DELAMINATION ANALYSIS OF CARBON FIBRE REINFORCED LAMINATES

António T. Marques*, Luís M. Durão**, António G. Magalhães**, João M. Tavares* [A. T. Marques]: marques@fe.up.pt
*DEMEGI/FEUP, Univ. Porto,Portugal, **DEM/ISEP, Polytech. Inst. Porto, Portugal

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Abstract

Drilling of carbon/epoxy laminates is normally carried out using standard drills, like twist or Brad drills. However, it is necessary to bear in mind the need to adapt the processes and/or tooling as the risk of delamination, or other damages, is high. These problems can affect the mechanical properties of the produced parts, hence, lower reliability. Production of higher quality holes, with damage minimization, is a challenge to everyone related with composites industry.

In this paper, four different drills are compared in terms of thrust force during drilling and delamination caused by this machining operation. In order to evaluate delamination damage, enhanced radiography is applied. The resulting images were then processed using a previously developed image analysis and processing platform. Results show that a correct choice of drill geometry, cutting speed or feed rate can reduce delamination.

1 Introduction

The use of fibre reinforced plastics has increased in the last decades due to their unique properties. Advantages are related with their low weight, high strength and stiffness. Although the development of these materials has been related with aerospace and aeronautical applications, recent years have seen the spread of their use in many other industries like automotive, railway, naval, sport and many others.

The use of composite laminates in dynamic structures had enabled a considerable weight reduction and, consequently, an improvement in their characteristics. Although composite components are produced to near-net shape, machining is often needed, as it turns out necessary to fulfill requirements related with tolerances or assembly needs. Machining operations in composites can be carried out in conventional machinery with some adaptations. Among the usual machining processes, drilling is one of the most frequently used to make holes for screws, rivets and bolts. Drilling is a complex process which is characterized by the existence of extrusion and cut mechanisms. The former is caused by the drill chisel edge that has null or very small linear speed and the latter by the existence of rotating cutting lips at a certain speed.

As composites are neither homogeneous nor isotropic, drilling raises specific problems that can be related with subsequent damage in the region around the hole. The most frequent defects caused by drilling are delamination, fibre pull-out, interlaminar cracking or thermal damages [1]. These defects can affect not only the load carrying capacity of laminated parts but also reliability [2]. Rapid tool wear, as a result of material abrasiveness, can also be an important factor in damage occurrence [3].

Koplev et al. [4] examined the cutting process of unidirectional carbon fibre reinforced plastics and stated that the machining of CFRP consists in a series of fractures, each creating a chip. The examination of these chips revealed that they are not subjected to large plastic deformation as is normally found in metal chips.

The importance of tool geometry in delamination reduction is evidenced by several published papers on the subject. Piquet et al. [5] suggested the use of a great number of cutting edges, from three to six, in order to increase the contact length between tool and part, a point angle of 118º for the main cutting edges and a small rake angle. Chisel edge should be as reduced as possible. The use of pre-drilling neutralizes the chisel edge effect. A low feed rate can reduce delamination, but a better improvement can be accomplished by applying a variable feed rate. This requires the use of CNC drilling machines.

Park et al. [6] applied the helical-feed method to avoid fuzzing and delamination. Stone and Krishnamurthy [7] 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. Persson et al. [2] presented an orbital drilling method, where the hole is machined both axially and radially. This method eliminates the stationary tool centre, thus reducing the axial force. Davim and Reis [8] studied the effect of cutting parameters on specific cutting pressure, delamination and cutting power in carbon fibre reinforced plastics. The authors concluded that feed rate has the greater influence on thrust force, so damage increases with feed. Tsao and Hocheng [9] analyzed the effect of a backup plate on delamination, in order to understand and explain the advantage of its use in composite laminate drilling. Two drill geometries were used – saw drill and core drill. Results show that the use of a backup plate causes an increase in the critical thrust force, allowing for higher feed rates. In another paper [10], the same authors conducted a series of practical experiences to prove the benefit of using special drill when compared to commercially available tools, like twist drill. The effect of their use on delamination was evaluated. Based on experimental observation, it is possible to state that fracture resistance is lower than that of common steels and that almost no plastic deformation occurs during cutting. Delamination extent was determined with the help of ultrasonic C-scan. Mathematical models to the determination of critical thrust force for each tool geometry were presented. At the end, it was possible to conclude that thrust force varies with drill geometry and with feed rate. That enables for the use of higher feed rates if adequate drill geometry is selected. Fernandes and Cook [11] investigate the thrust force during drilling with ‘one shot’ drill bit. Their objective was to extend tool life and improve hole quality. For that, a mathematical model leading to the calculation of feed in order to keep thrust force under a critical threshold was developed. Finally, Tsao [12] evaluated the importance of pilot hole on delamination reduction when using core drills. Pilot hole eliminates the chisel edge effect, reducing delamination significantly. The ratio of pre-drilled hole to drill diameter must be controlled in order to drill with higher feed rate without delamination. In his experimental work, Tsao has found an optimal ratio of 0.85 for the use of the largest feed rate – 0.012 mm/rev.

