



25<sup>th</sup> ABCM International Congress of Mechanical Engineering  
October 20-25, 2019, Uberlândia, MG, Brazil

## DRILLING IN NATURAL FIBER COMPOSITES WITH POLYURETHANE DERIVED FROM CASTOR OIL.

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**Abstract.** Composites made from natural fibers from waste crop or manufacturing processes appear as an alternative to non-renewable raw materials. The polyurethane derived from castor oil is a renewable and biodegradable material that can be used as matrix to obtain these composites used by industries such as furniture or building. Machining operations, including drilling, are necessary to enable the assembly of parts of the product. This work investigated the drilling process in three different types of composites, one with eucalyptus sawdust, one with pine nut shells and one with banana stem fibers, all with PU matrix derived from castor oil. Different drilling parameters were used and the hole quality obtained was verified by microscopy. The results showed that composites with smaller particle size and mechanically mixed presented better hole quality. A significant reduction of fiber fraying in banana stem fiber composite was observed at higher cutting speed and lower feed rate.

**Keywords:** Composites, Natural fibers, Drilling, Hole quality

### 1. INTRODUCTION

The growth of global environmental awareness about the use of non-renewable resources and the disposal of solid waste in the environment led to the development of materials such as composites that take vegetable fibers and biodegradable polymers as matrix (Ho et al, 2012). Although they do not have properties as high as synthetic fiber composites, they may find applications in low mechanical stresses such as furniture or building (Nassar et al, 2016). The polyurethane derived from castor oil is a renewable, biodegradable material and can be used as a matrix in composites (Cangemi et al, 2008). Among the natural fibers used in composites, the banana stem fiber is justified because it is obtained from the fruit picking residue (Satyanarayana et al, 2007), as well as the pine nut shell (Protzek et al, 2016). Eucalyptus sawdust is an unused residue from the wood cutting process (Kienen et al, 2017). The materials obtained with these composites require operations such as drilling to allow assembly of the products and this process can lead to defects such as layer delamination, fiber pull-out or insufficient fiber cutting (Patel et al, 2015). Research has been developed for drilling of composite using vegetable fibers with synthetic matrices (Nassar et al, 2017; Babu et al, 2013; Rezgui Maleki et al, 2019) and fully biodegrade polymers (Díaz-Álvarez et al, 2018; Bajpai et al, 2017), but studies for PU matrix composites derived from castor oil were not found.

Díaz-Álvarez et al (2018) analyzed drilling in natural fibers with PLA (Polylactic acid) matrix composite and concluded that cutting speed, feed rate, and drill angle are the main factors that contribute to damage in the holes, as well as the type of fiber used. Bajpai et al (2018) analyzed drilling behavior in natural fibers (sisal and *Grewia optiva* fiber) with PLA matrix composite in terms of drilling forces (thrust force and torque) and drilling-induced damage. He concluded that cutting speed, feed rate, and the drill geometry affect the drilling behavior. He pointed that drill geometry for synthetic fiber composite laminates is not suitable for natural fiber-reinforced laminates because of the difference in the material removal mechanisms.

The aim of this work is to analyse the drilling process with twist drill on three different types of natural fiber composites (eucalyptus sawdust, pine nut shells and banana stem fiber) with polyurethane derived from castor oil matrix taking in consider the quality of the drilled holes.

## 2. EXPERIMENTAL PROCEDURE

The two-component PU AG101 from Kehl Company was used as composite matrix followed the manufacturer's instructions in the 1: 1 weight ratio. The fibers of the banana tree from Parana state coastline was hand-divided into strips and they were dried naturally for seven days protected from climate action, without the aid of equipment. After, they were cut manually into pieces and kept in an oven for approximately 24 hours at 60 ° C. The pine nut shell was a donation from Embrapa Florestas. These shells were put into a stove at 100°C by 24 hour. After that, they were mashed by a kinetic mixer and were not undergone chemical treatment. The eucalyptus sawdust came from furniture factory in the Curitiba region; it was separated from the wood chips, sieved with 200 mesh and kept in an oven at 50°C.

