DELAMINATION IN CARBON/EPOXY PLATES DRILLING: TOOL AND FEED RATE EFFECT

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Abstract. The attractive characteristics of carbon fibre reinforced plastics had widespread their use. In order to join different components, drilling is often necessary. It is known that a drilling process that reduces the drill thrust force can decrease the risk of delamination. In this work, three combinations of the drilling process are compared: tool diameter, tool geometry and feed rate. The parameters studied were: thrust force, delamination extension and mechanical strength of the drilled region – bearing test. This work demonstrates that a proper combination of the drilling variables can contribute to reduce the delamination damage and, consequently, enhance mechanical resistance of the joint.

## 1 INTRODUCTION

Since the beginning of the 21st century, composites were one of the most promising groups of materials. Their main characteristics, such as low density and high strength to weight ratio, turn these materials into an ideal selection when high stiffness, high strength and low weight needs are required. The importance and usage of composite materials has been growing in recent years, which can be confirmed by their intensive use in the new Airbus A380 or Boeing 787 airplanes. Regarding the latter, 50% of the weight of its primary aircraft structure will be made of composite materials (Gilpin, 2009). One can now find composite materials not only in the aeronautical field, but also in other industries like automotive, railway, marine or of sport goods.

Although composite parts are produced to near-net shape, finishing operations as drilling, commonly done  to allow parts' assembly, are usually required. It is known that these operations can be carried out with conventional tools and machining equipments with proper adaptations. Generally, machined parts have poor surface appearance and tool wear is higher than with metals. One of the problems related with composites' machining is the nature of the fibre reinforcement, usually very abrasive and causing rapid tool wear and deterioration of the machined surfaces (Abrate, 1997). Koplev, Lystrup and Vorm (1983) examined the cutting process of unidirectional carbon fibre reinforced plastics in perpendicular and parallel directions to fibre orientation. A series of quick-stop experiments was carried out to examine the area near the tool tip. The authors stated that the machining of CFRP consists in a series of fractures, each creating a chip.

Drilling is one of the machining operations most frequently used on composites. It is a complex process, characterized by the existence of extrusion and cut mechanisms. The first is performed by the drill chisel edge that has null or negligible linear speed and the latter by the existence of rotating cutting lips at a certain speed. The most common drill is the conventional conical point drill. The cutting process is unique and can be divided into two distinct regions: chisel edge and cutting lips. In a common drill, there is a small region around the centre of the chisel edge, called the indentation zone, where the tool does not cut the material, but extruding it instead. On the region outside the indentation zone, called the secondary cutting edge area, the rake angle is highly negative. As fibre reinforced plastics are more brittle than metals, it is unlikely that extrusion really takes place and orthogonal cutting could be assumed for the entire chisel edge. However, model predictions based on this assumption do not agree with the experimental data. Along the cutting lips, cutting action of a drill is a three-dimensional oblique cutting process. The cutting speed, rake angles and other geometrical parameters vary along the cutting lips with the radial distance from the centre. The cutting action is more efficient at the outer regions of the cutting lips than near the drill's centre (Chandrasekharan, Kapoor and DeVor, 1995; Langella, Nele and Maio, 2005). When considering the drilling of a composite part, good results are mainly fibre related and less dependent on the matrix material (Boldt and Chanani, 1987). Due to the inhomogeneity of composites, drilling can cause several damages, including delamination, fibre pull-out and thermal damages (Wern, Ramulu and Schukla, 1994), as well as other minor damages. The most frequent and noticeable evidence of these damages is the existence of an edge around the machined hole, namely at the exit side of the drill, as a consequence of the drilling process. By visual or enhanced inspection, it is possible to observe in this region the separation of adjacent plies of the laminate. This damage is known as delamination, and it is recognizable by the existence of a darker region, nearly shaped as a ring, bordering the outside edge of the machined hole, Figure 1.

The drilling process can be understood by the observation of thrust force and torque evolution, Figure 2. As drilling progresses, thrust force increases until a nearly constant value, which corresponds to steady drilling through the thickness of the laminate, is reached. Then it drops sharply as the tool bit exits through the opposite side (Abrate, 1997). The torque increases rapidly until the cutting edges of the tool are completely engaged. Subsequently, it increases linearly until a maximum value is reached and is followed by a slight drop after hole completion (Wern, Ramulu and Schukla, 1994). Fernandes and Cook (2006) followed a similar procedure in order to divide force and torque into stages and discuss common problems and damages associated with each stage, Figure 2a). Stage I corresponds to the tool entrance, and the possible identified problems were skidding, wandering or deflection of the drill bit. Stage II is drilling and the main associated problems are delamination and tool wear. The risk of delamination is higher at the end of this stage as the last plies of the laminate are pushed by the drill chisel edge. Stage III is drilling and reaming that corresponds to the moment after drill tip reaches the bottom surface of the workpiece. The drilling action is replaced by the reaming action and maximum torque is reached. Stage IV is reaming and stage V is backing out where drill translation is reversed for withdrawal. The thrust and torque curves, resulting from the drilling of a carbon/epoxy plate with a twist drill, are presented in figures 2b) and 2c). Notice the existence of noise from tool vibration leading to signal irregularity.

