ANALYSIS AND QUANTIFICATION OF DAMAGE IN POLYMER COMPOSITE MATERIALS

Pedro Silva[1], João E. Matos[2], Luís Miguel P. Durão[1,3(*)],
[1] School of Engineering, Polytechnic of Porto (ISEP), Porto, Portugal
[2] Laboratório Engenharia Matemática (LEMA), School of Engineering, Polytechnic of Porto (ISEP), Porto, Portugal
[3] Centro de Investigação e Desenvolvimento em Engenharia Mecânica (CIDEM), School of Engineering, Polytechnic of Porto (ISEP), Porto, Portugal, lmd@isep.ipp.pt

Keywords: Composite materials, Drilling damage, Damage quantification, Mechanical testing

ABSTRACT

The specific characteristics of composite materials, like carbon fibre reinforced plastics, have been leading to their rising importance and widespread use. As these parts are normally produced in a near-net shape, secondary operations, like drilling, are necessary prior to their assembly in complex structures. It is still difficult to define a machining process that enables free damage holes, due to the peculiar laminar nature of these materials. So, the definition of a drilling process that minimizes delamination and increases reliability in produced parts combined with satisfactory cost and productivity is still of major importance in the composites manufacturing industry.

In this paper two sets of unidirectional coupons from plates with carbon fibre as reinforcement and epoxy resin as matrix, are drilled using five different drilling tool strategies and two feed rates for uneven damage extension. One of the strategies is the use of a pre-drilling option. Then the delamination is assessed using enhanced radiography and, finally, two diverse mechanical tests are performed on the resulting coupons: three point bending and pin bearing.

The results allowed establishing and modelling, with the help of statistical tools, the relations between the damaged area caused by drilling and the material's mechanical resistance. The bending resistance does not vary greatly with the damage area. On the other hand, the bearing resistance decreases with the increase of the damaged area.

1 INTRODUCTION

Composite materials have been assuming a growing importance in engineering and their use is becoming more common. Important characteristics of these materials, such as high mechanical properties along with low specific weight, have allowed a wide application in distinct areas like medicine, sports, aeronautics, defense or automotive industry.

The majority of the composite materials are produced in the form of functional parts, in a net or near-net shape. However, their use does not fully exclude yet the need of additional machining processes, particularly the drilling process. So, the drilling of composite materials remains a very frequent finishing operation and, despite several advances in this area in recent years, this process causes damages to the composite materials whose effects must be taken in consideration. Among the main problems resulting from drilling, delamination is one of the most important as it causes concerns about mechanical and fatigue resistance of the parts [1].

The objective of this study is to evaluate the magnitude of the area damaged by drilling in carbon fibre reinforced laminates with an epoxy matrix and how does the resulting damage of the drilling process affects the mechanical properties of the produced plates.

With this purpose, thirty-nine test coupons in carbon epoxy were manufactured and thirty five of them drilled with five different drill geometries – Twist drill with and without the pre-drilling strategy, Dagger Drill, Brad drill, High Speed Steel drill – to obtain different damage areas. All the drills had a 6 mm diameter and, to avoid a large diversity of cutting parameters and evaluation factors, the cutting speed was kept constant and equal to 1120 rpm whereas the feed rate had two levels: 0.12 and 0.30 mm/rev. These cutting parameters were selected according to tool manufacturer's recommendation and former experience of the authors.

After the drilling process, the delaminated region around the drilled hole was evaluated using enhanced digital radiography. In order to generate a contrast, the laminates were first immersed in di-iodomethane for some minutes. Then the radiographic images were acquired using a 60 kV, 300 kHz Kodak 2100 X-ray system associated with a Kodak RVG 5100 digital acquisition system. An example of the processing sequence of a radiographic image can be found in [2]. From the resulting images it was possible to calculate the damaged area, using an image editing software. Finally, the test coupons went under two mechanical tests – Three point bending and Pin-Bearing test – to assess the mechanical properties and consequences of the machining of holes in the composite plates. The determined damaged areas were related to the loss of mechanical properties verified during the tests, using appropriate statistical tools.

The achieved results allowed establishing and modelling the relations between the damaged area during drilling and the material's mechanical resistance. The bending resistance does not vary greatly with the damage area. On the other hand, the bearing resistance decreases with the increase of the damaged area. The results will demonstrate the importance of an adequate assessment of damaged area and proper selection of machining parameters to extend the life cycle of these laminates by reducing delamination and other damages.

2 DRILING OF POLYMER COMPOSITE MATERIALS

Drilling of composite materials is, for the most part, a necessary finishing operation when the fabrication of parts in complex structures has to be accomplished, mostly because of assembly purposes. The selection of appropriate tools and drilling conditions is of the utmost importance on the attainment of damage-free holes, as can be found in [3-5].

