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ANALYSIS OF ORTHOGONAL CUTTING OF BIOCOMPOSITES

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Abstract

The use of 100% biodegradable composites in the industry is increasing significantly over the years, mainly due to their excellent properties as well as to the growing ecologic concern. However, after their manufacture, the composite pieces do not always have the final shape, requiring subsequent processing operations, usually drilling and trimming. The performance of cutting processes on fully biodegradable composites are often limited by induced damage as fraying and delamination. This type of phenomena is related, among others, with the cutting parameters and geometries of the tool. Orthogonal cutting is a simplified process that could help in the understanding of damage mechanisms, it is a well-known technique in traditional composites but its use in biocomposites is an almost unexplored field.

This work focuses on flax/PLA 100% biodegradable woven composites. The specimens have been manufactured with different angles of orientation, ranging from 0° to 60°, being subjected to orthogonal cutting in a special machine developed for that purpose that allows to develop cutting tests with linear displacement at high speeds. Damage extension, failure modes, and cutting forces are analyzed allowing the extraction of important experimental information.

Keywords: *Biocomposite; Flax; Orthogonal Cutting; Natural fibers*

1. INTRODUCTION

For centuries, the use of the flax has been linked to the textile industry, its use as reinforcement in the manufacture of composites is more recent, in the 1940s [1]. Its use has increased exponentially thanks in part to the growing ecologic concern and the legislations to reduce the environment footprint [2]. Natural fibers are a real alternative to synthetics, thanks in part to their low density, their high specific mechanical properties, high availability and their cost-efficiency, properties that make them suitable for its use in composites [3,4]. In addition, they stand out due to their positive impact on CO2 emissions [5] and the possibility of using, in some cases, waste materials from different processes both as matrix and reinforcement. In this sense, the use of lignin from paper production [6] as well as others from farms [7] stands out.

Normally, natural fibers are used as reinforcement with synthetic matrices by many researchers [8,9], greatly reducing their ecological properties among others, however, its use together with natural matrices is also increasing in recent years, enabling the creation of 100% biodegradable composites. Polylactic acid (PLA) is one of the most popular matrices used to produce fully biodegradable composites. Moreover, PLA is similar to other synthetic matrices like polystyrene

(PS) and polyethylene terephthalate (PET), highlighting among its main properties the biocompatibility, high mechanical strength, no toxicity and thermal plasticity, besides it is biodegradable [10], properties that make it suitable for the food industry [11] and the obtain of biodegradable composites [12].

After composite manufacture, machining processes in general are necessary to give them its final shape and tolerances [13,14]. The heterogeneity and anisotropy of composites make the mechanisms of material removal of this type of materials completely different and more complex from those present during the machining of more common homogeneous materials such as metals [15]. Thus, homogeneous materials such metals during its machining are characterized by plastic deformation and continuous or semi-continuous chip formation [16]. On the other hand, composites machining involves several types of damage mode such as: fiber breakage and matrix cracking that derives in delamination, fraying and fuzzing as main defects [17–19]. Therefore, to get its final shape and quality surface it is necessary to understand the whole material removal and chip formation phenomena that involves the machining processes by means of cutting forces and surface morphology [20].

The orthogonal cutting is the most used configuration to simplify the complex geometries of drilling and other machining processes in the analysis of the cutting process mechanics [21]. Thus, it is a two-dimensional machining operation that simplified the geometric complexities related to three-dimensional cutting processes, where the cutting edge of the tool is orthogonal to the direction of relative tool-workpiece motion. There are several studies that develop the orthogonal cutting at the experimental level or as a base for the validation of posterior numerical models in different materials being the most common those related to unidirectional carbon fiber composite (UD-CFRP) [22–26].

Bhatnagar et al. [27] analyzed the orthogonal cutting of UD-CFRP laminates with different fiber orientations of 0°, 10°, 30°, 45° and 75° quantifying the cutting forces and the chip formation. They concluded that the minimum forces are those obtained for 0° to 30° fiber orientation, whereas the higher values of cutting forces were the ones for the range of -30° to -60° fiber orientation. Wang et al. [28] developed orthogonal test in UD-CFRP with 0°, 30°, 60°, 90°, 120° and 150° fiber orientation measuring both the surface quality and the cutting forces. The results showed that fiber orientation is a key factor on the surface integrity and the generation of cutting forces. Thus, in general, both cutting forces components (cutting and thrust force) increases as the fiber angle increase. They also found that the fiber damage was more severe when the fiber orientation is between 120° and 150°. An et al. [29] analyzed orthogonal cutting test on high-strength UD-CFRP laminates at 0°,15°,30°,45°,60°,75°,90°, 105°, 120°, 135°, 150° and 165° fiber orientation. They concluded that for fiber angles less than 90°, Fc (main cutting force) and Fp (radial thrust force) increased for increments in θ (angle of fiber orientation) showing a peak value at 90°. Moreover, as cutting speed increases both Fc and Fp decreases. On the contrary, Fc and Fp showed upward trends when the feed increases. In a more recent study, they analyzed the thermal characteristics of the T700/LT-03A UD-CFRP during orthogonal cutting tests [30]. Li et al. [31] conducted orthogonal cutting test on UD-CFRP with fiber orientations from 0° to 75° for develop a new energy analytical method in order to predict the cutting forces during the process. They concluded that the fiber orientation has a significant effect on the generation of the cutting forces, obtaining on it with increments in θ.

Despite the growing interest in 100% biodegradables composites, there is a lack of research that deals with the analysis of the orthogonal cutting on this type of materials, not existing in the literature up to date any research on this field. Chegdani et al. [32] analyzed the machinability of hybrid composites made from flax as natural fiber reinforced by polypropylene as synthetic matrix. They studied the chip formation and the quality surface through orthogonal cutting tests, considering the fiber orientation always perpendicular to the cutting direction, assuming it as the worst cutting condition. Cutting speed ranges from 12 to 80 m/min while feed ranges between 100 to 500 µm. They found long continuous chip formation during the orthogonal cutting, being it a contrary behavior from the one present on fully synthetic composites where the chip is in general discontinuous. Moreover, they concluded that the feed parameter presents the greatest influence on the quality surface. Thus, increments on the feed derives on increments on the cutting forces and subsequently on the quantified damage, showing up uncut fibers, debonding zones and plastic deformation of flax fibers at the surface. The influence of the cutting speed is not significant, being able to observe in general a slight tendency, according to which, increments on the cutting speed derives on increments in the cutting forces.

This paper focuses on the analysis of the orthogonal cut on 100% biodegradable composites manufactured by compression molding from flax and PLA in different orientations (0°, 30°, 45° and 60°). The influence of the different cutting parameters on the cutting forces and surface finishing has been analyzed. A special machine developed for that purpose that allows to develop cutting tests with linear displacement at high speeds has been used. Thus, three cutting speeds of 15, 60 and 120 m/min and three feeds of 0.05, 0.1 and 0.15 mm were studied, being found a general trend in which increments on the feed derives in increments in both the cutting and thrust forces. On the other hand, contrary tendencies have been obtained for the effect of the cutting speed, where increments on it leads to decrements in the cutting and thrust forces.

2. EXPERIMENTAL WORK

2.1. Workpiece manufacturing

100% biodegradable composites were manufacture using flax fibers as reinforcement and PLA as matrix through compression molding method. Basket weave flax (BF) with no chemical pre-treatment were subjected to uniaxial tensile test in an Instron 8516 machine, determining its main mechanical properties (peak force has been used for the Tensile strength). Therefore, its mechanical properties and information related to woven thickness, areal and yarn linear density, and crimp ratios are summarized in Table 1.

10361D PLA provided by Natureworks LLC in pellets shape has been used as thermoplastics resin. 10361D PLA has a density of 1.24 g/cm^3 and a melting temperature within the range of 145-170 °C, being used primarily as a binder of natural fibers in the manufacture of composites. Its main mechanical properties obtained from [33] are shown in Table 1.

Table 1. Mechanical properties of BF fibers and 10361D PLA; fabric information.

	Mechanical Properties

Material	***Tensile strength (MPa)***	***Young modulus (GPa)***	***Yarn linear density (tex)***	***Woven thickness (mm)***	***Areal density (g/m²)***	***Warp crimp ratio (%)***	***Weft crimp ratio (%)***
BF fibers	271.62	7.84	127-135	0.94	463.3	2	7
PLA [33]	54.27	3.18					

Figure 1 summarizes the different steps of the compression molding method. To remove the water content, both woven flax and PLA were dried in an oven at 95 °C for 30 minutes before the manufacturing process starts. The molding process begins with the obtaining of PLA films from pellets. The dried PLA pellets are introduced between the thermo-heated plates at a temperature of 185 °C for 3 minutes to obtain the homogeneity of the film. The PLA films were cut into 160 x 200 mm^2 being stacked alternately with the flax fabric and dried together for 30 minutes in a mold. 16 MPa of pressure at 185 °C have been applied to the mold for 3 minutes through a universal machine Servoris ME-404/100 + PCD-1065 after a preheat of 2 minutes. Once the biocomposite plate is shaped, it is dried at room temperature and stored at 46% relative humidity (RH) and 20 °C.

