DRILLING OF BIOCOMPOSITE MATERIALS: MODELLING AND EXPERIMENTAL VALIDATION

*A. Díaz-Álvarez[1], J. Díaz-Álvarez[1], N. Feito[2], C. Santiuste[3]**

1 Department of Mechanical Engineering, University Carlos III of Madrid, Avda de la Universidad 30, 28911, Leganés, Madrid, Spain

2 Centre of Research in Mechanical Engineering – CIIM, Department of Mechanical and Materials Engineering, Universitat Politècnica de València, Camino de Vera, s/n, 46022, Valencia, Spain

3 Department of Continuum Mechanics and Structural Analysis, Universidad Carlos III de Madrid, Avda de la Universidad 30, 28911, Leganés, Spain

*Corresponding author: Phone +34916249156, andiaza@ing.uc3m.es

Abstract

Induced damage during biocomposites drilling is significantly different to that produced on

composites based on synthetic reinforcement such as carbon or glass fibers. In composites reinforced with carbon or glass fibers, induced damage increases with feed rate, however damage was observed to decrease with feed rate in biocomposites reinforced with natural fibers. This work is focused on the explanation of this differences between biocomposites and traditional composites based on the effect of strain rate on the material behavior during machining. A FEM model has been developed in ABAQUS/Explicit to verify this hypothesis. This numerical model has been used to explain the differences found between traditional composites and biocomposites in the influence of the main drilling parameters on induced damage during drilling. Experimental tests were conducted to validate the model through the comparison between thrust forces and damage factor for two different drills geometries on Flax/PLA bio composites. The results indicate that the decrease of induced damage with feed rate is only predicted when the constitutive model accounts for experimental behavior observed in this type of composites. Additionally, the numerical model demonstrated the ability to reproduce the effect of the different cutting conditions (cutting speed, feed, thickness and drill geometry) observed during experimental tests on induced damage during drilling.

Keywords: Biocomposite; Drilling; Numerical modeling; Natural fibers

1. INTRODUCTION

The final stages of composite manufacturing process commonly require drilling operations prior to mechanical joining of different components [1]. Overall industry, composites are well known as one of the most challenging materials during machining due to the trend to experience machining induced damage [2–5] and also tool wear during drilling [6]. Delamination has been reported as the main damage mode presented during the machining of composite materials [7]. Delamination is an inter-ply failure phenomenon induced by drilling, which is a highly undesirable problem and has been recognized because not only reduces drastically assembly tolerance and bearing strength, but also has the potential for long term performance deterioration under fatigue loads [8,9].

Researchers have reported that the extension of delamination is, in first place, related with the cutting parameters which was investigated by many researchers [10–13]. In general, increasing feed rate resulted in higher compressive forces and higher hole surface quality could be obtained because of increased cutting speed and reduced feed rate [10,14].

In second place, the drill geometry has a significant impact on the quality of drilled holes. Parameters as point angle, helix angle, cutting edge radius, chisel edge, rake angle, etc. were analyzed deeply in the literature [7,15]. General recommendations to avoid increase the damage around holes are to use sharp point angles around 90° [6,16], define the rake angle as positive as possible to increase the thrust-fracture effect rather than the compressive-bending effect on the fibers [17] and use a cutting edge radius as small as possible to avoid the bending-dominated fiber fracture mode [18]. Related with the different drillings tool available in the market, dagger drills were chosen as a good solution for drilling small diameter holes, while brad & spur drills were the best option to minimizing defects at the exit of the holes in CFRPs [19,20].

Finally, the wear progression in the drill influences the delaminación damage as has been reported by several authors. [21–23]. It was observed that increasing tool wear results in cutting force components of higher values, and consequently the damaged area [24]. It was stated that abrasion is the main wear mechanism when machining CFRP composites, and they also noted that flank face is the main wear type impacting the primary cutting edge of the tool and the cutting edge rounding the main wear type impacting the secondary cutting edge [23,25,26]. Both wears made changes in the geometry, which increases the damaged area. Other researchers observed that a higher number of holes results in an increase in the cutting-edge radius, which causes the bending of fibre reinforcements instead of crushing them [27–29].

Composites based on natural fibers are promising materials that can replace composites based on carbon or glass reinforcement in some applications [7,8]. Early research deals with the study of composites materials developed by means of natural fibers as reinforcement and synthetic matrix (polyethylene, epoxy, or polypropylene) [9,10]. However, recent studies analyze composites based on natural fibers and biodegradable matrix (polysaccharides, lignin, proteins, etc..), obtaining 100% biodegradable composites [11–13]. 100% biodegradable materials are progressively replacing the non-degradable ones, being used in diverse and different products [14,15], by means of their promising properties and sustainability: low density vs strength, cheap raw materials for its manufacturing and few energy consumption for its development (4 GJ/ton) in comparison to for instance glass fiber (30 GJ/ton) [16]. Natural fibers are easily accessible, and even the surplus material from the farms can be used as a reinforcement element [17,18]. Therefore, biodegradable composites compared to non-degradable materials are a true alternative [19].

Only few works have deal with the drilling of biocomposites (see [3,11]) while it is possible to find several works analyzing the drilling of hybrid composite materials manufactured by means of natural fibers and synthetic matrix [9,20–22]. Main contributions of different researches have been highlighted below:

Sidharan and Muthukrishnan [9] analyzed the drilling of a hybrid composite with sisal (untreated and alkali treated) as fibers and polyester as matrix with a HSS helical drill (118° and 6 mm of point angle and diameter respectively). Delamination was observed as the main damage mode during the machining of the hybrid composite, which increased with increments in both the feed and the cutting speed. Moreover, they studied the relationship between the damage generation and the chemical treatment of the composites, concluding that the treated composites showed a higher decrease at the push out delamination rather than the one obtained for the peel up when it was compared with no treated composites, being in general the influence of the treatment over the delamination almost negligible.

Bajpai et al. [11] analyzed the drilling operation on a biocomposite manufactured with sisal as reinforcement and PLA as matrix. Composite plates were machined using three different drill geometries (Jo, twist, parabolic), obtaining for increments in the cutting speed a decrease in the damage mode (mainly delamination), and a contrary effect with feed rate increments. They observed that for getting free damage holes both the drill geometry and the feed are the most influential cutting parameters for the drilling of fully biodegradable materials. They concluded that the optimum drill geometry and cutting parameters for biocomposite materials are not the same as for the non-biodegradable composites mainly due to both their difference mechanical behavior and the phenomena that involve the composite machining.

Abilash et al. [20] drilled bamboo/polyester composites finding the feed rate as one of the most relevant condition together with the drill diameter and cutting speed which showed minor influence on the delamination generation. Moreover, they developed a model through regression modelling that let them to analyse the delamination for a certain range of both cutting speed and feed rate during the drilling of composites developed with bamboo as reinforcement and polyester as matrix, getting values of cutting speed and feed of 6.3 m/min and 0.04 mm/rev respectively for a delamination parameter of 1.073 (push out).

Ramesh et al. [21] drilled sisal-glass fiber reinforced polymer determining fiber breakage as the main defect. The increment of the feed rate together with the use of solid carbide (SC) drills caused the increment in damage extension during machining. They found increments on the thrust forces while the feed rate increases for all cutting combinations, being the maximum value that obtained for the HSS drill. Moreover, the maximum delamination was obtained with HSS drill bit, not being recommended for drilling S-GFRP hybrid composites.

Nasir et al. [22] drilled an hybrid composite developed with flax as reinforcement and epoxy as matrix, finding increments in the damage generated with the feed rate, and, on the contrary, a decrease on it by the influence of the cutting speed. They used Taguchi and ANOVA to evaluate the residual tensile strength and the delamination generated by means of the influence of the main drilling parameters during the drilling of flax/epoxy samples. They obtained higher delamination at the peel up than at the push out for thehybrid composite analyzed, which was unexpected. The best value of delamination factor (1.07) was obtained at the exit for the Step drill geometry at 150.8 m/min and 0.16 mm/rev of cutting speed and feed rate respectively.