Drilling is a particular kind of material removal process where the tool has a rotating motion combined with a vertical feed movement along the part. So, during the cutting process, the fibre orientation angle is variable, thus causing a change on the cutting mechanisms identified by Klocke et al [6] and the correspondent fibre fracture mode – tensile, compression or bending. Chip removal mechanism is similar to oblique cutting with continuously changing cutting speeds, from zero at the centre to nominal cutting speed at the external edges. When considering the drilling operation, several factors are to be analysed for optimization, minimizing the negative effects on mechanical strength and fatigue life: tool material, tool geometry and drilling conditions [7-9].

Tool material plays an important role as different tool materials result in different hole finishing quality and damage extension. Generally, tungsten carbide tools are the most used, whereas high speed steel tools cause greater damage extension and polycrystalline diamond tools are too expensive. Tool wear is a consequence of composites abrasiveness and affects the possibility of performing a clean cut during the entire tool life. Another issue related to the tool material is thermal damage as the temperature rise normally observed during machining softens the matrix thus facilitating delamination or fibre pull-out.

The tool geometry is a key factor on the design of experimental works concerning damage assessment. New drills geometries have been developed or experimented for composite materials drilling with less delamination [10-13]. The main focus on this tool development is the reduction of the thrust force, the improvement of drill quality considering the existence of visual defects such as burrs and productivity enhancement. A tool geometry that is able to reduce the thrust force has a great effect on delamination reduction.

The effect of the drilling conditions is a broad theme where a great diversity of approaches can be considered. Some of these approaches consider the spindle speed, the feed rate, the existence of coolant, the use of a backup plate, the pre-drilling strategy or workpiece damping [14-16]. All of these possible drilling strategies intend to reduce delamination. It is known that delamination onset and propagation is a complex function that depends not only on the drilling conditions intending to reduce the thrust force but also on the material properties, as demonstrated by the Critical Thrust Force model first presented by Hocheng and Dharan [17].

When considering the drilling of composites materials with zero-defects, good results are mainly related with the reinforcement rather than with the matrix material.

3 MATERIALS AND METHODS

This section will describe the experimental procedure, addressing the methods, the materials and the equipment used. Then, the image processing sequence for damage quantification is explained. Finally, in section 4, the mechanical tests and statistical correlations are demonstrated.

3.1 Composite plates fabrication

For the experimental work, two unidirectional carbon epoxy plates fabricated from prepreg HS 160 T700 UD REM tape 36%, from CIT, Italy were used. The plates were cured for 2 hours at 135 ºC, followed by cooling. The final thickness of the plates was 3 mm. The typical mechanical characteristics of the material can be found in Table 1.

Cured material property	Unit	Typical values
Tensile modulus 0º	[GPa]	123
Tensile strength 0º	[MPa]	2294
Tensile strain	%	1.72
Compression Modulus 0º	[GPa]	109.8
Compression strength 0º	[MPa]	1152
Flexural Modulus 0º	[GPa]	134
Flexural strength 0º	[MPa]	1850
ILSS	[MPa]	81.5

Table 1: Typical mechanical characteristics of HS160 T700 UD REM Tape 36%.

The plates were cut into 19 test coupons of 100 × 18 mm and 20 test coupons of 35 × 135 mm that would be used for the drilling and subsequent mechanical tests, the Three point bending test and the Pin-Bearing test. All the coupons were numbered for traceability.

3.2 Drilling

The drilling operations were carried out using a MAS VR2 radial drill machine and every drill was performed with the coupon supported by wooden tabs on the drill zone, to prevent further damage due to coupon bending. The entrance and exit sides of the drill were marked in the coupon surface using markers.

There were used five types of drilling using four types of drill geometry: Twist (TWI), Twist with previous drilling of lower diameter (TPD), Dagger (DAG), Brad (BRA) and High Speed Steel (HSS), as presented in Figure 1.

Figure 1: Drill geometries used: a) Twist; b) Dagger; c) Brad; d) HSS.

The Twist drills are very commonly used in composite drilling. The Dagger drills have a very sharp angle and require a long exiting space for completing the hole at the nominal diameter. The Brad drill has cutting edges with sickle shape, tensing the fibers before cutting, which results in a cleaner hole. All these drills are made of tungsten carbide.

The High Speed Steel drills are geometrically identical to Twist drills but are made of high speed steel, a material that is not recommended for fiber composites drilling due to the abrasiveness of the reinforcement phase, producing larger damage areas around the hole.

The pre-drilling with a lower diameter drill before the final twist drilling is favorable as it reduces the tension at the exit of the drill from the hole, producing also a cleaner hole.

The tool diameter for every drill used was 6 mm with the exception of the one used to perform the pre-drill for the TPD type, which had a diameter of 1.6 mm, corresponding to 27% of the nominal final diameter, greater than the optimum ratio of 12% recommended in [18].