Murphy et al. [13] compared the performance of three different types of tungsten carbide drills, TiN (titanium nitride) and DLC (diamond like carbon) coated and an uncoated drill. The use of coatings was found to be of no benefit when machining carbon/epoxy laminates, reducing neither tool wear nor composite damage.

Dharan and Won [14] conducted a series of machining experiments in order to propose an intelligent machining scheme that avoids delamination by peel-up at entrance and by push-out at exit.

As some of these defects are not visible in a visual inspection, it is needed to establish non-destructive testing (NDT) in order to be able to determine the existence of internal damages, like delamination, between the laminate plies. Carbon/epoxy laminates are opaque, so radiography is needed for plate damage evaluation after drilling.

A good deal of information about composite quality can be obtained as long as the damages are orientated perpendicular to radiation beam. In order to detect delamination, it is necessary to use a penetrating fluid, so the method used is known as enhanced radiography.

Advantages in the use of composite plates are growing everyday, therefore an increase in parts production and need for higher quality machining and dedicated tooling is to be expected.

2 Composites Delamination

2.1 Damage Models

When delamination is considered, it is necessary to tell from two types of damage that are different in their causes and effects: peel-up delamination and push-down delamination.

Peel-up delamination is a consequence of the cutting force pushing the abraded and cut materials to the flute surface – figure 1. The material spirals up the drill flute before it is completely machined. A peeling force pointing upwards is introduced that tend to separate the upper laminas of the uncut portion held by the downward acting thrust force. Normally a reduction in feed rate can reduce this delamination.

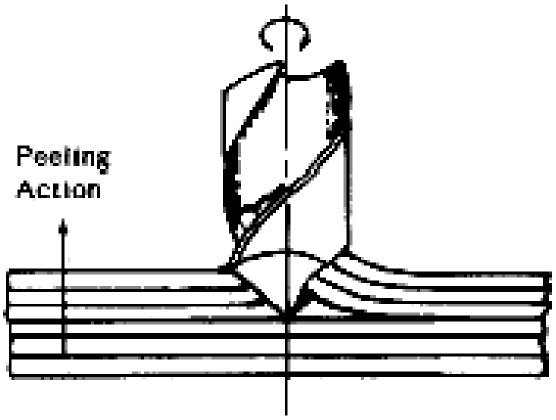


Fig. 1. Peel-up delamination mechanism [15].

Push-out delamination is a damage that occurs in interlaminar regions, so it depends not only on fibre nature but also on resin type and respective properties. This damage is a consequence of the compressive thrust force that the drill tip always exerts on the uncut laminate plies. There is a certain point at which the loading exceeds the interlaminar bond strength and delamination occurs – figure 2.

The reduction of this delamination type is the focus of this paper.

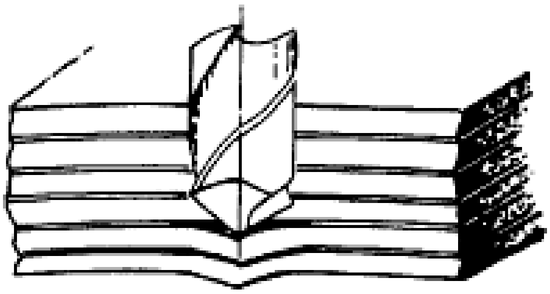


Fig. 2. Push-out delamination mechanism [15].