Díaz-Álvarez et al. [3] drilled different biocomposites manufactured with natural fibers as reinforcement (flax, jute or cotton) and a natural matrix of polylactic acid (PLA), testing both helical and customized (specially aimed for drilling natural fibers) drill geometries with 6 mm diameter. They found a decrease in the Fraying extension with increments of both cutting speed and feed rate, demonstrating that the point angle of the drill is a key parameter in the damage generation: thus, the smaller the drill point angle, the less the damage extension. They concluded that in terms of damage generated during drilling, the best response of all biocomposites analyzed was the one obtained for cotton and flax fibers (being those fibers the ones with less tensile strength).

Despite the propensity of variation in properties of the natural fibers, which leads to inconsistency and variation of composite response, some general trends are like those found in synthetic fiber composites. However, the influence of feed rate found in [3] is significantly different: it was demonstrated in most studies in the literature related to machining of composites that the increment in feed during drilling results in enhanced induced damage on carbon fiber reinforced polymers (CFRPs) [6,23] and composites reinforced with aramid fibers [24]. However, in the drilling of fully biodegradable composites, a contrary tendency from that found for synthetic materials has been observed, according to which, a decrease in the damage generated has been caused by increments on the feed rate. This trend is mainly based on the different modes of failure, being delamination the most common damage mode identified by other authors, while fraying was found as the main damage mode in Díaz-Álvarez et al. [3]. This phenomenon can be explained through the viscoelastoplastic behavior of the materials reinforced with natural fibers [25]. The main goal of the present paper is analyzing this effect using a methodology based on numerical modeling of the mechanisms governing this phenomenon.

Finite elements (FE) modeling has been successfully applied to model machining processes of synthetic fiber composites in order to obtain a better understanding upon the damage generation process, for instance CFRPs [26].

Simple 2D simulations [27,28], typically analyze different cutting conditions or material features such as fiber orientation in different composites. However due to the complexity of the drilling operations sorted by current industry, the 3D simulations are required for proper simulation of the removal process [29]. 3D simulations are more complex and time consuming [30], however, 2D simulations are unable to model the damage mechanisms at the out-of-plane [31]. Early works developed simplified 3D simulations based on the approximation of the drill to a punch [32,33]. The main objective of these studies was to establish a relationship between the thrust force and the damage mode present during the machining of CFRP. Moreover, these studies also attempted to analyze the damage found during the process due to the drill point angle. The simulation of chip removal requires 3D simulation modelling the entrance of the drill bit in the composite and damage [34,35]. The simulation of the drilling operation involves a complex process in which the rotation and entrance of the tool in the composite and the consequent damage and erosion generated are involved [36].

Concerning biocomposites, numerical simulations have been focused on establishing certain mechanical properties [25,37,38]. It should be noted that no publications including numerical simulation of drilling processes on 100% biodegradable composites have been found up to date. Thus, taking into account the lack of researches that exist in relation to the experimental analysis of drilling of biodegradable materials, the study of Fraying as a predominant mode of damage during its processing, as well as the non-existence of numerical drilling models that reproduce its phenomenology, a deeper discussion of this topic is necessary.

The analysis of drilling is important for industrial implementation of 100% biodegradable composites since one of the drawbacks of this family of materials is the difficulty in postprocessing and joining between components. This work focuses on the development and validation of a new 3D FE model for the drilling of 100% biodegradable composites, which, does not exist up to date in the literature. Moreover, this 3D FE model allows to simulate the chip formation reproducing the drill bit entrance in the composite. The aim is analyzing the cutting conditions effect and explaining the influence of feed rate on damage extension. In this model, two different drill geometries, different thicknesses of biodegradable composite (2, 3 and 4 layers) and different cutting parameters are studied, obtaining the thrust forces and the damage factor for each case. Predictions of the model were accurate when compared to experimental results, proving its ability to simulate drilling of biocomposites. Moreover, the developed model is able to explain the trend observed experimentally during the drilling of 100% biodegradable composites, showing the decrease in damage when feed rate is increased and reproducing the viscoelastoplastic behavior of composites reinforced with natural fibers through a constitutive model.

2. MATERIALS AND METHODS

This section focuses on the materials and methods used during experimental work. The characteristics of the 100% biodegradable composites are firstly presented, followed by the description of machining devices and tools used during drilling tests.

2.1. Workpiece material

Specimens of biocomposites were developed through the compression molding method. Within natural fibers, flax has been one of the most used throughout the world since its discovery [39] and nowadays flax fiber is being widely used in the industry to obtain new composite materials [17]. Therefore, basket weave (2 × 1) flax (BF) with 463.3 g/m^2 and 0.94 mm of areal density and thickness, without chemical treatment were used as reinforcement (Figure 1), which was cut into 150 mm x 150 mm plates.

Figure 1. Basket weave (2 x 1) flax (BF) used for manufacture biocomposite specimens through compression molding.

Before its use for manufacturing biodegradable composite materials, woven flax was tested under uniaxial traction on an Instron 8516 universal test machine for obtaining its main mechanical properties (see Table 1).

Table 1. Tensile strength for the manufactured biocomposite [16].

Material	***Tensile strength (MPa)***	***Young Modulus (GPa)***
Basket Weave Flax	271.62	7.84
PLA	54.27	3.18

A thermoplastic resin of PLA was used as matrix in the manufacturing of the biocomposites. The PLA thermoplastic resin used was 10361D (from NatureWorks), which is specifically aimed as a binder for the manufacture of composites from natural fibers. 10361D resin exhibit a 1.24 g/cm^3 density and a melting temperature that range from 145 to 170°C.

Different stages involve the compression molding method, which begin with obtaining PLA films (previously hold at 95°C during 30 minutes in order to dry off it) by means of maintaining it placed between heated plates at 185°C for 3 minutes. The final measures of the layers obtained were 160 × 200 mm^2. Subsequently, PLA layers were alternatively heaped with the flax plies (all plies oriented in the same direction) and introduced in the heated plates at 185°C for 2 minutes. Afterwards, 16 MPa has been applied during 3 minutes by means of the Instron 8516 machine at the pre-heating stage. At the end, the specimens of biodegradable composite materials were kept at ambient temperature (Figure 2).

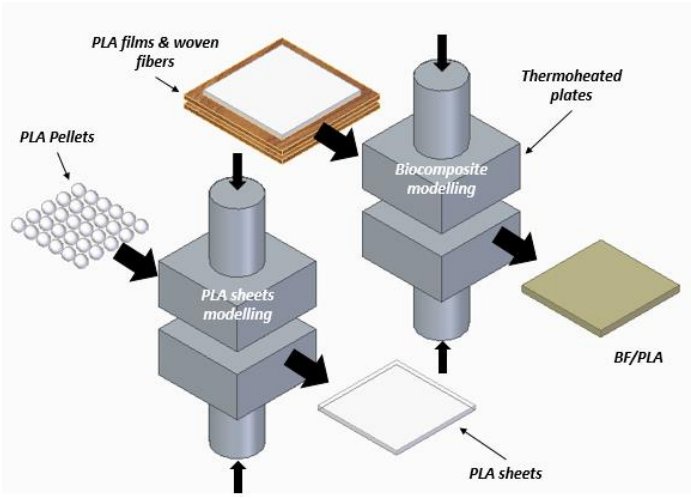

Figure 2. Scheme of the manufacturing process to obtain the biocomposite from natural fibers woven plies and PLA in pellets.

The fraction of fiber volume for the natural fibers was 58.6%, being quantified the weight ratio by means of different PLA films, according to ASTM D2584. Mechanical properties obtained in tensile tests according to ASTM D3039 using an Instron 8516 are summarized in Table 2. These properties were found in warp direction using 8 specimens, the maximum strain was 1.2% and the strain rate was fixed at $2.08 \cdot 10^{-4}$ s^{-1}.

Table 2. Tensile strength for the manufactured biocomposite [12].

