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Evaluation of Delamination Damages on Composite Plates using Techniques of Image Processing and Analysis and a Backpropagation Artificial Neural Network

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1. Abstract

Nowadays, drilling of carbon/epoxy laminates is extremely frequent in manufacturing and assembling processes and is normally carried through using standard drills, like twist or Brad drills. However, it is always necessary to have in mind the need to adapt properly the drilling operations and/or the drilling tools used as the risk of delamination occurrence in the laminates involved, or other kind of damages, is very high. Moreover, delamination can be critical because the mechanical properties of the produced parts can be severely affected. Thus, the production of higher quality holes, with damage minimization, is a key challenge to everyone related with composites industry to develop adequate methodologies to delamination characterization and assessment. In this paper, the delamination caused on laminates by drilling machining operations is analytically evaluated by processing and analyzing enhanced conventional radiography images of the laminates involved. In resume, in order to evaluate the delamination damage in laminates plates caused by drilling operations, the radiography images acquired are processed using a computational methodology that uses techniques of image processing and analysis and a backpropagation artificial neural network. Experimental results show that the proposed methodology can be successfully used to measure and characterize the delaminated area. Hence, using our methodology, the damage evaluation on laminates can become more accurate, efficient and simple.

2. Keywords: Image Processing and Analysis, Neural Networks, Composite Materials, Drilling, Delamination.

3. Introduction

For the past decades fibre reinforced plastics are increasing their importance as one of the most interesting group of materials, due to their unique properties as low weight, high strength and stiffness. Although their earlier developments were mostly related with aerospace and aeronautical industries, recent years had seen the spread of their use in many other industry areas like automotive, railway, naval, of sport goods and others. Concerns related to their high cost and marginal manufacturability have been satisfactorily addressed through high volume production and innovative design. In spite of these advances, their use is still limited, mainly due to high cost normally associated to their machining and finishing operations. In fact, although composite components are produced to near-net shape, their machining is often needed, as it turns out necessary to fulfill requirements related with their dimensional and geometrical tolerances or assembly needs. Machining operations in composites can be accomplished using conventional machinery with some adaptations. Among the usual machining processes used on composite materials, drilling is one of the most frequently adopted to make holes for screws, rivets and bolts. As composites are neither homogeneous nor isotropic, drilling raises specific problems that can be related with subsequent damage in the region around the holes done. The most frequent defects caused by drilling are delamination, fibre pull-out, interlaminar cracking or thermal degradation [1]. These machining defects cause not only a loss of the load carrying capacity of the laminate, which is undesirable [2], but also affect its reliability [3]. A high rate of tool wear is usually associated with fibre reinforced plastic laminates machining, due to the high abrasiveness effect of the reinforcement fibre, increasing the total operation time by the need of frequent tool changes. Therefore, it is very important to obtain good quality holes, based on a correct knowledge about the material used and concerning the operation involved.

Drilling is a complex process which is characterized by the existence of extrusion and cut mechanisms. The first one is caused by the drill chisel edge that has null or very small linear speed and the second mechanism by the existence of rotating cutting lips at a certain speed.

Several approaches had been presented in order to reduce delamination, commonly considered as the most important damage during drilling as, for example, [4 - 11].

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

As some of the defects caused on the laminates by the drilling operations are not visible by visual inspection, it is needed to establish non-destructive tests in order to be able to determine the existence of internal damages, like delamination, between the laminate plies. Moreover, as carbon/epoxy laminates are opaque, enhanced radiography can be considered needed for plate damage evaluation after drilling.

In the present work, in order to evaluate the delamination damage on composite laminates, techniques of image processing and analysis and a backpropagation artificial neural network are used. In resume, the methodology developed in the scope of this work is able to accomplish the task of identify and characterize the delaminated regions from radiographic images in order to evaluate the degree and the effect of delaminated damages on composite materials.

This paper is organized as follows: In the next section, are presented the main theoretical fundaments considered, as damage models and criteria in composite delamination, image processing and analysis techniques and artificial neural networks. In the third section, the steps of the experimental work concluded are described. The experimental results obtained and their analysis are presented in section fourth. In the fifth and last section, some conclusions are presented.