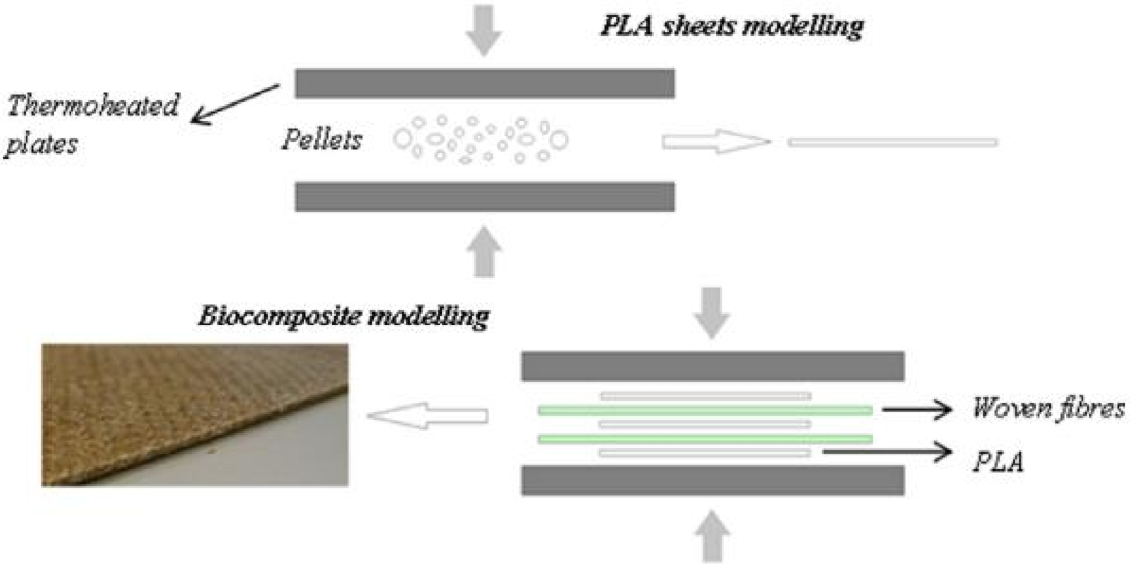


Figure 1. Compression molding method stages for the manufacturing of fully biodegradables composites [12].

Fully biodegradable composites were manufacture in two layers and four different fiber orientation of 0°, 30°, 45°, and 60° as shown in Figure 2. Fiber orientation refers just to one of the two yarn orientation that make each layer, since the other one is oriented perpendicular to the former. Along the manuscript the references to each specimen will be done accordingly to the orientation of one of the yarns following the sketch of Figure 2. Specimens were cut in 100 x 25 x 2 mm^3 shape.

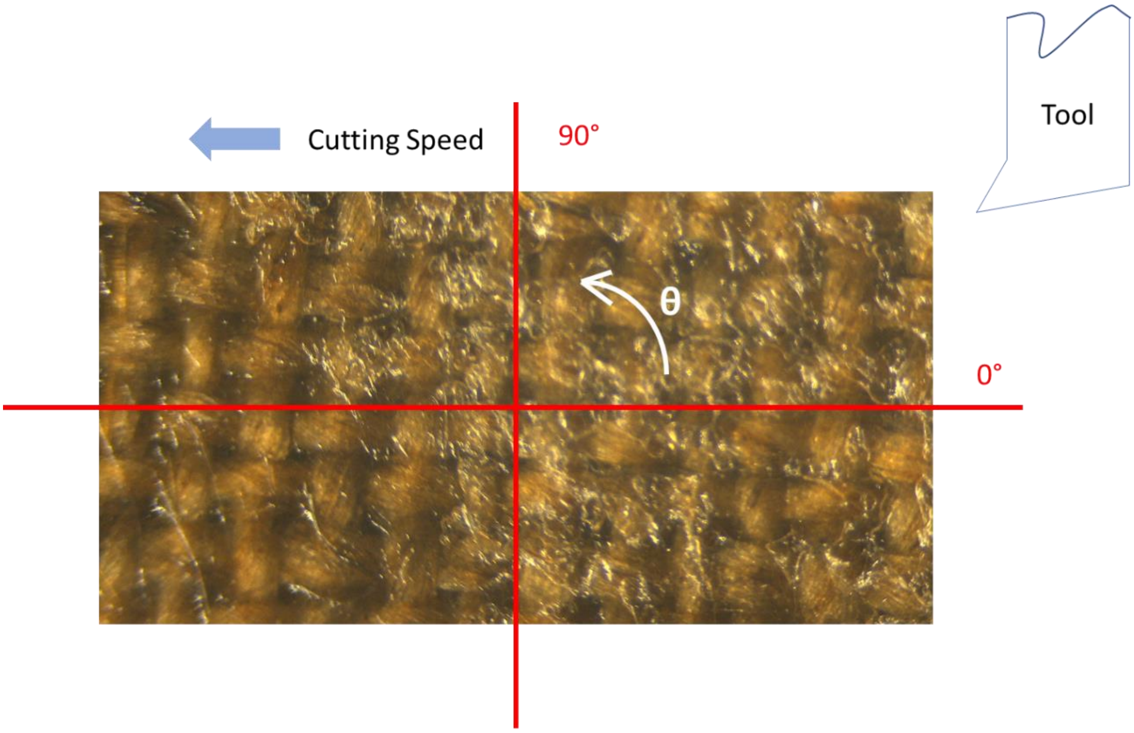


Figure 2. Angle of fiber orientation.

65% of weight reinforcement ratio has been obtained for the manufactured biocomposites, being acceptable through the comparison with the one obtained by Ochi et al. Moreover, following the ASTM D2584, the flax fiber fraction was 58.6%.

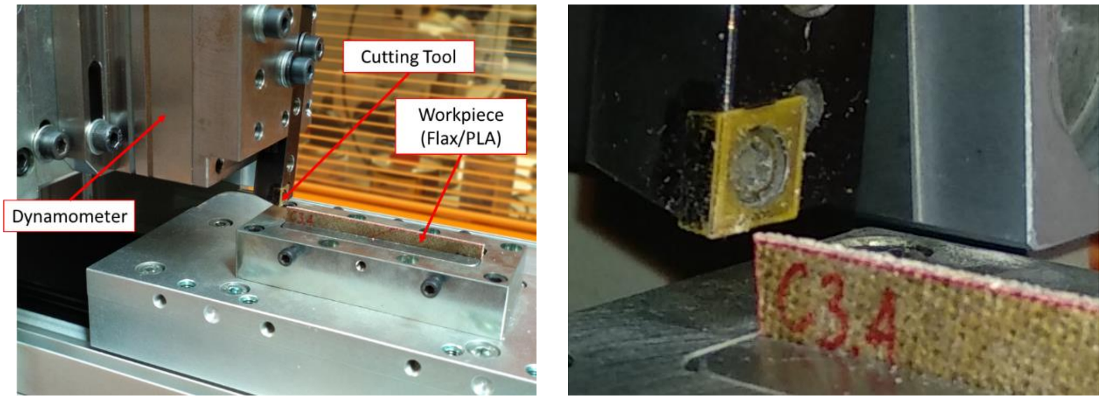
Tensile strength (calculated with the peak force) obtained through tensile tests carried out in an Instron 8546 test machine is summarized in Table 2. More information regarding the manufacture of fully biodegradable composites and their mechanical properties can be obtained in Rubio-López et al. [12].

Table 2. Tensile strength of fully biodegradable Flax/PLA composites.

Material	***Tensile strength (MPa)***	***Standard deviation (MPa)***	***Elastic modulus (GPa)***	***Ultimate strain***	***Layers***
Flax fabric/10631D PLA	104.0	4.71	7.84	0.061	2

2.2. Orthogonal cutting tests

The orthogonal cutting tests have been carried out in a machine specially manufactured for the realization of this type of tests (see Figure 3a and 3b).



a) b)

Figure 3. a) Orthogonal cutting set up. b) Cutting area detail.

The machine controlled by a computer is capable of providing a constant velocity to the specimen (which is clamped in the carriage) against the cutting tool, following a linear movement along the rails. The cutting tool is fixed on the tool bridge, which has been implemented with a dynamometer Kistler 9257B capable of measuring the cutting forces during the process. Feed is established manually with the help of a dial gauge (resolution = ± 0.005mm) installed in the equipment. Moreover, the machine has a polycarbonate enclosure that wraps the set, being mobile, and enabling its removal after each test for taking measurements and analysis of both the test pieces and the tool. It is possible to install a vacuum system in those cases in which the material to be tested needs it.