Since the diversity of damage areas was supposed to be achieved using different types of drills and not through different drilling parameters, only one spindle speed and two feed rates, low and high, were used. The spindle speed was set to 1120 rpm at all times, the low feed rate was 0.12 mm/rev and the high feed rate was 0.30 mm/rev, this last one being only applied when drilling with HSS drills, to produce even greater damage around the hole.

The drilling parameters are presented in Table 2.

Coupon Dimensions	Drill Type	Number of Coupons	Spindle Speed (rpm)	Feed Rate (mm/rev)
100×18	No Drill	4	---	---
100×18	TPD	3	1120	0.12
100×18	BRA	4	1120	0.12
100×18	DAG	4	1120	0.12
100×18	HSS	4	1120	0.30
135×35	TPD	4	1120	0.12
135×35	BRA	4	1120	0.12
135×35	DAG	4	1120	0.12
135×35	HSS	4	1120	0.30
135×35	TWI	4	1120	0.12

Table 2 – Experimental drilling parameters.

After the process of drilling the coupons, it was possible to observe that the use of Dagger and HSS drills cause larger areas of damage in the holes periphery than those observed using Twist drills – independently of the use of previous drilling – or Brad drills. (Figure 2). Similar observations were possible when looking at both sides - drill entry and drill exit side of the plate.

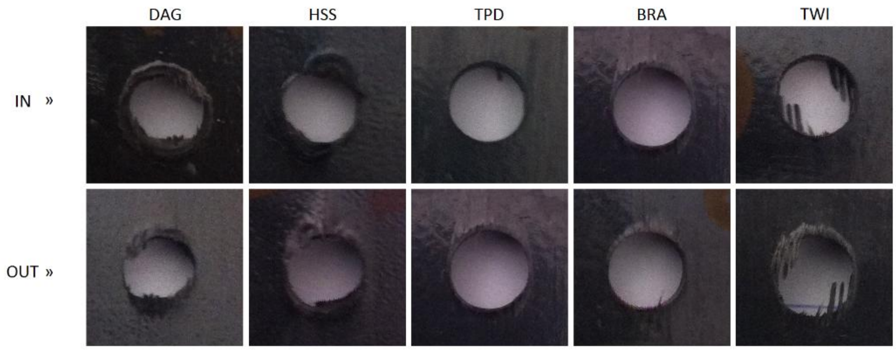

Figure 2: Visual inspection of damage after drilling from both entry (IN) and exit (OUT) sides.

The entry damage is normally known as peel-up delamination and the determination of the corresponding extension was not considered in this study. The exit damage, normally known as pushdown delamination is considered as more severe from the mechanical point of view and was more thoroughly studied, as it will be discussed further. It is obvious that at the entry side (Figure 2a), some plates had almost no peel-up delamination, while at the exit side there is always some identifiable delamination merely by visual inspection (Figure 2b).

3.3 Delamination Assessment

After completing the drilling process, the delaminated area around the drilled holes was determined using enhanced digital radiography. Prior to the assessment was the immersion of the drilled coupons in a contrasting liquid, diiodomethane AnalaR NORMAPUR® analytical reagent from VWR, for approximately 15 minutes, to generate a registrable contrast during the radiographic process.

The radiographic images were obtained using a Kodak 2100 X-Ray device linked to a Kodak RVG 5100 digital sensor. The exposition time was 0.125 seconds, resulting in good quality images with a 14 lp/mm resolution. The images were saved as bitmap (.bmp) format files, as this format does not cause any compression or loss of resolution. (Figure 3)

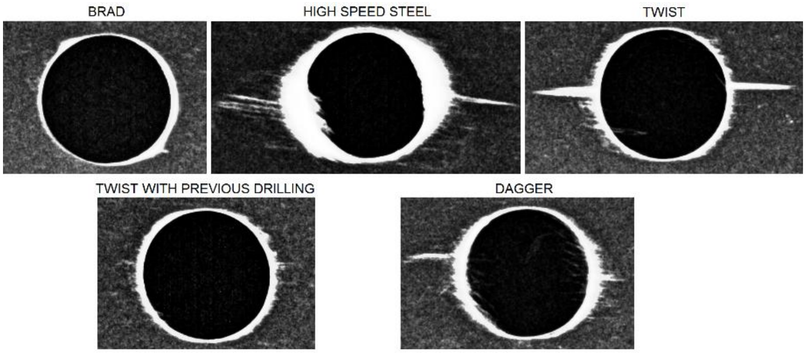

Figure 3: Radiographic images with different drills used.

A digital image can be considered as an array of its smallest addressable element, named the pixel. The numerous pixels that form an image have different colours and brightness. (Figure 4)

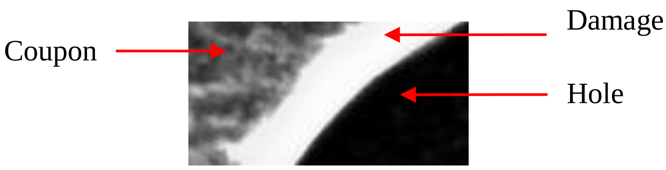

Figure 4: Example of the borders of a damaged area: black region is the hole; white region is the damaged area; grey region is the undamaged coupon.