### 1.1 Delamination mechanism

Delamination is a damage that occurs in interlaminar regions, i.e., in the contact plan between adjacent layers, therefore it depends not only on fibre nature but also on resin type and respective adhesive properties. Delamination mechanisms are divided according to the laminate region where it occurs, exit or entrance, called push-out and peel-up,

respectively.
Peel-up is caused by the cutting force pushing the abraded and cut materials to the flute surface. Initially, the cutting edge of the drill will abrade the laminate. As the drill moves forward it tends to pull the abraded material along the flute, and the material spirals up before being effectively cut. This action creates a peeling force upwards that tends to separate the upper laminas of the plate, Figure 3a. This peeling force is a function of tool geometry and friction between tool and workpiece (Hocheng and Dharan, 1990).
Push-out is a consequence of the compressive thrust force that the drill always exerts on the workpiece. The laminate under the drill tends to be drawn away from the upper plies, breaking the interlaminar bond in the region around the hole. As the drill approaches the end of the laminate, the uncut thickness becomes smaller and the resistance to deformation decreases. At some point before the laminate is totally penetrated by the drill, the loading exceeds the interlaminar bond strength and delamination occurs, Figure 3b. A different tool geometry that lowers the thrust force can reduce the delamination damage (Hocheng and Dharan, 1990).
After the drilling is completed, circularity shall be observed, as there is a bouncing back tendency of the material that causes hole deformation. The return to its initial position causes tightening around the drill and the drilled diameter is inferior to the tool's diameter. This roundness error is due to the anisotropy of the material (Piquet et al, 2000).
A recent advance on machining strategy was achieved by Schulze et al (2011) by minimizing the damage by directing the process forces towards the centre of the workpiece. This is accomplished through a combined process of circular and spiral milling on a three-axial machining centre. The advantages of this process still require further research.
There is an important contribution from the work of Hocheng and Tsao to the understanding of the delamination mechanism associated with different drilling conditions, like drill geometry (Hocheng and Tsao, 2003; 2006), the use of a core drill (Tsao and Hocheng, 2007) or the influence of using an exit back-up plate on delamination depending on drill geometry (Tsao and Hocheng, 2005). In Hocheng and Tsao (2003; 2006), distinct drill bits are compared for drilling-induced delamination. The different drill geometries considered in these works are the twist drill, the saw drill, the candle stick drill, the core drill and the step drill. In Tsao and Hocheng (2007) only the core drill was studied, showing that grit size and feed rate are the most important parameters for delamination reduction and should be kept low. According to authors, there are advantages in using special drill bits for composites' drilling. The traditional twist drill provides a reduced threshold of the thrust force for delamination onset when compared to other geometries. Taking into account these geometries, the higher threshold feed rate at delamination onset was obtained with core drill, followed by candle stick drill, saw drill and step drill (Hocheng and Tsao, 2006).
A comparative study taking into account distinct drill geometries and feed rates was presented in Durão et al (2010). The authors assessed the thrust force, the surface roughness and the delamination extension for five different drill geometries and two feeds, concluding that twist drills are well suited for carbon/epoxy plates drilling. However, only one drill diameter was considered. A study on the cutting variables on thrust force, torque, quality of hole and chip was presented in Zitoune, Krishnaraj and Collombet (2010). In this work, the authors addressed the effects of drill diameter variation when drilling CFRP/aluminium stack. No study was performed concerning the effect on carbon/epoxy plates. Additionally, it was noted that the circularity issues are more pronounced when feed rate increases.
As composites are taylor-made parts, it is possible to include holes while molding the part as suggested by Zitoune et al (2011). The authors propose that molded holes are preferable to drilling after molding. Using a charge-coupled device (CCD) camera, it was possible to observe that damage mechanisms are different between the plates with drilled holes and those with molded holes. Moreover, it was demonstrated that the mechanical resistance has increased by 28%. This possibility is not included in the scope of the present work; however, it surely deserves attention in the future.
In this work, the effect of three variables on the drilling process of carbon reinforced epoxy plates is studied: tool diameter, tool geometry and feed rate. Parameters considered in the study include the thrust force monitoring during drilling, the assessment of the delamination extension from enhanced digital radiographic images that are automatically segmented and, finally, mechanical testing of drilled coupons, using bearing test for the evaluation on the loss of mechanical properties in the joint region of the plates. The analysis of variance (ANOVA) is used to understand the relative importance of each experimental factor in the mechanical resistance loss. Due to the coupons' dimensions, bearing tests were only performed on plates with 6 mm diameter hole. It should be noted that hole diameter is a project condition meaning that drilling conditions has to adapt accordingly.
At the end, a third drill geometry – step drill – is compared in terms of thrust force, delamination extension and mechanical properties using 6 mm diameter holes.
The work here presented shows that a proper combination of the factors involved in drilling, like tool geometry and adequate cutting parameters regarding the diameter of the hole, which is a project condition, can lead to the reduction of delamination damage with the consequent enhancement of the mechanical properties of laminated parts.