4. Theoretical Fundaments

4.1. Damage Models on Composite Delamination

Giving a closer look on delamination, it should be divided into two types, according to their grounds and consequences: one is commonly known as peel-up delamination and the other as push-down delamination.

Peel-up delamination is caused by the cutting force pushing the abraded and cut materials to the flute surface – Figure 1. At the beginning of the contact, 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. A peeling force pointing upwards is introduced that tends to separate the upper laminas of the uncut portion held by the downward acting thrust force. Normally, a reduction in the feed rate adopted can reduce this effect.

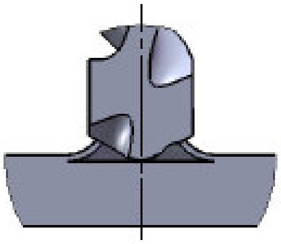

Figure 1. Peel-up delamination mechanism.

On 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 of the workpiece. At some point, the loading exceeds the interlaminar bond strength and delamination occurs, before the laminate is totally penetrated by the drill – Figure 2. All these defects are unwanted and lead to rejection or rework of the composite part involved. Both options are very costly and time consuming. These damages are especially difficult to detect by visual inspection and reduce severely the load carrying capacity of the laminate part, in particularly under compression loading [2], as already mentioned.

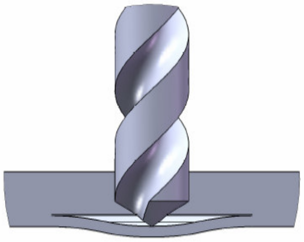

Figure 2. Push-out delamination mechanism.

Analysis of delamination mechanisms during drilling using a Linear Elastic Fracture Mechanics approach have been developed and different models presented. The contribution of thrust force to delamination onset and propagation has been first demonstrated by Hocheng and Dharan [12], by their development of a model based on Fracture Mechanics to determine the critical thrust force for delamination. This is the most referred analytical delamination model. In this model, the critical thrust force for the onset of delamination (F_{crit}) is related with material and geometrical properties of the unidirectional laminate as 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):

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

Besides the Hocheng-Dharan model, other models have been presented with the aim to derive the thrust force for delamination onset and propagation, see for example [13, 14, 15]. In some of these models, the shape of delamination area is considered elliptical. Other models are more concerned with the effect of the pilot hole dimensions, like the ones presented in [10, 16].

Recent models use a different approach, based on specific drill geometry [17] or in a comparison of geometries using Taguchi's techniques [18] or the influence of stacking sequence [19]. 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 approach.

4.2. Damage Criteria on Composite Delamination

After laminate drilling it is important to establish criteria that allows for the comparison of the delamination extent using different strategies. Note that these criteria can only be applied to composites with the same lay-up regarding reinforcement orientation and number of plies.

Damaged extension can be evaluated by using radiography, C-Scan or computerized tomography imaging modalities in order to obtain the images of the hole surrounding areas [20 - 23].

Chen [20] proposed a comparing factor that enables the evaluation and analysis of delamination extent in composites. The proposed Delamination Factor (F_d), defined as the quotient between the maximum delaminated diameter $D_{\max}$ and the hole nominal diameter D according to:

$$F_d = D_{\max} / D \quad . \tag{2}$$

A different ratio was suggested by Mehta et al [21], the Damage Ratio (D_{RAT}), that was defined as the quotient of Hole Peripheral Damage Area (D_{MAR}) to Nominal Drilled Hole Area (A_{AVG}):

$$D_{RAT} = D_{MAR} / A_{AVG} \quad . \tag{3}$$

An original approach was given by Davim et al [24] by suggesting another criterion named Adjusted Delamination Factor. This new criterion is intended to deal with the irregular form of delamination containing breaks and cracks, and it is defined as a sum of two contributions:

$$F_{da} = \alpha \frac{D_{\max}}{D_O} + \beta \frac{A_{\max}}{A_O} \quad , \tag{4}$$

where the first quotient is the delamination factor given by Eq. 2 multiplied by a constant α, $A_{\max}$ is the area related to the maximum diameter of the delamination zone ($D_{\max}$) and A_O is the area of the nominal hole (D_O). Constants α and β are used as weights, being their sum equal to 1 (one).

