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Drilling tool geometry evaluation for reinforced composite laminates

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ABSTRACT

In this work, a comparative study on different drill point geometries and feed rate for composite lami- nates drilling is presented. For this goal, thrust force monitoring during drilling, hole wall roughness mea- surement and delamination extension assessment after drilling is accomplished. Delamination is evaluated using enhanced radiography combined with a dedicated computational platform that inte- grates algorithms of image processing and analysis. An experimental procedure was planned and conse- quences were evaluated. Results show that a cautious combination of the factors involved, like drill tip geometry or feed rate, can promote the reduction of delamination damage.

Keywords: Drill geometry Thrust force, Roughness measurement Damage, Enhanced radiography, Image processing and analysis

1. Introduction

In recent years reinforced composite laminates have become one of the most interesting groups of materials, due to their unique properties like low weight, high strength and stiffness. In spite of their growing demand and usage, there are still some issues when considering the use of composite laminates. Some of these issues are cost-related, but considerations about machining also lead to some difficulties and lack of acceptance for the implementation of these materials.

Besides the relative complexity of the production process, machining operations like drilling are widely needed in composite structures, as it is required to use bolts, rivets or screws when joining different parts. Usually, it is accepted that drilling can be carried out using conventional machinery with suitable adaptations. However, as composites are non-homogeneous, drilling causes some difficulties. The most frequent damages are delamination, fibre pull-out, interlaminar cracking or thermal [1], in addition to other minor damages. These defects can affect not only the load carrying capacity of laminated parts but also strength and stiffness, thus reliability [2]. Rapid tool wear, due to material abrasiveness, can also be an important factor in damage occurrence [3]. Another consequence is the need of frequent tool changes that affects the production cycle and raises the final cost.

Usually, some damage in the region around the hole boundary is evident after a drilling operation is completed, being delamination the most serious one as it can reduce considerably the load carrying capacity of the joint. The main mechanism responsible for delamination is the indentation effect caused by the quasi-stationary drill chisel edge. This effect can be diminished by a correct choice of tool geometry and/or cutting parameters. In general, it is accepted that a drilling process that reduces the thrust force exerted by the drill chisel edge can prevent delamination risk.

According to Piquet et al. [4], a custom drill for composite laminates should have a small rake angle to prevent peel-up risk, greater number of cutting edges, to increase the contact length between the tool and the part, and reduced chisel edge, to diminish the indentation effect. Dharan and Won [5], suggested that feed should be controlled when the drill tip makes contact with the plate and in drill breakthrough to prevent delamination. Persson et al. [2], developed an orbital drilling method, reducing the axial thrust force by the elimination of the stationary tool centre, besides other advantages. Davim and Reis [6], 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. Hocheng and Tsao [7], conducted several practical experiences to prove the benefit of using special drills instead of twist drills. In this work, authors concluded 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. More recently, Tsao and Hocheng [8], have presented the advantages of a core drill. The influence of spindle speed was relatively insignificant. Durão et al. [9], confirmed the influence of appropriate drill geometry selection on delamination reduction as well as the advantage of the use of a pilot hole strategy.

Another related issue is the importance of the stacking sequence of the laminate. As this sequence can be varied according to the desired final part specifications, there is the possibility that the results presented in one study are not directly transferable to other. It is possible to observe that there are more published papers on cross-ply sequence [6–8,14] or on quasi-isotropic [4,5,10] than on unidirectional laminates [11]. It must be noted that according to [12] results obtained for unidirectional laminates can be conservatively used for multi-directional laminates. The relative contribution of feed or cutting speed are comparable, except that drilling of unidirectional laminates without delamination is far more demanding than drilling using other stacking sequences.

In this work, a total of five different drill geometries – twist with 120° and 85° point angles, Brad type, Dagger type and a customized step – were compared, concerning thrust force during drilling, hole wall roughness and delamination extension after drilling. Delamination is evaluated by using enhanced radiography combined with computational algorithms of image processing and analysis. An experimental procedure was planned and results were evaluated by direct comparison. This modus operandi demonstrated that a cautious combination of the factors involved, like drill tip geometry or cutting parameters can promote the reduction of delamination damage.

This paper is organized as follows: in the Section 2, analytical damage models are presented. In the Section 3, experimental drilling work carried out is described. Experimental results as well as their discussion are presented in Section 4. In the Section 5, main conclusions from this work are presented.

2. Analytical damage models

Delamination during drilling in composite laminates can be an outcome of two types of damage mechanisms that are different in their causes and effects, usually known as peel-up delamination and push-down delamination.