Analysis of delamination mechanisms during drilling using a Linear Elastic Fracture Mechanics – LEFM – approach have been developed and different models presented. The one most referred to is the Hocheng-Dharan [15] delamination model. In this model, the critical thrust force for the onset of delamination (F_{crit}) is related with properties of the unidirectional laminate like the elastic modulus (E_1), the Poisson ratio (ν_{12}), the interlaminar fracture toughness in mode I (G_{Ic}) and the uncut plate thickness (h),

$$F_{crit} = \pi \left[\frac{8 G_{Ic} E_1 h^3}{3(1-\upsilon_{12}{}^2)} \right]^{1/2} \tag{1}$$

Lachaud et al. [16] considered that a normal stress is applied to the ply surface and modeled the uncut plate under the drill as a thin orthotropic plate clamped on the laminate surface. This model is valid only if a small number of uncut plies are involved. In a distributed load model the resultant critical thrust force is

$$F_{crit} = 8\pi \left[\frac{G_{Ic} D}{(1/3) - (D'/8D)} \right]^{1/2} \tag{2}$$

and in a point load model hypothesis

$$F_{crit} = 8\pi \left[\frac{2 G_{Ic} D}{1 - (D'/8D)} \right]^{1/2} \tag{3}$$

where D and D' are calculated using relations of laminates theory.

Tsao and Chen [17] started from equation 1, and tried to predict the location of delamination, determining a value of h corresponding to critical thrust force – $h_{isotropic}$. The authors also stated that, in fact, each ply is highly anisotropic and a more realistic shape of delamination should be elliptical. Resultant equations, both for critical thrust force and delamination location, are more elaborated. Finally, delamination height for critical thrust force can be calculated using

$$h_{anisotropic}{}^{*} = \left\{ \frac{4(1-\upsilon_{12}\upsilon_{21})}{3 G_{IC} \pi} \left(\frac{E_{11}}{E_{22}} \right) \frac{1}{4E_C^{*}} \right\}^{1/2} \tag{4}$$

where E_{11} and E_{22} are the Young's modulus in the parallel and transverse directions and E_c* is a result of an expression relating Young's modulus and Poisson coefficients in different directions.

Won and Dharan [18] determined quantitatively the effect of chisel edge and pilot hole in composites laminates drilling. Results showed a large thrust force reduction when using pilot hole, by the removal of chisel edge contribution. Potential of delamination can be reduced if drilling in two stages, to eliminate the disadvantage of chisel-induced thrust force. A model using equation 1 as a starting point was also presented.

Recent models use a different approach, based on a specific drill geometry [19] or in a comparison of geometries using Taguchi's techniques [20] or the influence of stacking sequence [21]. In each case, a different model for the calculation of critical thrust force for delamination onset is derived, all of them based on Linear Elastic Fracture Mechanics.

2.2 Damage Criteria

After drilling, it is necessary to define criteria that allow the comparison of the delamination caused by different drilling parameters, even though they can only be applied to composites with the same stacking sequence and reinforcement fibre in nature and volume fraction. Two ratios were established for damage evaluation.

The first is *Delamination Factor* (F_d) [22], a quotient between the maximum delaminated diameter (D_{max}) and hole nominal diameter (D),

$$F_d = D_{\max} / D \qquad (5)$$

In the experimental work presented, Chen [22] examined the effects of tool geometry and cutting parameters on delamination. Feed rate was identified as a factor of strong influence on thrust force.

Tsao and Hocheng [20] evaluated the delamination factor results when using three different drills and images obtained from ultrasonic C-Scan. It was found that feed rate and drill diameter had the largest influence on delamination.

The second is *Damage Ratio* (D_{RAT}) [23]. It was defined as the ratio of hole peripheral damage area (D_{MAR}) to nominal drilled hole area (A_{AVG}),

$$D_{RAT} = D_{MAR} / A_{AVG} \qquad (6)$$

This evaluation method is based on the existence of digitized damage images that must be analyzed using suitable image processing techniques, like pixel counting [24, 25].

In this work, only the former criterion is applied for parameter and bit geometry evaluation.

3 Experimental Work

3.1 Materials and Tools

In order to perform the experimental work, a carbon/epoxy plate was fabricated from pre-preg with a stacking sequence of $[(0/\text{-}45/90/45)]_{4s}$, giving the plate quasi-isotropic properties. The laminate was cured, in a hot plate press, under 3 kPa pressure and 140 ºC for one hour, followed by air cooling. The final thickness of the plate was 4 mm.