In order to assess the delamination extension, it is firstly necessary to define better the areas and borders of the hole, the damaged zone and the coupon area. This can be achieved by turning the image into a binary image where the delaminated area is white and the hole and coupon areas are black. To turn the radiographies into binary images, it was used an image editing software, the GIMP®, using its threshold tool.

The threshold tool calculates an average level for the image colours, turning the pixels with colours below the defined level into black pixels and the pixels with colours above the defined level into white pixels. For every single radiography it was defined a threshold level that would result in a binary image as close as possible to the original image.

The following step consisted in removing the "noise" from the images. The "noise" consisted in white spots and stains that resulted from irregularities on the surface of the coupons. Eliminating these areas, using the paint tool of GIMP® would guarantee that the white pixels in the binary image would correspond only to the delaminated area around the hole (Figure 5).

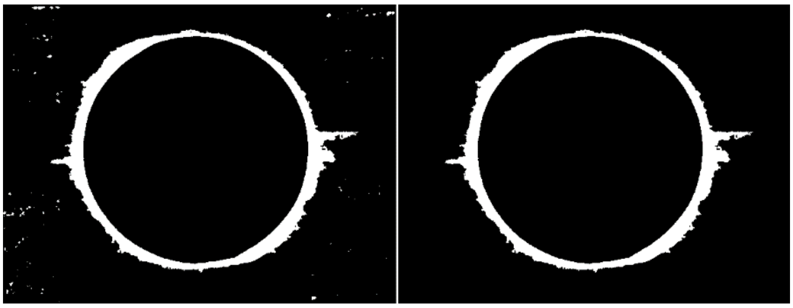

Figure 5: Example of a binary image before (left) and after (right) the “noise” removal sequence.

The final step in image processing was the circular reconstruction in cases where the burrs resulting from the drilling process prevented the holes contour to appear as a complete circle. This was made using the circular selection tool of GIMP® and selecting sections of the hole contour where the circular shape was visible. (Figure 6)

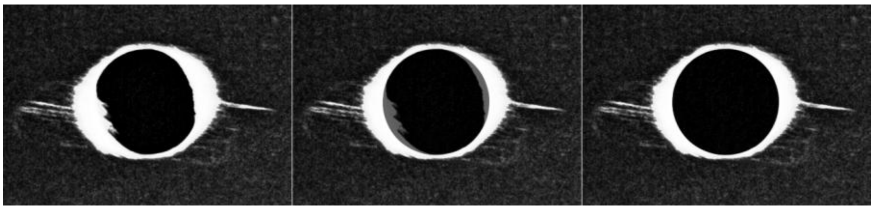

Figure 6: Circular reconstruction of a hole contour originally with burrs.

The “noise” elimination and the circular reconstruction abilities as well as an easier threshold definition constitute advantages of the GIMP® software regarding the MatLab®.

The colour histogram tool of the GIMP® software gives an account of the total number of pixels by colour. Filling the circular drill area in the binary image with a third colour (for instance, red) allows for the determination of the hole (red) and damaged (white) areas, in pixels (Figure 7).

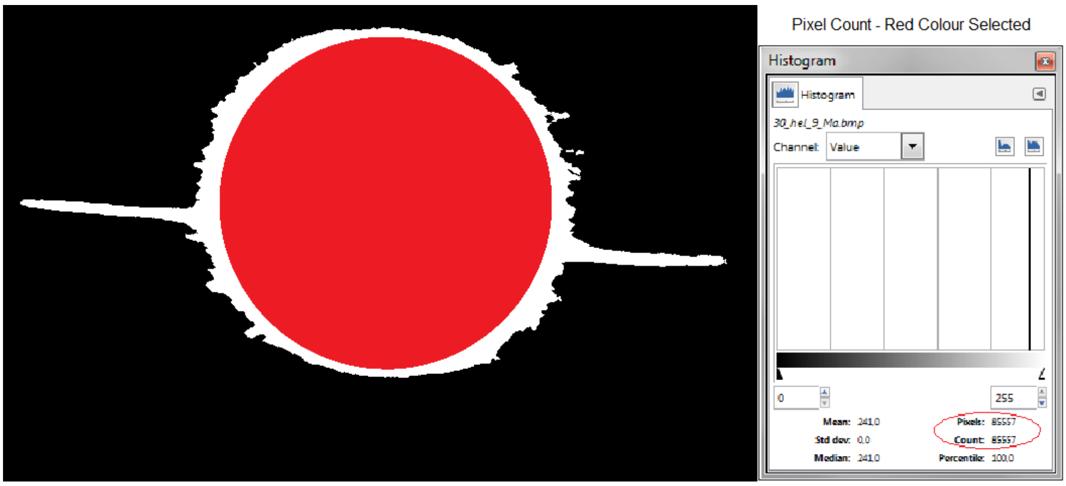

Figure 7: Example of a damaged area determination with colour histogram from GIMP®.

