Cutting behavior of flax fibers as reinforcement of biocomposite structures involving multiscale hygrometric shear

Faissal Chegdani[a] *, Mohamed El Mansori[a,b], Amen-Allah Chebbi[a]

[a] Arts et Métiers Institute of Technology, MSMP, HESAM Université, F-51006 Châlons-en-Champagne, France;

[b] Texas A&M Engineering Experiment Station, Institute for Manufacturing Systems, College Station, TX 77843, USA.

ABSTRACT

This paper aims to investigate the effect of water absorption on the cutting behavior of biocomposites using flax fiber reinforced polylactic-acid (PLA) and the orthogonal cutting process. Different immersion times have been considered from 1 to 150 days in order to investigate both transient and saturated hygrometric regimes. Machining forces are measured during the cutting process and the machined surfaces are analyzed using a scanning electron microscope and an optical interferometer. The in-situ removed chip morphologies are captured by a high-speed camera. Results show a functional relationship between the multiscale hygro-mechanical properties of flax fiber composites and their shear mechanisms that are controlled by the water content. The water uptake modifies the cellulosic structure of natural flax fibers in the transient regime and damages the fiber/matrix interfaces in the saturated regime, which affects considerably the cutting mechanisms and the machinability of the biocomposite structure at different scale levels.

KEYWORDS

A. Biocomposite; B. Environmental degradation; D. Surface analysis; E. Machining

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* corresponding author (F. Chegdani)

- E-mail: faissal.chegdani@ensam.eu
- ORCID: 0000-0002-7643-9701
- Phone: +33 3 26 69 91 81

1 Introduction

The use of natural fiber composites is nowadays highly recommended in many engineering applications for different industrial sectors due to their technical and eco-friendly properties [1–6]. When biocomposite materials are made with long natural fiber reinforcement, machining remains an essential process to finish and transform the industrial biocomposite part toward its desired engineering functionality [7]. However, the machining behavior of natural fiber composites is not similar to that of synthetic fiber composites because natural fibers are characterized by a multiscale cellulosic structure (from nanoscale of cellulose to mesoscale of fiber bundles [6]) that engenders critical issues in biocomposite materials such as poor wettability, degradation at the fiber/matrix interface, and damage of the fiber during manufacturing processes [8].

Many research works have thus been performed to investigate the cutting behavior of natural fiber composites using different machining processes such as drilling [9–12], milling [13,14], and orthogonal cutting [15–17]. It has been found that the cutting behavior of natural fiber composites is different from that of synthetic fiber composites in terms of chip formation, fiber shearing, and interfaces' fracture [15]. The removed chip of natural fiber composites remains continuous for a wide range of cutting conditions, while the chip curling is reduced when increasing the cutting speed and/or the cutting depth [15,16]. This chip formation behavior is different from that of synthetic fiber composites that may have a discontinuous chip at dry and high loading cutting conditions [18–20]. Unlike synthetic fibers that have linear elastic behavior with a brittle fracture [21,22], the cutting behavior of natural fiber composites results from the combined ductility of natural fibers and polymer matrix that induces a ductile behavior of the resulting composites at large loading conditions, avoiding hence a brittle fracture of the biocomposite and a premature failure of the interfaces [15,16].

However, the complex cellulosic structure of natural fibers makes the machinability of biocomposites highly sensitive to their multiscale anisotropy. Typically, the effect of fiber orientation has been revealed as highly significant on the machinability of biocomposites [16,23]. Indeed, the cellulose microfibrils are oriented toward the fiber axis, which provides largely higher fiber stiffness in the longitudinal direction comparing to the transverse direction of the fiber. Hence, the transverse fiber direction suffers from high transverse elasticity, which causes a transverse deformation of fibers before being sheared during the cutting process, provoking hence uncut fiber extremities and interfaces' fracture in form of debonding zones, especially when natural fibers are not enough stiff to encounter the transverse deformation [24]. However, and even natural fibers are oriented perpendicular to the cutting feed direction, the longitudinal fiber stiffness contributes to the cutting behavior by enhancing the shear efficiency and reducing the interfaces' fracture as shown in [24] by changing the fiber type, and in [25] by lowering the fiber temperature. Indeed, even if the cutting feed is in the transverse direction of the fiber, the cutting tool solicits the fiber in longitudinal and transverse directions because the shear force is inclined toward the cutting feed direction whatever the fiber orientation as shown in [16]. In particular, for fiber orientation values of 0°, 45°, and 90° with respect to the cutting feed direction, it has been found that the shear angle between the shear force direction and the cutting feed direction is equal respectively to 35.3°, 40°, and 43.5°. Consequently, for a fiber orientation of 90°, the resulting shear force is not perpendicular to the longitudinal fiber direction even though the cutting feed direction is perpendicular to the longitudinal fiber direction. The fiber orientation of 45°, for which the shear force direction is the nearest to the longitudinal fiber direction, induces the most efficient shearing of fibers during the machining operation [16]. It can be concluded that both longitudinal and transverse properties of natural fibers should be considered to investigate the machinability of biocomposites structures.

The multiscale anisotropy of natural fibers is related to their chemical composition that includes cellulose, hemicellulose, pectin, lignin, waxes, and water in form of moisture content [26]. Each chemical component influences the mechanical properties of the natural elementary fiber, typically the moisture content that has been assessed between 8% and 10% of the fiber weight [26]. This moisture content is reduced during the manufacturing process of the composites because of the high temperatures used for the molding but it is recovered after processing from the humidity of the storage environment [27]. The moisture content can affect considerably the mechanical properties of natural fiber because water molecules act as a plasticizer in the cellulosic structure of natural fibers [28]. Therefore, this hygrometric parameter should be considered in the machinability investigation of natural fiber composites.