By one hand, peel-up delamination is a consequence of the cutting force pushing the abraded and cut materials to the flute surface. 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 lamina of the uncut portion held by the downward acting thrust force. Normally, a reduction in feed rate can reduce this delamination type. By the other hand, 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, Fig. 1.

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

Analysis of delamination mechanisms during drilling using a Linear Elastic Fracture Mechanics (LEFM) approach have been developed and different models presented. From these, the one most referred to is the Hocheng–Dharan delamination model [13]. In this model, the critical thrust force for the onset of delamination (F_{crit}) is related with properties of the unidirectional

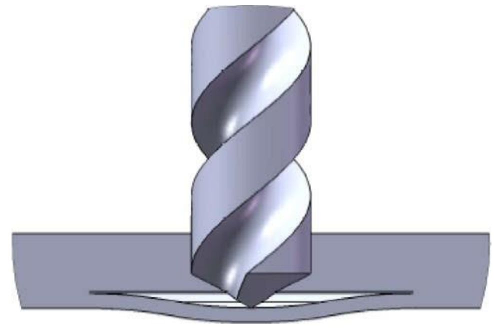

Fig. 1. Delamination mechanism.

laminate like the elastic modulus (E_1), the Poisson ratio (υ_{12}), the interlaminar fracture toughness in mode I (G_{Ic}) and the uncut plate thickness (h):

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

Lachaud et al. [10] 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:

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

and in a point load model hypothesis:

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

where D and D^0 are calculated using relations of laminates theory.

Tsao and Chen [11] started from Eq. (1), and tried to predict the location of delamination, determining a value of h corresponding to critical thrust force ($h_{isotropic}$).

Zhang et al. [14] considered a different approach. In their model, the delamination has an elliptical shape, even for multi-directional composites drilling.

Tsao and Hocheng [15] analyzed the effect of pre-drilling in delamination, showing that the existence of a pre-drilled pilot hole can reduce significantly the occurrence of this damage.

Jung et al. [16] proposed a new formulation for the critical thrust force to propagate delamination, in the case of angle-ply laminates. In their model, the authors have considered the existence of twisting and mid-plane extension of the delamination zone.

Won and Dharan [17] determined quantitatively the effect of chisel edge and a pilot hole in composites laminates drilling. Results showed a large thrust force reduction when using a 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 Eq. (1) as a starting point was also presented.

Recent models use a different approach, based on specific drill geometry [18], or in a comparison of geometries using Taguchi's techniques [19].

Yet, no analytical model can predict the location of damage onset, in terms of uncut thickness, accurately.

An alternative and economical approach is given using finite element models (FEM). In these models, the objective is to derive a computational model predicting the deformations, stresses and strains in the workpiece. Frequently, three-dimensional elements

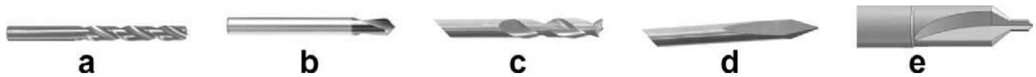

Fig. 2. Drills: (a) twist 120; (b) twist 85°; (c) Brad; (d) Dagger; and (e) step.

from Abaqus® are used to predict the delamination onset and propagation [20–22].

After laminate holes are drilled, it is important to establish criteria that can easily compare the delamination degree of various processes, even though they can only be applied to composites with the same lay-up regarding orientation and number of plies.

Chen [23] proposed a comparing factor that enables the evaluation and analysis of delamination extension in laminated composites. The proposed ratio was called *delamination factor* (F_d) and it was defined has the quotient between the maximum delaminated diameter (D_{max}) and the hole nominal diameter (D):

$$F_d = D_{max}/D. \quad (4)$$

3. Experimental work

In order to accomplish the experimental work planned, a batch of plates using prepreg CC160 ET 443 with a cross-ply stacking sequence and 24 layers were produced, for a final thickness of 4 mm. The plate was then cured under 300 kPa pressure and 130 °C for one hour, followed by cooling. Then, the plates were cut in test coupons of 165 × 96 mm^2 for the drilling experiments.

The experimental work was divided in drilling of the laminate plates for thrust force monitoring, hole wall roughness measurement and delamination evaluation by enhanced radiography and computational algorithms of image processing and analysis.

Drilling operation was carried out in a 3.7 kW *DENFORD Triac Centre* CNC machine. A total of five tungsten carbide drills with 6 mm diameter and different geometries were used: a twist drill with a point angle of 120°, a twist drill with a point angle of 85°, a Brad drill, a Dagger drill and a special step drill, Fig. 2.