Drilling experiments were executed in a machining centre *OKUMA MC-40VA*. All drills are made of K20 carbide and have a diameter of 6 mm. Four types of drills were experimented for comparison: twist, Brad, Dagger and a specially designed step drill. Five cutting speeds and three feed rates were employed – table 1. The cutting parameters were combined along experimental work, in a total of fifteen diverse setups.

Table 1. Drilling parameters.

Level	Cutting speed [m/min]	Spindle speed [rpm]	Feed rate [mm/rev]
1	30	1600	0.025
2	38	2000	0.05
3	53	2800	0.01
4	80	4200	
5	102	5400	

Twist drill is a standard drill with a point angle of 118º. In order to reduce the thrust force during drilling with this tool, pre-drilling with a 1.1 mm drill was used.

The Brad drill was originally developed for the cutting of wood. The main characteristic of this drill is the scythe shape of the cutting edges, tensioning the fibres in order to obtain a clean cut and a smooth machined surface.

Dagger drill has a very sharp point angle – 30º - and need to have enough space available at the exit side of the plate. This can be a limitation of its use.

The special step drill was designed to reduce delamination during composites drilling. The basic design was suggested in a lecture by H. Dharan [26]. It has two drilling diameters – 1.25 and 6 mm – dividing the drilling operation, and consequently the thrust force, in two stages. This division of the machining operation is entitled to cancel the chisel edge effect for the final hole drilling. The diameter transition has a conical shape, for softer transition. The drill tip was designed in a way to promote the initiation of the cutting action immediately after touching the plate, thus reducing the indentation effect – figure 3.

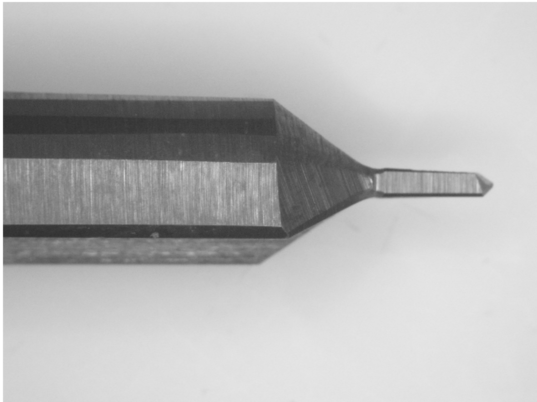


Fig. 3. Special step drill

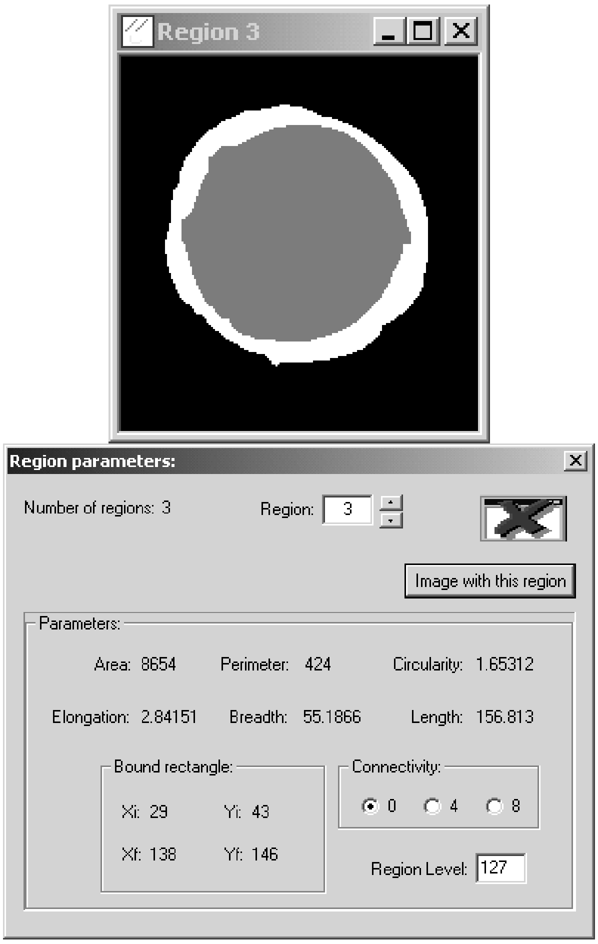
During drilling, thrust force was monitored with a Kistler 4782 dynamometer. The signal was transmitted via an amplifier to a PC to data collection. For each cutting condition, drill and cutting parameters, a total of five holes were made and the thrust force was always averaged over one spindle revolution, in order to reduce signal variation that occurs during drill rotation.