The PU/banana stem composite was obtained by using the same process described in Ellenberger et al. (2017). For the composite PU/pine nut shell fibers the procedures presented by Protzek et al (2016) were followed, using the proportion of 50% fibers and 50% PU. For the composite PU/eucalyptus sawdust the procedures adopted in the work of Kienen et al. (2017) were followed. Density analysis was performed according to EN317: 2002. Mechanical characterization was performed using the three-point flexural test according to ASTM D790-03 using a universal EMIC DL10000 test machine with a load cell of 5 kN and a test speed of 2 mm / min .

Drillings were performed on a 3-axes CNC milling machine Brand Vetor CNC model FR2012 using a 5 mm diameter HSS twist drill, point angle 118° with two teeth. Spindle speed was measured with an Icel digital TC-5010 laser tachometer. Cutting speed ( $V_c$ ) and feed rate ( $V_f$ ) values for drilling were based on previous works on drilling similar composites (Patel et al, 2017; Babu et al, 2013). Three drillings were performed for each parameter. Drill holes quality was observed by Evo MA15 scanning electron microscope and Olympus SZX10 optical microscope.

The internal and external damages were observed and measured at the holes. The external damages at the nominal diameter were calculated by the ratio between the maximum diameter of the damage and the nominal diameter of the hole obtaining the damage factor (Fd), as used by Diaz-Álvarez et al (2018). The internal damages at the nominal diameter were obtained by calculating the compromised area of the hole (Figure 1) as used by Davim et al (2007). The damage areas were obtained by the images of the holes captured by microscope and treated in GIMP 2.10.6 and Inkscape software for color adjustment, edge detection and bitmaps creation. Autocad 2019 Student version software was used to calculate the compromised internal area. Hole damages were evaluated at drill entry and exit.

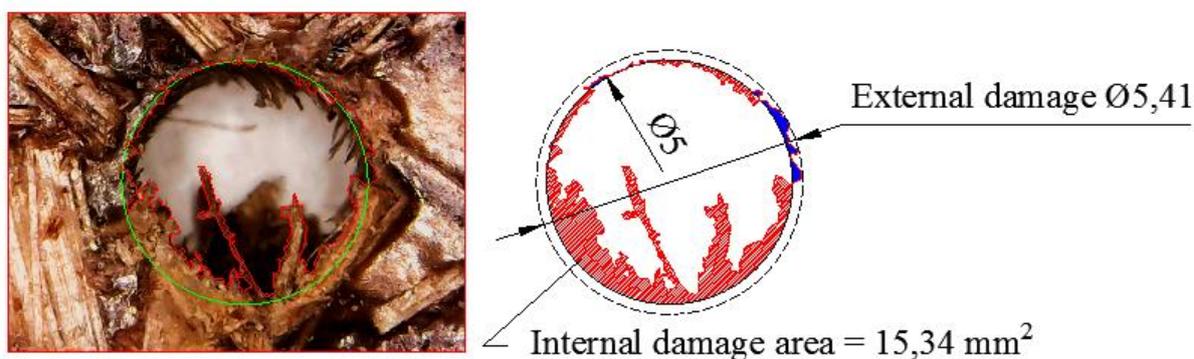


Figure 1. Process of detection and measurement of the defects at drill entry in test 3.

## 3. RESULTS

### 3.1 Materials characterization

Table 1 shows the density and maximum tensile bending stress for the composites. PU/banana composite showed the lowest result of bending stress using a manual process of cutting fibers and mixing. On the other hand, the pine and eucalyptus that used mechanically crushed fibers and mixing presented better fiber/matrix interface resulting in higher resistance.

Table 1. Properties of composite materials

Composites	Banana stem (ELLENBERGER et al, 2017)	Pine nut shell (PROTZEK et al, 2016)	Eucalyptus sawdust (KIENEN et al, 2017)
Density	(710.0±30)kg/m <sup>3</sup>	(1161,70±46,65)kg/m <sup>3</sup>	(670±45)kg/m <sup>3</sup>
Maximum tensile bending stress	3,51 MPa	20.55 MPa	38,62 MPa

Figure 2 shows the fiber-matrix interface of (a) banana stem, (b) pine nut shell and (c) eucalyptus sawdust composites. As noted in the material properties, the composite of pine nut has fewer voids between the fibers with higher density than the other two composites.