Considering that all the holes had a 6 mm diameter and thus, a 28.27433 mm^2 area, by dividing this last value by the total of red pixels on an image, made it possible to determine the area factor by pixel for that single image. In other words, how many mm^2 represented a pixel for that particular image.

By multiplying the total number of white pixels of an image by the area factor determined for that image, it was possible to obtain the delaminated area in mm^2.

With the determination of the damaged area accomplished, it was possible to use one of the existent damage criteria. The Damage Ratio, as presented in [19], was selected for this work. As this criterion considers the damaged area, it seems more appropriate when, as in Figure 7, the damaged area has a long delamination in a single direction, thus increasing the Delaminated diameter while the real area does not match to such an elevated value.

Table 3 shows some values of delaminated areas and Damage Ratio obtained after image processing, for the 100x18 mm^2 coupons.

Coupon Number	Drill Type	Spindle Speed (rpm)	Feed Rate (mm/rev)	Damage Area (mm^2)	Drat
1	BRA	1120	0.12	7.501	0.265
2	BRA	1120	0.12	7.261	0.257
3	BRA	1120	0.12	4.392	0.155
4	BRA	1120	0.12	2.797	0.099
5	TPD	1120	0.12	5.639	0.199
6	TPD	1120	0.12	5.964	0.211
7	TPD	1120	0.12	3.354	0.119
8	DAG	1120	0.12	7.644	0.270
9	DAG	1120	0.12	6.926	0.245
10	DAG	1120	0.12	12.201	0.432
11	DAG	1120	0.12	8.543	0.302
12	HSS	1120	0.30	11.036	0.390
13	HSS	1120	0.30	14.181	0.502
14	HSS	1120	0.30	11.854	0.419
15	HSS	1120	0.30	14.744	0.522

Table 3: Delaminated areas and Damage Ratio calculated for the 100x18 coupons' holes.

3.4 Mechanical testing

To assess the effects that the delamination and its extension have on the mechanical properties of the drilled plates, there were carried out two mechanical tests: Three point Bending and Pin-Bearing Test.

For the Tree point Bending test the 100 × 18 mm coupons were used, including those without hole for reference. This test was carried out according to ISO 14125:1988 [20]. It consisted in applying a downward load until rupture. This load was applied at a speed of 3.5 mm/min, across the section of the coupon that contained the drill diameter, with a span of 80 mm. The side of the coupons facing the load anvil was always the drill exit side.

The Pin-Bearing test, proposed by Wang et al. [18], used a part cut from the 135 × 35 mm coupons, containing half of a hole. The parts used respected the dimension ratios proposed in [21], guaranteeing a rupture purely by compression, without any bending (Figure 8).

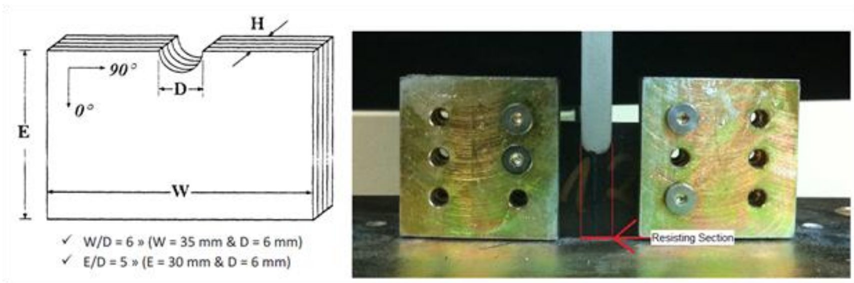

Figure 8: Dimension and Shape of coupons and apparatus for Pin-Bearing test.

This test consisted in applying a downward load with a semi-circular edge inside the half-hole part until rupture, at a speed of 1.27 mm/min.

All the tests were performed in a Shimadzu AG-X/100 kN Universal Testing machine equipped with the necessary accessories to run the different tests and connected to a computer for machine control and data acquisition.

4 RESULTS AND DISCUSSION

From the experimental procedure described above, it was possible to derive the results of the Damage Ratio grouped according to the type of drill used as is presented in Figure 9.

The holes drilled with Twist or Brad drills had the smallest damaged area and, consequently, the lower values of the Damage Ratio. Moreover, the use of the pre-drilling had reduced the damaged area by around 9%, showing that this can be a good procedure when trying to have no-damage holes. The holes with HSS drills were the most damaged, as expected.