In this paper, the hygro-mechanical properties of natural fibers are first outlined from the literature review to apprehend the different hygrometric phenomena arisen in natural fibers, polymer matrix, and interfaces. Then, the hygrometric effect on the machinability of natural fiber composites is investigated on a biocomposite structure including unidirectional flax fibers and polylactic-acid (PLA) polymer matrix. The hygrometric variation is carried out by immersing the composite samples in water for different immersion times. Machining operations are performed using the orthogonal cutting process. Chip formation, machining forces, scanning electron microscope (SEM) observations, and topographic measurements of machined surfaces are considered to evaluate the influence of water content on the machinability and the cutting mechanisms of flax fibers reinforced PLA composites.

2 Hygro-mechanical properties of natural fiber composites: An overview

The hygrometric effect on the mechanical properties of natural fiber composites has mainly been investigated in the literature using water immersion because it is the most aggressive method for water absorption in natural fiber composites [29]. Flax fiber reinforced thermoset epoxy composites are the most considered material in the hygro-mechanical investigations [30–36]. Another thermoset matrix type was considered in literature when investigating the effect of water absorption on the fracture properties of flax fiber reinforced vinyl ester composites [37,38]. For thermoplastic matrices, a hygro-mechanical study has been performed on flax fiber reinforced acrylic composites [34], flax fiber reinforced bio-based PLA composites [39], and fine particles of different natural chopped fibers as a filler for bio-polyethylene composites [40]. The hygro-mechanical properties of single natural elementary fibers have also been investigated with flax fibers [41] and hemp fibers [42].

Figure 1 illustrates an overview of water content and elastic modulus evolution in function of water immersion time for unidirectional long flax fiber reinforced epoxy composites (compared to unidirectional long glass fiber reinforced epoxy composites) and random short flax fiber reinforced PLA composites. In general, the effect of water content follows the Fick’s law despite the neat epoxy where the water content generates a quasi-linear behavior. From Figure 1(a,b), it can be clearly seen the strong impact of natural fibers on the water absorption process. Both epoxy and PLA matrices generate very low water content without natural fibrous reinforcement (about 1%). Increasing the volume fraction of flax fibers increases significantly the water content in the composite. However, glass fibers do not influence the water absorption because the water content of epoxy matrix reinforced with 40%vt of unidirectional glass fibers has been found equal to 1.05% at saturation [32] which is similar to the water content of the neat epoxy shown in Figure 1(a). From all these results, it can be concluded that natural flax fibers are the main responsible for the water absorption mechanism and moisture content in the composite.

The influence of water content on the elastic modulus is shown in Figure 1(c,d). It can be seen that the effect of water immersion time on the elastic modulus of neat epoxy, neat PLA, and glass fiber reinforced epoxy composite is negligible since the water content of these three materials does not exceed 1.05% at saturation. For flax fiber composites, increasing the water immersion time decreases the elastic modulus of the composite. This hygrometric effect is as more intense as the volume fraction of flax fibers is high and it is valid for natural fiber reinforced thermoset [32,33] and thermoplastic [39] composites.

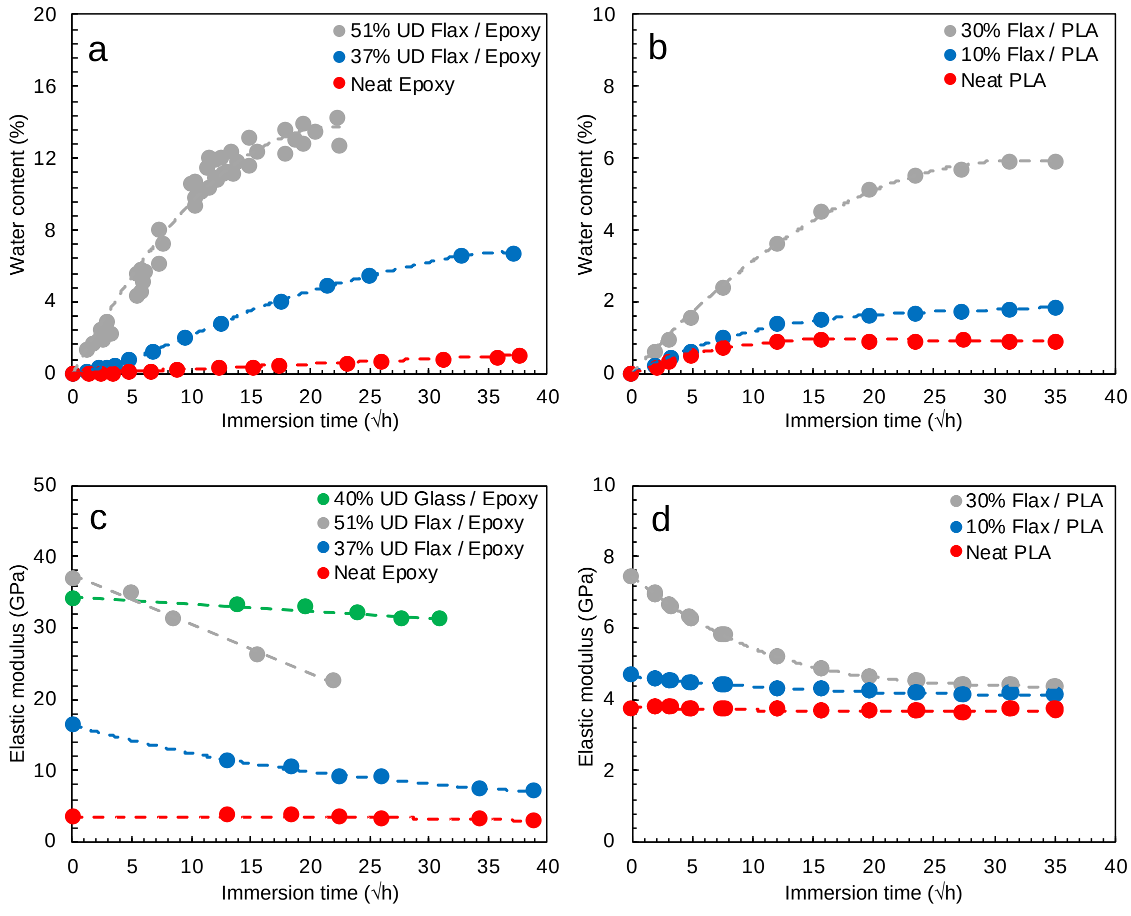

Figure 1: Hygrometric effect on water content and elastic modulus of natural fiber composites. Figures are reproduced from data of [32,33,39]