Coated (TiAl/TiAlN) carbide tools provided by SECO (CCMT09T304-F2 TS2000) were used in the orthogonal tests. The insert was positive, with a tip radius equal to 0.4 mm and a tip angle of 80°. The cutting tests were performed by machining with the middle area of the active edge whose geometry is shown in Detail B (see Figure 4). Cutting edge preparation corresponds to a chamfer honing (width 0.17mm) rounded with 25 µm radius. Cutting edge geometry is defined by a relief angle of 7° and a rake angle of 15º.

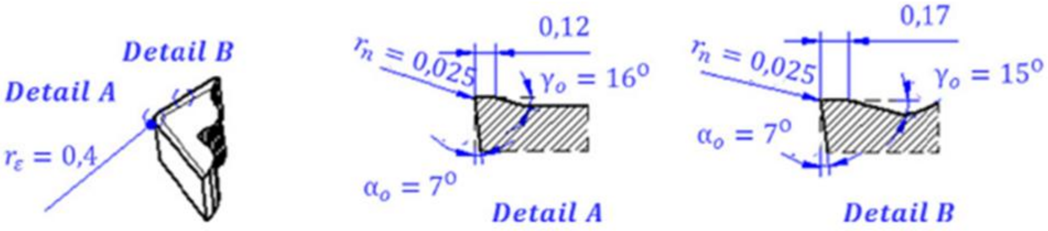


Figure 4. Cutting tool configuration [34].

The cutting parameters of the process have been chosen taking into account the existing bibliography for orthogonal cutting processes in the more similar composites found [32], as well as to studies related to the machinability of this biocomposite carried out by the authors [14,17]. Thus, three cutting speeds of 15, 60 and 120 m/min and three different feeds 0.05, 0.1 and 0.15 mm have been chosen. All tests have been carried out in dry, without cutting fluids.

The main damage found in each test has been measured through images obtained by a stereo microscope (Optika SZR). Figure 5.a) shows the fibers breakage derived from fraying, which is the main mode of damage that can be observed during the orthogonal cutting of this type of material. Moreover, this damage mode is contrary to the one found during the machining of synthetic composites [15,27], mainly CFRP or hybrid composites [32] in which the main damage observed is delamination, cracks formation along fiber breakage and debonding. Regarding the biocomposite tested in this work, no evidence of delamination has been found, which is consistent with what was obtained by the authors in previous studies on the drilling of Flax / PLA. Thus, in figure 5.b), an energy-dispersive X-ray spectroscopy image (SEM) of the transversal section through a drilled hole in two layers BF/PLA composite can be observed without existence of delamination [17].

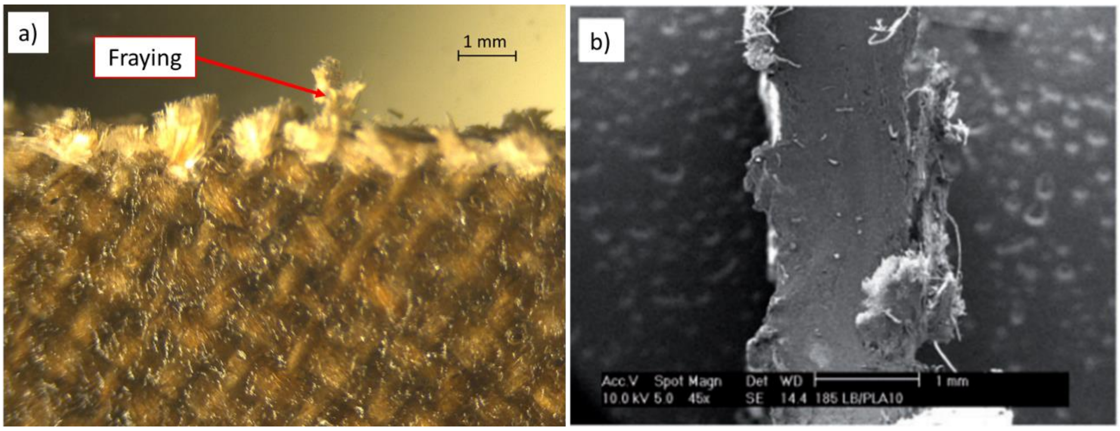


Figure 5. a) Fraying observed in BF/PLA composites during the orthogonal cutting tests; b) SEM image through a transversal section of a drilled hole in BF/PLA composite [17].

During the development of orthogonal cutting tests, both the cutting force and the thrust force have been quantified for each condition tested. Moreover, each condition has been tested two times, being shown in the graphs their mean value, with a variation less than 10% in all the cases analyzed.

3. RESULTS AND DISCUSSION

3.1. Cutting Force

The evolution of the cutting force was recorded during each test. The values of the cutting forces vs feed for each fiber orientation are summarized in Figure 6. For all the cases analysed, the values of the cutting force ranged from 86 N (case: V_c = 15 m/min; feed of 0.15 mm and 45° of fiber orientation) to 22.5 N (case: V_c= 120 m/min; feed of 0.05 mm and 0° of fiber orientation).

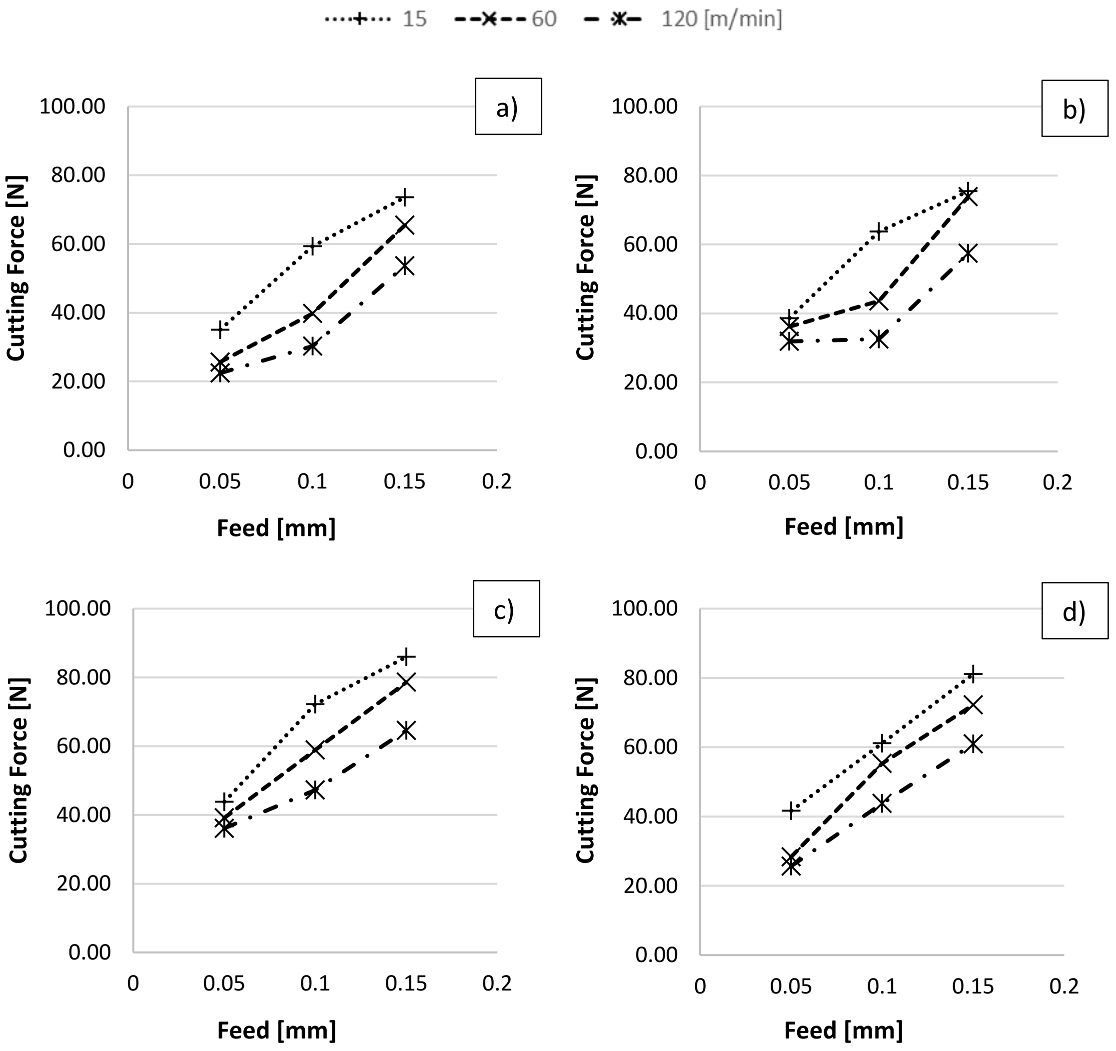


Figure 6. Cutting forces vs feed for orthogonal cutting tests in BF/PLA composite at different fiber orientation: a) 0°; b) 30°; c) 45° and d) 60°.