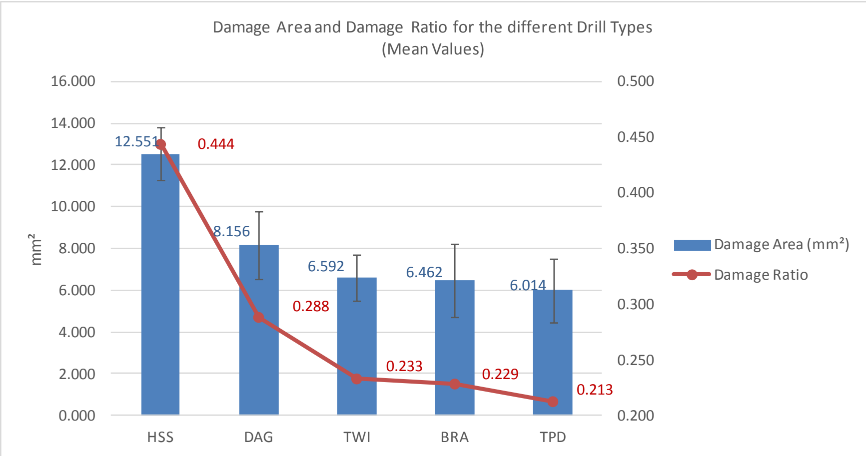

Figure 9: Average values of Damage area and Damage Ratio for the several drills used.

The next step was the analysis of the results from the Three point bending test and the comparison with the non-drilled coupon, as a reference value, identified as coupons 100_0.1 to 100_0.4. Resulting values of Flexure strength were calculated not considering the existence of a hole and are presented in Table 4. As expected, the flexure strength of the drilled plates was lower than the reference plates but there was a large scattering of the results from the drilled plates, as can be better observed in Figure 10.

Despite the scattering, it was possible to observe that the highest values of the flexure strength were from those plates drilled with the Twist drill with previous drilling (TPD) with values exceeding the average of the remaining coupons by about 4% when considering all the other drilling options or by 3% if taking into account only the other carbide drills (BRA/ DAG). It was expected that the coupons drilled with HSS drills returned the lower results and this outcome was checked on average, although the variation was also high.

Therefore it was analyzed if this scattering was more important than the damaged area and the Prism5® statistical tool was used to find a correlation, returning a plateau model also visible in Figure 10, with an asymptote around 733 MPa and a correlation of 91%. It is possible to conclude that the existence of a hole is the highest factor for this strength reduction and the damage extension importance is not relevant when we consider the Three point bending test for the evaluation of damage extension consequences.

The final step was the performing of the Pin-Bearing test. Considering the test setup with the use of an anvil causing compression on the drilled wall, it was not possible to use the reference coupons with no hole. The results are presented in Table 4 and in Figure 11. The results of this mechanical test turn out evident that, on the whole, the pin-bearing strength decreases as the damaged area increases. This outcome was expected and is in accordance with previous results presented in several papers referred along this study.

Coupon Number (100x18)	Drill Type	Flexure Strength (MPa)	Damage Area (mm^2)	Coupon Number (135x35)	Drill Type	Pin-Bearing Strength (MPa)	Damage Area (mm^2)
0.1	No Drill	1098.00	-	1	TPD	301.97	5.497
0.2	No Drill	1170.19	-	2	TPD	309.84	3.902
0.3	No Drill	1293.30	-	3	TPD	346.01	5.646
0.4	No Drill	1145.19	-	4	TPD	343.47	6.643
1	BRA	802.07	7.501	5	BRA	289.71	7.523
2	BRA	746.20	7.261	6	BRA	346.02	5.273
3	BRA	623.13	4.392	7	BRA	313.11	5.923
4	BRA	718.26	2.797	8	BRA	355.91	5.526
5	TPD	752.21	5.639	9	TWI	350.49	7.544
6	TPD	751.21	5.964	10	TWI	291.65	4.723
7	TPD	764.79	3.354	11	TWI	330.85	5.636
8	DAG	729.27	7.644	12	TWI	278.74	6.855
9	DAG	704.92	6.926	13	DAG	287.55	6.323
10	DAG	720.95	12.201	14	DAG	310.89	7.372
11	DAG	792.52	8.543	15	DAG	323.26	7.308
12	HSS	677.44	11.036	16	DAG	275.16	9.661
13	HSS	660.93	14.181	17	HSS	264.69	11.639
14	HSS	748.29	11.854	18	HSS	284.20	12.088
15	HSS	797.09	14.744	19	HSS	217.83	12.716
				20	HSS	192.04	13.756

Table 4: Values for Flexure and Pin-Bearing Strength test and their corresponding Damage Areas.

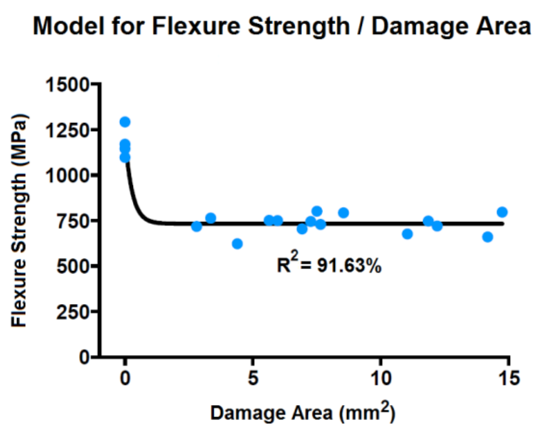

Figure 10: "Plateau" model describing the relation between Flexure Strength and Damage Area.