Material	*Tensile strength (MPa)*	*Standard deviation (MPa)*	*Elastic modulus (GPa)*	*Ultimate strain*	*No. of plies*
BF/PLA	104.0	4.71	7.84	0.069	4

Samples have been manufactured in different thickness of two, three and four plays, being cut in 120 mm x 30 mm format. Further information regarding the development of the biodegradables composites and it main mechanical properties could be seen in [12].

2.2. Drilling test

The drilling process were developed in a B500 KONDIA machining center. During each tests the thrust force and also the torque have been quantified by means of a rotary dynamometer (Kistler 9123C), with a range of -2 to 2 kN for F_z; a range of −20 to 20 Nm for M_z and a sensitivity of ≈0.5 mV/N for F_z. To minimize the damaging effects that the fibers may cause on the operator health during the machining, a confining device connected to a vacuum was installed, allowing air entrance and the fibers removal and evacuation to the vacuum storage (Figure 3.a)). The confining device consists of a main body of 100 × 80 × 52 mm^3 to hold two plates inside, being fixed the lower one, and allowing the material to be held while drilling. These plates allow the free delamination of the material by having a 10 mm diameter counterbored hole in the case that the drill used was 6 mm of diameter.

The cutting conditions (cutting velocity 15–25 m/min and feed 0.03–0.12 mm/rev) has been chosen by taking into account the advice of drill industry for similar composite families. The drilling tests were developed at three values of cutting speed (15, 20 and 25 m/min) and feed rate (0.03, 0.06 and 0.12 mm/rev) without coolant. Two different twist drill drill geometries based on high speed steel (HSS) were used with the aim of study the effect of the drill geometry: Drill-A a helical drill with a 118° point angle, and Drill-B with a point angle of 80° (see Figure 3. b) and c)). Moreover, small values of tip angles are commonly recommended for drilling CFRP avoiding machined induced damage (Feito et al. [6])

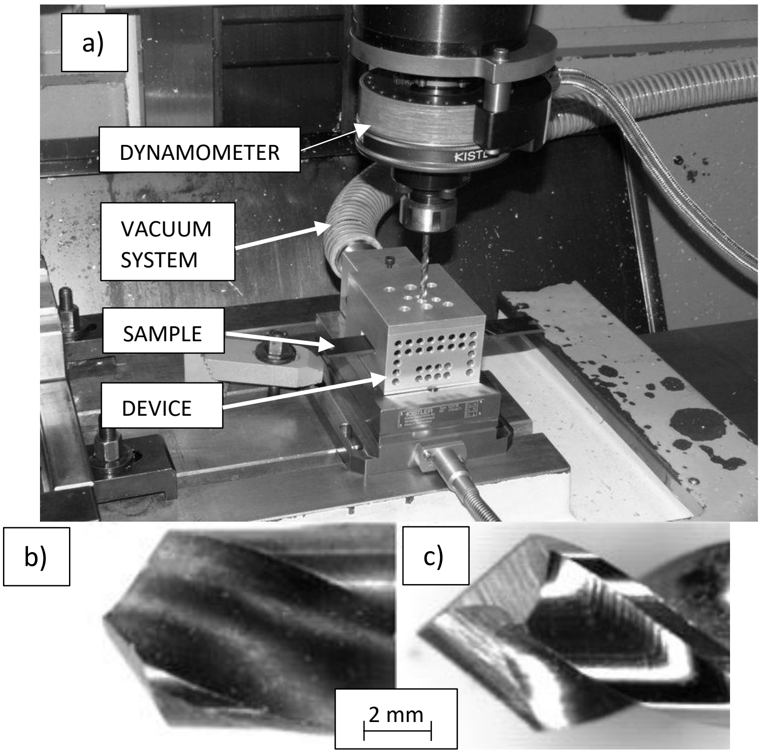

Figure 3. a) Configuration used in the machining center B500 Kondia to carry out drilling tests; b) Drill-A. HSS drill (118°); c) Drill-B: Custom HSS drill (80°) [2].

The damage extension generated in the material during drilling was assessed by means of the damage factor (F_d), which is defined as the relationship between the diameter that involves the maximum damage area (D_{max}) (including all fiber breakage, as there is an absence of delamination) and the nominal drill diameter (D) (Figure 4) [6].

Therefore, the damage extension has been quantified through the analysis of the images taken both at the entry and exit of the drill through the composite material. For the images capture, an Optika SZR microscope has been used. More details regarding the experimental analysis of machining induced damage in biocomposites can be seen in [3].

During the experimental tests, no visual changes were observed due to the effect of the temperature on the biocomposite, special attention was taken when the Drill-A was used, since it is the tool with the largest point angle. Larger point angle means that larger areas of the tool and workpiece are exposed to heat generation due to the friction phenom between tool and workpiece, also less areas of the tool may dissipate the heat generated, hence larger tool temperatures were expected in Drill-A that could have affected the integrity of the workpiece. Moreover, images of the cross section of the hole taken with energy-dispersive X-ray spectroscopy [3] has been used to analyzed the biocomposite, where it can be observed that there is no evidence of burns or delaminations in fiber, matrix or plies. Thus, its influence on the numerical model will not be taken into account.

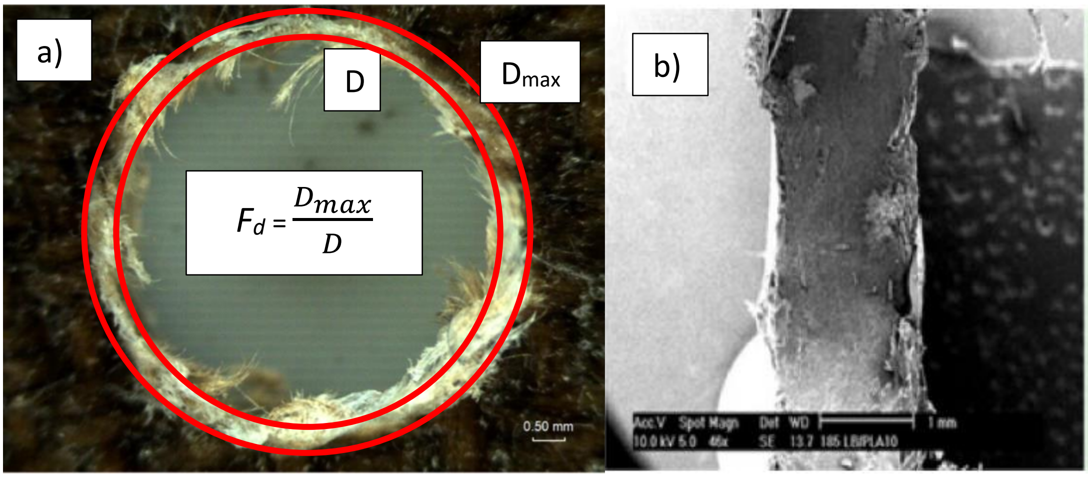

Figure 4. a) Damage factor (F_d) calculation for two-layer flax biocomposite drilled with Drill – A at 20 m/min and 0.06 mm/rev (push out). b) Scanning electron microscopy-energy-dispersive X-ray spectroscopy image of the transversal section of the drilled hole (two layers), drilled with Drill-A at a cutting speed 20 m/min and feed rates 0.12 mm/rev [3].

3. RESULTS AND DISCUSSION

The numerical work carried out to model the drilling process of biocomposites is described. Firstly, constitutive model of the composite is presented, following with the description of meshing, boundary conditions and analysis procedure.

3.1. Constitutive model for biocomposite

The constitutive model reproducing the mechanical behavior of the workpiece material explains both the mechanical behavior and the strain rate result on the biodegradable composite through a rheological model. The constitutive model used was developed in a previous research where the effect of the strain rate and the isotropic behavior has been taken into account by means of experimental tests. The model, based on rheological elements (based on the use of elastic, plastic, and viscous elements) takes into consideration the non-linear elastic behavior, viscous effects and plastics strains, being validates in the previous study [25] for three different biocomposites: flax/PLA, jute/PLA and cotton/PLA woven laminates. The constitutive model was defined with three branches in parallel, in the first branch a Yeoh model was used to define the non-linear elastic behavior of the material, in the second branch, Maxwell model was used to define the viscous behavior of the material and in the last branch, the plasticity was defined by a frictional analogy to the Maxwell model [25].