For all the cases analyzed the same tendency was fulfilled, according to which, increments in the cutting speed derives in a decrease in the cutting force. In general, this decrease in the cutting force was more significant at feeds of 0.1 and 0.15 mm, with decreases of 49 % (feed of 0.1 mm and 0° of fiber orientation) and 27 % (feed of 0.15 mm and 0° of fiber orientation) at 15 to 120 m/min. Despite the differences in the material behavior, these results agree with those obtained by An et al. [29] during the orthogonal cutting tests of UD-CFRP, where increments in the cutting speed derives in a decrease of the cutting forces. However, Chegdani et al. [32] during the orthogonal cutting tests of flax/polypropylene composites did not obtain a clear trend.

A great impact of feed can be observed on the cutting forces. An increase in the feed results in an increase in the cutting force, mainly due to the increase of the cross-sectional area of the underformed chip section, being observed increments in the cutting force up to 61 % for a cutting speed of 60 m/min and fiber orientation of 60° when feed increases from 0.05 to 0.15 mm. These results are consistent with those existing in the literature during the orthogonal cutting tests developed on synthetic (UD-CFRP) and hybrid (flax/polypropylene) composites [29,32].

Regarding the influence of the fiber orientations, in figure 7 can be observed the influence of feed on the generation of the cutting forces for the three analyzed cutting speeds (15, 60 and 120 m/min).

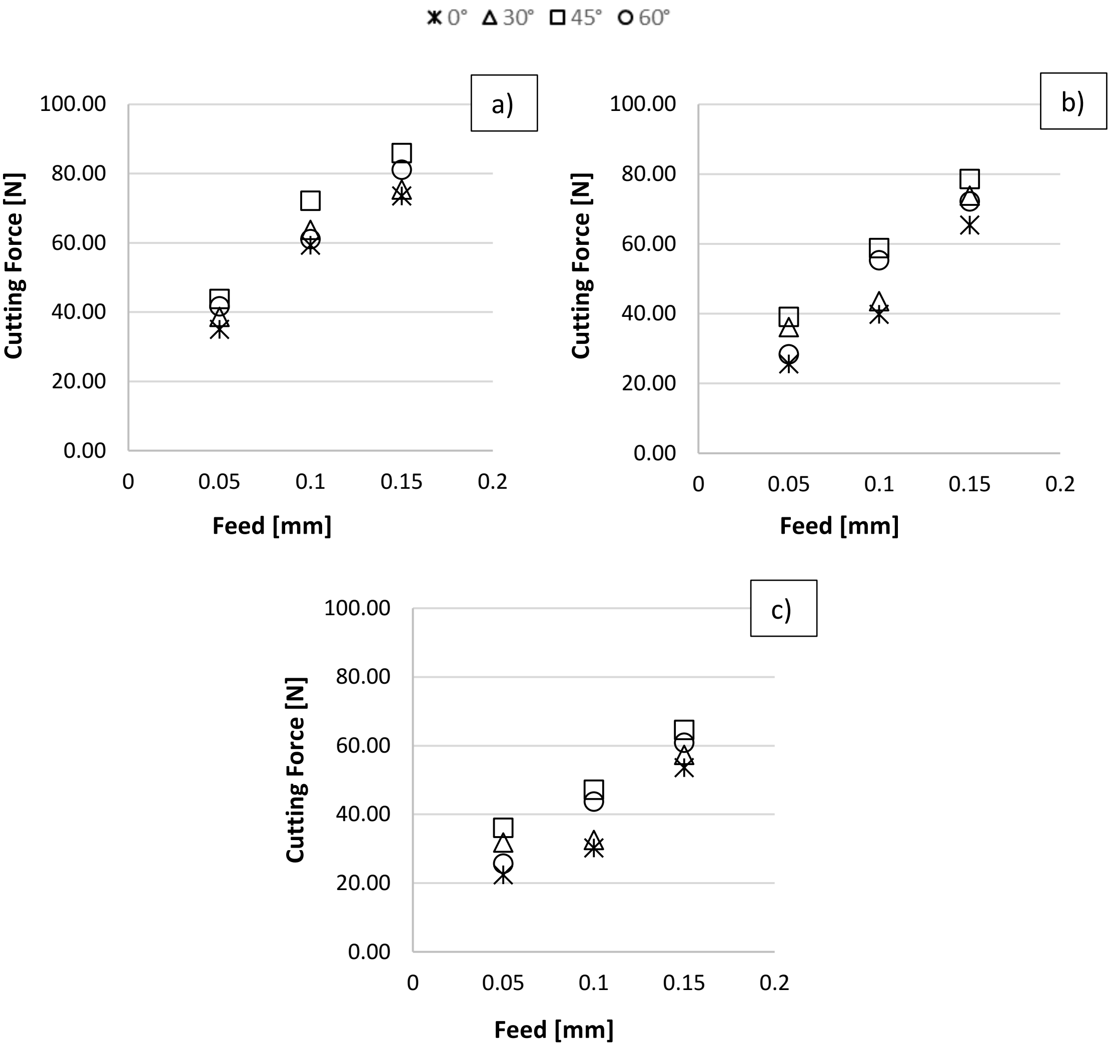


Figure 7. Cutting forces vs feed for orthogonal cutting tests in BF/PLA composite at different cutting speed: a) 15 m/min; b) 60 m/min; and c) 120 m/min.

If we take a look at the different orientations and their influence on the cutting forces, it is observed how the lowest values are those related to the orientation of fibers of 0°, on the contrary, the highest values were obtained for the angle of 45. This phenomenon is related to the different modes of failure and it can be linked with the obtained finish surfaces of the test workpieces after the orthogonal cutting tests. To understand the mechanisms by which the material is torn, figure 8 has been included, where the orientation of the fibers with respect to the tool is showed.

Regarding the fiber orientation effect on the resultant cutting forces it must be highlighted that the maximum variation found was 49% on the cutting force for 15 m/min and 45°

Taking into account the figure 8, cutting forces obtained for the orientation 0° were the smallest of all the tested specimens due to the fact that the number of fibers to be cut was smaller than for the rest of fiber orientations (only those that were perpendicular to the cutting direction were cut completely, on the contrary, the ones at 0° were torn off in most of the matrix without the need to be cut). This fact did not take place when the orientation of the fibers was 30°, 45° and 60°, in which most of the fibers were effective cut of the fibers instead of pushing and extracting them out of the matrix. In case of UD-CFRP, the lowest forces are obtained for the 0° fiber orientation, however, the mechanism through which the material is cut is totally different. In case of UD-CFRP where the fiber orientation is 0°, fibers bend due to de action of the tool till they collapse [27].

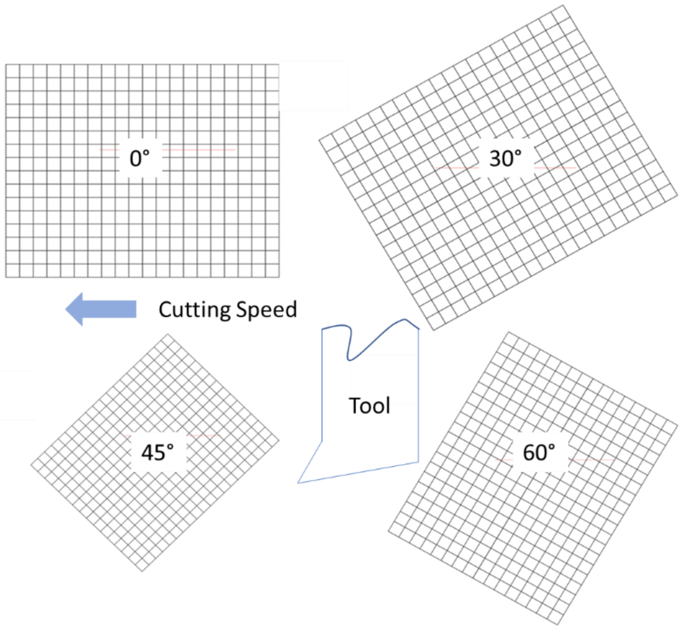


Figure 8. Fiber orientation in relation to cutting movement direction.