When comparing the use of previous drilling (TPD) with Twist drilled coupons without previous drilling (TWI), it was observed that the average increase of the pin-bearing strength was about 4%. This result remarks the importance for damage reduction of lower thrust forces generated during drilling and the absence of the pushing effect during final diameter drilling on TPD drilled holes. The pin-bearing strength results of the coupons with BRA drilled holes were on the same range of the TPD drilling sequence, showing the good performance of Brad drills when machining composite materials. Remind that Brad drills were intentionally designed for the drilling of this kind of materials, being a development of drills normally used for wood. The use of Dagger drills had not evidenced any advantage from any point of view considered and for pin-bearing test the final result was lower by 9%

when compared with the highest values in this mechanical test. Finally, it was confirmed that HSS drills are not adequate for carbon/epoxy composites drilling, as the pin-bearing strength was lower than the averaged values of all carbide drills by around 24%.

As for the precedent results, Prism5 ® was used for data correlation, and the final result is also presented in Figure 11. Based on the data correlation, it was possible to conclude that for a 1 mm^2 increase in the damaged area, the pin-bearing strength reduces by around 11.5 MPa, with a 95% confidence interval between 9.3 and 13.8 MPa. This is evidenced by the negative slope of the correlation line that can be seen in Figure 11.

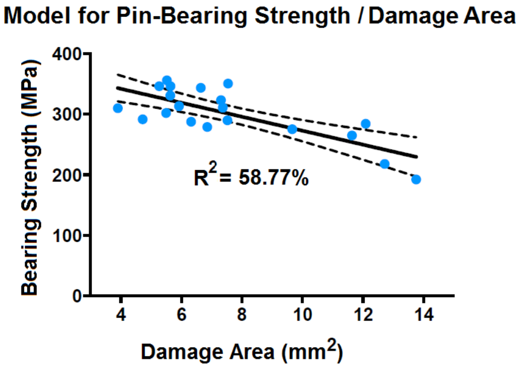

Figure 11: Linear Regression describing the relation between Pin-bearing Strength and Damage Area.

This result of the pin-bearing test highlights the importance of delamination reduction on the mechanical confidence, life cycle extension and reliability of machined composite plates.

5 CONCLUSIONS

In this work, unidirectional carbon/epoxy laminate plates were produced and drilled with the purpose of evaluating the resulting damaged area and how this damage extension affected the mechanical properties of the drilled plates. Five different drilling tool options combined with two feed rates were used for this study. Relevant results considered for evaluation of these experimental parameters were the delamination extension by the Damage Ratio and the mechanical strength of the drilled holes by the Three point bending and the Pin-bearing tests. According to the results of the experimental work presented along this paper, the following conclusions are possible.

Delamination assessment is possible using the image processing technique here described, using the tools provided by the GIMP® software, particularly the threshold tool, for the turning of the original image in a binary image, reducing operator error dependence. With this process, it was possible to determine the damaged area around the hole for damage assessment.

Three point bending test did not seem to be adequate for the evaluation of damage outcome on mechanical characteristics of the drilled plate. After an initial reduction of the flexural strength due to the existence of the drilled hole, the scattering effect was larger than any other, resulting in a plateau line. So, other bending test should be tried, like the Four point bending test.

Pin-bearing test was already extensively used for hole quality evaluation and a good correlation from damage to mechanical strength was found, showing a negative slope, thus showing that higher delamination extension will result in a lower mechanical resistance of the composite plate. This results is in accordance with previous studies, as those referred to along this paper.

The use of a pre-drilling strategy has resulted as a good option for the relevant results of this study, showing a good reduction of delaminated area and higher strength results of the two mechanical tests considered, as the thrust force during final drilling is reduced. Smaller values of the pre-drilling, closer to 12% of the nominal hole diameter should be used for possible result optimization.

As expected, the HSS drill should not be considered as an option for the drilling of carbon/epoxy composites. Dagger drill did not prove any advantage in the results considered, as the holes presented burrs, higher delamination extension and lower mechanical strength than other conditions. Moreover the machining time needed was always longer when compared to other tools. So, Brad or Twist carbide drills are more appropriate for the drilling of composite plates, considering the experimental conditions of this study.

Based on previous experience from the authors, plates drilled with the low feed rate had the better results for both delamination extension and mechanical strength. So, due to composites laminar nature, lower feed rates are always preferable.

The present experimental work shows the importance of the characteristics of a composite plate for an adequate definition of the drilling tool, selecting the most appropriate machining conditions, including a low feed rate, to reduce delamination damage extension and improve mechanical resistance, reliability and life cycle of the parts.