The water content does not affect only the elastic modulus but also the tensile strength and the failure strain. It has been shown that water uptake increases the failure strain [32–34,36]. The decrease of the elastic modulus and the increase of the failure strain were attributed to the plasticization of the composite constituents caused by the infiltration of water molecules that can be bonded with the hydroxyl groups in the hydrophilic components of flax fibers and act thus as a plasticizer, which makes the material more ductile [34,43,44]. However, the literature reported divergent outcomes about the hygrometric effect on the tensile strength. Indeed, while some studies show a decrease of both the elastic modulus and the tensile strength in function of the water aging time [32,34–36,45], other investigations demonstrate also a decrease of the elastic modulus but an increase of the tensile strength [31,33,46]. The decrease of the tensile strength on natural fiber composites with water aging has been explained in literature by a multiscale degradation of the composites' structure. On one hand, the fiber structure is composed of stacking of cellulosic cell-walls and water can directly affect the hydrophilic constituents of the flax fiber and then weakens the interface between these cell-walls which leads to damage the fiber [34]. On the other hand, the decrease of the tensile strength can also be due to the weakening of fiber-matrix interfaces because of water aging that contributes to the hydrolysis of the polymer matrix and thus the breakage of its molecular chain [47]. The increase of the tensile strength is attributed to the swelling of flax fibers within the composite structure as a result of water absorption, which can strengthen the interfacial bonding between fibers and matrix due to the hygrometric fiber expansion [27,31,44]. Nevertheless, it has been shown that even if the tensile strength increases with water content, the interlaminar shear strength decreases with water content [33]. Therefore, the hypothesis of enhancing the interfacial properties with the hygrometric fiber expansion appears to be questionable. The most probable explanation for the increase in mechanical strength with water content is related to the cellulosic structure of natural fibers. Indeed, the hygro-mechanical behavior of natural fibers has been investigated with elementary flax and hemp fibers [41,42]. These studies have demonstrated that tensile modulus and strength of natural fibers increase by increasing the relative humidity (i.e. the water content). This behavior is explained by the rearrangement of the cellulosic structure. It is well known that natural fibers, typically plant fibers, are mechanically controlled by the secondary cell-wall (S2) where the cellulose microfibrils are embedded in an amorphous natural matrix and are oriented from the fiber axis with a microfibrillar angle that is around 10º for flax fibers and 6º for hemp fibers [26,48]. Water absorption could induce plasticizing of the amorphous matrix because of water adsorption and the creep of cellulose microfibrils in the relaxed amorphous matrix after a certain water uptake threshold, leading to their re-arrangement, with more parallel orientations with respect to the fiber axis which increases the elastic modulus and the tensile strength of the fiber [41,42].

It can be concluded from this review section that the moisture content affects differently the mechanical properties of natural fiber composites at different scale levels, from the nanoscale of cellulose microfibrils to the macroscale of the overall biocomposite structure, passing by the microscale of natural elementary fibers and interfaces. This specific multiscale hygrometric behavior of natural fiber composites will be considered in this paper to investigate their machinability.

3 Materials and methods

3.1 biocomposite material and water immersion

The biocomposite material used in this study is provided by "*Kairos Biocomposites – France*". The samples are manufactured by stacking 10 layers of a unidirectional non-woven flax fabric and 11 layers of PLA thin films using the thermo-compression technique. The density of the flax fabric is 110 g/m^2. PLA layers have a thickness of 250 µm and a density of 285 g/m^2. biocomposite plates of flax/PLA are performed with 200 ºC of molding temperature and 1 bar of mold pressure for 5 min. Then the cooling process is executed at 7 bars of mold pressure from 200 ºC to 25 ºC in 5 min. Flax/PLA composite workpieces used for the machining experiments have the dimensions of 30 × 20 × 3.5 mm^3. The fiber volume fraction is estimated to be equal to 23.7% using the equation (1) [49] where m_f and m_c are the mass of the flax fiber fabric and the composite, respectively. ρ_f= 1.4 g/cm^3 and ρ_m= 1.24 g/cm^3 are the density of flax fibers and the polymer matrix, respectively [39].

$$V_f = \frac{1}{1+\left(\frac{m_c-m_f}{m_f}\right)\left(\frac{\rho_f}{\rho_m}\right)} \qquad (1)$$

To investigate the effect of water content on the machinability of flax/PLA composites, the samples are immersed in tap water for different durations from 1 day to 150 days at a constant room temperature of 25 ºC. The detailed hygrometric parameters are presented in Table 1. Reference samples are used to evaluate the water content after each considered immersion time where 4 samples are considered for each configuration to assure the repeatability of the results. Each sample is taken out of the water and wiped just before the cutting operation to ensure the water content of the hygrometric condition.

