust force for delamination onset. Durão et al. [9] confirmed the influence of appropriate drill geometry selection on delamination reduction as well as the advantage on the use of a pilot hole. Park et al. [10] applied the helical-feed method in order to avoid fuzzing and delamination using a core drill. Holes with this tool had no delamination and tool life time was superior to tungsten carbide ones used for comparison. Stone and Krishnamurthy [11] studied the implementation of a neural network thrust force controller. The control scheme can minimize delamination varying feed rate in order to control thrust force during drilling. Davim and Reis [12] studied the influence of cutting parameters, like feed rate and cutting speed, on specific cutting pressure, delamination and cutting power when drilling carbon fibre reinforced plastic plates. The authors concluded that feed rate has the greater influence on thrust force, so damage tends to increase more with feed than with other variables evaluated in the study. Hocheng and Tsao [13] conducted a series of experiences to prove the benefit of using special drills when compared to commercially available tools, like twist drill, on delamination reduction. Delamination extent was determined with the help of ultrasonic C-scan. At the end, it was possible to conclude that damage varies with drill geometry and with feed rate. Tsao and Hocheng [14] have presented the advantages of a core drill instead of a twist drill. The influence of spindle speed was relatively insignificant. Selection of adequate drill geometry enables the use of higher feed rates leading to productivity gains.

Another possible option to consider in order to reduce “push-out” delamination, is the pilot hole drilling. The use of a pilot hole enables a thrust force reduction by dividing the operation in two, hence reducing the indentation effect of the final drill. In [15, 16], the authors showed the importance of pilot hole on delamination reduction when using core drills. Pilot hole eliminates the chisel edge effect, reducing delamination significantly. A thrust force reduction of 25% to 50% can be found when comparing holes with and without pilot hole. The ratio of pilot hole to drill diameter must be controlled in order to drill with higher feed rate without delamination. Pilot hole diameter should be identical to the chisel edge length of the final diameter drill in order to reduce delamination hazard. Preferable range of the Pilot hole diameter is from 0.09 to 0.2 of the final drill diameter.

In this work, laminates with a cross-ply stacking sequence and 4 mm thickness were produced using prepreg carbon/epoxy plies. Experimental drilling tests were carried out on these plates and thrust force was monitored. Five different drill geometries are used for comparison: two twist drills with different point angles (85° and 120°), a Brad drill, a Dagger drill and a special step drill. During drilling, thrust forces were monitored. After drilling, hole wall roughness was measured and “push-out” delamination extent was determined using enhanced radiography combined with computational techniques of image processing and analysis. This work is concerned with the reduction of this type of delamination. Conclusions from experimental work demonstrate the influence of drill geometry and drilling parameters - feed rate or cutting speed - in delamination occurrence.
Experimental work

The experimental work was divided in three main steps: drilling of the laminate plates for thrust force monitoring, hole wall roughness measurement, delamination evaluation by enhanced radiography and the use of a numerical criterion, like the Delamination Factor \[17\], for results comparison.

In order to accomplish this work, a batch of plates using prepreg CC160 ET 443 with a cross-ply stacking sequence and 24 layers were produced. The plate was then cured under a pressure of 300 kPa and a temperature of 130 °C for one hour, followed by air cooling. Final plate thickness was 4 mm. The plates were cut in test coupons of 165 * 96 mm² for drilling experiments.

Drilling operation was carried out in a 3.7 kW DENFORD Triac Centre CNC machine. A total of five different drill geometries, all in K20 tungsten carbide, were used: a twist drill with a point angle of 120º, a twist drill with a point angle of 85º, a Brad drill, a Dagger drill and a special step drill, Fig. 1. All the holes performed had a diameter of 6 mm

![Drills](image)

Fig. 1. Drills used: a) twist (120º); b) Brad; c) Dagger; d) special step.

Twist drill is a standard drill commonly used. Two point angles, 85º and 120º, are compared in this work. Brad drill has a specific point geometry causing the fibre tensioning prior to cut thus enabling a “clean cut” of the fibres. In consequence, machined surfaces are smoother. Dagger drill has a small point angle of 30º, reducing the indentation effect but need more space available at the exit side of the plate. The special step drill has the intention of performing pilot and final hole in one operation only, dividing the thrust force and, consequently, the delamination risk. The helix profile was maintained, in order to compare the cutting performance of this drill with twist or Brad drills.