## 2MATERIALS AND METHODS

### 2.1 Composite Plates Production and Drilling

For the experimental work, a batch of carbon/epoxy plates using prepreg CC160 ET 443 with a cross-ply stacking sequence of [(0/90)6]s with 24 layers was produced. The plates were then cured for one hour under 300 kPa pressure and 130 ºC, followed by cooling. Final plate thickness was equal to 4 mm. Then, the plates were cut into test coupons of 165x96 mm2 for the drilling experiments and in coupons with dimensions according to the bearing test specifications.
The experimental work was divided in drilling of the laminate plates for thrust force monitoring, delamination measurement by enhanced radiography and computational algorithms of image processing and analysis and mechanical tests.
The drilling operation was carried out in a 3.7 kW DENFORD Triac Centre CNC machine. As it has been previously

identified the main importance of feed rate when compared with spindle speed in thrust forces development (de Albuquerque, Tavares and Durão, 2010), the spindle speed was kept constant and equal to 2800 rpm and the feed rate had two levels: low feed rate equal to 0.05 mm/rev, and high feed rate of 0.20 mm/rev. These cutting parameters were selected according to previous published works (Durão et al, de Albuquerque, Tavares and Durão, 2010; Durão et al, 2009) as well as tool manufacturer's recommendation. Two tool diameters, respectively of 6 mm and 10 mm, were used, together with two drill geometries: twist and Brad. On a posterior phase of the experimental work, a third drill geometry was used: a step drill according to the outcome of several published works (Hocheng and Tsao, 2003; 2006; Durão et al, 2010).

During drilling, the axial thrust force was monitored with a Kistler 9257B dynamometer associated to an amplifier and a computer for data acquisition and processing. No backup plate was used. The experimental setup is presented in Figure 4. Drills used in this work are presented in Figure 5: twist drill, Brad drill and step drill, respectively. Details on the drills can be found elsewhere (Durão et al, 2010).

### 2.2 Delamination Assessment

After drilling, the delaminated region around the drilled hole was evaluated using enhanced digital radiography. To produce a contrast the plates were first immersed in di- iodomethane for half an hour. Then the radiographic images were acquired using a 60 kV, 300 kHz Kodak 2100X-Ray system associated with a Kodak RVG 5100 digital acquisition system. An example of original image obtained for each drill studied is presented in Figure 6. The original images were converted from the Kodak original format to bmp format and then automatically processed by as described in the following.

Each radiographic image was computationally processed to identify and characterize the regions of interest for this study: hole region, delaminated and non-delaminated regions. The hole region corresponds to the central area, the delaminated region consists on a dark border around the machined hole, and the non-delaminated regions are lighter areas located outside the damaged region, Figure 7 (de Albuquerque, Tavares and Durão, 2010).

The final objective of the image processing performed was to measure the damaged diameters and areas in each radiographic image. This was achieved initially by segment the images using a neuronal network with 1 input layer with 3 neurons, 1 hidden layer with 7 neurons (Bodyanskiy, Kolodyazhniy and Otto, 2005), 1 output layer with 3 neurons, the logistic function (Elliott and Better, 1993) as the activation function, which was trained using the backpropagation learning algorithm (Singh and Rao, 2005). The inputs of the network were each pixel of the image to be segmented, and the output was the correspondent image with the desired regions identified. Further details of the neuronal network used can be found in (de Albuquerque et al, 2011). After the identification of the three regions presented in the input image by the neuronal network, the diameter and area values were automatically computed: the diameter by searching for the longest diagonal within the delaminated region, and the areas by summing up the pixels within the associated regions.

In comparison to the traditional visual inspection, the fully automated process has clear advantages: is not subjective, and so has higher repeatability and efficiency, is more pruned to errors and faster. In addition, it should be noted that the traditional images segmentation algorithms are not as efficient and robust as the solution here adopted in this particular application of image processing and analysis. Particularly, the segmentation of these images is not an easy task as there are several differences among them in terms of dimensions, of desired region shapes and of the intensity values of the image pixels. Also, the acquired images are considerable corrupted by noise which challenges their effective segmentation.

The values obtained from the radiographic images can be used to determine the delamination factor ($F_d$) (Chen, 1997) or the adjusted delamination factor ($F_{da}$) (Davim, Rubio and Abrão, 2007). The first criterion is based on the measurement of the damaged diameter that is prone to mislead the results if a preferential direction of delamination happens to occur. In fact, one limitation of Chen's criterion is related to situations when the delamination involved is not round, but presents breaks and cracks. In such cases, the values of the delaminated area are more appropriated for the damage quantification. Based on this, Davim, Rubio and Abrão, (2007) suggested the adjusted delamination factor, $F_{da}$,

$$F_{da} = \alpha \frac{D_{\max}}{D} + \beta \frac{A_{\max}}{A_0} \tag{1}$$

where $D_{max}$ is the maximum delaminated diameter, D is the hole nominal diameter, $A_{max}$ is the area corresponding to the maximum delaminated diameter and A is the nominal hole area. The first term in Eq. 1 is the conventional delamination factor, the second term takes into account the damaged area contribution, and the parameters α and β are used as weights, being their sum always equal to 1 (one).

So, taking advantage of the computational imaging analysis, the adjusted delamination factor was the criterion used in this work for damage assessment.