These damage evaluation criterions are based on the existence of measurements obtained from images of the damaged regions. Thus, those images should be analyzed using suitable image processing and analysis techniques like the ones described in the following.

4.3. Digital Image Processing and Analysis

Digital Image Processing and Analysis is an important knowledge field that is able to acquire, process and analyze digital images. The first process in a usual system of image processing and analysis is image acquisition. In this process, the use of a correct technique to make easily represented and the desired objects in the acquired images is fundamental for the success of the consequent steps and so for the quality of the final analyze results obtained using them. Many techniques can be used, as visible light, infrared, microwaves and X-rays, depending deeply on the environment and materials involved. To acquire the images, a specific imaging device must be used as video cameras, digital cameras, digital X-rays equipments, etc. If the output of this device is analogical then an Analogical/Digital converter need to be applied to obtain the associated digital images.

After image acquisition, a pre-processing step can be necessary. Basically, it consists in the use of Digital Image Processing operations with the main objective of noise reduction, image restoration, image enhancement and wrong data removal. In fact, in many applications, the accomplishment of this step is a conditioning necessary for a successfully following step, which often is the image segmentation step.

During a segmentation process, the input image is divided in regions of interest, according to their properties. This process is the most important in a typical computational system of image processing and analysis. A successfully segmentation step is the main condition to get adequate results in the following image analysis steps. Often, the next process is to obtain characteristic measurements from the segmented images. Normally, measurements of the regions segmented are considered as perimeter, area, texture and other descriptors. These measurements and descriptors can then be used as attributes to next process usually designated Pattern Recognition, in which are used pattern recognitions strategies to recognize the regions presented in the input images.

4.4. Artificial Neural Networks

Artificial neural networks can be applied in problems of function approximation, classification, among others, as well as in cases in which exist nonlinear relations between the dependent variables and the independent ones. Nowadays, artificial neural networks are being used in Material Sciences for welding control [25], to obtain the relations between process parameters and correlations in Charpy impact tests [26], in the modeling of alloy elements [27, 28], in the prediction of welding parameters in pipeline welding [29], to model the microstructures and mechanical properties of steel [30], to model the deformation mechanism of titanium alloy in hot forming [31], for the prediction of properties of austempered ductile iron [32], to predict the carbon contents and the grain size of carbon steels [33], to build models for predicting the flow stress and microstructure evolution of a hydrogenised titanium alloy [34], for example.

The fundamental paradigm of the neural networks is to construct a composed model using a considerable number of units, which are the neurons and each one constitutes a very simple processing unit, with a great number of connections between them. The information among the neurons employed in the network is transmitted through the synaptics weights.

Artificial neural networks flexibility, its capacity to learn and to generalize the learned information are very attractive and important aspects that justify the choice to use solutions based on neural network in many complex problems. In fact, the generalization, associated with the capacity of the network to learn through a training set of examples, representative of the problem to be modeled, and then the ability to supply correct results to input data that was not presented in the training done, demonstrates that the capacity of the neuronal networks goes further than the easily verified relations between the inputs and the outputs.

Hence artificial neural networks are capable to extract information not presented in explicit forms in the training examples considered [35]. Different topologies and algorithms of neural networks can be found in the literature. In this work, it was used a multilayer perceptron neural network, which is a neuronal network of the feedforward type [36]. Usually, a multilayer perceptron network is composed of several layers lined up with neurons. Then, the input data is presented into its first layer, which distributes it trough the internal hidden layers. The last layer is the output layer of the neural network from each the solution of the problem is taken. The input layer and the output layer can be separated by one or more hidden layers, also called hidden or intermediate layers. In many applications of neuronal networks, it is considered just one hidden layer. Beyond this, the neurons of a layer are connected to the immediately neurons, so there are not unidirectional communication, nor connection among the neurons of the same layer. All the neural layers are totally connected. For the training of the multilayer perceptron network used, we adopted a backpropagation algorithm which is the most used and classical one for this neuronal network architecture.

Many systems of digital image processing and analysis have been developed using artificial neural networks. This is possible because of their main characteristics, like robustness to the presence of noisy data in the input image, execution speed and their possibility to be parallel implemented. A review of several neuronal networks use in systems of digital image processing and analysis is presented by Zhang in [37].