3.2 Delamination Measurement

Delamination extension is not possible to be measured by a visual inspection as carbon/epoxy plates are opaque. So, the plates need to be inspected by enhanced radiography. Radiography is suitable on the detection of delaminations only if a contrasting fluid is used. In this work, the fluid was di-iodomethane, a radio-opaque chemical reagent. The plates were immersed for one and a half hour and then radiographed with an exposition time of 0.25 seconds. The resulting images were then processed using a previously developed image analysis and processing platform [25, 27, 28]. This platform turned possible the use of some standard Computational Vision techniques in order to obtain the necessary values for damage delamination criteria.

The processing sequence is as follows:

- manual selection of the interest zone, to reduce computational time;
- pre-processing of the sub-image by a smoothing filter to reduce existing noise;
- segmentation of interest areas;
- elimination of noise areas by the application of erosion and dilation morphologic filters;
- use of a region processing and analysis algorithms to differentiate the several regions in an image and presentation of measurements.



Number of regions: 3

Region: 3

Parameters:

Area: 8654

Perimeter: 424

Circularity: 1.65312

Elongation: 2.84151

Breadth: 55.1866

Length: 156.813

Bound rectangle:

Xi: 29

Yi: 43

Xf: 138

Yf: 146

Connectivity: ● 0 ○ 4 ○ 8

Region Level: 127

Fig. 4. Example of area identification and measurement results in an image obtained by radiography using Computational Vision techniques (grey area is the hole region; white area is the delaminated region).

With this procedure it is possible to determine the results for any of the delamination criteria mentioned above.

4 Results

4.1 Drilling parameters

During drilling tests, the thrust force was continuously monitored as referred before. For each combination of tool geometry and cutting parameter, a total of five coupons were drilled. So, the results here presented are an average. It is possible to remark that the standard deviation was always very low, regarding thrust force values considered. As delamination onset and propagation are largely dependent on the maximum value of thrust force, this was the value regarded as useful for result comparison.

The first set of results here presented are concerned with parameter influence – feed rate and cutting speed – in thrust force and delamination around the drilled hole. Feed rate is normally considered as having a major role in the indentation over the uncut thickness of the material, resulting in higher influence on delamination onset. Compared to feed rate, the cutting speed effect is minor. The evaluation of the relative contribution of each factor will not be addressed in this paper.

Independently of the drill geometry or the cutting speed, a clear trend was found regarding the effect of feed rate. The best results, either for thrust force or delamination, were always found when a low feed rate was used. Regarding the experimental set used in this work, it is not surprising to observe that a feed of 0.025 mm/rev has resulted as the best option – figure 5, table 2. However, it must be remembered that a low feed rate also increases the heating of the hole machined walls during machining. In some cases, the possibility of matrix softening should be taken into account. In that case, thermograph techniques should be used in order to assess this risk. The use of CNC machines, enabling a variable feed rate strategy is a good option to consider when drilling laminate plates.

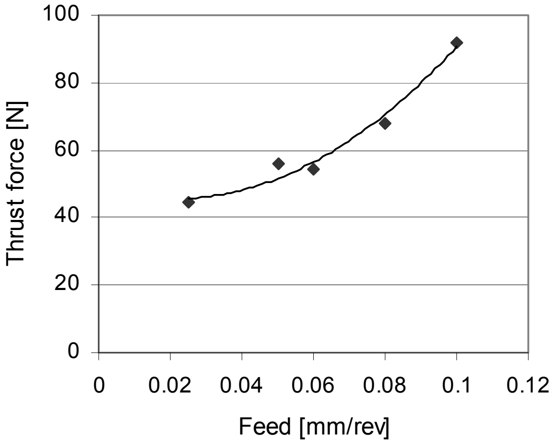


Fig. 5. Feed rate influence on maximum thrust force during drilling.

Figure 5 and table 2 show the results found for maximum thrust force and delamination factor – F_d – for the feed rates considered in this work. In figure 5, data is correlated by a 2nd polynomial curve. It is interesting to note that a simple mathematical calculation of the minimum returns a feed rate of 0.022 mm/rev, consistent with the results here presented.

Looking at the results in table 2, it can be said that the use of great feed rates is not recommendable in laminate drilling. Besides these results, peel-up delamination was observed when the higher feed rate – 0.1 mm/rev – was used.