### 2.3 Mechanical Testing

One of the mechanical tests carried out is the "Bearing test", according to ASTM D5961M-08, procedure A, double shear, tension. According to this procedure, a rectangular cross-section test specimen with a centerline hole located near the end of the specimen is loaded at the hole in bearing. The bearing force is normally applied through a close-tolerance, hand lightly torqued fastener that is reacted in double shear by a fixture as shown in ASTM standard (ASTM, 2008). The bearing force is created by loading the assembly in tension in the testing machine. This test was used to

assess the effect of the delamination extension on the mechanical properties of the drilled plates in the joint area. Test coupons of 135x36 mm2 were cut and drilled under the same experimental conditions described in section 2.1, for all the drill geometries studied. The head displacement speed was set to 2 mm/min.
The second test is the “Open-hole Tensile Strength”, according to ASTM D5766M – 07, designed to produce notched tensile strength data for structural design allowables, material specifications, research and development, and quality assurance (ASTM, 2007). In accordance with the conditions expressed in this standard, the 250x36 cards mm2 were drilled with a 6 mm diameter drill and subsequently subjected to tensile stress until breakdown, being recorded the breaking force value. The open-hole tensile strength is the result of dividing the maximum strength for the plate section, being this considered without hole for the calculation purposes. The head displacement speed was set to 5 mm/min. For both tests, the resultant force-displacement curves are very similar to those of a normal tensile strength test of a material – see Figure 8. After an almost linear rise from zero to a maximum value, there is a sudden drop of the force, corresponding to the initial failure of the material surrounding the machined hole. According to the ASTM standard, after a 30% drop the test should be stopped without further deformation of the compressed region above the hole. Both tests were performed in a Shimadzu AG-X/100 kN Universal Testing machine equipped with the necessary devices to run the different tests and connected to a computer for machine control and data acquisition.

# 3 RESULTS AND DISCUSSION

## 3.1 Thrust force during drilling

The results referred here as thrust force were the maximum values acquired during drilling since according to the published analytical models, see, for instance, Hocheng and Dharan (1990), higher thrust forces correspond to a higher risk of delamination onset. Due to the occurrence of signal variations during drill rotation, the thrust force values were averaged over one spindle revolution. Also, to reduce the influence of outlier values, the final results used were the average of five experiments run under identical conditions.
As expected, both increases of feed rate or tool diameter had an effect of ramping up the maximum thrust force values, Figure 9. Moreover, the values observed during the drilling of the plates using the Brad drill were always inferior to those observed when drilling using twist drills. When comparing the different results, it is possible to distinguish that the change in diameter corresponded to an average increase of the maximum thrust force of 2.7 times. This was an expected outcome. However, it has to be noted that other contributions to thrust force are more related with the drilling conditions, like feed rate or tool geometry. In fact, the thrust forces were superior for higher feed rates, which were observed for both geometries. This second result was also expected and it is a known consequence of using a higher feed rate. But it is also interesting to note that, for every pair of drilling conditions, the forces for the Brad drill were always inferior to those for the twist drill. This suggests that the drill geometry, and particularly the drill tip, has a crucial influence on the thrust forces over the uncut plies of the laminate.

## 3.2 Delamination assessment

Delamination assessment was carried out according to the procedure described in section 2.2. The results are presented in Table 1. From the values in Table 1, it is possible to say that the influence of the tool diameter was not so evident, as the damaged area is divided by the tool nominal area, so the diameter handicap is someway cancelled.
There is a clear connection between the thrust force results and the delamination extension. The drilling conditions with less damage correspond to the coupons where the thrust force was lower. In fact, the damage extension for the twist drill holes was 10% higher, on the average, than those measured for the Brad drilled holes. Also, the feed rate increase corresponded to a higher damage extension, about 3% on the average. This outcome confirms the assumption referred in section 3.1 about the correlation between higher thrust forces during drilling and superior delamination extension. The smaller increase due to tool’s diameter can be explained by the criteria itself, as the damage assessment equation takes into account the hole’s diameter and area (see Eq. 1).

## 3.3 Mechanical testing

The results of the two mechanical tests performed in this work are presented in Figure 10. In this figure, the result for the step drill geometry, to be discussed in section 3.5, is already included. From the graphs of Figure 10, a correlation between feed rate and mechanical loss by the bearing strength can be easily identified. Larger values of feed, although promoting productivity, had an adverse effect on damage extension, leading consequently, to mechanical loss. Independently of the tool used, all plates had worst results for the holes drilled with higher feed rate. This result means that higher feed rates are to be avoided when drilling composite plates.
On the other hand, the same correlation could not be pointed out for the drill geometry. In spite of larger extension of damaged area, plates drilled with the twist drill returned higher values of bearing stress, as it is easily observed in Figure 10. This result suggests that the drill geometry is a key factor in damage onset and propagation. So, a good selection of the tool, combined with the feed rate can reduce damage extension.