4.4.1. Topology used

The topology of the neuronal network applied in this work is a two layer multilayer perceptron network and its main task is to recognize if a composite material radiographic image pixel belongs to a hole, damaged or non-damaged area. Hence, for the image segmentation step, we choose a topology made of 3 inputs, 2 perceptrons in the hidden layer and 3 perceptrons in the output layer (3/2/3). To the 3 network inputs is assigned the color components R, G and B of the image pixels. The outputs are related with the possible pixels classifications: hole, damaged or non-damaged area. The number of perceptrons at the hidden layer was calculated using the equation proposed by Yin, Liu e Han [38].

4.5. Experimental steps done

In this section we specify the experimental steps done in this work to obtain the final results from the preparation of the composite plates samples, Figure 3. Initially, the samples are prepared to be drilled using different types of drills. Then, conventional radiography is used to obtain the images to be analyzed and digitalized afterwards. Later on, we used our computational system, that integrates image processing and analysis techniques and a multilayer perceptron network, to accomplish the segmentation of hole and delaminated regions and to obtain their measurements from each digital image.

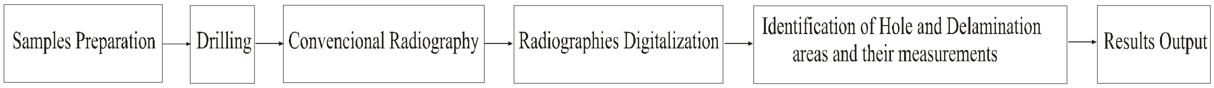

Figure 3. Block diagram of the steps done in this work.

In order to perform the experimental analysis, a carbon/epoxy plate was fabricated from pre-preg with a stacking sequence of [(0/-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. At the end, the plate thickness was 4 mm. From these plates, a total of five test coupons for each test batch were cut.

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. Several standard drills were experimented for comparison purpose: twist, bi-diametric, ‘Brad’ type and ‘Dagger’, Figure 4. Twist drill is a standard drill with a point angle of 118º. Bi-diametric drills were originally designed for the production of through holes together with the screw head lodging cavity. The type of drill available has a transition angle between the first and second diameter of 180º. 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 fibers in order to obtain a clean cut and a smooth machined surface. Dagger drill has a sharp tip and right blades, promoting cut right after the contact with the plate. However, it is less suitable to be used in situations with limited space on the exit side of the laminate and is relatively unable to remove chips.


a) b) c) d)

Figure 4. Drills considered in this work: a) twist; b) Brad; c) bi-diametric; d) Dagger.

A cutting speed of 80 m/min, corresponding to a spindle speed of 4200 rpm, and a feed rate of 0.05 mm/rev were considered. Thus, the existing difference was just related with the drill geometry. Besides this comparison, the effect of a pilot hole was also analyzed, having in mind the evaluation of the reduction in thrust force that is possible to achieve with pilot hole drilling as well as the consequence for delamination around the hole which is expected to decrease. Thus, combined with twist drill use, three pilot hole diameters were used: 1.1 mm, 2.3 mm and 3.5 mm. For the remaining drills, no advantage was found in the use of a pilot hole.

During drilling, thrust force was monitored with a Kistler 4782 dynamometer. The signal was transmitted via an amplifier to a PC for data acquisition. 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 necessarily occurs during drill rotation.

Delamination extension is not possible to be measured by visual inspection since carbon/epoxy plates are opaque. So, 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 images acquired by radiography showed several grades of grey, where dark grey areas correspond to damaged regions and light grey to undamaged regions of the plate. The delaminated area is located in a relatively circular region around the hole, Figure 5.

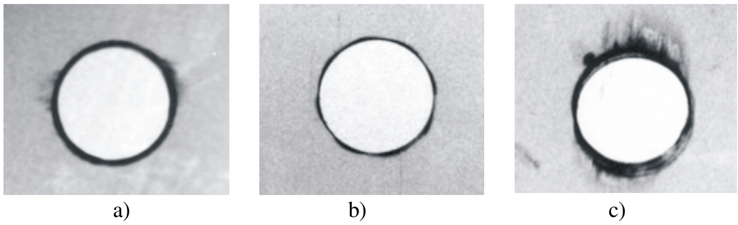

Figure 5. Drilled plate radiography: a) twist drill; b) Brad drill; c) bi-diametric drill.