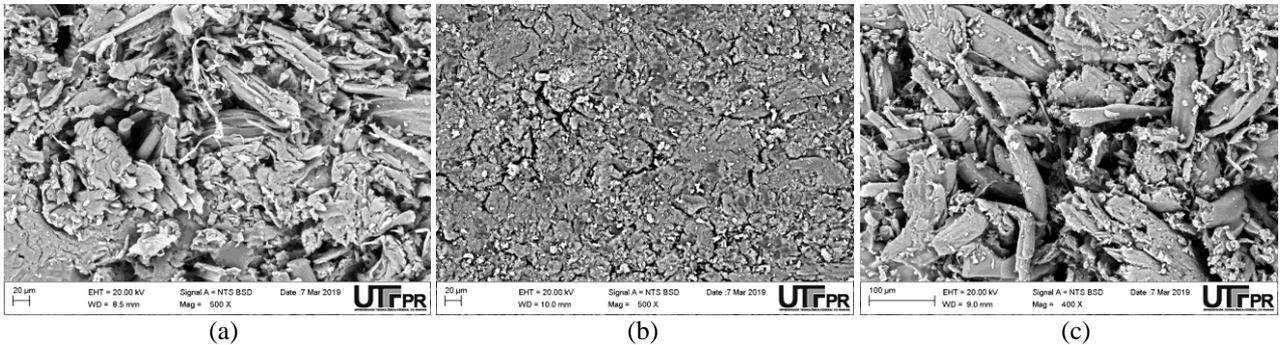


Figure 2. Fiber-matrix interface at (a) banana stem, (b) pine nut shell and (c) eucalyptus sawdust composites.

### 3.2 Damages

Figure 3 shows drilling parameters used and the finishing condition of the holes at the drill entry and exit. Banana stem fibers composite presented the worst visual results.

Test	Cutting speed (m/min)	Spindle speed (RPM)	Feed rate (mm/rev)	Banana stem		Eucalyptus sawdust		Pine nut shell	
				Drill entry (pell-up)	Drill exit (push-out)	Drill entry (pell-up)	Drill exit (push-out)	Drill entry (pell-up)	Drill exit (push-out)
1	15,7	1000	0,30						
2	15,7	1000	0,20						
3	23,5	1500	0,20						
4	31,4	2000	0,15						
5	23,5	1500	0,13						
6	15,7	1000	0,10						
7	31,4	2000	0,10						
8	23,5	1500	0,06						
9	31,4	2000	0,05						

Figure 3. Drilling parameters and holes aspect.

Figure 4 shows the damage factor (Fd) values for drill entry (a) and exit (b) around de nominal hole area. Damage factor (Fd) values were found between 1.01 and 1.12, similar to those found in drilling of composites with natural fibers (Diaz-Álvarez et al, 2018; Bajpai et al, 2015). Composite with eucalyptus fibers presented better results, maintaining constant values, except for feed rate 0.06 and 0.05 mm/rev where a trend of increasing damage factor was observed at drill entry. The pine nut and banana fibers showed oscillation in the results. Pine nut showed a great oscillation in drill exit for feed rate 0.10 mm/rev with spindle speed 2000 rpm (test 7). Best results were achieved for feed rate between 0.20 and 0.13 mm/rev (tests 3,4 and 5) at drill entry and feed rate 0.20 mm/rev (test 2) at drill exit, except for eucalyptus with 0.10 mm/rev (test 6).