Table 2. Results of Delamination Factor (F_d) for different feed rates.

Feed rate [mm/rev]	Delamination Factor F_d
0.025	1.065
0.05	1.075
0.1	1.125

Regarding cutting speeds, a broad range was used, since the first indications and experiments were based on tool manufacturers' recommendations. Lately, as the results start to give some orientation, it was possible to identify a narrower range of cutting speeds, from 38 m/min to 80 m/min, corresponding to a spindle speed between 2000 and 4200 rpm.

Bearing in mind that cutting speed is less significant in delamination and thrust force for laminate drilling, a similar procedure as described for feed rate was carried out. Again, it was possible to identify a best option regarding cutting speed – 53 m/min – and once again the correlation of data with 2nd polynomial curves had returned a minimum of thrust force for a cutting speed of 50 m/min (2650 rpm), for a 6 mm diameter drill.

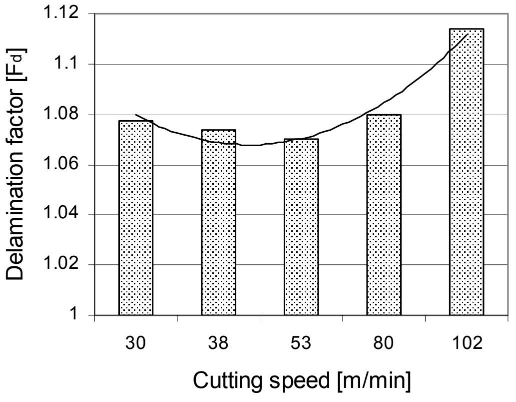


Fig. 6. Cutting speed influence on Delamination Factor (F_d) of drilled holes.

In table 3 and figure 6 the results obtained for the maximum thrust force and delamination for the different cutting speeds used in this work are presented.

Based on these results, it seems as it is possible to identify a 'critical cutting speed' for the drilling of carbon/epoxy plates. The use of speeds above or below this value will cause an increase in thrust force and, consequently, on delamination around the hole. This result has to be confirmed with other tool diameters.

Table 3. Results of maximum average thrust force for different cutting speeds.

Cutting speed [m/min]	Maximum thrust force [N]
30	59
38	61
53	48
80	56
102	63

4.2 Tool geometry

Tool geometry plays an important role in delamination reduction as the value of critical thrust force for delamination onset and propagation is dependent on drill bit geometry. Besides delamination, other issues need to be taken in account.

Twist drill, being a common drill of universal use, tends to be less expensive and so, costs associated to tool replacement are lower. Hole quality is fair if pilot hole is used and there is no need for reaming.

Brad drill machined surfaces have a clean cut, presenting a smooth hole surface. No advantage in the use of pre-drilling was identified when using this drill.

As already referred, the main drawback for the use of Dagger drills is the need of available space for drill exit at the opposite side of the plate. If that is not a problem in an experimental work, it can be the ground of some limitations in workshop area. Another problem noted during this work was the increased vibration, at the drill tip, with greater cutting speeds. This fact can be explained by the longer length of the drill.

The special step drill was designed to be as short as possible, preventing the possibility of vibrations. This can be a limitation if plates of greater thickness are to be drilled, leading to the need of dedicated tooling for several ranges of plate thickness. The final appearance of the holes indicates the need for reaming, just like those obtained with Dagger drills. For the purposes of the present work, reaming was not done, as it could modify the delaminated area. The clean cut look of the machined walls was not obtained, leading to the conclusion that some changes in tool design are needed. The main objective when using this tool was the separation of the thrust force in two steps, corresponding to first and second drill diameters, reducing the maximum thrust force and, consequently, the risk of delamination onset. Only one diameter of pilot hole was used, based on the conclusions in [18] and in previous experimental work using different pre-drilling diameters, from 1.1 to 3.5 mm. However, it will be necessary to confirm this feature in tool design, using different diameters for the first stage of drilling.

Results considered for comparison are, once again, the maximum thrust force during drilling – table 4 – and the delamination measured after holes drilled – figure 7.

There is an influence of drill bit geometry on thrust force measured during drilling. Consequently, a more favorable geometry enables the use of higher feed rates without delamination hazard. In this work, the results considered are not only the average of the different cutting speeds used, but also the best value found for each drill type.