## 3.4 Analysis of variance

To understand the effect of the experimental variables on the results considered as relevant, an analysis of variance (ANOVA) was performed to the results of the bearing test. The influence of tool geometry was higher than the feed rate. This demonstrates the importance of tool geometry selection in carbon/epoxy plates’ drilling. Values considered for the ANOVA study were the same used for calculating the average and standard deviation values presented in Tables 1 and 3. Only for delamination, and in presence of scattered results, the analysis was made considering the average values instead of the individual ones.
The ANOVA results for the “Thrust force”, “Adjusted Delamination Factor” and the “Bearing Test” are presented in Tables 2a), 2b) and 2c), respectively. The levels addressed for each factor are indicated in the upper lines of the table and best solution in each case is indicated in bold for a better understanding. From the results, it is possible to say that

the diameter contribution for the adjusted delamination factor was of minor importance, only 5%, and inferior to the experimental error. Although the experimental error was significant, results on the delamination extension showed that the contribution of feed rate was higher than drill geometry effect. Yet, more accurate data is needed to validate this assumption. The geometry and feed had an F-test result above four, meaning that these factors have a strong effect on the result.

Finally, for the bearing stress, only the tool geometry and feed rate were considered as experimental factors. Both factors had an important contribution to the results and were physically and statistically significant, as the F-test result was greater than four. The tool geometry influence was higher than the feed rate influence.

3.5 Comparison with a step drill

Finally, as the step drill was only available with a diameter of 6 mm, as it is yet an experimental tool, the correspondent results were compared in terms of thrust force, delamination and bearing stress, Table 3 and Figure 10.

From the data shown in Table 3, it is possible to say that the step drill represented a compromise solution enabling values for thrust force and adjusted delamination factor that were always lower than those obtained with the twist drill. The advantage here resides on the possibility of dividing the drilling into two steps, lowering the axial thrust force during each step. According to the analytical models, like those presented in Hocheng and Dharan (1990) and in Piquet et al (2000), lower forces reduce the delamination risk and this outcome was confirmed by the values of the adjusted delamination factor of the holes drilled with step drill when compared with those of the holes drilled with the twist drills. Yet, comparison with the Brad drills is not so favorable regarding these criteria.

On the other hand, looking at the mechanical test results depicted in Figure 7, the plates drilled with the step drill had higher results than those drilled with the Brad drill. For bearing stress this can be the result of a better performance of the tool when the mechanical resistance is concerned.

4CONCLUSIONS

Carbon fibre reinforced laminates were drilled with the objective of comparing the performance of three different tool geometries, two feed rates and two diameters. Relevant results considered for assessment were the maximum thrust force, the delamination extension by the adjusted delamination factor and the mechanical strength by bearing stress test and open-hole tensile test. According to the results of the experimental work and analysis of variance, the following conclusions were possible.

The feed rate influence is well known and the results confirmed that higher feeds correspond to higher thrust forces and delamination extension. So, feed rates should be kept as conservative as possible.

As expected, the use of larger diameter drills led to higher thrust forces, but not to higher delamination, as it is measured as a function of hole diameter or area.

The thrust forces were largely influenced by the tool diameter, as expected. Drill geometry has a strong influence in this outcome.

The mechanical tests showed the influence of both drill geometry and feed rate. The step drill could be a good choice, as it represents a balance of the two other drill geometries used in this work.

From the experimental work accomplished, it can be concluded that, according to the hole's diameter, which is a project demand, it is possible to combine the tool geometry and feed rate according to the material to be drilled to reduce the delamination damage.

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FIGURES

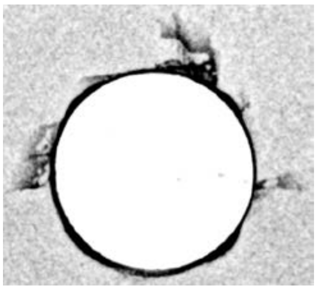
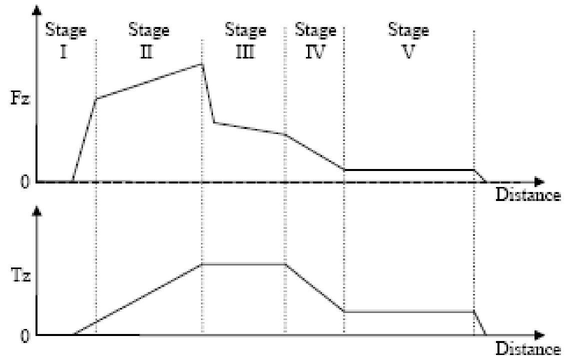
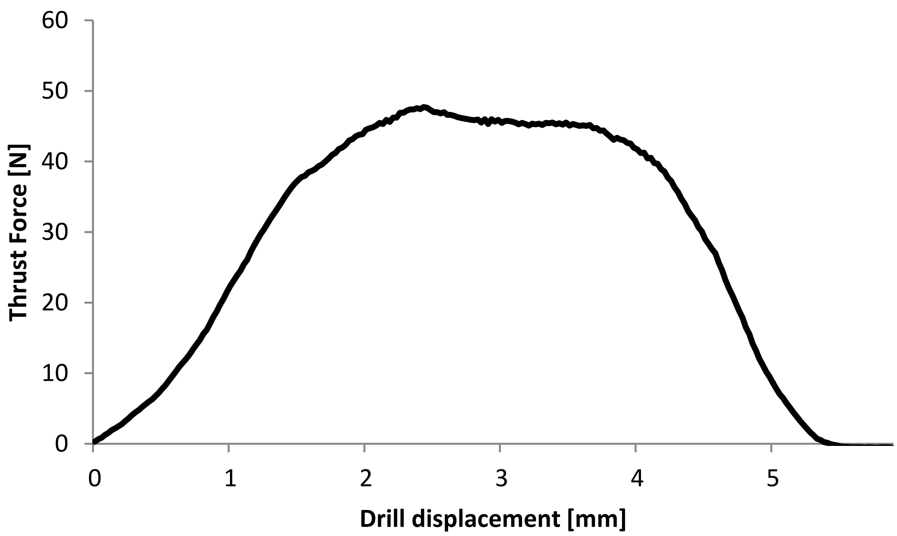


