Drilling of carbon fibre reinforced laminates – a study

Luís M. P. Durão[1a], Daniel J. S. Gonçalves[1b], João Manuel R. S. Tavares[2c], Victor H. C. Albuquerque[2c], A. Torres Marques[2c], A. M. Baptista[2c]

[1]ISEP – Instituto Superior de Engenharia do Porto /CIDEM
R. Dr. António Bernardino de Almeida, 431 – 4200-072 PORTO, PORTUGAL

[2]FEUP – Faculdade de Engenharia da Universidade do Porto /INEGI – Instituto de Engenharia Mecânica e Gestão Industrial, R. Dr. Roberto Frias, 400 – 4200-465 PORTO, PORTUGAL

[a]lmd@eu.ipp.pt, [b]daniel.j.s.goncalves@gmail.com,
[c]{tavares, victor.albuquerque, marques, amb}@fe.up.pt

Keywords: composites, carbon fibre, drilling, thrust force, delamination, roughness.

Abstract. The distinguishing characteristics of carbon fibre reinforced laminates, like low weight, high strength or stiffness, had resulted in an 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 thrust forces, thus 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 takes 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. Several approaches had been presented in the last years [3, 5-9]. Generally, it is accepted that delamination can be reduced with an adequate combination of feed rate, cutting speed and drill geometry [5, 10-14]. Apart from that, 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]. Normally, the adoption of low feed rates can avoid this delamination.

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, thus reducing the indentation effect of the final drill [15, 16].

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 (85º and 120º), 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 an algorithm of image analyis and processing. 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 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 ºC for one hour, followed by air cooling. Final plate thickness was 4 mm. The plates were cut in test coupons of 165 * 96 mm^2 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 had a diameter of 6 mm

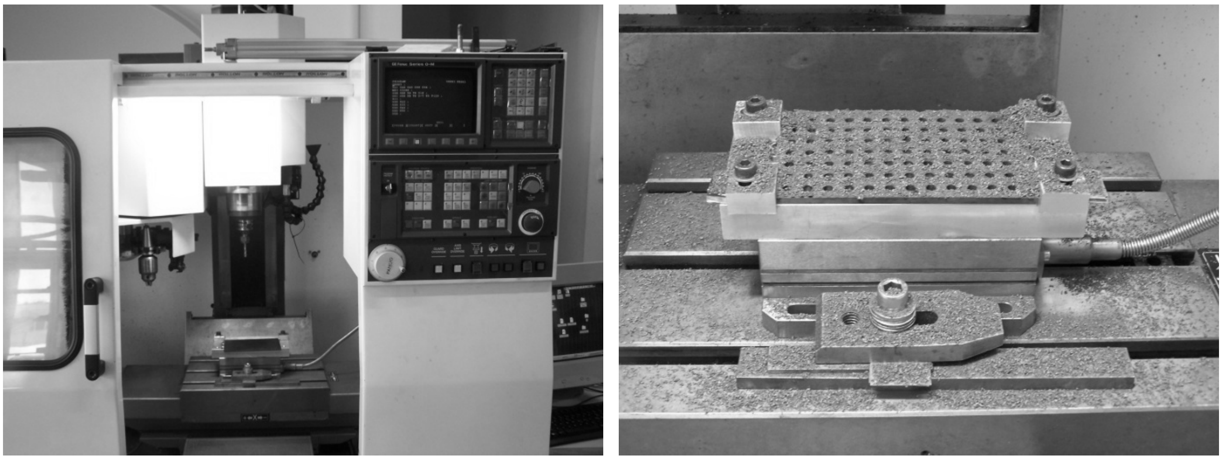
a) b) c) d)

Figure 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, 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 collection. No sacrificial plates were used, Fig. 2a), b).

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).



a) b)

Figure 2 – a) Experimental setup adopted; b) aspect of a drilled plate.

After drilling, hole wall roughness was measured with a *Hommelwerke* profilometer, with a cut-off length – λ_c – of 0.25 mm and an evaluation length – l_m – of 1.25 mm. In this work, the roughness parameter considered was R_{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.

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 scanned for delamination around the hole measurement and *Delamination Factor* results. The *Delamination Factor* (F_d) [17] is a ratio between the maximum delaminated diameter (D_{max}) and hole nominal diameter (D),

$$F_d = D_{\max} / D \qquad (1).$$

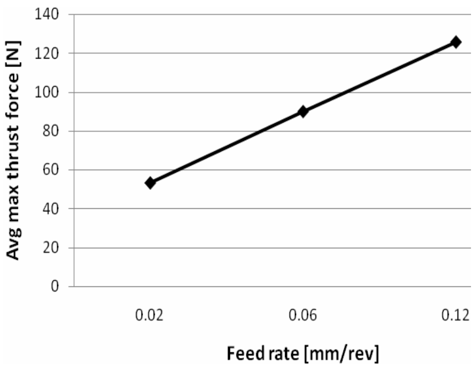
Details of the process can be found elsewhere [9].