Naturally, the variation of thrust force values when feed rates were increased was not the same for all the drills experimented. The drills that had registered less variation with feed were the Dagger and the Brad drill. The geometry that resulted to be more affected for feed rate variation was the twist drill.

Table 4. Results of maximum average thrust force for different drill geometries.

Drill geometry	Maximum thrust force [N]
Twist	58
Brad	67
Dagger	63
Special step	56

The second comparison was the delamination caused by the drills. The procedure of delamination measurement was already described in section 3.2

and the results considered were for the best set of parameters for each drill geometry.

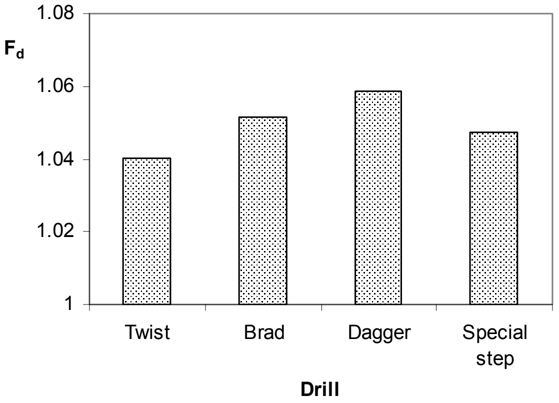


Fig. 7. Comparison of delamination factor (F_d) results for each drill geometry.

It is interesting to note that the holes with less delamination were those obtained with twist drill and special step drill. These two geometries have also presented the lower values of maximum thrust force during drilling. So, the tool geometry influence on delamination onset is more dependent on the force developed during drilling. That force is different for each geometry and can be related mainly with the chisel edge effect. However, the plate properties play an important role on the phenomena of delamination occurrence, due to ply orientation, material stiffness and Young modulus as demonstrated by the several models presented in section 2.1. In all these models, the critical thrust force is only a function of laminate properties and uncut plate thickness. The role of the drill bit geometry and parameter selection is the reduction of the thrust force during drilling.

The work here described is applied for 6 mm diameter tools and it has to be adjusted if other diameters are to be analyzed.

5 Conclusions

Drilling of carbon/epoxy laminates using different cutting parameters and four drill geometries was completed for the purpose of the work here presented. The aim of this study was to reduce the risk of delamination, considered the most frequent and harmful defect in this type of machining. In order to compare the best cutting parameters and the best drill geometry, thrust forces during drilling were monitored and delamination measured with the help of enhanced radiography and computational vision techniques. As the plates were of the same thickness, the results of the maximum thrust force during drilling were only dependent on tool geometry and cutting parameters. Maintaining the cutting parameters identical during an experimental batch, it was possible to compare tool geometry influence. Finally, a delamination criterion was used to have indications on the best tool geometry and machining parameters. Based on the experimental work here presented it is possible to draw some conclusions.

A correct selection of cutting parameters in order to reduce thrust force and, consequently, delamination around the hole, is possible. For the experimental conditions here described and a hole diameter of 6 mm, the setting of parameters that allowed for delamination minimization was:

- a feed rate of 0.025 mm/rev;
- a cutting speed around 50 m/min.

It must be remembered that an increase in feed rate has greater consequences in terms of delamination than a variation in cutting speed.

Besides the selection of cutting parameters, the choice of a tool that is dedicated to the drilling of fibre reinforced laminates can be useful. A drill bit geometry that reduces the indentation effect of the chisel-edge is preferable when drilling these materials. Particularly the use of a pilot hole has presented the best results for delamination reduction. That was the basic design of the special step drill here presented, returning good results when compared with the remaining three geometries of this study.

In spite of the need for dedicated tooling, the minimum delamination was found when a pilot hole strategy was applied with a twist drill. The pilot hole cancels the chisel edge effect, reducing the risk of delamination which was evident when considering the results obtained during experimental work.

The damage around the hole, normally delamination between inner plies of the laminate, can be evaluated by a non-destructive test like enhanced radiography. The only drawback of this technique is the need of parts immersion in a contrasting fluid, which may not always be possible at workshop area.

The image processing techniques based in the use of computational vision showed to be adequate to analyze the image objects involved. With these techniques it was possible to determine and quantify the damage caused by drilling, namely delamination, around the hole. The processing and analysis sequence here applied can be used for evaluation and measurement of damages in other materials.

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