Figure 1 – Example of delamination occurrence around a drilled hole.




2a) Drilling stages identified according to Fernandes and Cook (2006)




2b) Example of thrust force/ displacement curve during twist drill machining.

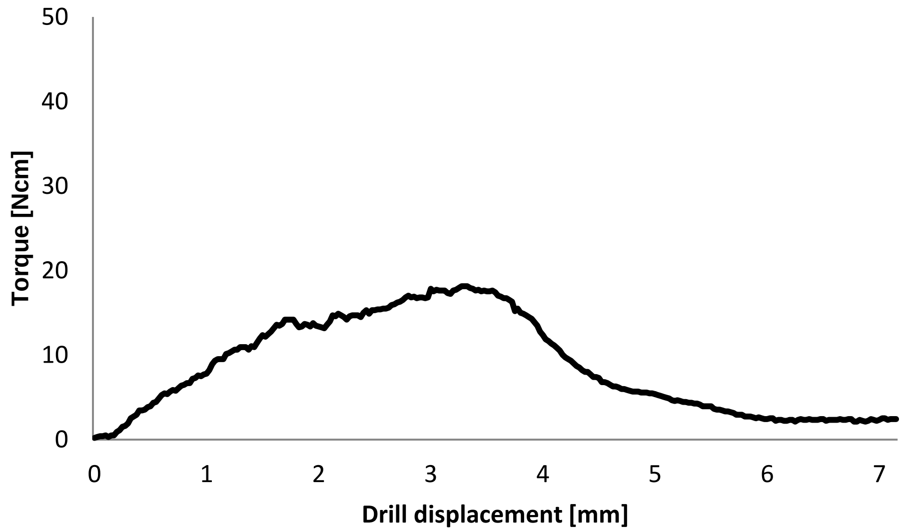



Figure 2c) Example of torque/displacement curve during twist drill machining.

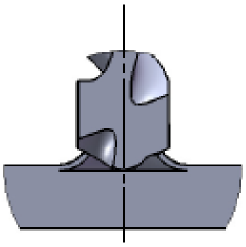


Figure 3a

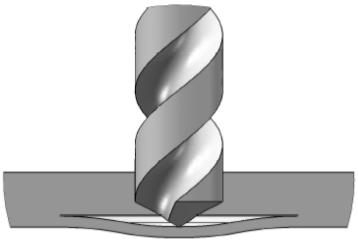


Figure 3b

Figure 3 – Delamination mechanisms: a) Peel-up delamination at entrance;
b) Push-out delamination at exit.

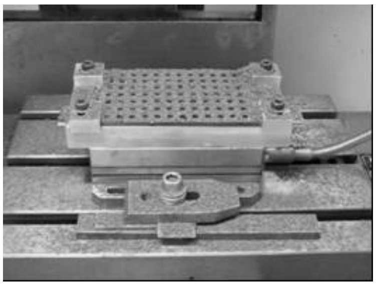


Figure 4 – Experimental setup.


Figure 5a) Twist drill


Figure 5b) Brad drill

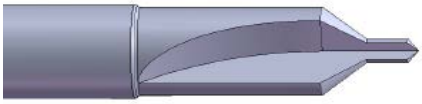


Figure 5c) Step drill

Figure 5

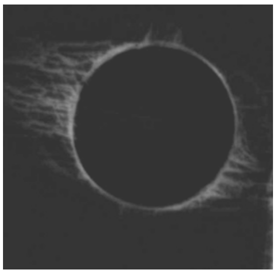


Figure 6a) Original radiographic image – twist drill

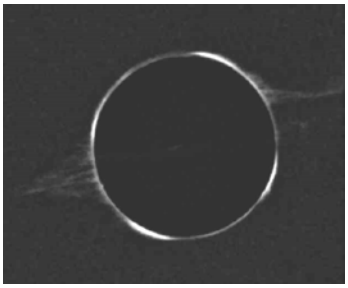


Figure 6b) Original radiographic image – brad drill

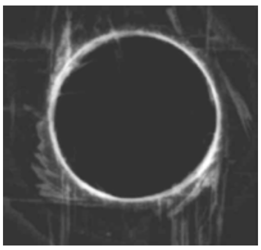


Figure 6c) Original radiographic image – step drill.

