DRILLING DELAMINATION OUTCOMES ON GLASS AND SISAL REINFORCED PLASTICS

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Abstract. Nowadays, fibre reinforced plastics are used in a wide variety of applications. Apart from the most known reinforcement fibres, like glass or carbon, natural fibres can be seen as an economical alternative. However, some mistrust is yet limiting the use of such materials, being one of the main reasons the inconsistency normally found in their mechanical properties. It should be noticed that these materials are more used for their low density than for their high stiffness.

In this work, two different types of reinforced plates were compared: glass reinforced epoxy plate and sisal reinforced epoxy plate. For material characterization purposes, tensile and flexural tests were carried out. Main properties of both materials, like elastic modulus, tensile strength or flexural modulus, are presented and compared with reference values.

Afterwards, plates were drilled under two different feed rates: low and high, with two diverse tools: twist and brad type drill, while cutting speed was kept constant. Thrust forces during drilling were monitored. Then, delamination area around the hole was assessed by using digital images that were processed using a computational platform previously developed. Finally, drilled plates were mechanically tested for bearing and open-hole resistance. Results were compared and correlated with the measured delamination.

Conclusions contribute to the understanding of natural fibres reinforced plastics as a substitute to glass fibres reinforced plastics, helping on cost reductions without compromising reliability, as well as the consequence of delamination on mechanical resistance of this type of composites.

Introduction

The increased knowledge of their properties and the advances on its processing techniques have allowed an increasingly wide use of polymer matrix composite materials. Although the most common applications are related to the use of glass or carbon fibres as reinforcement material, the use of natural reinforcement fibres has deserved greater attention. One of the reinforcement materials whose interest has increased is sisal fibre. According to Silva [1] this interest in sisal fibres as reinforcement material emerged due to the increasing search for low-cost materials from renewable environmental friendly materials. The use of natural fibre composites is still limited to the mistrust on their properties. Recent studies [2-8] involving the addition of nano-particles in composite laminates, has shown an improvement of mechanical properties such as impact resistance, fracture toughness, tensile and flexural strength, elastic modulus, structural damping, decomposition and glass transition temperatures. The comparison of different types of composites, having in common the matrix material, allows the assessment of mechanical performance improvements obtained. The synthetic reinforcement material whose properties have minor differences to the composites reinforced with sisal is glass fibre.

Although composite parts are produced to near-net shape, finishing operations as drilling, to allow the assembly of parts, are usually required. It is accepted that these operations can be carried out with conventional tools and machining equipments with some adaptations. However, as a result of composites anisotropy, this operation can lead to different kind of damages. The most frequent and visible evidence of damage is the existence of a damage border around the machined hole, namely at the exit side of the drill. The most referred damages that can occur, in consequence of drilling operations are delamination, fiber pull-out and thermal damages [9]. From these damages, delamination is considered the most serious one as it can lead to a reduction of the mechanical properties of the laminate [10]. Thus, it is evident that minimization or even the elimination of this damage is of paramount importance to the industries associated to composite materials. However, this outcome has to be the result of increased knowledge of the damage mechanisms and control of the cutting conditions that lead to its onset and propagation. Focusing on delamination, two different mechanisms are normally referred to: peel-up and push-out. The first mechanism is a consequence of the drill entrance in the upper plies of the plate and can be avoided with the use of low feeds [11]. On the other hand, the second mechanism is a result of the indentation effect caused by the quasi-stationary drill chisel edge, acting over the uncut plies of the laminate. Then, the plies tend to be pushed away from the plate, causing the separation of two adjacent plies of the laminate [11]. Finally, if the thrust force exerted by the drill exceeds the interlaminar fracture toughness of the plies, delamination takes place [11]. The reduction of delamination has been the subject of several studies, see for example, [12-16]. The reduction of delamination can be achieved through the proper selection of machining conditions involving feed or cutting speed [13-14], the material and the tool geometry [15] as well as drilling parameters monitoring and control [16].

In this work, two materials for composite plates are compared for thrust force during drilling, delamination extension and mechanical properties of drilled plates, using two different drill geometries: twist and Brad, and two feed rates: low (0.05 mm/rev) and high (0.20 mm/rev). Thrust forces were monitored during drilling for thrust force data collection; delamination extension was carried out through digital scanner and enhanced digital radiography; mechanical testing was performed in order to evaluate mechanical strength loss due to hole machining. Finally, the consequences of hole drilling in these two types of composite plates are discussed.