The stress-strain values resulted in the experimental tests at strain rates from $2.08{\cdot}10^{-4}$ to $8.33{\cdot}10^{-3}$ s^{-1} are shown in Figure 5.a), significant influence of the strain rate is observed. When the strain rate increases, both stiffness and resistance increase, whereas the ultimate strain suffers the opposite trend. Moreover, the mechanical behavior can be described as clearly non-linear. The increase of stiffness with strain rate can be explained by the friction forces generated by the relative displacements between adjacent yarns. This friction forces can also explain the increment in strength. On the other hand, the decreases in ultimate strain is a consequence of the increasing stiffness because the maximum stress is reached for lower values of strain. In

Figure 5.b) and c) the predictions of the model for the strain rates of $2.08{\cdot}10^{-3}$ to $8.33{\cdot}10^{-3}$ s^{-1} can be observed, being the $2.08{\cdot}10^{-4}$ rate used for the calibration.

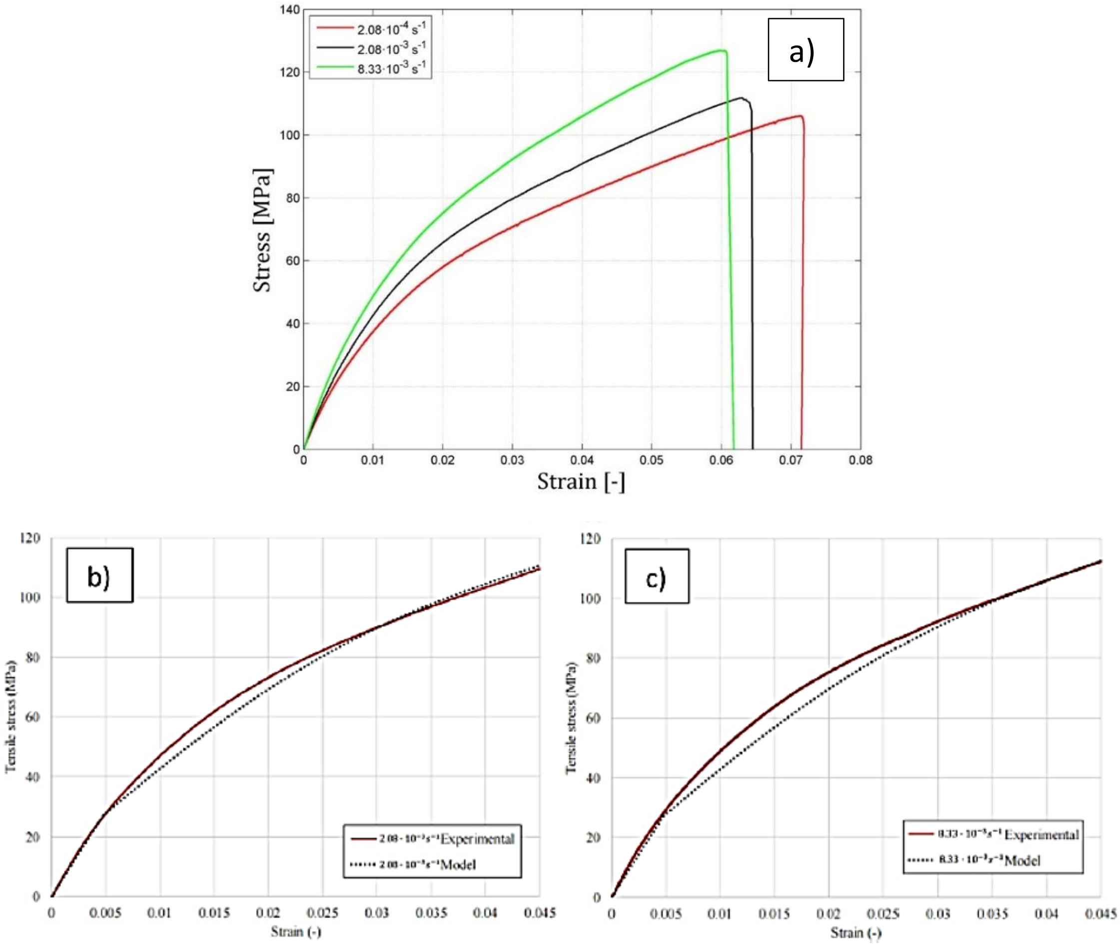

Figure 5. Tensile stress-strain curves obtained experimentally under different strain rates: $2.08{\cdot}10^{-4}$ s^{-1}, $2.08{\cdot}10^{-3}$ s^{-1} and $8.33{\cdot}10^{-3}$ s^{-1} [30].

Once the yield stress is reached, the plastic response of the biocomposite was established through the strain rate by follows the specific stress-strain curve. An interpolation has been performed for intermediate strain rates values not available from experiments. Strain rate has been used also to stablish the yield stress, being for example, 23 MPa for a strain rate value of $2.08{\cdot}10^{-4}$ s^{-1}.

A VUSDFLD subroutine for ABAQUS/Explicit has been implemented with the aim of simulating chip removal, allowing elements erosion when the failure criterion is reached. Failure strain criterion is established, once ultimate strain is reached in the element, it is eroded.

The ultimate strain was established by means of the strain rate. The process carried out by the subroutine begins with the evaluation of the strain rate, to subsequently quantified the ultimate strain. Once the ultimate strain has been calculated, it is compared with the strain values in the three coordinates. Thus, if higher values have been obtained when it is compared to the threshold the element is eroded. The calculation procedure is illustrated in the flow chart in Figure 6.

As it was commented previously, fraying was the main damage mechanism observed in this family of materials due to fiber breakage. Thus, there is no delamination damage when specimens are analyzed, in comparison to synthetic composites where it is reported as the main damage found. This phenomenon can be observed by means of images of the cross section of the hole taken with energy-dispersive X-ray spectroscopy [3], where there is no failure between plays at both entry and exit of the drill through the Flax/PLA composite. Thus, cohesive elements commonly used to simulate debonding between plies has not been included in the model.

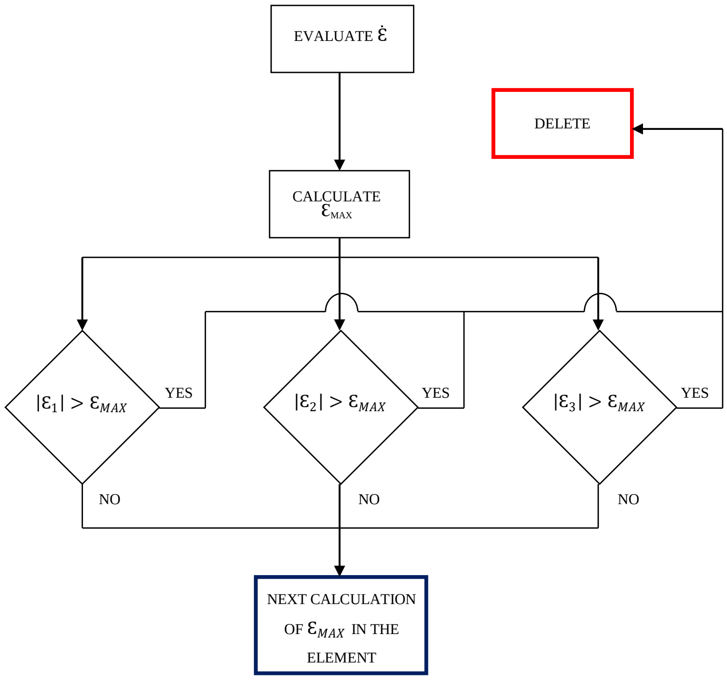

Figure 6. Flow diagram representing the process carried out by the subroutine during for element removal.