Results and discussion

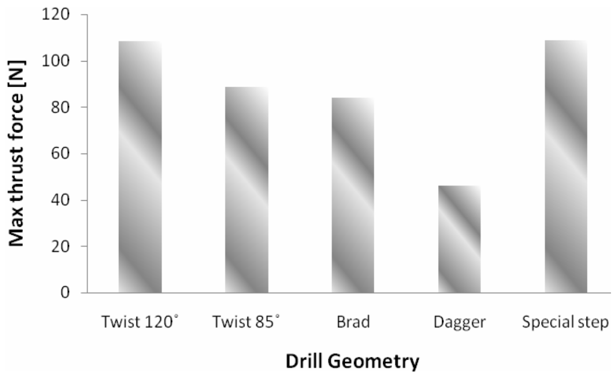
Thrust forces. Results considered for thrust force are the maximum value observed during drilling. This result is regarded as a good indication of delamination occurrence as, according to published analytical models [4], higher thrust forces normally correspond to higher delamination possibility. Due 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 thrust force variation with feed rate – a) – and average of maximum thrust force for the five tools used – b) – can be observed. Independently of 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 is to be reduced. Yet, a reduction in feed rate also has a consequence on temperature build-up, increasing the risk of thermal damages. This feature should be taken into account.

Minimum thrust forces correspond to the use of Dagger drills. This result can be explained by the sharp drill tip of this drill. Brad and twist 85º drills are a fair combination of thrust force and good visual appearance of the plate exit side. Finally, higher results were obtained when twist 120º or special step drills were used. Variation from the three levels here identified is relatively large as it is almost twice from Dagger to Brad/twist 85º and 2.4 times from Dagger to special step/twist 120º. These outcomes need to be related with sub sequential analysis of roughness and delamination extent.



a)



b)

Figure 3 – Thrust force results for experimental feed rate and drill geometries.

Hole surface roughness. There is still some doubt about the importance of roughness in mechanical behavior of drilled plates. The result can be influenced by the number and orientation of fibers that are within the stylus evaluation length. In order to reduce this indecision, every result is the average of three measurements in three diverse 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 is presented in table 1. Higher feed rates correspond to higher values of R_{max}.

Looking at the results of roughness measurement, the influence on drill selection should be less when compared to the significance of axial thrust force.

Table 1 – Surface roughness for different feed rates.

Feed rate [mm/rev]	R_{max} [μm]
0.02	5.51
0.06	5.83
0.12	6.61

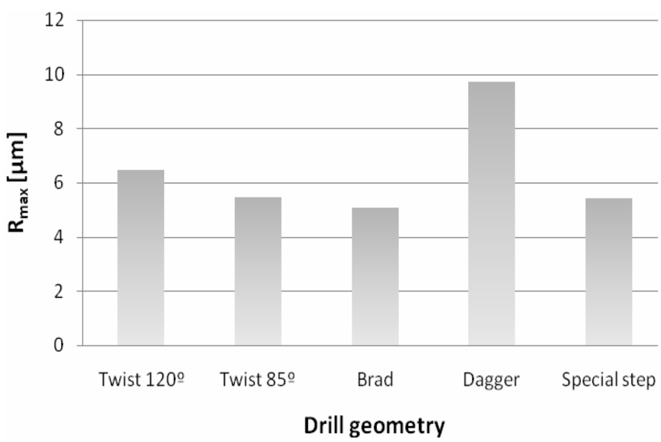
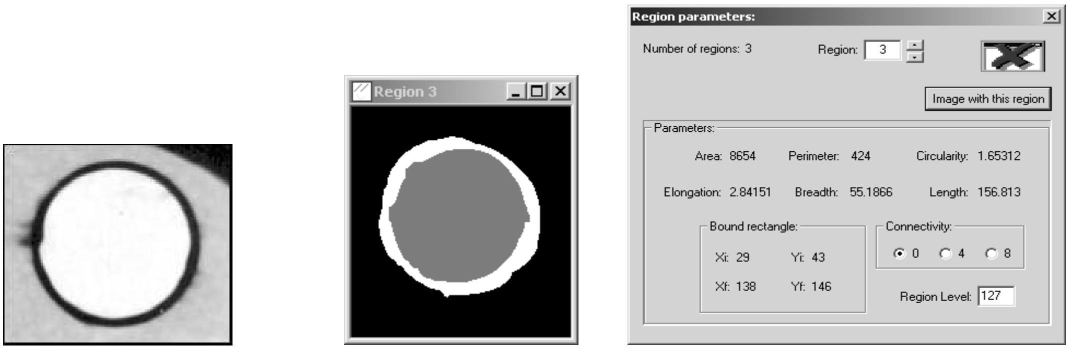


Figure 4 – Comparison of surface roughness – R_{max} – for different drill geometries

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 scanned and processed using algorithms 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, 19]. In the end of the image processing and analysis pipeline considered it was possible to obtain the dimensions judged as necessary in order to have a damage evaluation, like 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.



a) b) c)

Figure 5 – Example of image processing and analysis results: a) original radiography; b) resultant image (in grey is the hole are; in white is the delaminated region); c) measurement results.