Materials and Methods

Glass/epoxy plates. Composite plates with glass fibre reinforcement were obtained by manual lay-up combining symmetrical tissue and mat. In order to have a final thickness of 2.5 mm, 7 plies were stacked according to Figure 1. Laminate was cured at room temperature until a Barcol hardness of 40 was reached.

Tissue	← Symmetry axis
Mat	
Tissue	
Mat	
Tissue	
Mat	
Tissue	

Figure 1 – Stacking sequence adopted for the glass/epoxy plates.

From these plates, coupons for drilling and mechanical tests were cut. Dimensions of coupons were according to ASTM D 5766M-07 - Open Hole Tensile Strength Test [17] and ASTM D 5961M-01 - Bearing Test [18].

Sisal/epoxy plates. For these plates, the fabrication method was also hand lay-up. Sisal fibres were used as received from SisalSul (São Paulo, Brazil). In order to ensure fibre alignment a special accessory was used. Laminate cure was at room temperature for 24h and then the plates were cut in the same dimensions as those used for glass/epoxy plates.

Final properties of both plates are presented in Table 1.

PROPERTY	GLASS/EPOXY	SISAL/EPOXY
Specific weight (g/cm^3)	1.70	1.14
Tensile strength (MPa)	223.0	156.9
Elastic Modulus (GPa)	11.8	5.7
Flexural strengthss (MPa)	176.0	62.5
Flexural modulus (GPa)	4.1	2.3

Table 1 – Mechanical properties of glass/epoxy and sisal epoxy plates.

Plate drilling. Drilling operation was carried out in a 3.7 kW *DENFORD Triac Centre* CNC machine. During drilling, axial thrust forces were monitored with a *Kistler 9257B* dynamometer associated to an amplifier and a computer for data collection. The composite laminate was fixed on the machine using an appropriate clamping device. No sacrificial plates were used.

Considering the purpose of this work, two different 6 mm tungsten carbide drills were used: twist drill and 'Brad' drill, Figure 2.

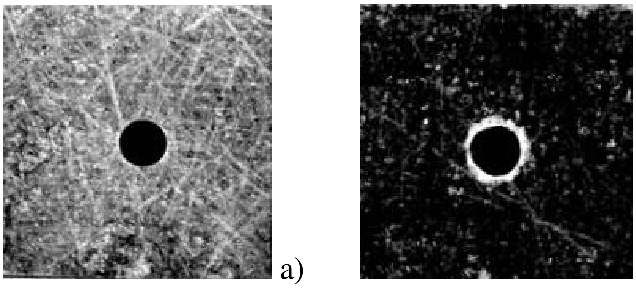
a) b)

Figure 2 – Drills: a) twist; b) Brad.

Twist drill is a standard drill commonly used in workshops. 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. Cutting parameters were selected in accordance with past experience [13, 14, 19]. Spindle speed was set to 2800 rpm for all tryouts, and two feeds, low and high, were used. Low and high feeds were set to 0.05 mm/rev and 0.20 mm/rev, respectively.

Damage extension assessment. After machining completion, it was necessary to evaluate the delaminated region around the drilled hole by using digital images. With this purpose, two different methods were used for further comparison: digitalization of the plate in a table scanner connected to a PC, and enhanced digital radiography.

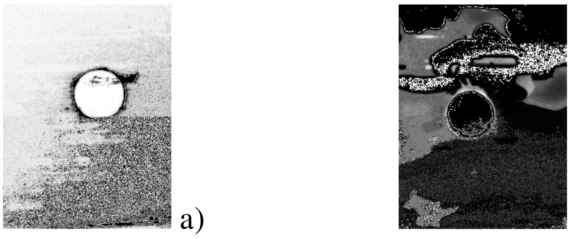
For the first method, grayscale images of the tool exit side of the plate were acquired. These images needed posterior processing in order to improve contrast and help on the separation of delaminated areas. The delaminated region corresponds to a circular area around the drilled hole, as shown in Figure 3.



a) b)

Figure 3 – Original scanner image a) and after contrast enhancement b).