As it was commented previously, fraying was the main damage mechanism observed in this family of materials due to fiber breakage. Although delamination is the dominant damage mode observed in conventional fiber composites, in the case of the samples analyzed in this work, there is no evidence of this phenomenon. The absence of delamination can be seen by means of energy-dispersive X-ray spectroscopy image of the transversal section of the drilled hole [2], where it can be observed that there is no evidence of breakage between layers either at the entrance or at the exit of the drill along the thickness of the biocomposites. Thus, cohesive elements commonly used to simulate debonding between plies has not been included in the model.

3.2. Drilling Model

The numerical model reproduces the experimental drilling tests for the composite based on flax and PLA 10 (10361D).

The simulations were developed by means of a FEM code ABAQUS/Explicit. A 3D model was carried out to simulate the complete drill movement, including both the cutting velocity and feed rate simulating drill penetration and chip removal. The diameter of the workpiece modelled is 10 mm, corresponding to the free surface in experiments thus reproducing the effect of the supporting plate of the confining device. The outside surface of the sample has been fixed to simulate the effect of the drilling tool implemented during the development of the experimental tests, which leaves a free surface of 10 mm in diameter. The free surface of 10 mm has been established through the execution of successive experimental drilling tests on biodegradable composite material without clamping it, stating that the damage derived from machining did not exceed this value (10 mm).

Different thicknesses of the work piece were modelled: 1.4 mm, 2.14 mm and 2.68 mm corresponding to 2, 3 and 4 layers respectively. Both different drill geometries used in experiments were modeled: helical drills of 118° (Drill-A) and 80° (Drill-B) point angle respectively. Figure 7 shows a scheme of the models developed.

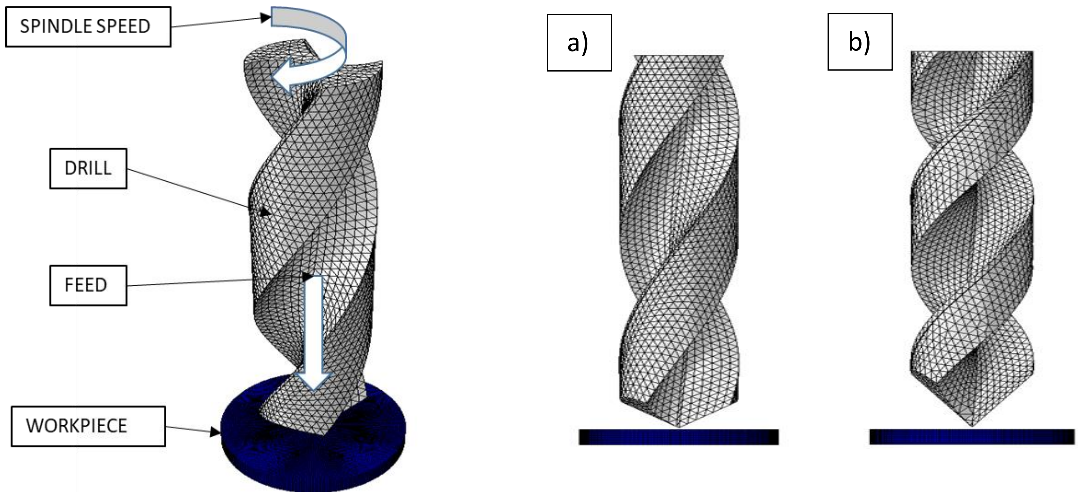

Figure 7. Scheme of the complete model: Drills in the initial position: a) 118° y b) 80°

An interaction contact has been stablished between the drill and the workpiece nodes, in order to simulate the interaction between the drill face and the sample after removing the first layer of material. The contact was based on kinematic contact formulation [40].

The optimal size of the element has been analyzed by means of different grid tests, giving a compromise between the accuracy of the results and the computational cost, was about 120 µm (element type CRD8R; Hexagonal). In order to reduce the results dependence with the mesh direction in the layer plane and adapts more easily to curved geometries, hexagonal elements have been used. The selected element size for the plate for the different thickness led to different number of elements in the model: 2 layers (72320 elements), 3 layers (108480 elements) and 4 layers (144640 elements). The drill has been imported to ABAQUS and assumed to behave rigid with a rough mesh (about 500 µm R3D3; Triangular)

3.3. Model validation

The numerical model has been developed by means of both thrust forces and damage extension comparison with the values obtained experimentally. In order to analyze the capability of the model to reproduce the effect of the main machining conditions (cutting velocity, feed rate, thickness, and drill geometry) seven different cases where studied (see Table 3 for Drill A and B).

Figure 8 shows the comparison between predicted and measured thrust forces, for the Drill A (118°). As could be seen, an appropriate prediction of the thrust force for all cases analyzed is observed for Drill A (118°). At elevated feed and cutting velocity (Cases 3 and 5) the error is lower with values about 5%. When both the feed rate and the cutting velocity are small, the error reached increases (Cases 4 and 1) with values about 13%. Therefore, the errors obtained are similar to numerical modeling commonly discussed in the researches [29].

Figure 9 shows the comparison between numerical predictions and experimental data for Drill B (80°). The Case 7 presents the highest level of maximum error equal to 13%. On the other hand, the best fit between the tests and the numerical model is exhibited for Case 2, where the error is about 11%. In general, the accuracy of numerical predictions for the case of Drill B (80°) are slightly worse than those obtained for Drill A (118°), however they are reasonably values comparable to similar modeling in the literature [29]

Table 3. Different conditions analyzed numerically and experimentally for drill A and B.

<table>
<tr><th>Case</th><th>Layers</th><th>V [m/min]</th><th>f [mm/rev]</th></tr>
<tr><td>Case 1</td><td rowspan="5">2</td><td rowspan="3">20</td><td>0.03</td></tr>
<tr><td>Case 2</td><td>0.06</td></tr>
<tr><td>Case 3</td><td>0.12</td></tr>
<tr><td>Case 4</td><td>15</td><td rowspan="4">0.06</td></tr>
<tr><td>Case 5</td><td>25</td></tr>
<tr><td>Case 6</td><td>3</td><td rowspan="2">20</td></tr>
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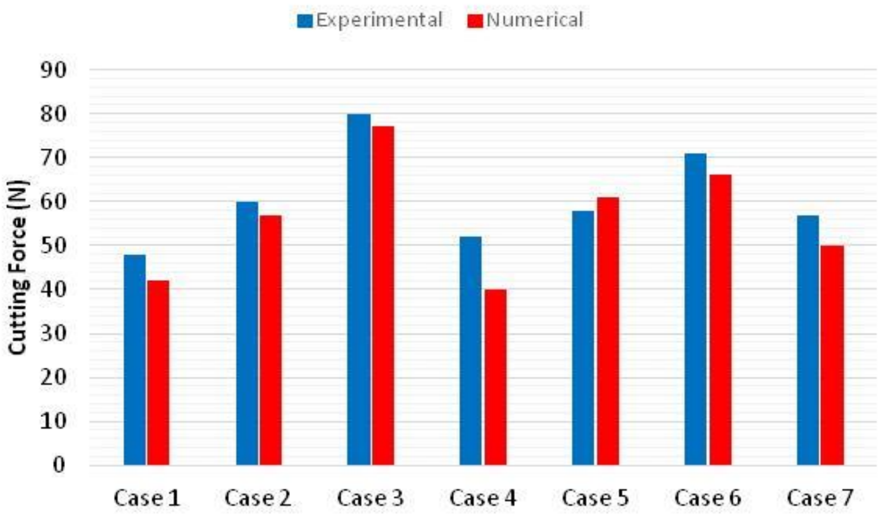

Figure 8. Thrust force comparison between the numerical model and the experimental test for Drill A during the drilling of flax-based composites.