Twist drill is a standard drill commonly used. Two point angles – 85° and 120° – are compared in this work. Brad drill has a specific point geometry causing the fibre tensioning prior to cut thus enabling a "clean cut" of the fibres. In consequence, machined surfaces are smoother. Dagger drill has a small point angle of 30°, reducing the indentation effect but need more space available at the exit side of the plate. Special step drill has the intention of performing pilot and final hole in one operation only, dividing the thrust force and consequently, reducing delamination hazard [24].


Fig. 3. Experimental setup.

Table 1
Main experimental drilling parameters.

Drill diameter (mm)	Cutting speed (m/min)	Spindle speed (rpm)	Feed rate (mm/rev)	Feed speed (mm/min)
6	53	2800	0.02 0.06 0.12	56 168 336

During drilling, axial thrust forces were monitored with a *Kistler 9257B* dynamometer associated to an amplifier and a computer for data acquisition and processing. Experimental setup is presented in Fig. 3.

Cutting parameters were selected according to authors' previous experience, published papers from other authors and fabricant recommendations [6,9]. As it has been previously confirmed the main importance of feed rate when compared with spindle speed in thrust forces development [6], cutting speed and tool diameter were kept constant and only feed rate was changed during experimental work, Table 1.

After drilling, hole wall roughness was measured with a *Hommelwerke* profilometer, with a total travelled length of 1.5 mm, a cut-off length of 0.25 mm, an evaluation length of 1.25 mm, a sampling length of 0.25 mm and a travel speed of 0.15 mm/s. For this work, the roughness parameter considered was R_{max}, corresponding to the maximum peak-to-valley dimension obtained from the five sampling lengths within the evaluation length l_m. Three measurements were made for each hole.

Finally, plates were inspected by enhanced radiography. With this purpose, plates were prior immersed in di-iodomethane for contrast for 1.5 h and carefully cleaned before radiography. Developed radiographies were scanned for delamination around the hole measurement. Details of this nondestructive testing approach can be found in [9].

4. Results and discussion

Results considered for thrust force are the maximum value observed during drilling and the value at the moment when the drill tip reaches the last uncut ply of the laminate. The latter is compared with numerical values of thrust force that result from the analytical models (Eqs. (1)–(3)). Due to signal variation along drill rotation, thrust force values were averaged over one spindle revolution. Results considered are the average of six experiments under identical conditions.

4.1. Thrust force

As expected, feed rate has a close influence on thrust force values as higher feed rates correspond to higher values of maximum thrust force. As feed rate increases from the lowest to the maximum value, the maximum thrust force more than doubles its value, on the average, Fig. 4. The drill geometry that represents a smaller difference is the Dagger drill while with step drill the last value is three times higher than the one observed with the lower feed. Based on these results, it is possible to say that low feed rates reduce maximum thrust force during drilling. Consequently, delamination around the hole should be reduced, as long as the drill geometry remains unaltered. However, a reduction in feed

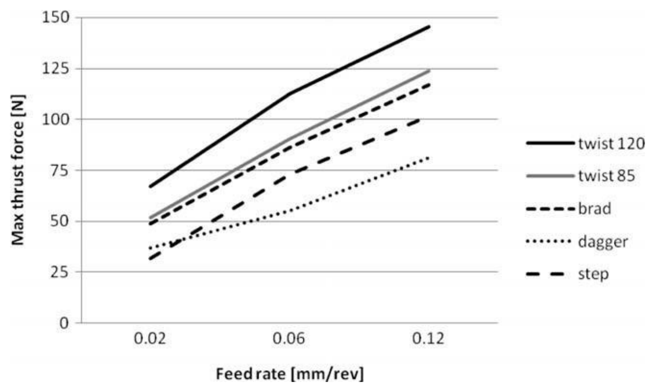

Fig. 4. Feed rate effect on maximum thrust force.

rate raises drill temperature and the drilled region of the plate softens, increasing the risk of thermal damages. Measurements of drill tip after six holes in a row showed temperatures from 50 °C with higher feeds to almost 80 °C when lower feeds were used. This aspect should be taken into account.

Another comparison from the results, see Fig. 5, shows that Dagger drill, due to its particular geometry, causes the full diameter engagement not to happen in 4 mm thick plates, which lead to lower thrust forces during the drilling operation. Twist drill with 120° point angle has always the highest force, independently of the thrust force selected. Reduction of maximum thrust force when using other drills are, on the average, 18% for twist drill with 85° point angle, 22% for Brad drills and 36% for step drill, confirming, from the thrust force examination, that is possible to reduce thrust force during drilling. This outcome is further compared with delamination results in the next section.