ACKNOWLEDGEMENTS

This work was partially funded by FCT (Fundação para a Ciência e a Tecnologia) – Portugal, in the scope of the projects UID/EMS/00615/2013 and UID/EMS/0615/2016.

REFERENCES

[1] Persson E, Eriksson I and Hammersberg P. Propagation of hole machining defects in pin-loaded composite laminates. Journal of Composite Materials; 31, 1997, pp. 383–408.

[2] Durão LMP, Panzera TH, Scarpa F, Sérgio LMR Filho, Oliveira PR. Damage Assessment of Fibre Reinforced Laminates. Composite Structures; 133, 2015, pp. 939–946.

[3] H Hocheng, CC Tsao. The path towards delamination-free drilling of composite laminates. Journal of Materials processing technology, 167, 2005, pp. 251-264.

[4] P. Rahme, Y. Landon, F. Lachaud, R. Piquet, P. Lagarrigue. "Delamination-free drilling of thick composite materials", Composites: Part A, 72, 2015, pp. 148–159.

[5] K. Palanikumar, J. Campos Rubio, A. Abrão, A. Esteves and J.P. Davim, "Statistical Analysis of Delamination in Drilling Glass Fiber-Reinforced Plastics (GFRP)", J Reinforced Plastics Composites, 27, 2008, pp. 1615-1623.

[6] F. Klocke, W. Koenig, S. Rummenhoeller, C. Wuertz. "Milling of Advanced Composites", in Machining of Ceramics and Composites, Ed. Marcel Dekker, NY, pp. 249-266, 1998.

[7] E. Persson, I. Eriksson, L. Zackrisson. "Effects of hole machining defects on strength and fatigue life of composite laminates", Composites A, 28, 1997, pp. 141-151.

[8] E. Persson, I. Eriksson, P. Hammersberg. "Propagation of hole machining defects in pin-loaded composite laminates" Journal of Composite Materials, 31, 1997, pp. 383-408.

[9] J. Montesano, H. Bougherara, Z. Fawaz. "Influence of drilling and abrasive water jet induced damage on the performance of carbon fabric/epoxy plates with holes" Composite Structures, 163, 2017, pp. 257–266.

[10] R. Piquet, B. Ferret, F. Lachaud and P. Swider, "Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills" Composites A, 31, 2000, pp. 1107-1115.

[11] H. Hocheng and C.C. Tsao, "Effects of special drill bits on drilling-induced delamination of composite materials", Int. J. Machine Tools & Manufacture, 46, 2006, pp. 1403-1416.

[12] Luís M. P. Durão, Daniel J. S. Gonçalves, João M. R. S. Tavares, Victor H. C. de Albuquerque, A. A. Vieira and A. T. Marques, "Drilling tool geometry evaluation for reinforced composite laminates", Composite Structures, 92, 201, pp. 1545-1550.

[13] L.M.P. Durão, D.J.S. Gonçalves, J.M.R.S. Tavares, V.H.C. de Albuquerque, A.T. Marques, "Comparative analysis of drills for composite laminates", J. Composite Materials, 46, 2012, pp. 1649-1659.

[14] C.C. Tsao and H. Hocheng, "Effects of exit back-up on delamination in drilling composite materials using a saw drill and a core drill", Int. J. Machine Tools & Manufacture, 45, 2005, pp. 1261-1270.

[15] J.C. Campos Rubio, A.M. Abrão, P.E. Faria, A.E. Correia, and J.P. Davim, "Delamination in High Speed Drilling of Carbon Fiber Reinforced Plastic (CFRP)", J Composite Materials, 42, 2008, pp. 1523-1532.

[16] U.A. Khashaba, I.A. El-Sonbaty, A.I. Selmy, A.A. Megahed. "Machinability analysis in drilling woven GFR/epoxy composites: Part I – Effect of machining parameters". Composites: Part A, 41, 2010, pp. 391–400.

[17] H. Hocheng and C. K. H. Dharan "Delamination during drilling in composite laminates" Journal of Engineering for Industry, 112, 1990, pp. 236-239.

[18] C.C. Tsao and H. Hocheng. "The effect of chisel length and associated pilot hole on delamination when drilling composite materials". International Journal of Machine Tools and Manufacture, 43, 2003, pp. 1087-1092.

[19] M. Mehta, T.J. Reinhart, A.H. Soni. "Effect of fastener hole drilling anomalies on structural integrity of PMR-15/Gr composite laminates". Proceedings of the Machining Composite Materials Symposium, ASM Materials Week, 1992, pp. 113-126.

[20] ISO 14125: 1998 (Rev 2013). "Fibre-reinforced plastic composites - Determination of flexural properties". ISO - International Organization for Standardization.

[21] H. S. Wang, C.L. Hung, F. K. Chang. "Bearing Failure of Bolted Composite Joints: Experimental Characterization" Journal of Composite Materials, 30, 1996, pp. 1284-1313.