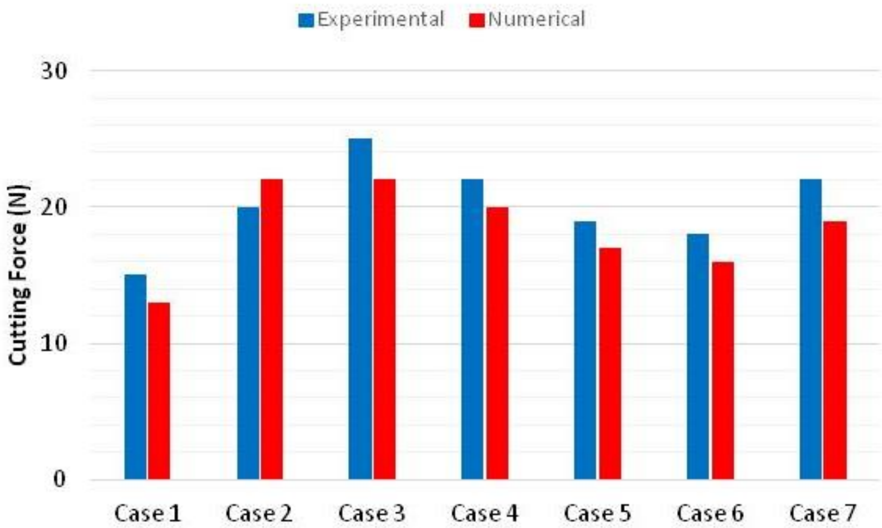

Figure 9. Thrust force comparison between the numerical model and the experimental test for Drill B during the drilling of flax-based composite.

Damage factor is obtained from numerical simulations through the post processing available in ABAQUS CAE (see Figure 10) damage extension quantification.

The damage is quantified in terms of plastic deformation obtained in the sample at the drilling process modelled, for both drill geometries, which is compared with that obtained experimentally. The damage obtained for the Drill A compared to the experimental tests (with an error of 2%) is shown in Figure 11.

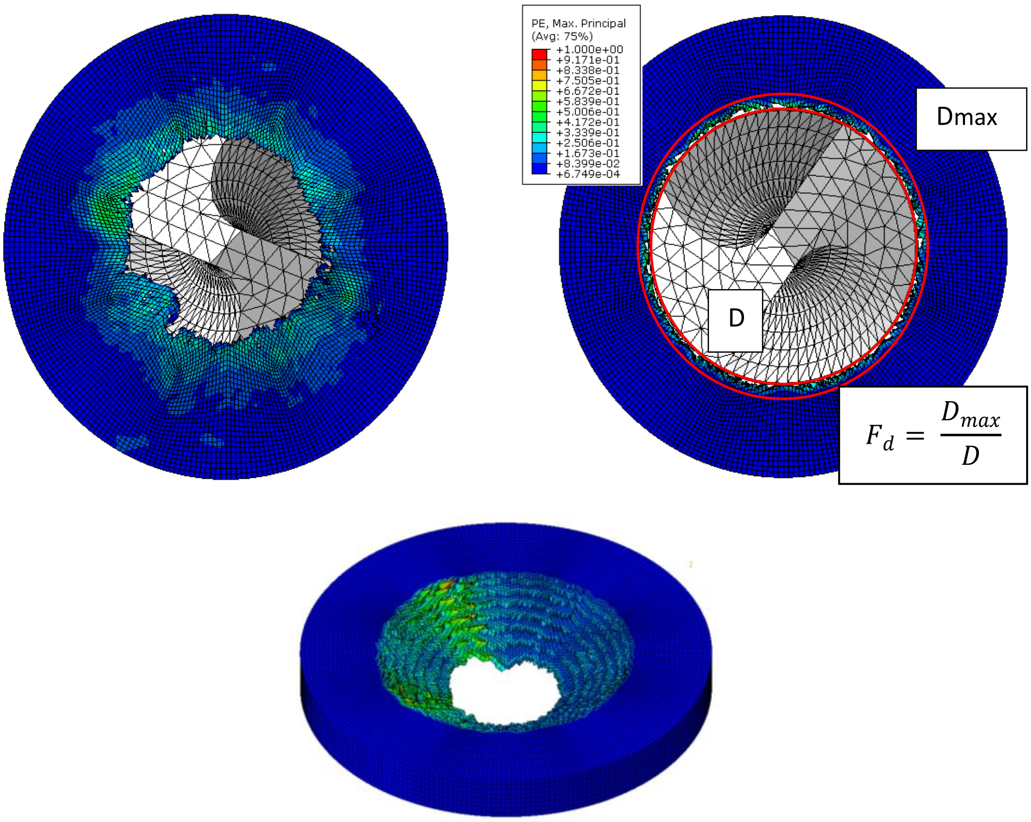

Figure 10. Numerical prediction of F_d (the images correspond to Case 3 with the drill A).

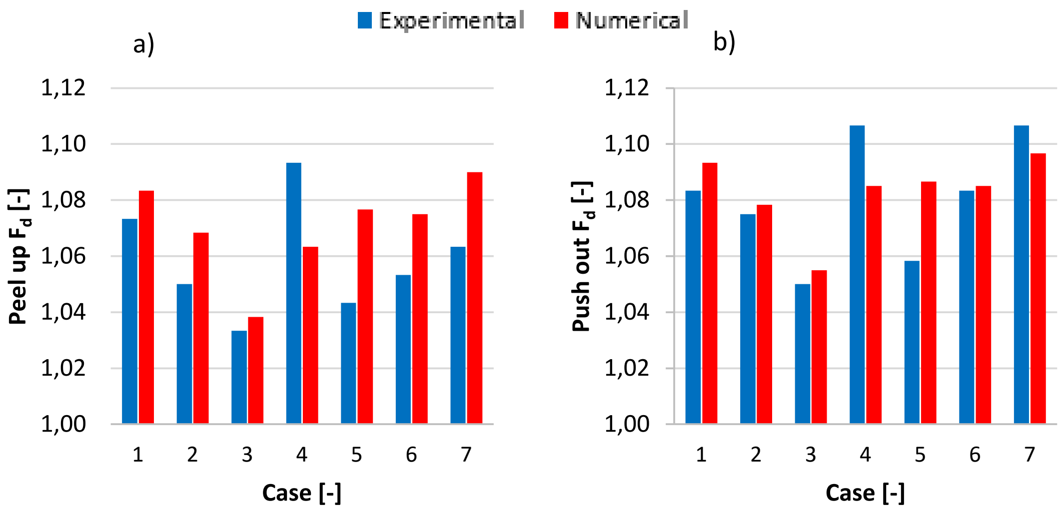

Figure 11. Comparison between the Damage factor [F_d] obtained for all cases (Table 1) experimentally and numerically with Drill A. a) Peel up; b) push out.

It is shown the values of predicted and measured damage both at the peel up and push out. The model quantifies with reasonably accuracy the value of the damage factor, being it higher at the entrance than at the exit for all conditions analyzed. This is also the trend obtained in the experiments. For the specific case of the peel up damage, the higher error value was 3.2% for Case 5. On the contrary, the best result was 0.5% for Case 3. In relation to the damage at the exit, the same trend has been observed, obtaining the maximum error for Case 1 with 2.7%. In contrast, the best value is found for Case 6, in which the accumulated error is around 0.2%.

The values obtained for the Drill B (80°) are shown in Figure 12. The predictions obtained in the simulation corroborate the trendobserved during experimental tests (with an error of 3%), with the damage at the exit higher in comparison to the one at the entrance. The peel up results show a reasonable correlation between experimental and numerical data, obtaining a maximum error of 2.7% for Case 1. On the contrary, the best result is obtained for Case 3, where the error has reached a value of 0.7%. Concerning the push out damage, the maximum error is obtained in Case 1 of 3%, while the minimum error, 1.4%, corresponds to Case 3.