Together with the phenomenon previously mentioned must also be taken into account the effect of the distance from the cutting edge to the nodes where two different fiber orientations intersect, being this point more rigid. Therefore, the existence of these more rigid areas, makes it easier for the tool to cut the fibers by traction instead of pushing them. This fact helps to explain the reason why the forces found for the different orientations did not present a very clear difference in trends for the case of 30°, 45° and 60° for the different feeds and cutting speeds, due to the selected feed will affect the proximity or not to these nodes.

Thus, while for the orientation of fibers of 45° there is hardly any fraying along the cutting edge surface, finding both the matrix and fibers cut and thus obtaining the highest values of force, for the orientation of 0°, the fraying is maximum (taking into account all orientations of fibers tested), showing a worse finishing surface and appearing a large number of uncut fibers, dragged during the cut, and with the consequent decrease in the cutting force values (see figure 9).

Similar results can be found in the literature for UD-CFRP, according to which, an increase on the fiber orientation angle suppose an increase of the cutting forces until the angle of 90° where a peak in the force takes place, to later descend while continuing increasing the fiber angle up to 90° [20,29]. In the present study this trend is fulfilled for all fiber orientations analyzed except for the 60° angle, whose cutting force values are below those obtained for the 45° angle, being this difference may be caused by analyzing woven flax/PLA composites instead of unidirectional fibers and in the difference between the material behavior compared. In woven flax/PLA composites, fibers are more prone to break due to tensile efforts while carbon fibers are far more brittle material which make them more sensible to shearing or bending efforts.

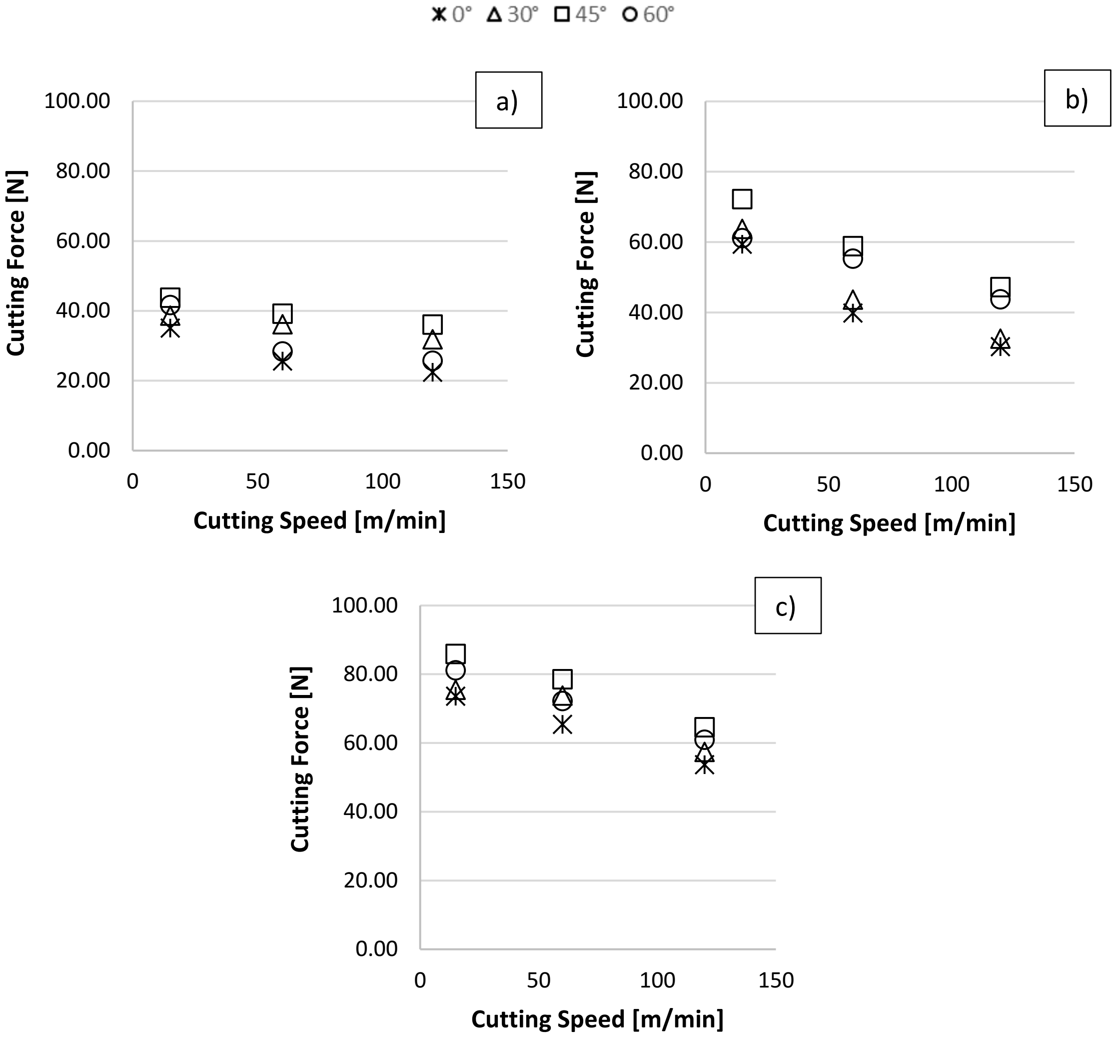


Figure 9. Cutting forces vs cutting speed for orthogonal cutting tests in BF/PLA composite at different feed rates: a) 0.05 mm; b) 0.1 mm; and c) 0.15 mm.

In relation to the influence of the cutting speed on the cutting forces, it is observed in figure 9 a tendency contrary to the one obtained for the feed influence. Thus, increments in the cutting speed result in a decrease in cutting forces for all conditions analyzed. The maximum variation obtained was 49 % in the case of 0.1 mm feed and fiber orientation of 30°.

3.2. Thrust Force

As in the case of the cutting force, thrust force evolution has been recorded during each test being used for the analysis of the results the mean values of the two obtained for each condition tested.

Thus, the values for thrust forces vs feed tested (0.05, 0.1 and .015 mm) with fresh tool for each fiber orientation are summarized in Figure 10. For all the cases analysed, the values of the thrust force ranged from 70 N (case: V_c = 15 m/min; feed of 0.15 mm and 45° of fiber orientation) to 17 N (case: V_c= 120 m/min; feed of 0.05 mm and 0° of fiber orientation).