3.2 Orthogonal cutting and surface analysis setup

Orthogonal cutting tests are made on a shaper machine (GSP – EL 136) with a carbide cutting insert (Sandvik – TCGX 16 T3 04 – AL H10) as shown in Figure 2. Cutting forces (F_c) and thrust forces (F_t) are measured using a piezoelectric dynamometer (Kistler – 9255B) that is connected to a multichannel charge amplifier (model 5019 B131) and a data acquisition board using the Labview software and a sampling rate of 10,000 Hz. To highlight the in-situ chip formation mechanisms during cutting, a high-speed camera (FASTCAM SA5 CCD) is used to record optical frames at an acquisition rate of 20,000 frames per second. The machined surfaces are then observed at a microscale using the scanning electron microscope (SEM) at low vacuum mode (JEOL – 5510LV). 3D topographic surface variations were measured by a three-dimensional optical interferometer (WYKO 3300NT). The orientation of unidirectional flax fibers is perpendicular to the cutting direction. Table 1 summarizes the machining parameters used for orthogonal cutting experiments. Each cutting configuration is tested at least three times to assure repeatability. Thus, the final outputs from the orthogonal cutting experiments are presented as the mean value of these three repeated tests. Measurement errors are considered as the average of the absolute deviations of data repeatability tests from their mean.

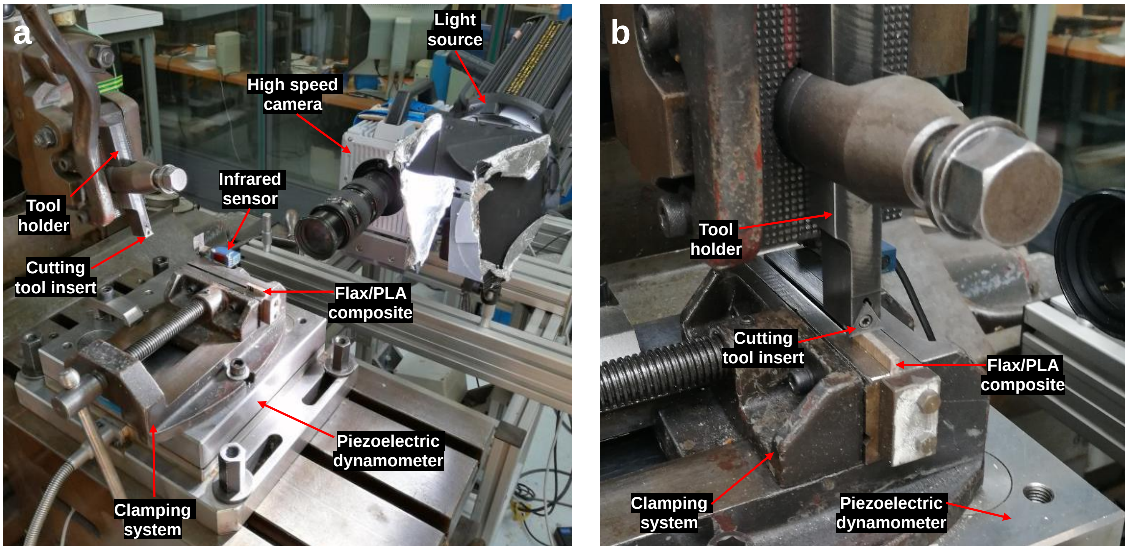

Figure 2: (a) Image of the experimental setup of the orthogonal cutting tests. (b) Zoom on the cutting zone.

Table 1: Machining and hygrometric parameters used for orthogonal cutting experiments

Parameter	Value	Unit
Tool rake angle (γ)	20	Degree °
Tool clearance angle (α)	7	Degree °
Tool edge radius (r_ε)	12	µm
Cutting speed (V_c)	50	m/min
Fiber orientation (θ)	90	Degree °
Cutting depth (a_p)	100 / 200 / 300	µm
Water immersion time (t_{im})	1 / 2 / 7 / 14 / 21 / 30 / 60 / 90 / 120 / 150	Day

4 Results and discussion

4.1 Hygrometric effect on the water content

Figure 3 presents the water content of flax/PLA samples after different water immersion times. The water content rate (W_c (%)) is calculated using the equation (2) where M_i is the initial sample mass and M_f is the sample mass after the water immersion.

$$W_c = \frac{M_f - M_i}{M_i} \times 100 \quad (2)$$

It is important to note that the so-called water content in this section is properly related to the water immersion process. Indeed, natural fibers can also absorb water from the ambient environment. Therefore, it should be an initial water content before water immersion that is not considered in this hygrometric investigation.

It can be seen that the water content increases by increasing the water immersion time until reaching the saturation of the composite samples. Then, the water content remains almost constant. The water content behavior of flax/PLA composites corresponds to Fick's law where the saturation is reached after about 21 days of water immersion. This corresponds to the saturation time of flax/PLA shown from literature in Figure 1(b) which is about 23 days. However, a difference in water content at saturation is noticed. Indeed, the flax/PLA composite investigated in this study generates about 8% of water content at saturation with 23.7% of fiber volume fraction while Figure 1(b) shows that flax/PLA generates about 1.8% and 6% of water content at saturation with 10% and 30% of fiber volume fraction, respectively. This difference in water content at saturation is probably due to the structure of the natural fibrous reinforcement. Flax/PLA used in Figure 1 is composed of short fibers while flax fibers used in this study are long, unidirectional, and continuous. For short fiber structure, only flax fibers located on the sample surfaces are directly exposed to water. Short fibers are provided with water from PLA diffusion that is low as shown in Figure 1(b). For long fiber structures, the extremities of fibers are directly exposed to water on the sample surfaces which caused more water absorption and diffusion in flax fibers by capillarity. Note that the moisture content in a humid environment of single flax fibers is between 10% and 14% depending on the applied fiber treatment [41]. For flax/PLA composites, the moisture content is reduced because the polymer matrix avoids direct exposure to the humid environment. Moreover, the polymer matrix avoids an important swelling of flax fibers that could allow more water uptake.