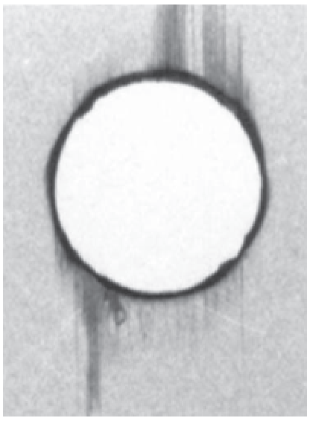


Figure 7a)


Figure 7b)


Figure 7c)

Figure 7 – Example of processing a radiographic image: (a) original image, (b) image segmented by using a neuronal network, (c) identified delamination region [20].

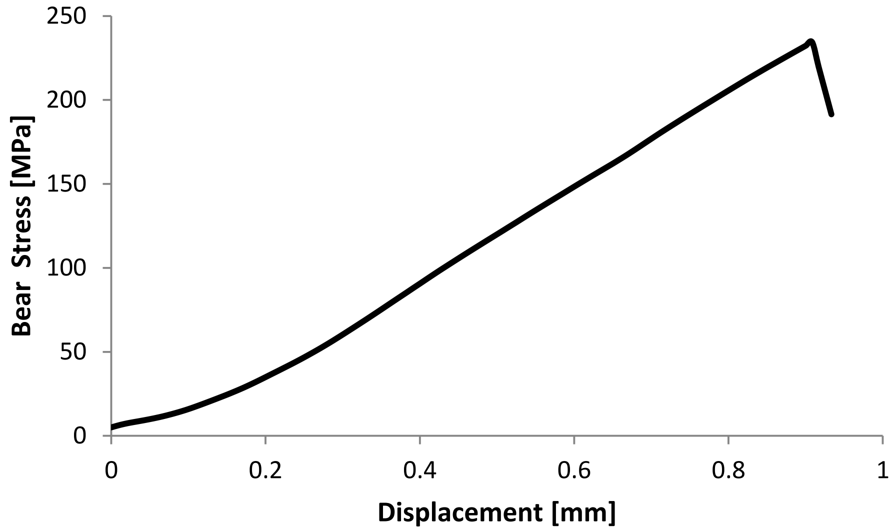



Figure 8 – Example of a stress-displacement curve of a bearing test for a plate drilled with a step drill.

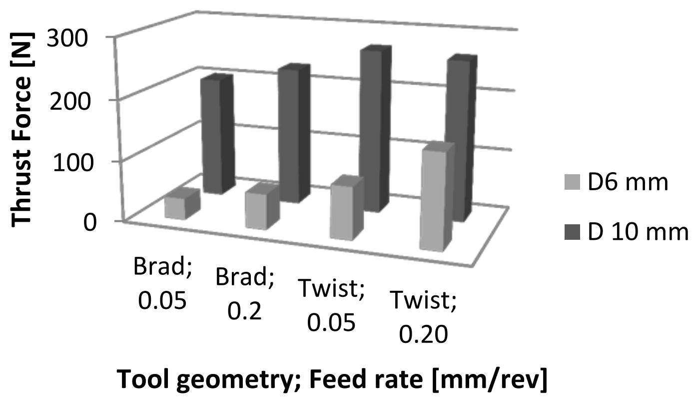



Figure 9– Maximum thrust force values during the drilling experiments.

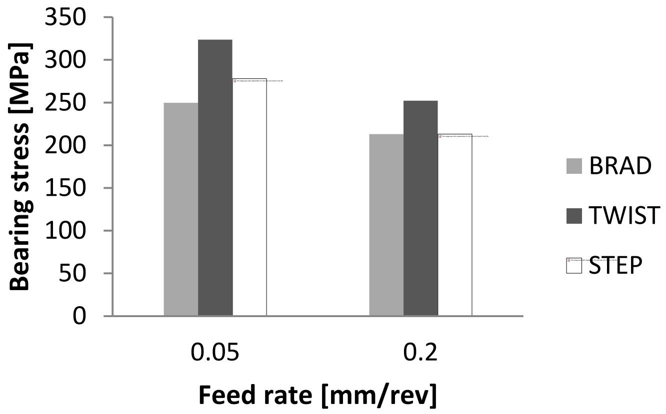



Figure 10a)

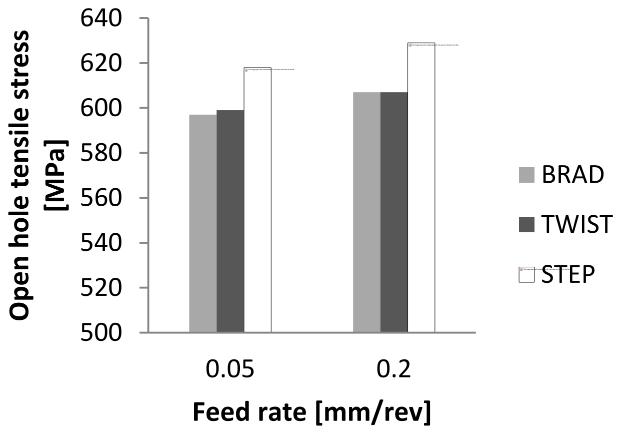



Figure 10b)

Figure 10 – Mechanical tests results for: a) Bearing stress; b) Open hole tensile stress.