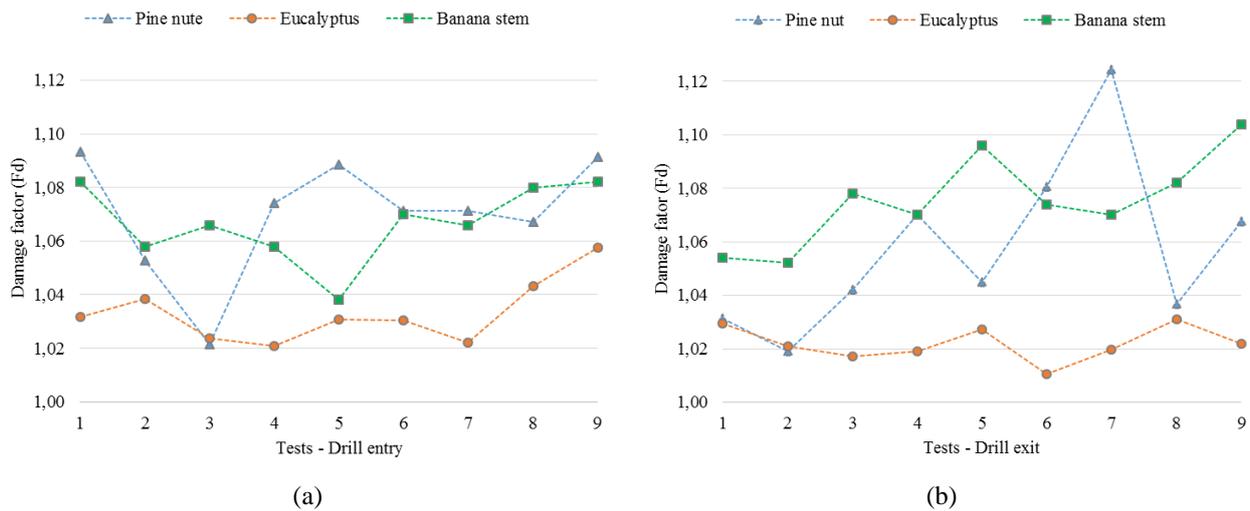


Figure 4. Damage factor at (a) drill entry and (b) exit.

Damage values found are influenced by the fiber fracture process during contact with the cutting edge of the drill bit. This process can cause the fiber to bend or be torn away from the last layer. When folded, it can open cracks in the matrix, and when torn away leaves void spaces, contributing to increase the value of the nominal diameter of the hole, as shown in Figure 5. This behavior was observed in the three types of composites.

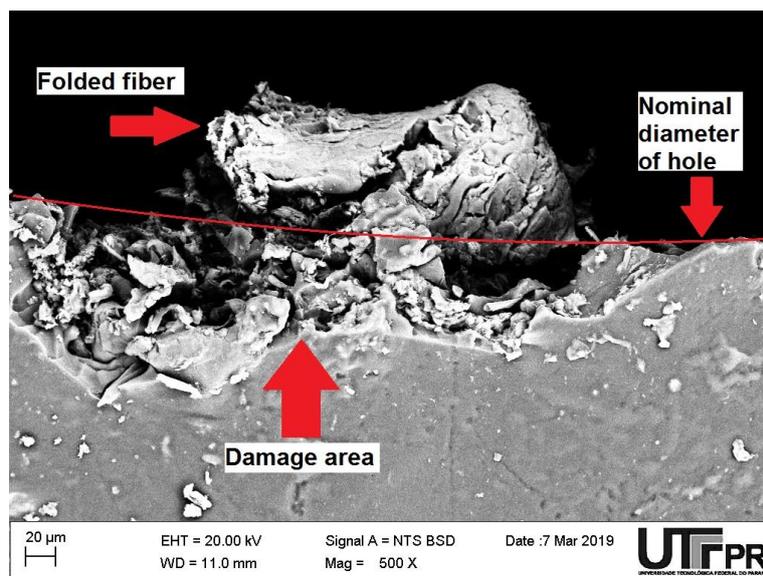


Figure 5. External damage to nominal diameter at the entrance of the composite drill with pine nut shell .

The compromised internal areas were measured and are shown in Figure 6 a (drill entry) and b (drill exit). The composite with pine nut fiber showed the lowest values of area compromised followed by the composite with eucalyptus fibers. Both showed constant results without interfering tendencies in the different cutting speed and feed rate parameters. The composite with banana stem fibers were the ones that presented the highest compromised internal

area values of the hole, both in the entrance and in the exit. In this composite a significant improvement was observed in test 7 with feed rate 0.06 mm/rev and higher cutting speed (31,4 m/min).