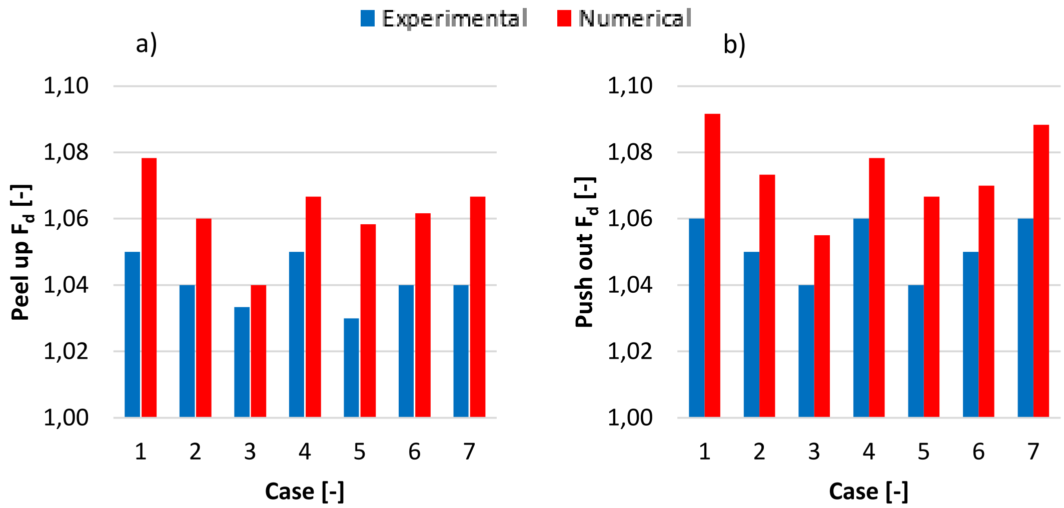

Figure 12. Comparison between the Damage factor [F_d] obtained for all cases (Table 2) experimentally and numerically with Drill B. a) Peel up; b) push out.

The values represented in Figures 8-12 are reasonably being in the order of error of numerical modeling in machining processes in the literature. Errors are due to simplifications assumed when modeling the drilling process, however the model demonstrated its ability to analyze different drill geometries, in a range of cutting parameters representative of real operations. The same trends for thrust force and damage area observed in experiments are reproduced by the numerical model.

3.4. Influence of feed rate on the thrust force and damage extension

From Figure 8 and 9 can be deduced that increments in the feed derives in a thrust force increase for both drill geometries and cases. This effect was predictable, as the feed is increased the cross section of the chip is increased, hence larger efforts are required to remove the material.

It can be also stablished that increments on the feed rate derives in a decrease in the damage generated during the process for both geometries and cases. However, researches on this field showed that increments on the feed rate cause an increase in the damage generated when drilling CFRPs, and hybrid composites from sisal and flax as natural fibers [20,36,41]. This trend may be related to the range of damage modes, being the delamination, the most common damage mode identified by other authors, while fraying has been found as the main damage in this work.

In Figure 11 and 12 could be seen the effect of the feed rate on damage extension for three configurations. Cases 1, 2 and 3 (Table 2) have been taken into account, cutting speed remains constant (20 m/min), Drill A (118°) geometry was used, and the feed ranges between 0.03 to 0.12 mm/rev.

The numerical model reproduces the experimental data published in [2] demonstrating that for the case of the fully biodegradable material studied in this work, the damage extension during machining is reduced with the increment of feed rate. Both, peel up and push out, show the same trend in the range of feed rate studied and it is completely contrary to the one showed in synthetic materials.

Numerical analysis of CFRPs drilling has shown the opposite trend for feed influence [33]. In CFRPs drilling, the mechanical response of the composite was assumed to be linear-elastic up to failure reproducing the experimental behavior of these composites. The different mechanical behavior of the material is help to explain the dissimilarities in the influence of feed on synthetic composites and flax/PLA composites. There are two important differences for the classical linear-elastic and the constitutive model implemented in the present work. Firstly, in the present model both stiffness and strength increase with strain-rate; and second, in the present model ultimate strain decreases with strain-rate. Two additional numerical models were developed with the aim of decoupling both effects. The objective is clarifying if the reduction of damage extension with feed rate is due to the increase with the strain-rate of the stiffness and strength, or to the decrease of ultimate strain with strain rate:

- Model SS: This model reproduces the influence of strain-rate on stiffness and strength, i.e. both stiffness and strength increase with strain-rate. However, the value of ultimate strain is independent of strain-rate. Thus, this model can reproduce the influence of the strength and stiffness on the results independently of the ultimate strain.
- Model US: This model reproduces the influence of strain-rate on ultimate strain, i.e. ultimate strain decreases with strain-rate. However, stiffness and strength do not depend on strain-rate. Thus, this model can reproduce the influence of ultimate strain on the results independently of the changes on stiffness and strength.

In Figure 13 the results for the experimental test have been compared (with an error of 3%) with the two additional models for cases 1, 2 and 3.

The trend observed in models SS and US (Ultimate strain decreases with strain-rate but stiffness while the strength remains constant) decoupling the influence of stiffness/strength and ultimate strain, is similar to that observed in CFRPs, both entrance and exit damages increases with feed rate. Model SS proves that while ultimate strain remains constant and stiffness and strength increase with strain-rate, damage increases with feed rate. While model US proves that if ultimate strain decreases with strain-rate but stiffness and strength remain constant, damage increases with feed. During a drilling process it is required to reach the material ultimate strain to properly cut the material. Thus, to reproduce the trend observed in drilling trials is required to consider both the effect of strainrate on stiffness, strength and ultimate strain to properly simulate the influence of feed rate on damage extension. As previously commented, for both tested tool as the feed was incremented the damage extension was incremented. It is explained through the material constitutive model. As the feed increases the strain rate increases, hence the ultimate strain decreases making the affected area of the hole during the drilling processes smaller.

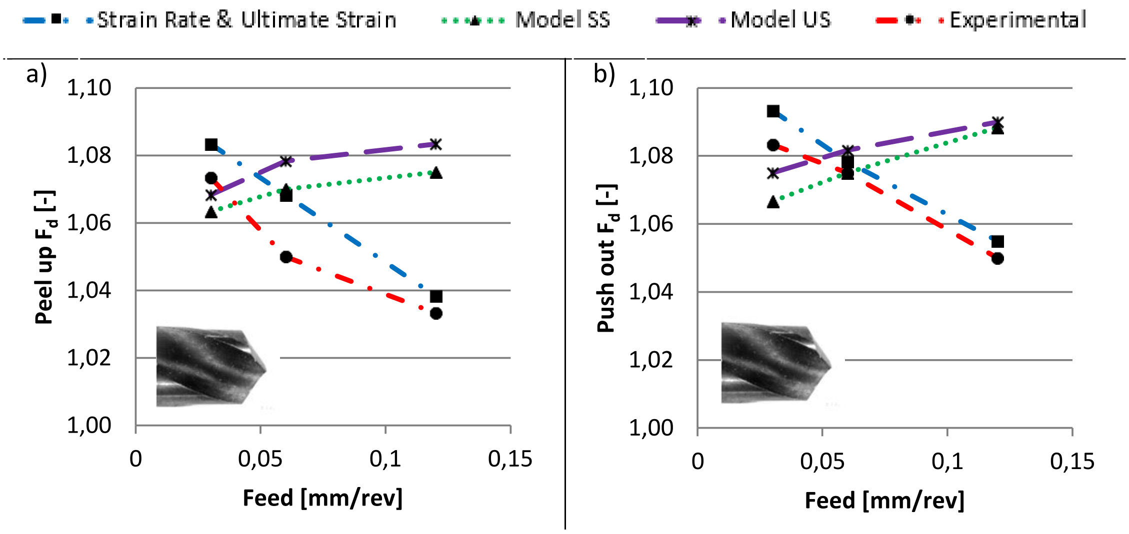

Figure 13. Analysis of the Damage factor [F_d] tendency both peel up (a)) and push out (b)) taking into account the feed for Drill A. Experimental and analytical analyses.