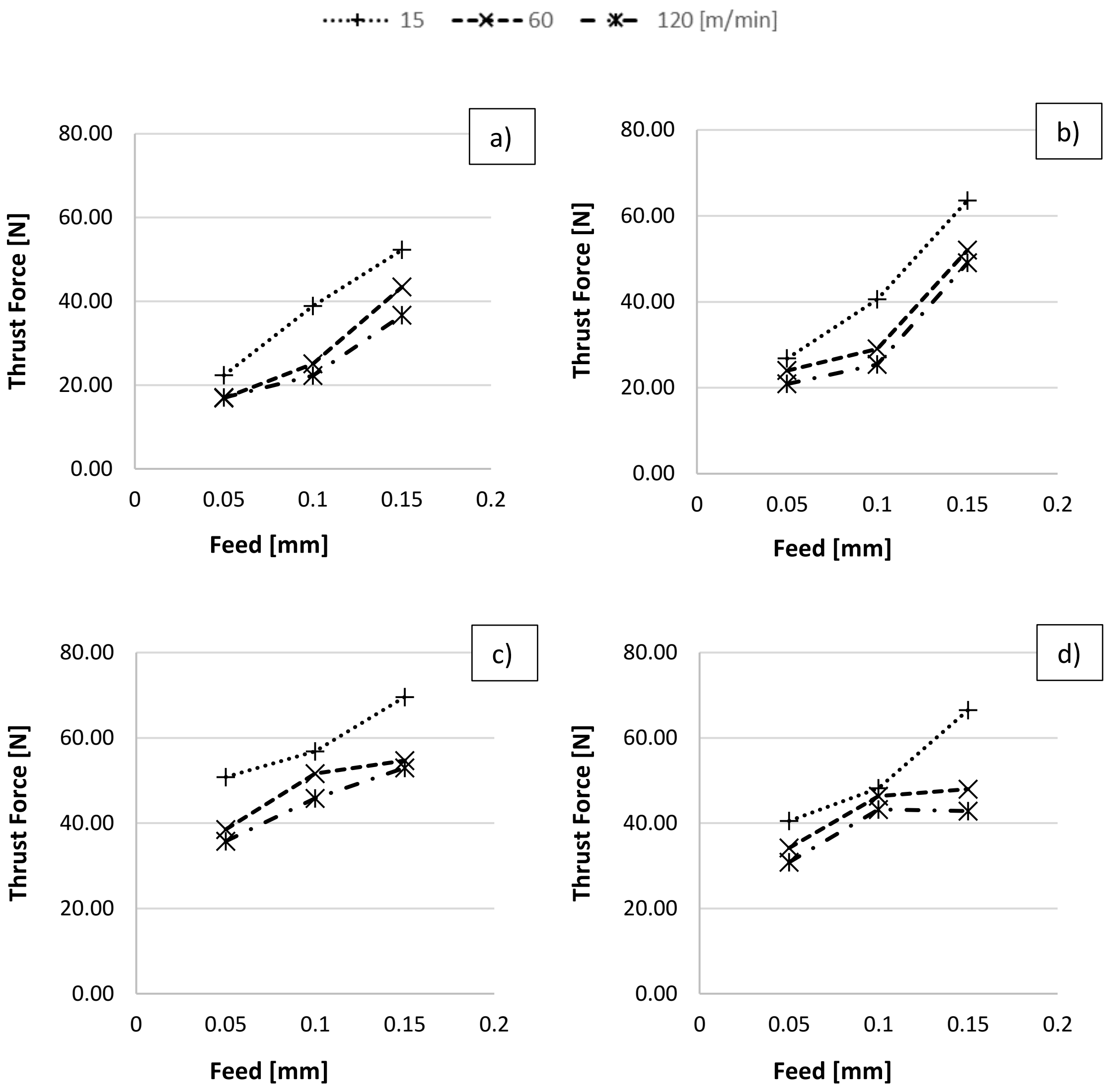


Figure 10. Thrust forces vs feed for orthogonal cutting tests in BF/PLA composite at different fiber orientation: a) 0°; b) 30°; c) 45° and d) 60°.

For all cases analyzed, the same trend can be observed, according to which, increments in cutting speed result in a decrease in the thrust force. This decrease in the thrust force due to increments in the cutting speed (from 15 to 120 m/min) is more significant in general, for the maximum feed analyzed (0.15 mm), where decreases of up to 35.8 % have been obtained in the case of 60° of fiber orientation. Although the behavior of the UD-CFRP compared to the 100% biodegradable composite is not the same, the results achieved in the present study are consistent with that obtained by An et al. [29] during orthogonal cutting tests on carbon fiber composites. One of the similarities of the biodegradable composites with the UD-CFRP is the fact that, the matrix of both get soften as the temperature incresased, and the temperature is increased as the cutting speed is increased. This fact may have an impact on the thrust force evolution found.

Regarding the effect of the feed on the thrust force, a clear trend can be observed. Thus, increments in the feed result in an increase in the thrust force for all the cases analyzed, reaching increments of up to 62.5 % when feed increases from 0.05 mm to 0.15 mm (cutting speed of 15 m/min and 30° of fiber orientation). This phenomenon is associated to the cross-sectional area of the undeformed chip, that is directly related to the feed. The results obtained are relative to those showed by An et al. [29] during the orthogonal cutting test carried out on UD-CFRP, where increasing feed they obtained increments in the thrust force. Moreover, these results are consistent with those obtained by the authors of this work in other studies related to the drilling of biodegradable composites with flax as fiber and PLA as matrix (BF/PLA) [14,17]. According to these studies, increasing the feed rate during drilling of this kind of materials derives on increments on the thrust force for all the cutting conditions raised, obtaining increments up to 50 % when the feed rate goes from 0.03 to 0.12 mm/rev.

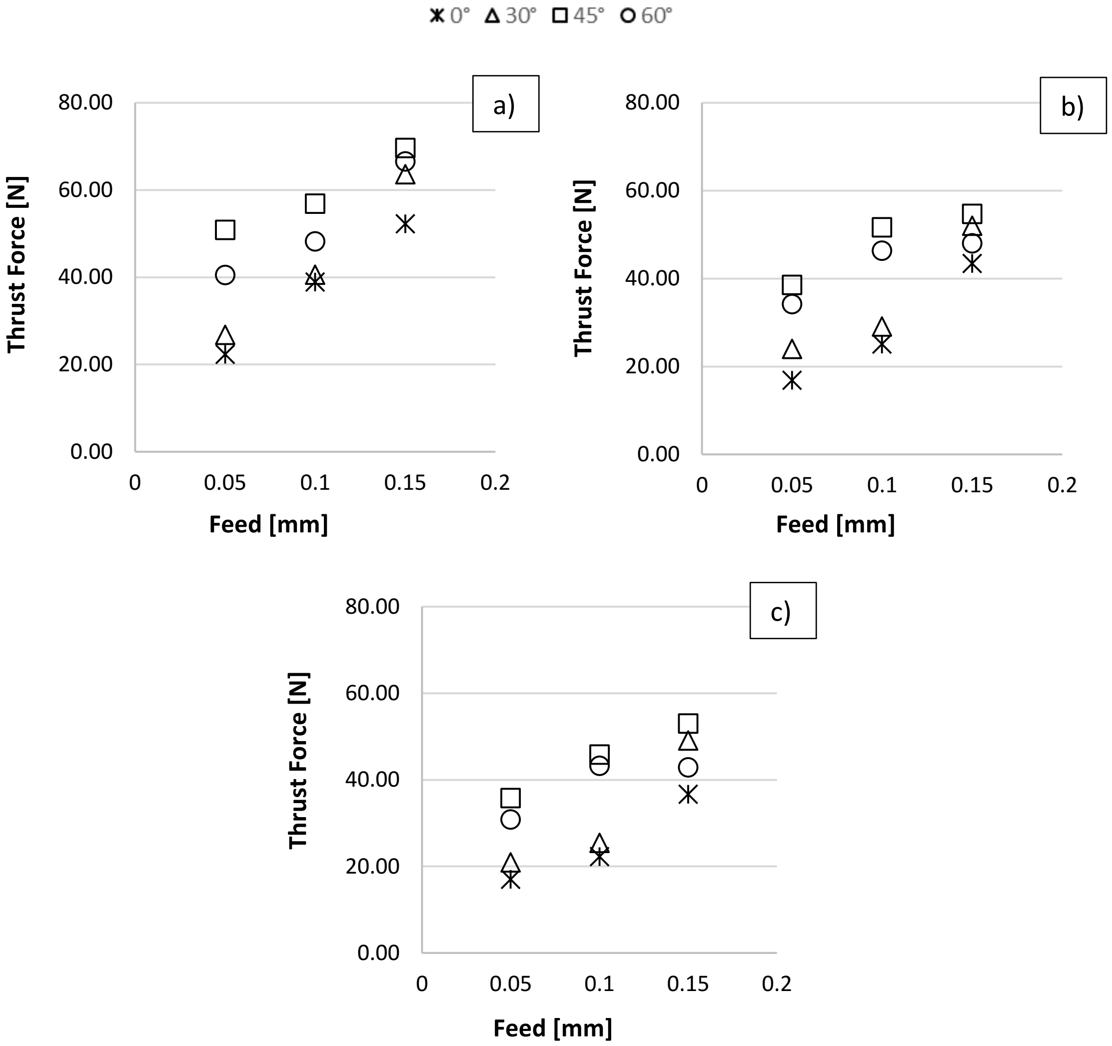
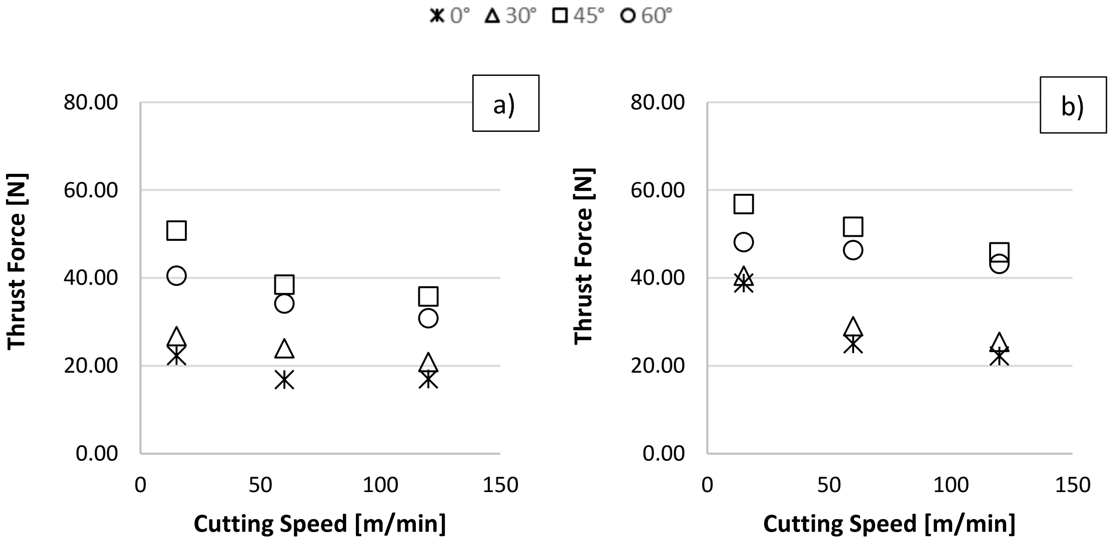


Figure 11. Thrust forces vs feed for orthogonal cutting tests in BF/PLA composite at different cutting speed: a) 15 m/min; b) 60 m/min; and c) 120 m/min.