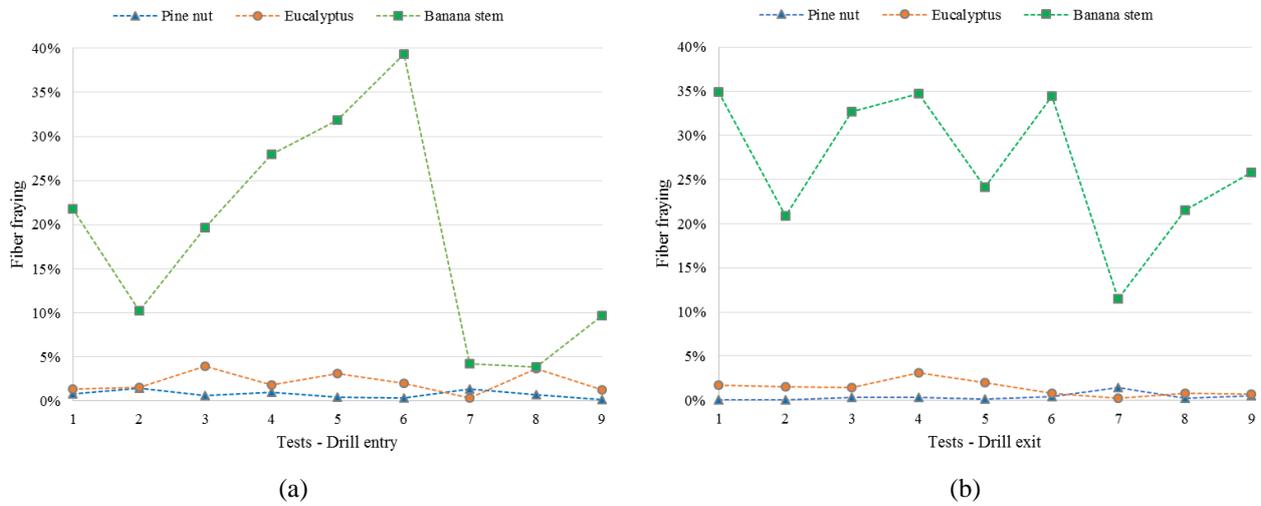


Figure 6. Internal damage area at drill (a) entry and (b) exit.

Defects in drilling natural fiber composites are described in the literature as a result of the entry and exit of the drill (Chegdani et al, 2015; Nassar et al, 2017; Díaz-Álvarez et al, 2018). At the entry, the drill bit upon contact with the free surface of the composite generates a pulling force in the axial direction of the tool through the inclination of the helical grooves, forcing the fibers upwards and avoiding the fracture by the cutting edge. With this, a complete fracture of the fiber does not occur. Also natural fibers have a viscoelastic behavior and when they come into contact with the cutting edge of the drill, they bend, avoiding the fracture, often breaking the fiber/matrix interface and returning to the initial position, as pointed out by Chegdani et al (2015). Figure 7 shows the detail of a non-fractured fiber on the drill entry of banana stem composite.