3.5. Influence of cutting speed on the thrust force and damage extension

Taken into account cases 2, 4 and 5 for both tools from Figures 8 and 9, it can be concluded that by increasing the cutting speed the thrust force is reduced. It may be explained by thermal softening of the material. As the cutting speed is increased, the generated heat that is accumulated into the workpiece due to the machining process increases since the material has less time to dissipate the heat that get into.

From Figures 11 and 12 it is observed that in general trend for both drill geometries and all conditions analyzed: increments in the cutting velocity derives in a decrease in the damage. This phenomenon is in accordance with the conclusions obtained by Nasir et al. [22], during the drilling of hybrid composite materials manufactured from flax and epoxy. On the contrary, this tendency does not agree with the results obtained during the drilling of synthetic materials in which the cutting velocity influence is less in comparison to the feed rate effect [6,41]. The strain rate increases as the cutting speed increases. As explained in the previous point, this phenomenon may be related with the effect of the strain rate on the mechanical properties which could be greater in this type of materials [25].

3.6. Influence of drill bit on the thrust force and damage extension

For all conditions analyzed, Drill-A showed the higher thrust forces in comparison to Drill-B. This can be related to the point angle, being it higher for the case of Drill A (118°). Therefore, to reduce the thrust forces obtained during the drilling of thin biodegradable composite materials a small point angle should be selected. It can be recommended for drilling biocomposites in order to moderate thrust force. Similar trends have been observed for synthetic materials [32,42].

There are two effects of using small drill point angles. On one hand, to drill thin plates, as the ones used in this research, the projected length on the plate of the active cutting edge of the drill B that is working at the same time which is smaller to the one found for drill B, which means less material being puss under the cutting edge (see Figure 14). On the other hand, smaller drill point angles penetrate easier into the woven, this is because once the continuity of the woven is broken the matrix is the main actor to withstand the thrust force generated by the drill making easier the forward movement of the drill.

Regarding the impact of the drill point angle on the damage area, none tendency was observed, being negligible its effect on this parameter.

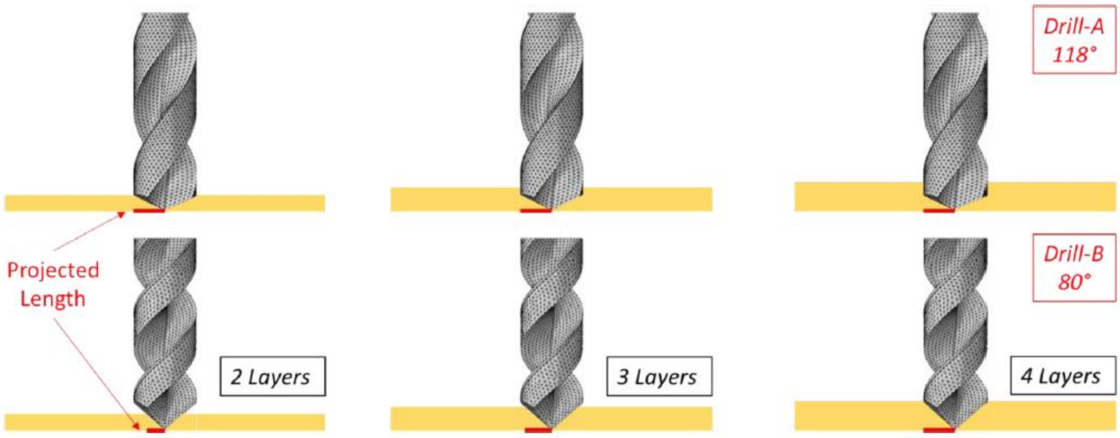

Figure 14. Projected length of the active edge during the drilling of 2, 3 and 4 layers of Flax/PLA composites with Drill-A and B.

3.7. Influence of specimen thickness on the thrust force and damage extension

In this section it is convenient to note that the thickness plays a very important role in the rigidity of the specimen.

In the case of the smallest stack, part of the force is used in an inefficient way to bend the plate under the drill, that is why higher values of the cutting force has been found for the two drill bit geometries in comparison to the other thickness analyzed (see Figures 8 and 9).

On the other hand, there is a previously commented effect relative to the projected length of the active edge, in Figure 14 the maximum projected cut lengths for each of the thicknesses are shown:

- For drill A, in the case of the two layers, the entire edge of the drill is not working at the same time explaining why in the case of three layers, that has a greater stiffness and should give less force, the results show greater values than for two layers. For this same drill at four layers, the rigidity increases and, as in the case of three layers, there is a time in which the same edge length is working, this would explain why the force drops for the case of four layers (because it increases the rigidity in comparison to three).
- For drill B, increasing the number of layers to three, increases the stiffness which reduces the cutting force. However, the entire cutting edge of the drill does not work, this is why when the thickness is increased to four layers the force does not decreases by increasing the stiffness, otherwise, it increases a little more by participating a greater proportion of the cutting edge at the same time.

Regarding the impact of the thickness on the damage area, it could be seen in figures 11 and 12 cases 2, 6 and 7 where the thickness of the specimens is incremented. Thus, increments on the number of layers derives in an increase of the damage on both at the entrance and exit.

For tool A, the damage at the entrance decreases with the thickness of the specimen, this can be explained because when using the smallest thickness, the rigidity of the specimen is less, which causes that the tension in the material increases due to the buckling of the specimen together with the machining action, being the tensions and the damage of the machining more localized. It should not be forgotten that the fibers used are ductile, unlike synthetic fibers such as carbon and glass, and it is necessary to put them under tension in order to be completely cut. Figure 4 shows uncut fibers exposed outside the matrix. For tool B, the damage at the entrance predicted by the model decreases with thickness of the specimen, however, it could not be demonstrated experimentally (being the differences negligible for the 3 thickness). For tool B the cutting force recorded is much lower than for tool A, it may be the reason why the buckling effect explained previously does not have a significant effect on the damages found (see Figures 8 and 9).

The above reasoning cannot be applied to the damage at the push out, this increase in the affected area may be influenced by a greater softening of the material due to the thermal softening of the material. Therefore, for the tested thicknesses it is possible that as the thickness of the material increases there will be a greater heating of the material that is below the cutting edge of the tool. Due to heat accumulation [43], increasing the softening makes it difficult for the fibers of the material to reach ultimate tension in a localized way.

4. CONCLUSIONS

This work deals with the study of the drilling of flax/PLA composite materials. A combined approach experimental and numerical was developed. Main contributions and concluding remarks of the study are highlighted below:

- It has been developed a numerical model to simulate the drilling of flax/PLA composite allowing the modeling of cutting movement and chip removal. Both the effect of drill point angle and cutting parameters was analyzed.
- The constitutive model has been used to reproduce the viscoelastoplastic behavior of biodegradable composites, enabling its implementation in modelling.
- After the validation of the numerical model with the data obtained from the experimental tests, the model can be considered suitable to reproduce the machining operation in the composites reinforced with natural fibers, as well as for the quantification of the damage derived from it. The differences between the values obtained by the model and the experimental tests relative to the thrust forces range between 5 and 13%.
- Through the 3D model it is possible to quantify the damage derived from the machining process in an optimal way, obtaining results that goes from 0.2 to 3.2% in all the cases under study.
- This model gives a physical explanation of the phenomenon observed experimentally, according to which, a decrease in the damage has been generated with the feed due to the drilling process. This trend is in opposition to the one obtained for synthetic composites.
- The reduction of damage extension with feed rate is related to the effect of the strain-rate on the properties of flax-PLA composites. The numerical model predicts this trend only if the coupled effect of strain-rate on stiffness, strength and ultimate strain is considered. Hence, all the models of the literature predict the opposite trend because they consider linear elastic behavior independent of the strain rate. This assumption is valid for traditional composites but not for natural fiber reinforced composites.

Moreover, the effect of the feed on the cutting force and the damaged area of the material has also been verified both numerically and experimentally, thus, as the thickness of the specimen increases, the damage both at the entrance and the exit of the drill decreases. It also highlights the not very significant effect of the tip angle in the area of damage at the entrance and at the exit of the specimen.

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