Figure 11 shows the influence of feed on thrust forces for the three analyzed cutting speeds (15, 60 and 120 m/min) to get a better understanding of the influence of fiber orientation. When analyzing the different orientations and their effect on the thrust forces, it can be clearly seen how the lowest values are those relative to the fiber orientation of 0°, mainly due to the fact that the fibers perpendicular to 0° do not develop a significant resistant effort, and the fibers at 0° if they are near the cutting edge they are torn off, decreasing the rigidity of the material and therefore the pushing force contrary to the tool. On the contrary, the highest values are those obtained for the fiber orientation of 45°, which is related to the different modes of fibers breakage and the surface finish of the workpieces after the orthogonal cutting test. Thus, in this case the integrity of the material is greater with the pass of the tool and this makes it pushes the tool with more force than with 0°. Therefore, for the fiber orientation of 45°, uncut fibers are not appreciated being the fraying minimal and thus obtaining the best finish (see figure 12) and the highest thrust force values. However, for the fiber orientation of 0° it can be seen many uncut fibers, which have been stretched during the orthogonal cutting tests, getting the maximum fraying damage and, consequently, the worst surface finish (see figure 12) and lower forces.

Moreover, for 60° fiber orientation, in general, thrust force values was higher in comparison to those obtained for 30° being obtained an opposite tendency, but not significantly, only for the feed of 0.15mm at cutting speeds of 60 and 120 m/min, where the values are very close. Likewise, all thrust force values for both 30° and 60° fiber orientation were between 0° and 45°, being its surface damage obtained quite similar. Similar results has been obtained by other researchers during the development of tests related to orthogonal cutting on UD-CFRP, according to which, when increasing the fiber orientation angle up to 90°, there is an increase in the thrust force [20,29]. In this work this trend has been fulfilled for all fiber angles analyzed except for the angle of 60°, whose values are below those obtained for 45°. This phenomenon may be related to the different behavior of the materials compared (UD-CFRP vs Flax/PLA) or for analyzing woven flax and not unidirectional fibers.



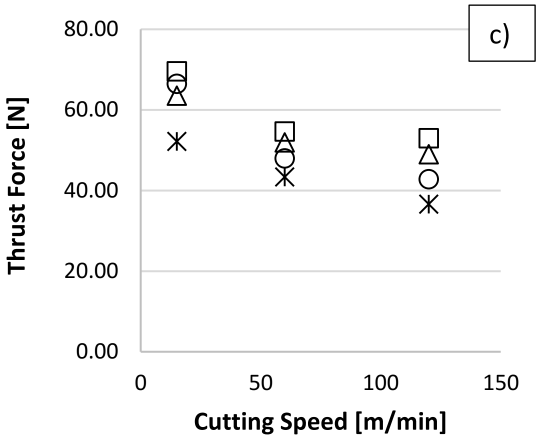


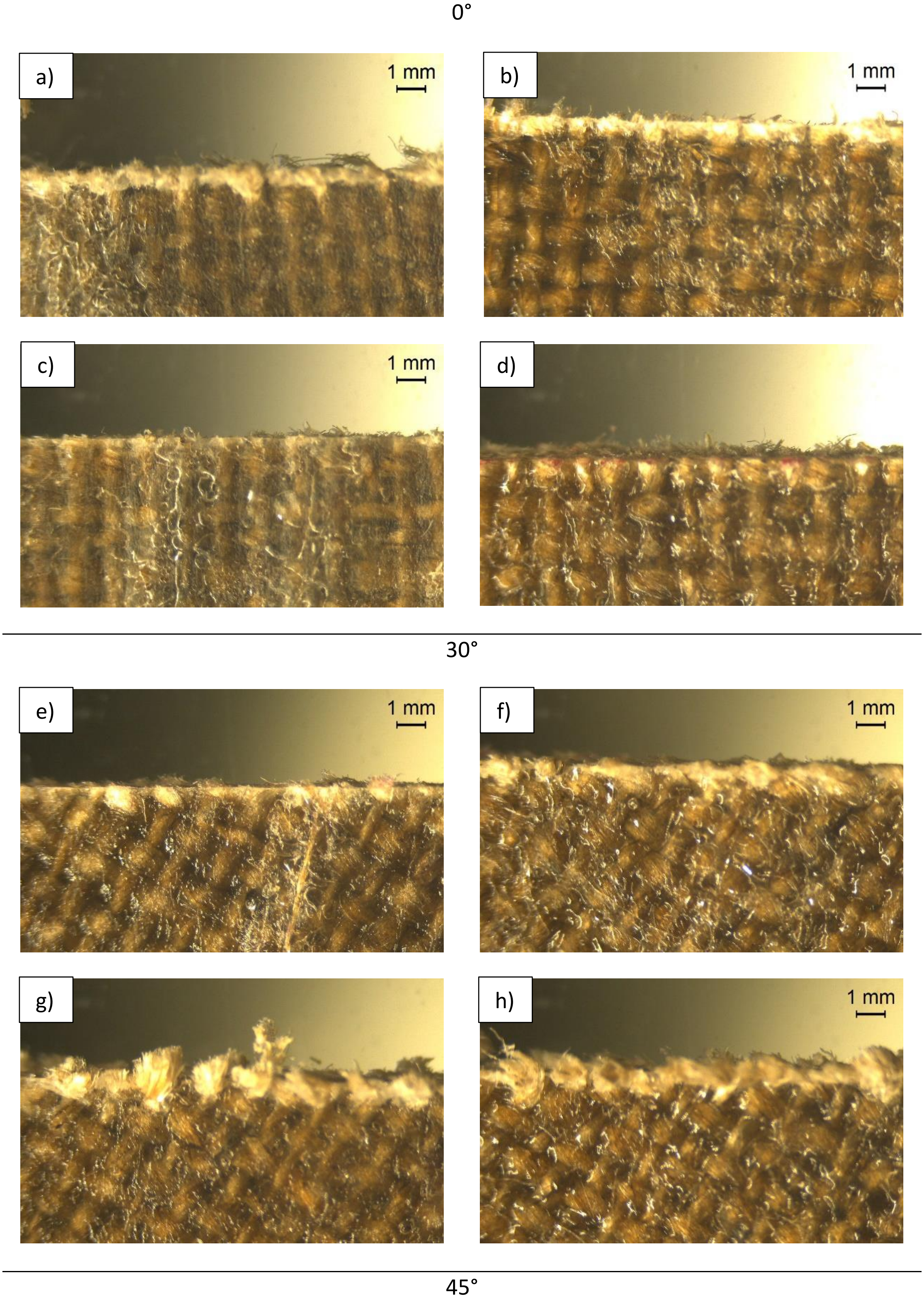
Figure 12. Thrust forces vs cutting speed for orthogonal cutting tests in BF/PLA composite at different feed rates: a) 0.05 mm; b) 0.1 mm; and c) 0.15 mm.

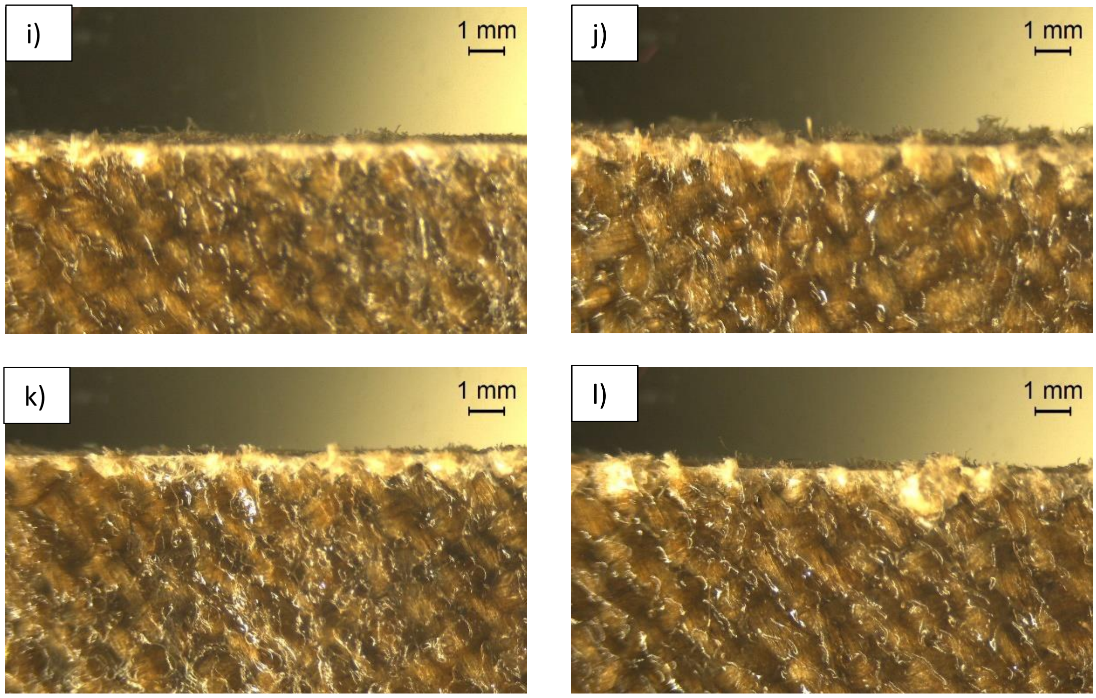
Figure 12 shows the influence of the cutting speed on the thrust force, finding a tendency contrary to that obtained in relation to the feed. According to this trend, increments in cutting speed result in a decrease in thrust force in all cases analyzed. Thus, the greatest variation obtained was 35.6 %, for a feed of 0.15 mm and a fiber orientation of 60°.