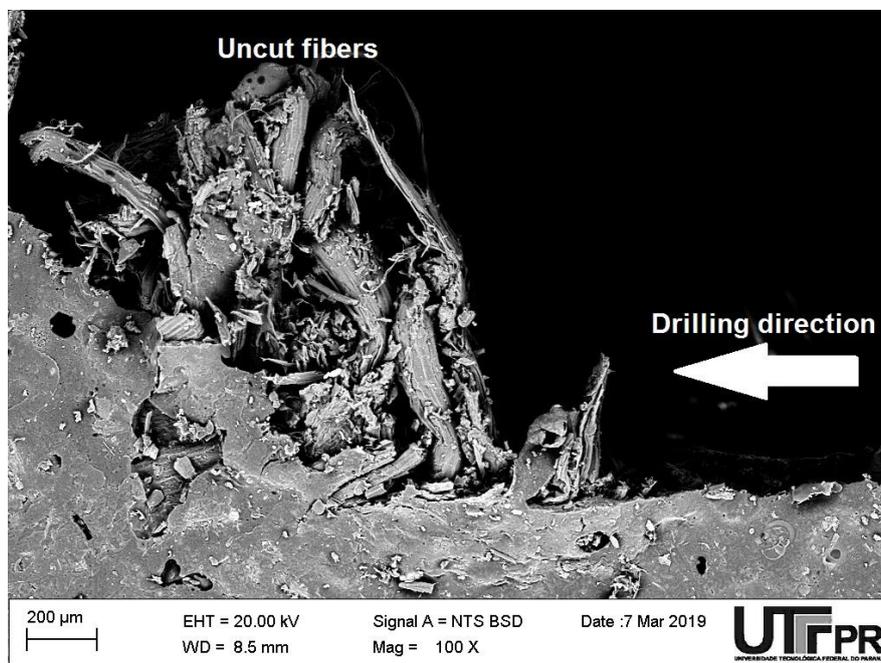


Figure 7. Uncut fibers under hole area in banana stem composite.

At the output, as the thickness becomes thinner, the deformation resistance becomes smaller and the forces involved in the process exceed the fiber/matrix interface strength forcing the delamination, as described by Nassar et al. (2016).

In this work, no delamination of layers was observed both at the drill entry and exit. However, the same process of the drill entry occurred in the drill exit, with some fibers not being completely fractured and remaining on the nominal area of the hole compromising the quality. Figure 8 shows an example of fiber fraying at drill exit in banana stem composite.

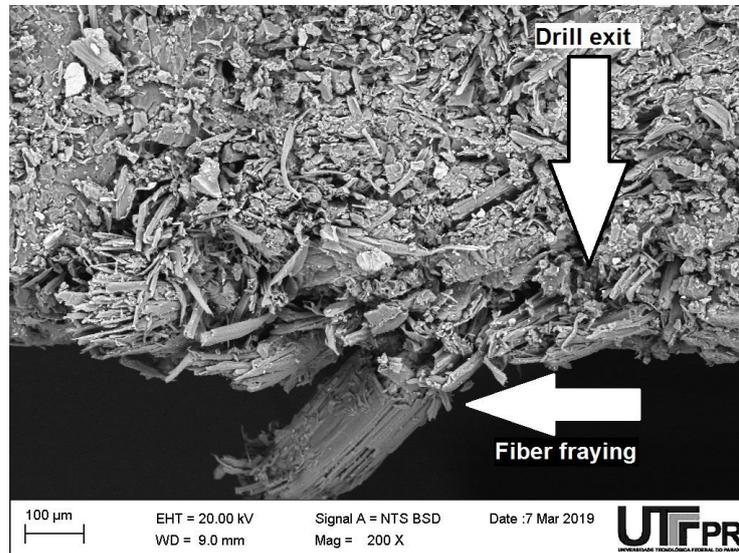


Figure 8. Aspect of uncut fibers in drill exit of banana stem composite.

This behavior causes the non-fractured fibers to remain over the hole, causing the defective appearance and may hinder the passage of fastening hardware. Manual fiber cutting process in banana composite leads to different sizes of pieces, making the cutting edge fracture difficult due to the natural interface in the fiber pieces, increasing the tendency of fiber fraying over the hole.

Eucalyptus sawdust and pine nut shell composites presented better results compared to the composite with banana stem fibers, regardless of the parameter used. These two composites used fibers ground in mechanical process resulting in small dimension fibers compare to hand-made cut of banana stem fibers. With this, drilling process was better performed, presenting few chipped fibers. Although some fibers did not fractured by the action of the drill, the hole quality was not compromise as much as the fiber of the banana stem composite due to smaller fiber dimensions.

Figure 9 shows the details of the entry edge of the drill bit in the composite with eucalyptus sawdust (a) and pine nut shell (b) fibers. Damages generated do not cause representative variations in the damage factor.