In Fig. 6, thrust force for the situation of one uncut ply, see Fig. 1, is compared for the five drills of the experimental work and Eqs. (1)–(3). For visualization simplicity, only the medium feed rate (0.06 mm/rev) results are presented. From the data presented it is possible to conclude that the standard drills had thrust forces that exceed the force considered as critical for delamination onset and propagation whatever is the analytical model considered for this comparison. The exceptions are the results for Dagger drill and special step drill. It must be noted that for Dagger drill the full engagement never occurs due to the specific geometry of the drill and for step drill the maximum thrust force is reached only at the second step of the drilling operation. This situation becomes better for the low feed rate due to the decrease of the maximum thrust

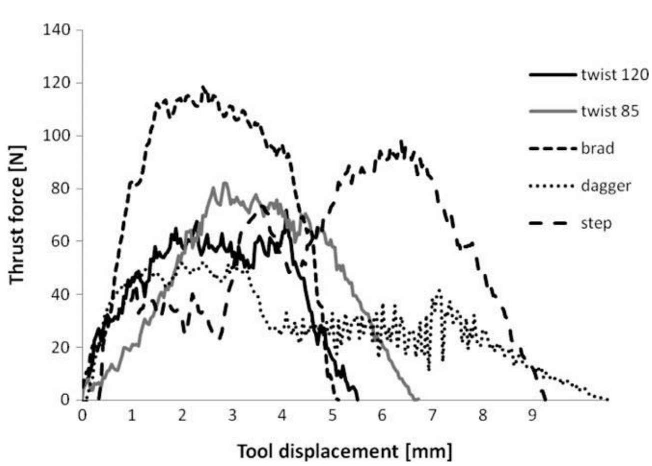

Fig. 5. Thrust force/displacement curves for the five drills.

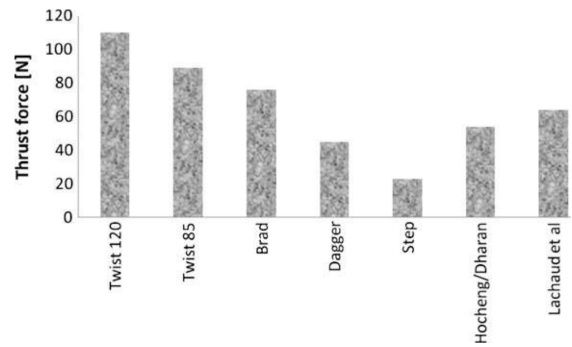

Fig. 6. Last ply thrust force comparison.

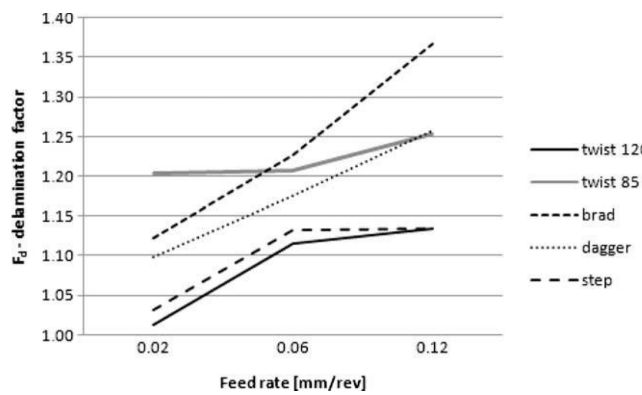

Fig. 7. Feed rate effect on delamination factor.

forces for all the drills while for the higher feed rate the possibility of delamination onset becomes aggravated. Evaluation of damage around the hole shows that delamination onset was always observed, independently of feed rate or drill geometry.

4.2. Delamination

Once again, delamination results follow a clear trend, correlated with thrust forces evolution. The increase of feed rate, with the consequences already discussed in previous section, causes an increase in delamination factor (Eq. (4)) as it is possible to observe in Fig. 7. However, the difference from the lowest to the highest feed rate is only around 10%, on the average. This difference is noted in all the drills used along the experimental work here described, although it is more significant when Brad drills were used. One can conclude that Brad drills are more reactive to feed rate changes, when delamination is to be considered.

If all the drills are compared, the results are not correlated with thrust force sequence, Fig. 8. Lower delamination was found when twist drills with 120° point angle were used as well as for step drill, giving good indications on this prototype design. Taking the twist 120° drill as a basis, delamination increases by 6% with Dagger drills, 12% when using twist 85° drills and 14% for Brad drills.

Particularly, it should be noted the excellent result of delamination when twist 120° drill combined with the lower feed was used. Delaminated diameter represents a small collar of 0.072 mm around the drilled hole. This result and the observation of the maximum thrust force during drilling, which was not the lowest one, reveal clearly the influence of a correct geometry selection when drilling composite laminates.