The digital images to be processed and analyzed by the computational methodology used were obtained by radiographies digitalization. Then, the multilayer perceptron network employed is trained by selection some sample pixels of each region to be identified. It should be noted that this task just needs to be done once for all analogous images to be segmented. After the network training, the images were segmented using, the trained network, and is employed on each segmented image the region growing technique, [39]. Finally, the desired measurements were obtained in order the delamination criteria can be calculated. In the output images were used pseudocolors to label the identified hole, non-damaged and damaged regions, as it can be seen in Figure 6.

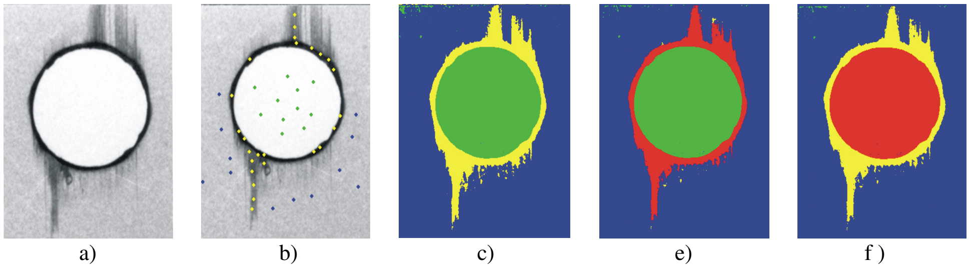

Figure 6. Example of areas identification and measurements: a) original image; b) pixels selection for the training phase; c) segmentation results; finally results (in red), d) delaminated region and e) hole region.

5. Experimental Results and Discussion

5.1. Thrust forces

During drilling, the axial thrust forces (F_x) were monitored using a Kistler 4782 dynamometer, a multichannel amplifier and a desktop computer for data acquisition. All the results here presented, and referred to as thrust force, consist of an average of five tests under identical experimental conditions. As there is a signal variation during one drill rotation due to the mechanics of the process itself, the thrust forces were always averaged over one spindle revolution. Considering that delamination onset and propagation are largely dependent on the maximum value of thrust force, this was the value regarded as practical for result comparison.

Observing the summary of results presented in Table 1, it is possible to say that the lowest value of thrust force was obtained when bi-diametric drill was used. This fact can be explained by the particular geometry of this drill, dividing the drilling work in two separate steps. The consequence of such drill geometry is a minimization of the thrust force that is distributed by the two steps of the machining operation. In Table 1, only the values corresponding to the second step – larger diameter drilling – are presented. This peculiar drill geometry clearly demonstrates the positive effect that is possible to attain when pre-drilling is involved, by a significant reduction of the thrust forces during hole machining. However, as it is showed in Figure 5c), the visual inspection of the drilled plate reveals that the hole quality is not the finest. The same occurred for holes drilled using the Dagger drill.

Table 1. Summary of the experimental results obtained.

Drill	Max. thrust force [N]	Delamination factor F_d	Adjusted delamination factor F_{da}
Twist	102	1.28	1.30
Brad	54	1.17	1.19
Bi-diametric	45	1.65	1.79
Dagger	65	1.22	1.57

Regarding thrust force, the worst result was found when twist drill was used. In fact, the value of the maximum thrust force almost doubles when compared with Brad drill. The value of maximum thrust force for Brad drill was 20% higher than the one of bi-diametric drill, which can explained by the clean cut enabled by this drill. Looking at the images associated, the hole obtained with this drill has the best look of the four.

In Table 2, the effect of a pilot hole in thrust force reduction can be analyzed. Not unexpectedly, there is a close link between the diameter of the pilot hole and the reduction of the thrust force during drilling. Thus, as predictable, greater diameters lead to larger reductions of the maximum thrust force for the final diameter drilling. However, this reduction cannot be seen as the only factor for the selection of a pilot hole diameter, as it has to be balanced to the delamination results.

Table 2. Summary of the experimental results obtained for pilot hole drilling.