TABLES

| Drill geometry | Tool diameter [mm] | Feed rate [mm/rev] | Thrust Force [N] | | Adjusted Delamination Factor ($F_{da}$) | |
|---|---|---|---|---|---|---|
| | | | Average | Average | Average | Std Dev |
| Brad | 6 | 0.05 | 35 | 3.5 | 1.06 | 0.13 |
| | | 0.20 | 58 | 8.5 | 1.34 | 0.20 |
| Twist | | 0.05 | 86 | 6.3 | 1.39 | 0.25 |
| | | 0.20 | 154 | 4.2 | 1.91 | 0.28 |
| Brad | 10 | 0.05 | 202 | 8.9 | 1.37 | 0.26 |
| | | 0.20 | 229 | 13.5 | 1.55 | 0.31 |
| Twist | | 0.05 | 242 | 21.3 | 1.43 | 0.20 |
| | | 0.20 | 263 | 22.0 | 1.68 | 0.25 |
| Step drill | 6 | 0.05 | 63 | 3.9 | 1.22 | 0.18 |
| | | 0.20 | 129 | 13.2 | 1.80 | 0.18 |

Table 1 – Thrust force and Adjusted delamination factor results.

| Factor | Level S/N 1 | 2 | SS | DF | V | % P | F |
|---|---|---|---|---|---|---|---|
| Geometry | Twist | **Brad** | | | | | |
| Feed [mm/rev] | **0.05** | 0.20 | | | | | |
| Diameter [mm] | **6** | 10 | | | | | |
| Geometry | -44.67 | --39.84 | 46.7 | 1 | 46.7 | 15 | 6 |
| Feed | -40.83 | -43.68 | 16.3 | 1 | 16.3 | 5 | 2 |
| Diameter | -37.13 | -47.39 | 210.5 | 1 | 210.5 | 70 | 27 |
| Error | --- | --- | 30.7 | 4 | 7.7 | 10 | --- |
| TOTAL | --- | --- | 304.2 | 7 | --- | 100 | --- |

SS – sum of squares; DF – degree of freedom; V – variance; %P – percentage of contribution; F- result of F-test.

Table 2a) – ANOVA for the Thrust force (L8). (Best parameter option in terms of smaller-is-better criterion is indicated in bold).

| Factor | Level S/N 1 | 2 | SS | DF | V | % P | F |
|---|---|---|---|---|---|---|---|
| Geometry | Twist | **Brad** | | | | | |
| Feed [mm/rev] | **0.05** | 0.20 | | | | | |
| Diameter [mm] | **6** | 10 | | | | | |
| Geometry | -4.02 | -2.40 | 5.3 | 1 | 5.3 | 33 | 6.6 |
| Feed | -2.30 | -4.12 | 6.6 | 1 | 6.6 | 41 | 8.3 |
| Diameter | -2.88 | -3.54 | 0.9 | 1 | 0.9 | 5 | 1.1 |
| Error | --- | --- | 3.2 | 4 | 0.8 | 21 | --- |
| TOTAL | --- | --- | 16.0 | 7 | --- | 100 | --- |

SS – sum of squares; DF – degree of freedom; V – variance; %P – percentage of contribution; F- result of F-test.

Table 2b) – ANOVA for the Adjusted Delamination factor (L8).

| Factor | Level S/N 1 | 2 | SS | DF | V | % P | F |
|---|---|---|---|---|---|---|---|
| Geometry | Twist | **Brad** | | | | | |
| Feed [mm/rev] | 0.05 | **0.20** | | | | | |
| Geometry | -49.12 | -47.26 | 3.5 | 1 | 3.5 | 51 | 23 |
| Feed | -49.08 | -47.30 | 3.1 | 1 | 3.1 | 47 | 21 |
| Error | --- | --- | 0.2 | 1 | 0.2 | 2 | --- |
| TOTAL | --- | --- | 6.8 | 3 | --- | 100 | --- |

SS – sum of squares; DF – degree of freedom; V – variance; %P – percentage of contribution; F- result of F-test.

Table 2c) – ANOVA for the Bearing stress (L4).

| Tool geometry | Feed rate [mm/rev] | Max thrust force [N] | | Adjusted Delamination Factor [$F_{da}$] | | Bearing test [MPa] | |
|---|---|---|---|---|---|---|---|
| | | Average | Std Dev | Average | Std Dev | Average | Std Dev |
| Brad | 0.05 | 35 | 3.5 | 1.06 | 0.13 | 250 | 3.5 |
| | 0.20 | 58 | 8.5 | 1.34 | 0.20 | 213 | 8.5 |
| Twist | 0.05 | 86 | 6.3 | 1.39 | 0.25 | 324 | 6.3 |
| | 0.20 | 154 | 4.2 | 1.91 | 0.28 | 252 | 4.2 |
| Step | 0.05 | 63 | 3.9 | 1.22 | 0.18 | 278 | 3.9 |
| | 0.20 | 129 | 13.2 | 1.80 | 0.18 | 213 | 13.2 |

Table 3 – Comparison of Brad, twist and step drills results.