A final note has to be addressed to the results of the step drill, which is still in a prototype phase, with delamination values very

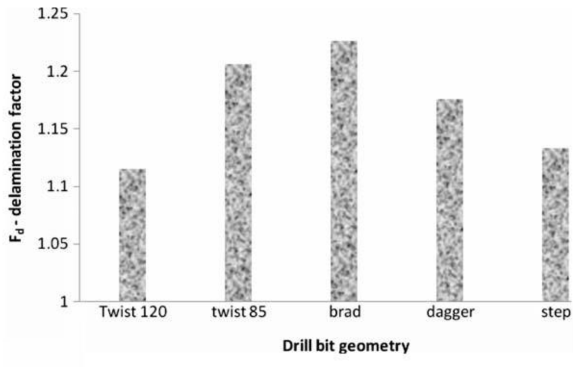

Fig. 8. Drill geometry influence on delamination factor.

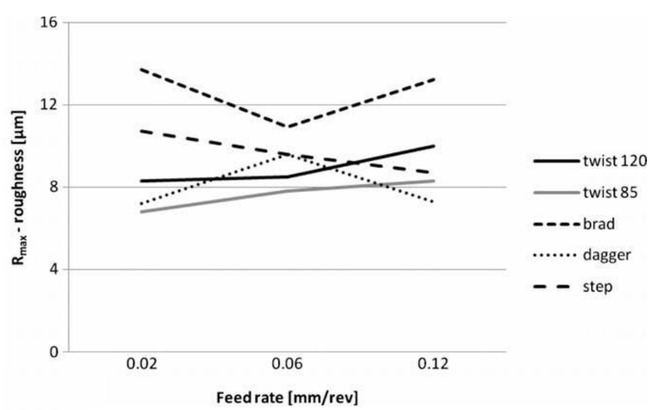

Fig. 9. Feed rate influence on hole surface roughness.

close to those found with twist 120° drills and identical behavior for the higher feed rate. Using the higher feed, the delaminated collar was approximately 0.8 mm wide for a 6 mm diameter hole – approximately 13% of the hole diameter. Although this can be considered as is an acceptable value, it depends on the demands from the final user of the manufactured products.

4.3. Hole surface roughness

The first impression that is necessary to point out is the scattering of the values for this measurement already noted during experimental work. There are no results that demonstrate the importance of hole surface roughness in the mechanical behavior of drilled laminates. The result can be influenced by the number and orientation of fibres that are within the stylus evaluation length. The results in Fig. 9 are the average of three measurements in three diverse zones of the hole wall, separated by around 60–90°.

Smoother surfaces were produced with any of the twist drills, followed by step drill. Strangely enough, in spite of the good appearance of the holes produced by Brad drills, roughness was high. That can be the consequence of the different fibre cut mechanism that is the main characteristic of this drill. No effect of feed rate was validated, even tough the higher values of roughness correspond to the medium feed rate used in this work.

The results of this parameter should not be considered as significant in a tool selection, mainly due to the large scattering of values. Clearly, this parameter is not so good to assess hole quality in composites as is common in metal parts drilling.

5. Conclusions

Carbon fibre reinforced laminates were drilled with the objective of comparing five different tool geometries. Results used for drill geometry comparison were the maximum axial thrust force during drilling, hole surface roughness and delamination. The results of thrust force for a situation of one uncut ply were compared with known analytical models. Experimental work has involved three feed rates and one cutting speed. From these, it is possible to draw some conclusions.

Low feed rates seem appropriate for laminate drilling, as it reduces the axial thrust force and consequently, the risk of delamination onset, as is demonstrated by the analytical models. However, this option can cause thermal degradation of the matrix and may not be suitable for industrial processes where productivity is generally considered as a priority.

The use of higher feed rates is possible, as long as there is knowledge about the effects on thrust force and delamination for each tool. Adequate tool selection can minimize delamination. For the experimental condition here presented the most adequate tool for higher feed rates is the twist drill with a 120° point angle. Special step drill could also be a good option.

Tool geometry had influenced the results both for thrust force and delamination around the hole. It is interesting to remark the diverse influence of feed rate on delamination according to the tool used. Twist drills and special step did not return considerable changes but for Brad and Dagger drills higher feed has a considerable impact on delamination factor.

Hole surface roughness results were too scattered to allow for any valid conclusion.

Based on the work presented, and considering the parameters used during the experimental procedure, a 120° twist drill should be used for minimal delamination. Special step drill could present a good alternative, but is not commercially available yet.

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