Figure 1(d) shows that the mechanical properties of flax/PLA composites decrease in the transient regime and become steady in the saturated regime. For this reason, the machining behavior in transient and saturated regimes of flax/PLA composites will be investigated separately in the next sections.

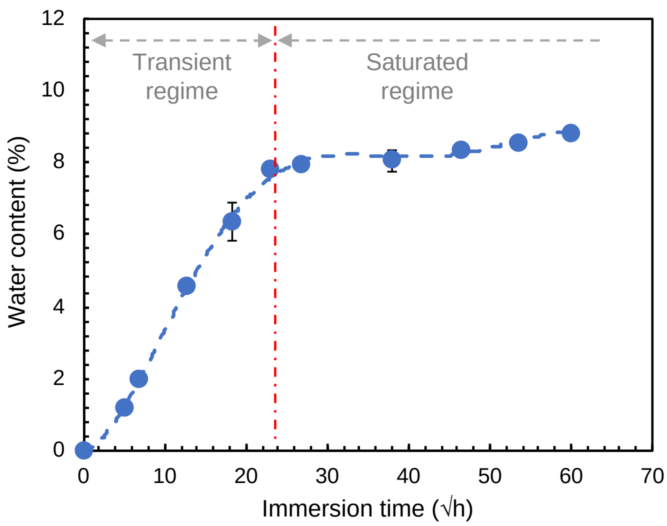

Figure 3: Evolution of water content rate in flax/PLA composites in function of water immersion time

4.2 Hygrometric effect on the chip formation

Figure 4 shows the chip morphology for different hygrometric configurations. Flax/PLA samples have not the same appearance on the high-speed camera images when increasing the water immersion time. Without water immersion, flax fibers are clearly obvious on the high-speed camera images as shown in Figure 4(a,e). By increasing the water content, flax fibers disappear from the high-speed camera images which means that flax fibers have absorbed water and changed the color to be like the color of the PLA matrix (Figure 4(d,h)).

The water uptake has a significant effect on the chip morphology. In the transient hygrometric regime, the chip curling increases significantly by increasing the water immersion time. This indicates an important modification on the tribo-mechanical properties of flax/PLA composites due to the water uptake. Indeed, in the context of machining science, the cause of chip curling is due to the bending moment formed at the deformation zone, owing to the non-collinearity of the resultant force on the rake face and the resisting force on the shear plane [50,51]. The bending moment required to change the radius of the chip curvature is called the "fully plastic bending moment" (M_{fp}) and it is given by the following the equation (3) where σ_0 is the flow stress, b is the chip width, and t_c is the chip thickness [50].

$$M_{fp} = \frac{\sigma_0 \, b \, t_c^2}{4} \qquad (3)$$

It can be noticed from equation (3) that increasing the cutting depth (i.e. increasing the chip thickness) will increase the flow stress and then the required bending moment, which will lead to reducing the chip curling. Inversely, water content inside the biocomposite structure increases the plasticity of the composite by reducing the elastic modulus and rising the elongation at break as shown in section 2. Consequently, the flow stress would decrease by increasing the water immersion time, which will decrease the bending moment and thus increases the chip curling.

Besides, it has been shown that biocomposite materials made from natural fibers and polymer matric can exhibit a self-shaping because of a moisture-induced bending actuation [52,53]. Indeed, the biocomposite structure shows a multiscale architecture (fiber bundles, elementary fibers, and constitutive cell-walls) which influences the water uptake and the swelling ability of natural fibers, and thus the water-induced bending of the biocomposite material [53]. The swelling ability of flax fibers acts as the driving force of bending in the removed chip of the biocomposite. The water-induced bending direction can be in the cutting plane and/or out of the cutting plane depending on the size and the distribution of flax fiber bundles, which are random in the actual biocomposite structure. The contribution of the water-induced bending can hence explain the high intensity of chip curling and its deformation out of the cutting plane when increasing the water immersion time.

In the saturated hygrometric regime, Figure 5 shows that increasing the water immersion time reduces the chip curling which is opposite to the curling trend of the transient hygrometric regime presented in Figure 4. This chip formation behavior indicates induced damage to the chip structure due to the water aging process that contributes to reduce the chip curling. Indeed, it can be noticed at the extreme hygrometric condition that the removed chip is subjected to fractures (CF in Figure 5(c,f)) without inducing fragmentation of the chip. These fractures weaken the curling process and are attributed to the moisture-induced damages of the interfaces in the saturated regime that cannot resist the high applied machining stresses.