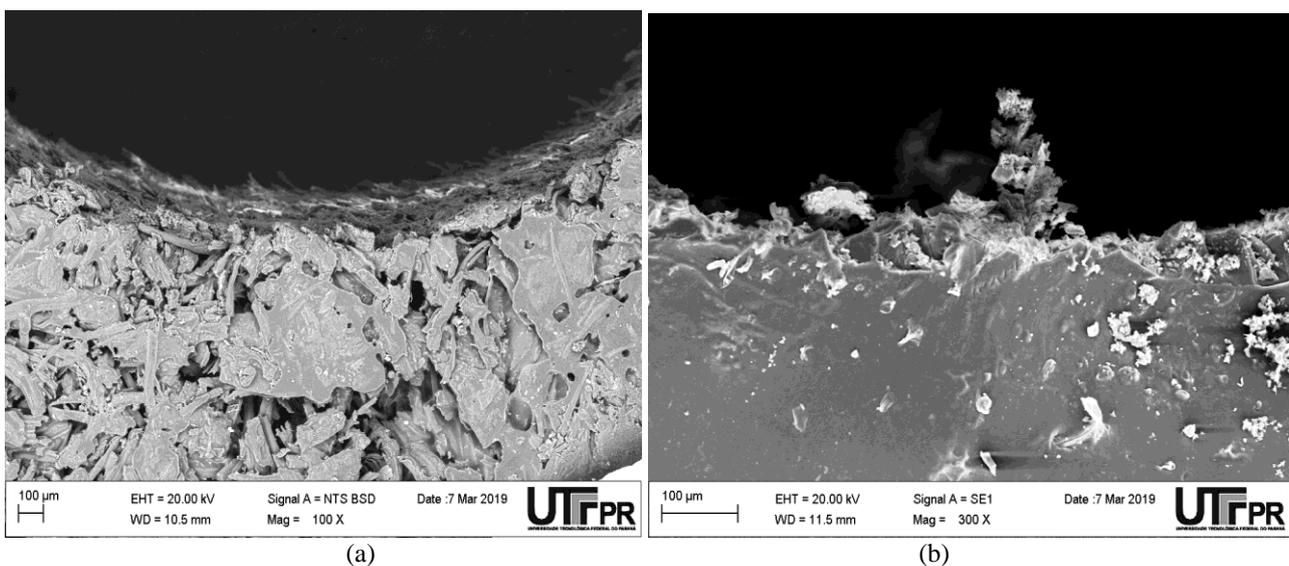


Figure 9. SEM of a detail from (a) eucalyptus sawdust and (b) pine nut shell edge hole composites.

#### 4. CONCLUSIONS

Natural fiber composites used in this research showed properties that allow their use in parts that do not receive a great mechanical load, as in decorative or furniture pieces. The size of the fiber used influences the properties of the final composite and its fiber-matrix interface as also influenced the results of the drilled holes in terms of the damage factor and the fiber fraying.

It was observed that higher cutting speed with intermediate feed rate obtained better results in the damage factor around nominal hole diameter at drill entry. At drill exit better results were obtained by using lower cutting speed with intermediate feed rate.

Pine nut fiber mechanically ground and the eucalyptus fiber obtained from the wood sawing process presented better results in the internal fiber fraying due to the smaller fiber dimensions compared to the banana fiber composite. A significant reduction of fiber fraying in banana stem fiber composite was observed at higher cutting speed and lower feed rate.

The viscoelastic behavior of the natural fibers used also contributed to the formation of the defects that were shown in this work. The highest compromise value of internal hole area in banana stem fiber composite can lead to a difficulty in the passage of fasteners used for assemblies with parts that uses this kind of material. Authors are working on the manufacture of this composite with smaller particle size for future evaluation of drill quality.

#### 5. ACKNOWLEDGEMENTS

The authors would like to thank CAPES, CNPQ, Araucária Foundation, Multi-User Center for Materials Characterization - CMCM of UTFPR-CT, Laboratory of Polymers and Composites – LAPOC of UTFPR-CT, Prototypes Laboratory - Academic Department of Industrial Design – DADIN of UTFPR-CT and Embrapa Florestas.

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