3.3. Surface Damage

The main damage found in each test has been measured through images obtained by a stereo microscope (Optika SZR). Figure 13 shows the fibers breakage derived from fraying, which is the main mode of damage that can be observed during the orthogonal cutting of this type of material. Moreover, no delamination or cracking was observed during the analysis. Thus, for the fiber orientations of 0° (especially in Figure 13.a)), it can be seen how there are several long uncut fibers on the surface (relative to the ones placed parallel to the cutting direction, while the fibers perpendicular to 0° appeared cut perfectly), which have been stretched and pulled during the orthogonal cutting test, instead of have been cut. This phenomenon explains why the cutting and thrust forces (Figure 6 and 8) for the orientation of 0° has been the lowest ones. On the contrary, the damage that can be observed in the workpieces of 45°, is the smallest of all analyzed (see for instance Figure 13.i) and k)) obtaining the highest values of cutting and thrust forces (Figure 6 and 10). The surface damage for the fiber orientations of 30° and 60° is intermediate between those obtained for 0° and 45°, being able to observe a clear fraying on its surface (see for instance Figure 13.g) and o)).

Regarding the evolution of the damage with the increase in the feed, a clear tendency can be observed for all the fiber orientations analyzed. Thus, by increasing the feed it is possible to observe an increase in fraying on the surface along the length of the cut. These results are consistent with those obtained by Chegdani et al. [32] during the orthogonal cutting tests of flax/polypropylene composites. Through SEM images as well as measuring the surface roughness after each test, they observed higher damage values in those workpieces with a greater feed. This is explained by the need to break the fiber, the more distance to the cutting edge of the free surface of the specimen less rigid is the layer of material to be removed and therefore, more difficult is to bring the fiber to the ultimate tension of breakage because it tends to buckling more easily. The influence of the cutting speed on the induced damage is not clear, none significant tendency was observed in the present results.





60°

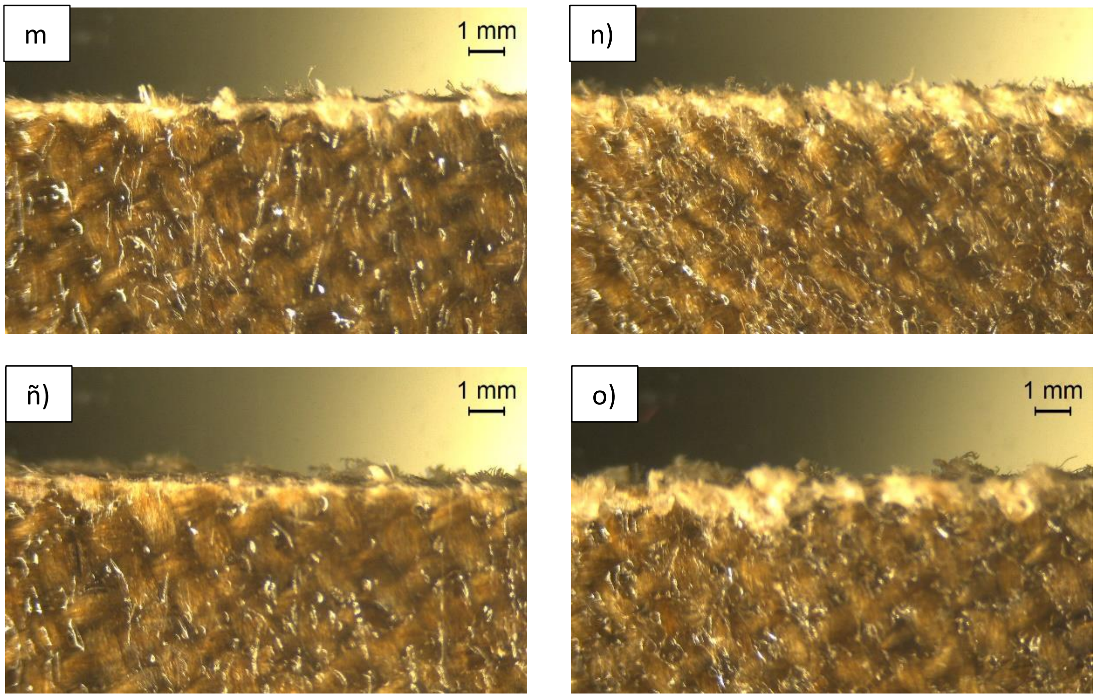


Figure 13. Damage surface for orthogonal tests on Flax/PLA at different cutting conditions and fiber orientations: a), e), i), and m) Vc = 15 m/min and feed of 0.05 mm; b), f), j), and n) Vc = 15 m/min and feed of 0.15 mm; c), g), k), and ñ) Vc = 120 m/min and feed of 0.05 mm; d), h), l), and o) Vc = 120 m/min and feed of 0.15 mm.

4. CONCLUSIONS

This paper has been focused on the analysis of the orthogonal cutting process on 100% biodegradable composites from flax fibers and PLA as matrix in different orientations.

The main contributions of the paper are summarized below:

One important contribution of the manuscript is the experimental data summarized relative to the orthogonal cutting of a 100% biocomposite under a large range of cutting speeds. This information may help to develop and to validate numerical model focus on more complex machining process as turning, drilling and milling.

The main conclusion is to highlight the fact that the best combination found in terms of surface integrity is the orientation of the fibers at 45°, where the fraying was the lowest found. However, for this orientation the required cutting forces were greater and therefore the expected wear on the tool.

Regarding the cutting parameters, it should be noted that the cutting speed did not significantly influence any of the orientations analyzed in the surface state of the specimen after machining, but not the forces, where increasing the cutting speeds, the cutting forces (cutting and thrust force) decreased.

- For all the orientations analyzed, the same tendency was fulfilled, according to which, increments in the cutting speed derives in a decrease in both the cutting and thrust force with maximum decreases of 49 % (feed of 0.1 mm and 0° of fiber orientation) and 35.8 % (feed of 0.15 mm and 60° of fiber orientation) respectively.
- About to the effect of the feed on the cutting and thrust forces, a great impact can be observed for all the cases analyzed. Thus, an increase in the feed results in an increase in both the cutting and thrust force, mainly due to the increase of material to be removed in each pass, being recorded increments of 61 % (cutting speed of 60 m/min and 60° of fiber orientation) and 62.5 % (cutting speed of 15 m/min and 30° of fiber orientation) respectively when passing from 0.05 to 0.15 mm of feed.
- Regarding the fiber orientation, highlight the fact that the best combination found in terms of surface integrity is the orientation of the fibers at 45° where the fraying was the lowest found. However, for this orientation the required cutting forces were greater and therefore the expected wear on the tool.
- Fraying has been observed as the main damage mode during the orthogonal cutting test on this type of material (Flax/PLA). Moreover, no delamination or cracking was observed during the analysis.
- The surface analysis shows several long uncut fibers on the surface fiber orientations of 0°, which have been stretched and pulled during test, instead of have been cut. This phenomenon explains why the cutting and thrust forces for the orientation of 0° has been the lowest ones. On the contrary, the damage that can be observed in the workpieces of 45°, is the smallest of all analyzed obtaining the highest values of cutting and thrust forces. The surface damage for the fiber orientations of 30° and 60° is intermediate between those obtained for 0° and 45°, being able to observe a clear fraying on its surface.
- The evolution of induced damage with feed shows a clear tendency for all the fiber orientations analyzed. Thus, by increasing the feed it is possible to observe an increase in fraying on the surface along the length of the cut. Nevertheless, the influence of the cutting speed on the generation of damage has not shown any significant trend.

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