For the second process, plates were prior immersed in di-iodomethane for contrast: ten minutes for glass/epoxy plates and fifteen seconds for sisal/epoxy plates, due to their hygroscopic nature. Then the radiography images were acquired using a 60 kV, 300 kHz Kodak 2100 X-Ray system associated with a Kodak RVG 5100 digital acquisition system. Figure 4a) shows an image obtained. Digital radiographies were processed by using a computational platform in order to obtain the segmentation and characterization of the interest regions [19]. From the measurement procedure, the values of the damaged area, according to the delamination factor criterion proposed by Chen [20] that is defined as the ratio of the maximum delaminated diameter to the nominal hole diameter, were obtained. Figure 4 shows an example image of a sisal/epoxy plate with correct immersion time (Figure 4a) and an extended immersion time (Figure 4b).



a) b)

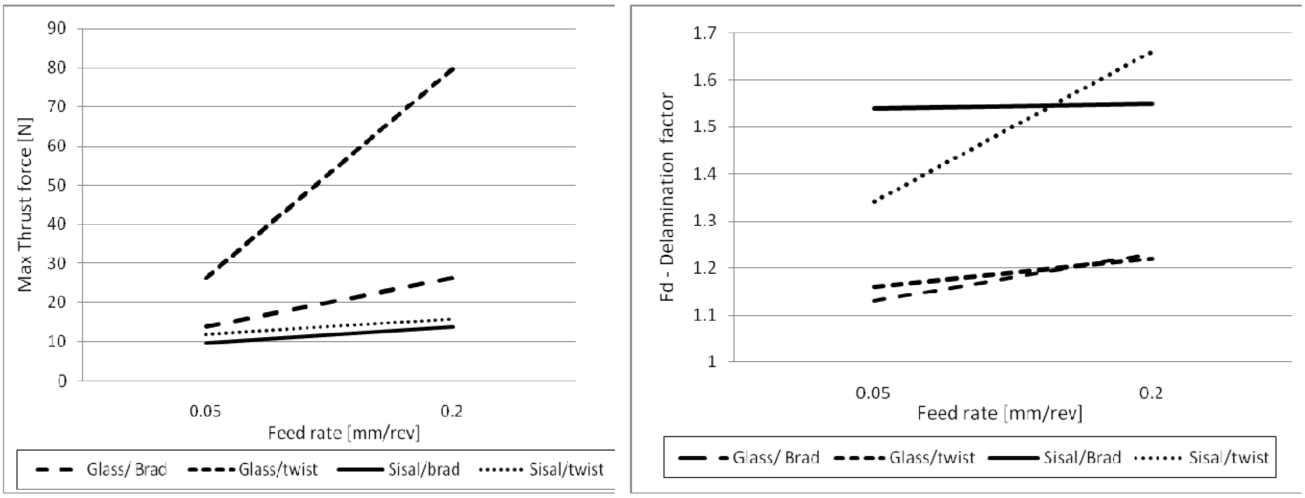
Figure 4 – Sisal/epoxy plate radiography image after an adequate immersion time a) and after a long immersion time b).

Mechanical Testing. The mechanical tests carried out were the Open-hole tensile strength test, ASTM D5766M-07 [17], and the Bearing test, ASTM D5961M-08 [18]. These tests were considered with the purpose of assessing the effect of delamination on the mechanical properties of the drilled plates. For that, test coupons of 250x36 mm^2 and 135x36 mm^2 were cut and drilled under the same experimental conditions previously described. The tests were performed in a *Shimadzu AG-X/100 kN Universal Testing* machine equipped with the necessary accessories to run the different tests and connected to a computer for machine control and data acquisition and processing.

Results and discussion.

Thrust forces during drilling. Results considered for thrust force are the maximum value observed during drilling. As the delamination onset largely depends on thrust force during drilling, higher thrust forces normally correspond to higher delamination, everything else remaining constant. Due to signal variation along drill rotation, thrust force values were averaged over one spindle revolution. Additionally, to reduce the influence of outlier values, the results considered were the average of four experiments under identical conditions.

Independently of the drill geometry or plate material, the thrust force was always superior with increased feed rates, Figure 5. This was an expected outcome and it confirms previous works [13, 14]. However, the variation due to feed increase was more evident for twist drill. Thrust force analysis shows that Brad drills are more recommendable for the drilling of these plates, under the experimental conditions described. Thrust forces in sisal/epoxy plates drilling were always lower. This can be attributed to the reduced mechanical resistance of these plates, when compared to glass/epoxy plates (Table 1).