Fig. 6 shows the results of delamination factor – F_d – for the three feed rates considered in experimental work. As expected, low feed rates permit damage minimization. On the other hand, an increase in feed rate has as a consequence higher delamination around the hole. This outcome agrees well with the thrust force values profile.

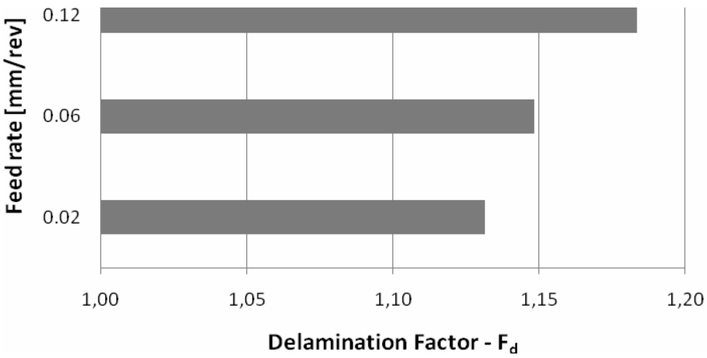


Figure 6 – Feed rate influence on delamination factor – F_d (Eq. 1).

Conclusions

Carbon fibre reinforced laminates were drilled with the objective of comparing five different tool geometries. Results used for this comparison 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 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 to minimize delamination and reduce 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.

Acknowledgements

This work was supported by FCT (Fundação para a Ciência e a Tecnologia) Portugal, in the scope of the project PTDC/EME-TME/66207/2006 "Machining of hybrid composites".

References

[1] E. Persson, I. Eriksson, I. and L. Zackrisson, Composites A: v. 28, (1997), p. 141.

[2] C. W. Wern and M. Ramulu, Experimental Mechanics: (1994), p. 33.

[3] H. Hocheng and C. C. Tsao, J. of Materials Processing Technology: v. 167, (2005), p. 251.

[4] H. Hocheng, C. K. H. Dharan, Journal of Engineering for Industry, v. 112, (1990), p. 236.

[5] R. Piquet, B. Ferret, F. Lachaud and P. Swider, Composites A: v. 31, (2000), p. 1107.

[6] C. H. K. Dharan and M. S. Won, Int. J. Machine Tools and Manufacture: v. 39, (2000), p. 415.

[7] M. S. Won and C. H. K. Dharan, Trans. of ASME J. of Manufacturing Science and Engineering: v. 124, (2002), p. 778.

[8] C. C. Tsao and H. Hocheng, Int. J. Machine Tools & Manufacture: v. 45, (2005), p. 1261.

[9] L. M. P. Durão, J. M. R. S. Tavares, A. T. Marques, A. M. Baptista, A. G. Magalhães, Int. Journal of Materials and Product Technology, v. 32, (2008), p. 226.

[10] K. Y. Park, J. H. Choi, D. G. Lee, J. Composite Materials, v. 29, (1995), p. 1988.

[11] R. Stone and K. Krishnamurthy, Int. J. Machine Tools & Manufacture, v. 36 (1996), p. 985.

[12] J. P. Davim, P. Reis, Materials and Design, v. 24, (2003), p. 315.

[13] H. Hocheng and C. C. Tsao, Int. J. Machine Tools & Manufacture, v. 46, (2006), p. 1403.

[14] C. C. Tsao and H. Hocheng, J. Materials Processing Technology, v. 192-193, (2007), p. 37.

[15] C. C. Tsao, Int. J. Machine Tools & Manufacture, v. 46, (2006), p.1653.

[16] C. C. Tsao, Int. J. Machine Tools & Manufacture, v. 47, (2007), p. 2172.

[17] W. C. Chen, Int. J. Machine Tools & Manufacture, v. 37, (1997), p. 1097.

[18] Luís M. P. Durão, A. G. Magalhães, A. T. Marques, A. M. Baptista, M. Figueiredo, Materials Science Forum, v. 587-588, (2008), p. 706.

[19] A. T. Marques, L.M. Durão, A. G. Magalhães, J. F. Silva, J. M. R. S. Tavares, Composites Science and Technology (2009), doi: 10.1016/j.compscitech.2009.01.025