During drilling, axial thrust forces were monitored with a Kistler 9257B dynamometer associated to an amplifier and a computer for data acquisition. No sacrificial plates were used, Fig. 2.

Cutting parameters were selected according to author’s previous experience, published papers from other authors and fabricant recommendations [6, 12, 18]. As it has been already demonstrated the major importance of feed rate when compared with spindle speed in thrust forces development [12], cutting speed was always equal to 53 m/min, corresponding to a spindle speed of 2800 rpm and three levels of feed rate were used: 0.02 (low), 0.06 (medium) and 0.12 mm/rev (high).

After drilling, holes’ wall roughness was measured with a Hommelwerke profilometer, with a cut-off length \( \lambda_c \) of 0.25 mm and an evaluation length \( l_m \) of 1.25 mm. In this work, the roughness parameter considered was the \( R_{\text{max}} \), corresponding to the maximum peak-to-valley dimension obtained from the five sampling lengths within the evaluation length. Three measurements were made for each hole performed.
Finally, plates were inspected by enhanced radiography. With this purpose, plates were prior immersed in di-iodomethane for contrast for one and a half hour. The acquired radiographies were digitalized in order to perform the computational assessment of the delamination around the holes drilled. The values considered for this assessment were the diameter and the area of the damaged region around the hole. Details of the process can be found elsewhere [9].

The use of well established criteria allows the comparison of delamination degree for the several geometries experienced in this work. One of the most used comparison factor is the Delamination Factor ($F_d$) [17] which is a ratio between the maximum delaminated diameter ($D_{\text{max}}$) and hole nominal diameter ($D$):

$$F_d = \frac{D_{\text{max}}}{D} \quad (1).$$

Another common criterion is the Damage Ratio ($D_{\text{RAT}}$) [19], suggested by Mehta et al, and based on the ratio of Hole Peripheral Damaged Area ($D_{\text{MAR}}$) to Nominal Drilled Hole Area ($A_{\text{AVG}}$) as:

$$D_{\text{RAT}} = \frac{D_{\text{MAR}}}{A_{\text{AVG}}} \quad (2).$$

This adopted evaluation method is based on the existence of digitalized images of the damage areas that must be analyzed using suitable computational techniques of image processing and analysis, like those used in [9] and in this work.

Recently, another criterion, the Adjusted Delamination Factor ($F_{da}$) was presented by Davim et al. [20]. This new criterion is intended to deal with the irregular form of delamination containing breaks and cracks, and it is defined as a sum of two main contributions:

$$F_{da} = \alpha \frac{D_{\text{max}}}{D_o} + \beta \frac{A_{\text{max}}}{A_o} \quad (3),$$

where the first quotient is the delamination factor given by Eq. 1 multiplied by a constant $\alpha$, $A_{\text{max}}$ is the area related to the maximum diameter of the delamination zone ($D_{\text{max}}$) and $A_o$ is the area of the nominal hole ($D_o$). Constants $\alpha$ and $\beta$ are weights, being their sum equal to 1 (one). Despite its interest, this criterion was not used in this work.
Results and discussion

**Thrust forces.** Results considered regarding thrust force are the maximum value observed during drilling. This value is commonly regarded as a good indication of delamination occurrence as, according to published analytical models [4], higher thrust forces normally correspond to higher delamination possibility. Due to signal variation along drill rotation, thrust force values were averaged over one spindle revolution. Results are the average of ten experiments under identical conditions.

In Fig. 3 the results of average thrust force variation with feed rate – a) – and maximum thrust force for the five tools used – b) – are showed. In spite of the drill geometry, an increase of feed rate caused an increase of thrust force, as expected. Based on these results, the use of a low feed rate is recommendable if delamination around the hole has to be reduced. Yet, a reduction in feed rate also has a consequence on temperature build-up, increasing the risk of thermal damages. Therefore, this feature should be taken into account.

Minimum thrust forces correspond to the use of Dagger drills, regardless of the feed rate considered. This result can be explained by the sharp drill tip of this drill. Brad and twist 85º drills are a reasonable combination of thrust force and visual appearance of the plate exit side. Finally, higher results were obtained when the twist 120º or the special step drills were used. Variation from the three levels previously identified is relatively large as it is almost twice from Dagger to Brad/twist 85º drills and more than 2 times from Dagger to special step/twist 120º drills. These outcomes need to be related with sub sequential analysis of roughness and delamination extent.