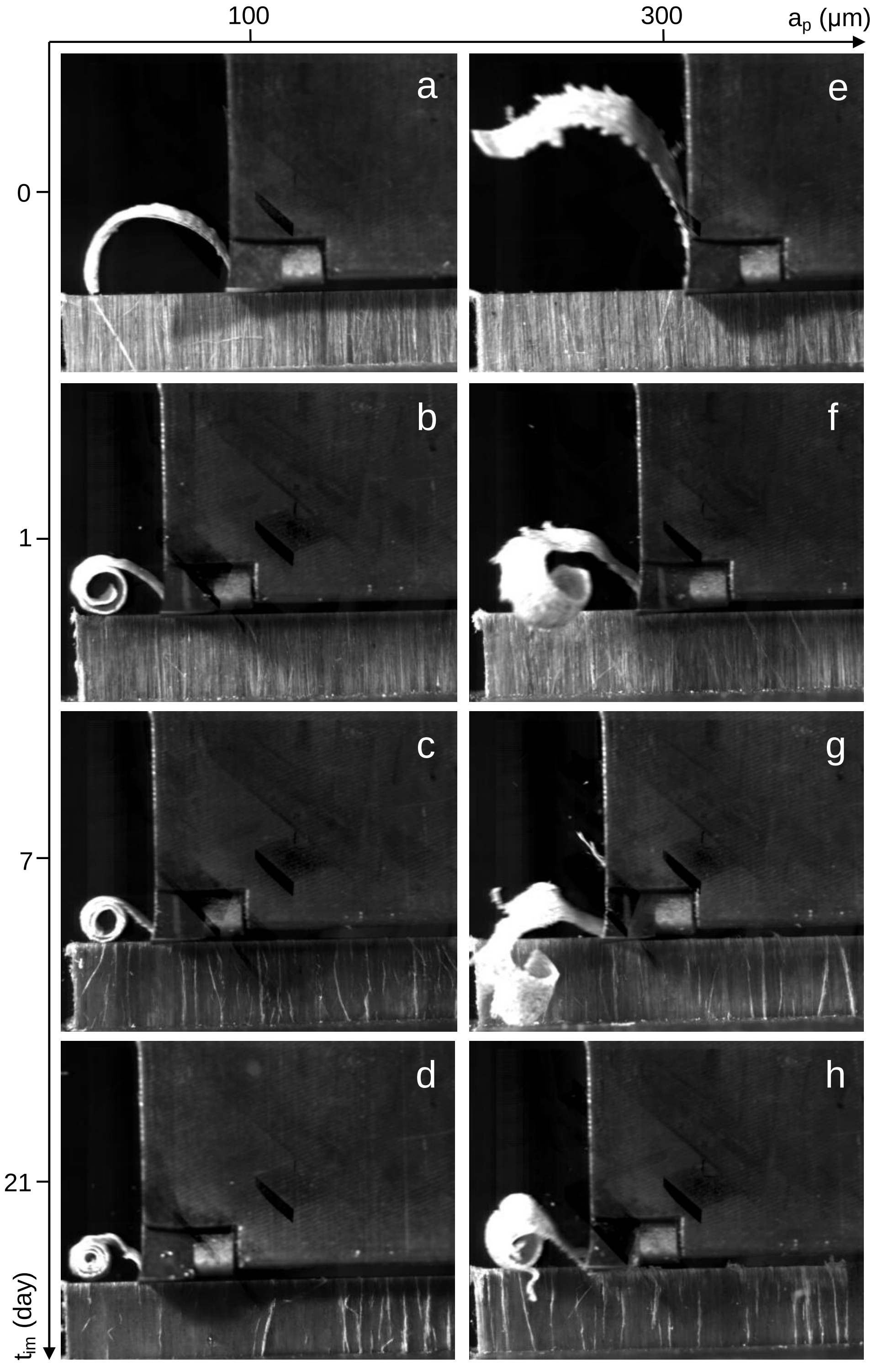

Figure 4: Chip morphology of flax/PLA composites in function of cutting depth and water immersion time in the transient hygrometric regime