Drill	Max. thrust force [N]	Damage Ratio D_{RAT}	Adjusted delamination factor F_{da}
No pilot hole	102	1.28	1.30
1.1 mm pilot hole	73	1.26	1.31
2.3 mm pilot hole	49	1.24	1.29
3.5 mm pilot hole	30	1.30	1.37

5.2. Hole and Delamination measurements

The comparison aimed in the experimental work concluded was the measurement of delamination caused by the drills, expressed with the help of Eq. 1 - delamination factor. The procedure of delamination measurement was described in section 4.5 and the results obtained indicated in Table 1. Looking at those results, it is clear that the best value (lower value) was achieved with Brad drill machining. In this case, bi-diametric drill has the worst result. This result indicates that the drill geometry has a strong effect on delamination that can be identified only after drilling. The images of the twist drills holes revealed a delamination factor only 9% higher than the one obtained with Brad drill. Delamination caused by Dagger drill was higher than the one caused by twist drill, and could be improved with secondary reaming. However, this operation is time consuming and leads to higher machining costs. On the other hand, the bi-diametric drill has a final result for delamination evaluation 40% higher that the Brad drill result. This bad result can be a consequence of the peculiar design adopted for this tool. Changes in this tool would be needed, like the profile of the diameter change section if it was intended to use this kind of drill for reinforced plastics.

It is possible to state at this point of our work that tool geometry influence on delamination onset has to be considered, together with force developed during drilling. That force is different for each tool geometry, under identical cutting parameters, 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 known analytical models. 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.

Other possible cause of these results is the lack of parameter optimization. A selection of cutting parameters for each different drill is needed in order to maximize the tool life together with a low amount of rejections due to delamination damage. It can be expected to find a set of cutting parameters that should be use for each geometry.

The effect of pilot hole in delamination is well evidenced in Table 2. A reduction in delamination was only achieved when using a pilot hole of 1.1 or 2.3 mm diameter. No advantage was found for the use of 3.5 mm pilot hole. This can be a consequence of the reduction of mechanical resistance of the plate that results from the pilot hole. Looking at Table 2, a pilot hole of 2.3 mm would be preferable.

6. Conclusions

Drilling of carbon/epoxy laminates using different cutting parameters and four drill geometries were accomplished for the purpose of experimental work here presented. The main aim of our work was to evaluate delamination, using techniques of image processing and analysis and a backpropagation artificial neural network that were integrated in a custom computational system. Delamination is usually considered the most frequent and harmful defect in drilling machining of composite parts. In order to compare and analyze the experimental results obtained regarding drill geometry, thrust forces during drilling were monitored and delamination measured with the help of enhanced radiography and the use of our computational system. As the plates were of the same thickness, the results of the maximum thrust force during drilling were only dependent on tool geometry. As the cutting parameters were always identical during the experimental work accomplished, it was possible to compare tool geometry influence successfully. Finally, a delamination criterion was used to obtain information on the best tool geometry. Based on the experimental work concluded it is possible to draw some main conclusions.

The selection of a tool 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 of selected diameter, like of 2.3 mm for a 6 mm final diameter, gave the best results regarding delamination reduction. In fact, we verified that the pilot hole cancels the chisel edge effect, reducing consequently the risk of delamination. Moreover, the use of Brad drills, due to its peculiar bit shape can give good results in terms of thrust force reduction and delamination minimization.

The damage around the hole, normally of type delamination between inner plies of the laminate, can be evaluated by a non-destructive test like using enhanced radiography. This method is only possible if parts are immersed in a contrasting fluid, which may not always be possible at workshop area.

The use of image processing and analysis techniques and the employ of an artificial neural network showed to be adequate to analyze the damage regions in the enhanced radiographies considered. These tools were integrated in a new computational system that made possible the identification and quantification of the damage areas caused by drilling, namely associated with the delamination process, as well as the hole area.

Additional advantages that can be observed when using the computational system developed are the easiness of use and its robustness to noise that are common presented in the analyzed images. Additionally, from the analysis of the experimental results obtained and considering the degree of significance usually adopted in this domain, we can also conclude that our computational system is efficient and accurate.

7. Acknowledgments

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