**Hole surface roughness.** There is still some doubt about the importance of roughness in mechanical behaviour of drilled plates. The result can be influenced by the number and orientation of fibres that are within the stylus evaluation length. In order to reduce this uncertainty, the results are the average of three measurements in three different zones of the machined wall. Nevertheless, results of this parameter should not be seen in the same way as when metallic parts are considered.

Higher values of roughness were obtained with Dagger drill, corresponding to worst visual look and lower values with Brad or twist drills, Fig. 4. The influence of feed rate for twist 85º drill is presented in table 1, although the trend is not equal for all drills. Higher feed rates correspond to higher values of $R_{\text{max}}$.

Looking at the results of roughness measurement, and when in comparison to the significance of axial thrust force, the influence on drill selection seems to be less relevant.
Fig. 4. Comparison of surface roughness $R_{\text{max}}$ for the five drill geometries; feed rate = 0.06 mm/rev.

Table 1. Surface roughness for different feed rates – twist 85° drill.

| Feed rate [mm/rev] | $R_{\text{max}}$ [µm] |
|-------------------|-----------------------|
| 0.02              | 5.51                  |
| 0.06              | 5.83                  |
| 0.12              | 6.61                  |

**Delamination.** Measurement of delamination extension is not possible by traditional visual inspection as the plates are opaque. So, they need to be inspected by enhanced radiography. With this purpose, plates are immersed in a radio-opaque fluid for one and a half hour before radiography. The resulting images were then digitalized and processed using computational techniques of image processing and analysis. This computational inspection approach has the high advantage of reducing operator dependence to measure the dimensions needed, thus increasing results reliability [9, 21]. In the end of the image processing and analysis pipeline considered it was possible to obtain the dimensions necessary in order to perform a suitable damage evaluation, as the delamination area and maximum delaminated diameter. Results obtained using the referred image processing and analysis pipeline from an example radiography can be seen in Fig. 5.

![Fig. 5. Assessment of the delamination parameters: a) original radiography; b) resultant image (hole area in grey; delaminated region in white); c) measurement results.](image)

Fig. 6 shows the results of delamination factor ($F_d$) for the five drills and the three feed rates considered in the experimental work accomplished. In this figure, a line representing the average for each feed rate is also represented. Note that results for twist 120° and special step drills are always...
below average, while for twist 85º and Brad drills are above this value. Delamination with Dagger drill follows approximately the average line. As expected, due to the progression of thrust forces with increased feed rate discussed above, low feed rates permit damage minimization. Additionally, an increase in feed rate has as a consequence of higher delamination around the hole. This outcome agrees well with the thrust force values profile.

Fig. 7 shows the results of Damage Ratio \((D_{RAT})\) for the five drills of this study are presented as well as their variation according to the three feed rates. Observing this figure, it is possible to state that, as expected, feed rate influence on damage extension is identical. Regarding the effect of tool geometry, the results of this criterion show that the twist 120º and the special step drills are the most adequate tools for carbon/epoxy plates drilling, under the experimental circumstances of this work. For the lowest feed rate, it seems that the difference on the damaged area is not so great as the damaged diameter results used for \(F_d\) in Fig. 6.

**Fig. 6.** Feed rate influence on delamination factor \((F_d)\), for the five drill geometries and average line.

**Fig. 7.** Drill geometry influence on damage ratio \((D_{RAT})\), for the three feed rates.

**Conclusions**

Carbon fibre reinforced laminates were drilled with the objective of comparing five different tool geometries. Results considered for this purpose were the maximum axial thrust force during drilling, hole surface roughness and delamination. Experimental work has involved three feed rates and one cutting speed. From the work presented, it is possible to draw some main conclusions:

- Low feed rates seem appropriate for laminate drilling, as it reduces the axial thrust force. However, this option can cause thermal degradation of the matrix and can be unsuitable for industrial processes where productivity is, as a rule, a priority.
- Tool geometry had influenced the results for all the measurements considered. Results are not coincident, but it is advisable to pay more attention in order to minimize the delamination and related thrust force.

- Based on the work here presented, and considering the parameters used during the experimental procedure, a Brad drill with a cutting speed of 53 m/min should be combined with a feed rate of 0.02 mm/rev for delamination minimization.

- Mechanical testing should complement the conclusions here presented.

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