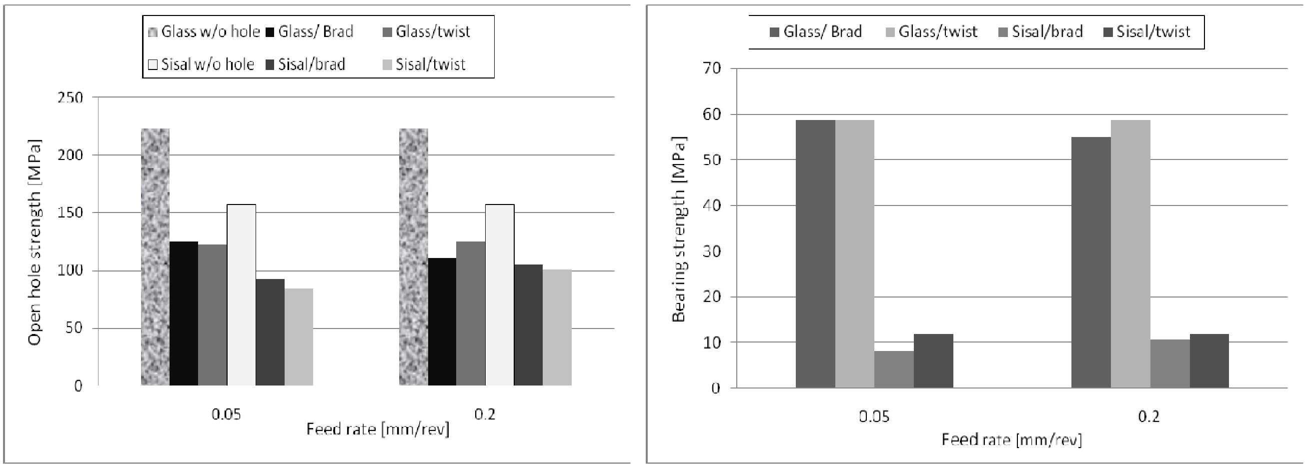


a) b)

Figure 5 – Effect of feed rate on: thrust force a) and delamination ratio b).

Delamination extension. Delamination extension was measured according to both procedures already described. Due to the bad quality of sisal images obtained by scanner process, the results from this method are only presented for glass/epoxy plates. As expected, for large feed rate, delamination is more extended, Figure 5b). This outcome stresses the general idea that low feed rates should be used when drilling composite laminates. Another result to be noted is the variation due to feed rate, more evident for twist drill in sisal/epoxy plates and for Brad drill in glass/epoxy plates. This can give an indication on the choice of drill geometry according to the type of composite plate to be drilled. In addition, it is possible to say that delamination at sisal/epoxy plates is always higher, due to their lower mechanical resistance.

Mechanical test results. Results from the two mechanical tests used to evaluate mechanical properties after drilling are presented in Figure 6. From the results, it is not clear that a correlation between cutting parameters or delamination extension with tensile strength or bearing strength can be established. However, it is possible to draw some conclusions. The results seem to be more dependent on the material properties than on the drilling conditions. A blunt effect appears to exist, decreasing residual stresses around the hole, thus increasing open-hole tensile strength for higher feed rate plates. Sisal/epoxy plates are not very reliable for screw or bolt connections as it is revealed by the low bearing test results. It should be noted that this can also be the consequence of the stacking sequence of sisal/epoxy plates, as the fibre orientation is unidirectional. Future tests with cross-ply plates should study this assumption.



a) b)

Figure 6 – Mechanical test results: open-hole tensile strength test a) and bearing test b).

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Summary

A comparison of glass/epoxy and sisal/epoxy plates mechanical performance after drilling was presented. Experimental work included thrust force monitoring during drilling and measurement of delamination extension and mechanical testing after drilling. Based on the experimental work and conditions presented, some conclusions can be drawn:

- maximum thrust force and delamination extension depend on drilling conditions, tool geometry and material;
- for higher feed rates, thrust force and delamination extension are superior;
- mechanical test results are more dependent of material nature than on drilling conditions;
- sisal/epoxy unidirectional plates are not well suited for screw or bolt connections;
- the result needs to be further confirmed by testing cross-ply or mat sisal/epoxy plates.

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