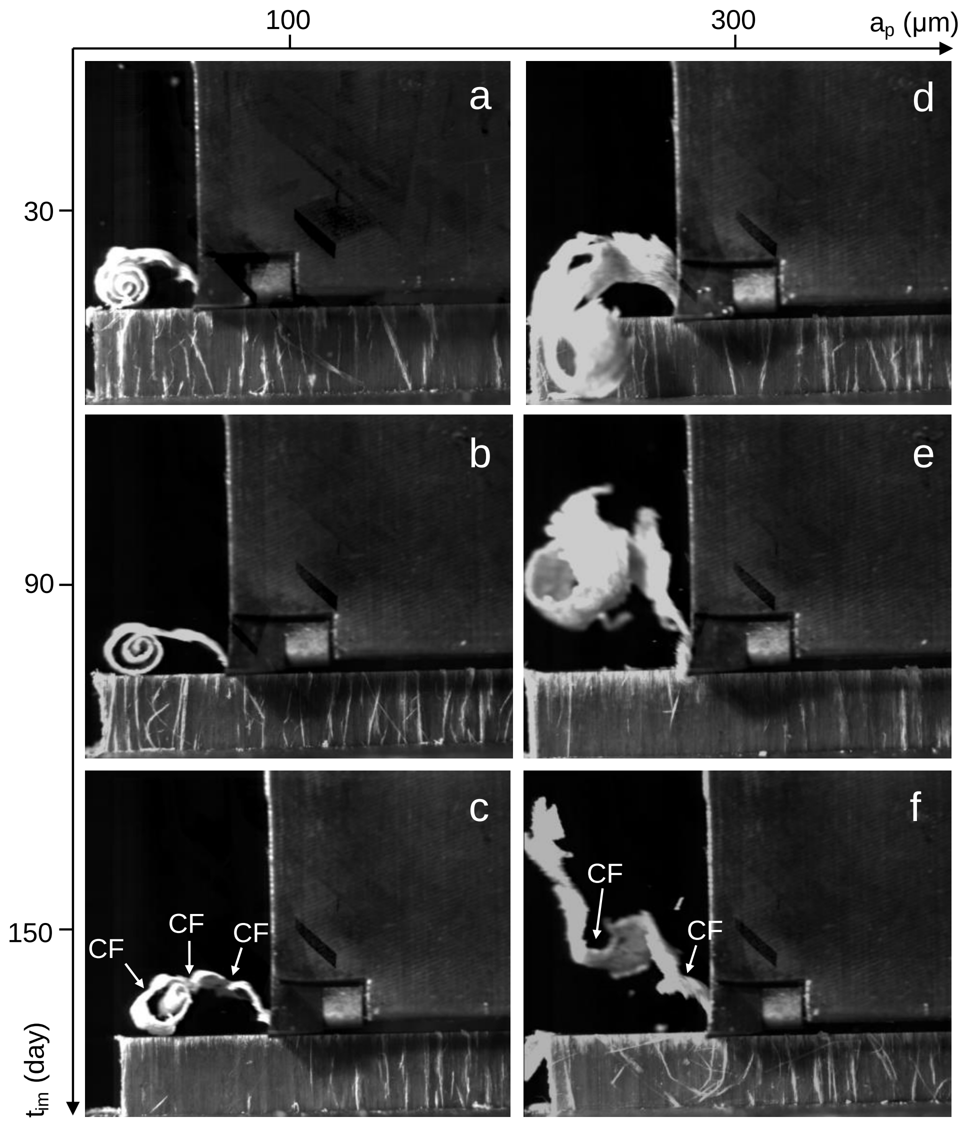

Figure 5: Chip morphology of flax/PLA composites in function of cutting depth and water immersion time in the saturated hygrometric regime. CF means chip fracture.

4.3 *Hygrometric effect on the machining forces*

Figure 6 shows the machining forces obtained at transient and saturated regimes separately. In general, machining forces increase by increasing the cutting depth which is, as well-known, due to the increase of the removed material quantity. Figure 6(a) and Figure 6(b) show a decrease in cutting forces in function of water immersion time at transient and saturated hygrometric regimes. However, the transition between the transient regime and the saturated regime reveals an increase in the cutting forces.

The decrease of the cutting forces in function of the water immersion time is explained by the fact that water content reduces the mechanical properties of the biocomposites as shown in section 2. Indeed, the insertion of water molecules inside the biocomposite structure implies a gradual degradation of the interfaces between elementary fibers and the polymer matrix, which leads to reduce the mechanical resistance of the biocomposite structure against the solicitations of the cutting tool.

For thrust forces, the hygrometric effect is different between the transient and the saturated regimes. In the transient hygrometric regime, thrust forces decrease by increasing the water immersion time until reaching a threshold of 7 days as shown in Figure 6(c). Then, thrust forces increase by increasing the water immersion time until reaching the saturation point. This behavior is more visible when increasing the cutting depth. In the saturated hygrometric regime, thrust forces decrease by increasing the water immersion time as shown in Figure 6(d).

The specific behavior of thrust forces in the transient hygrometric regime can be explained by the effect of water content on the fiber spring-back. In machining of composite materials, the fiber spring-back induces a significant force component in the direction of the thrust force [54,55]. The fiber spring-back force component is as significant as the fiber is rigid. In section 2, it has been shown from experimental investigations on single elementary natural fibers that the moisture content decreases the fiber rigidity until reaching a critical threshold after which the fiber stiffness increases again in function of the water content. The decrease of the fiber stiffness at the beginning of the water absorption process was attributed to the plasticization of the amorphous polymeric components of the fiber, while the increase of the fiber stiffness after the critical water content threshold was attributed to the rearrangements of cellulose microfibrils toward the fiber axis [42]. In the case of this study, it can be seen that the critical water content threshold that allows switching the stiffness behavior of flax fibers is reached at 7 days of water immersion, which corresponds to ~ 4.5 % of water content. Therefore, the decrease of flax fiber stiffness by increasing the water immersion time up to 7 days contributes to a decrease of the fibers spring-back during the cutting process, which leads to a decrease of the thrust forces. Inversely, the increase of flax fiber stiffness by increasing the water immersion time after the threshold of 7 days contributes to an increase of the fibers spring-back during the cutting process, which leads to an increase of the thrust forces.

In the saturated hygrometric regime, the water content in flax fibers is stabilized. However, the degradation of the interfaces is still activated due to the hydrolysis process [47]. This failure mechanism weakens the bonding between fiber and matrix, which decreases the stiffness of the fibrous reinforcement in the biocomposite structure and participates hence to reduce gradually the spring-back power of flax fibers as the water immersion time increases. This may explain the decrease of the thrust forces by increasing the water immersion time in the saturated hygrometric regime.

On the other side, the increase of the machining forces when switching from the transient to the saturated regime could be attributed to the surface reaction effect related to the wet tool/material contact. Indeed, section 2 shows that the mechanical properties of natural fiber composites are stabilized at the end of the transient regime when the water content reaches its maximum. Since the machining forces behavior in the transient regime is attributed to the multiscale mechanical behavior of the biocomposite, this hygro-mechanical effect will disappear at the end of the transient regime. At this critical hygrometric point, flax fibers are saturated with water molecules and the cutting operation will thus engender an important water content on the cutting contact interface. This will induce surface tension and surface pressure in the cutting contact interface due to the capillary rise [56,57]. In the case of dynamic solicitations such as machining, it has been shown that the dynamic surface tension is proportional to the water content in the fabric [57]. This can explain the increase of the machining forces at the transient – saturated hygrometric transition. This effect is more obvious when increasing the cutting depth because of the local increase of the hydrostatic pressure, induced by the water content, which intensifies the surface reaction forces.

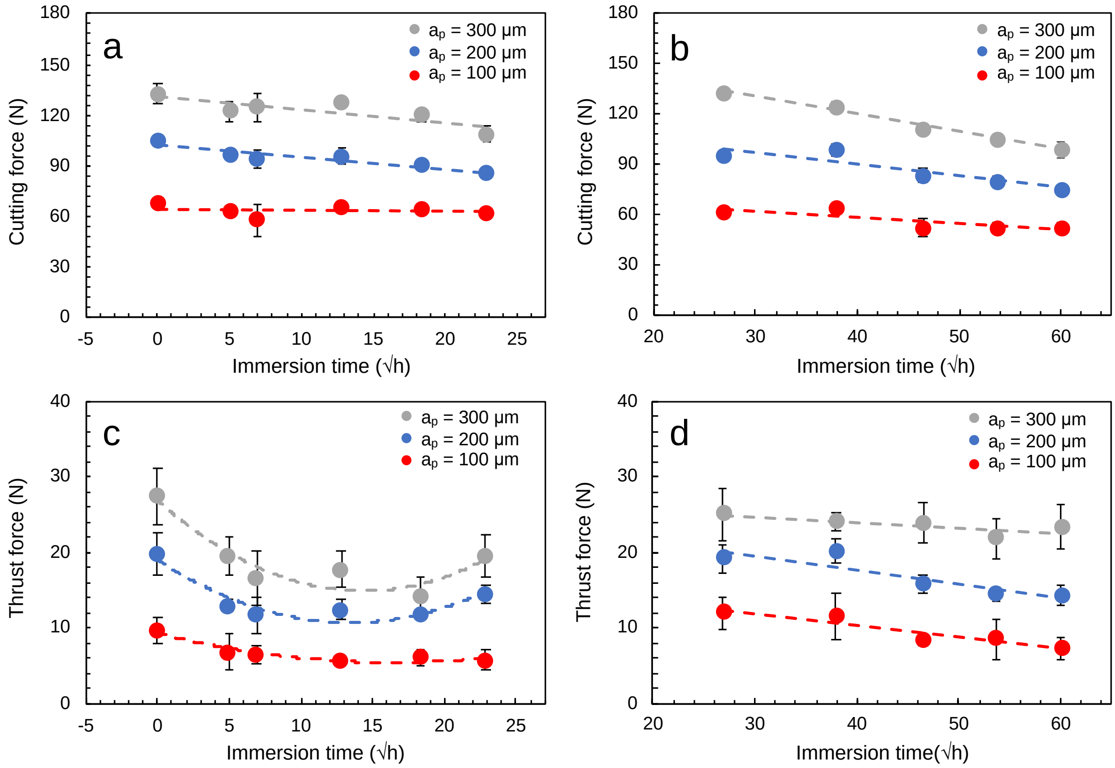

Figure 6: Cutting and thrust forces behavior in function of cutting depth and water immersion time. (a,c) the transient hygrometric regime, and (b,d) the saturated hygrometric regime

4.4 Hygrometric effect on the cutting mechanisms

Figure 7 presents typical SEM images of the machined surfaces in the transient hygrometric regime. The cutting mechanisms differ when varying both the cutting depth and the water immersion time. Without water immersion, flax fibers show a plastic deformation at their cross-sections during the cutting process because the shapes of elementary fibers are not obvious on the SEM images as shown in Figure 7(a).

Increasing the cutting depth intensifies the plastic deformation of flax fibers and causes slight uncut fiber extremities on the machined surfaces (Figure 7(d)). After 7 days of water immersion, no significant change is noticed at 100 µm of cutting depth (Figure 7(b)). However, the fiber shearing deteriorates at this hygrometric level when increasing the cutting depth as shown in Figure 7(e). Moreover, some debonding zones are generated on the fiber/matrix interfaces (DZ in Figure 7(e)). After 21 days of water immersion, the fiber shearing is improved where the shapes of the elementary flax fibers start to be visible (Figure 7(c,f)). Nevertheless, the debonding of the interfaces is more important at this hygrometric stage, especially when increasing the cutting depth as clearly shown in Figure 7(f).

Figure 8 shows typical SEM images of the machined surfaces in the saturated regime. It can be noticed that the fiber shearing is neatly improved in this hygrometric regime where the elementary fiber's shapes are observable from the SEM images. However, the debonding zones caused by the interfaces' fracture increase by increasing the water immersion time.

From the microscopic observations of Figure 7 and Figure 8, and the hygro-mechanical behavior of biocomposites described in section 2, it can be noticed that the cutting behavior of flax/PLA composites regarding the water immersion time involves different biocomposite properties at different scale levels. In the transient hygrometric regime, the cutting behavior of flax fibers depends on the water content. The flax fiber shearing is not initially perfect without water immersion and this shearing imperfection is as more critical as the water immersion time increases up to the threshold of 7 days determined in section 4.2. At this hygrometric stage, the first infiltration of water molecules can be bonded with the hydroxyl groups in the hydrophilic components of flax fibers and act thus as a plasticizer, which decreases the rigidity of the fiber as explained in section 2. Consequently, the shearing performances of flax fibers are reduced in this hygrometric stage because the shearing of natural fibers in machining is as more efficient as the fiber rigidity is higher [24,25].

Conversely, and from the threshold time of 7 days, the fiber shearing is improved by the increase of water immersion time. From this critical amount of water content inside flax fibers (~ 4.5 %), cellulose microfibrils are crept and rearranged toward the fiber axis which leads to an increase in the fiber rigidity (see section 4.2) and thus the enhancement of the fiber shearing efficiency during the cutting process.

When achieving the hygrometric saturation in flax/PLA composites, water content and mechanical properties become constant which can explain the similar shearing behavior of flax fibers observed from the end of the transient hygrometric regime and all over the saturated regime. However, the water exposure time in the biocomposite structure damages gradually the interfaces between elementary flax fibers and the PLA matrix, and these damages become critical after saturation. As shown in section 2, the mechanical properties of natural fiber composites are stabilized in the saturated hygrometric regime, but the hydrolysis of the molecular chain of the polymer matrix remains activated with the presence of water inside the biocomposite structure. The hydrolysis phenomenon contributes to intensify the deterioration of the polymer matrix from the interfaces because these latter constitute the contact surface with water molecules absorbed by flax elementary fibers. This may explain the expansion of the debonding zones on the machined surfaces by the increase of the water immersion time in the saturated hygrometric regime (Figure 8). It is important to note that the described phenomena are more obvious when performing the machining with high cutting depth since the machining interaction forces are more substantial (Figure 6).

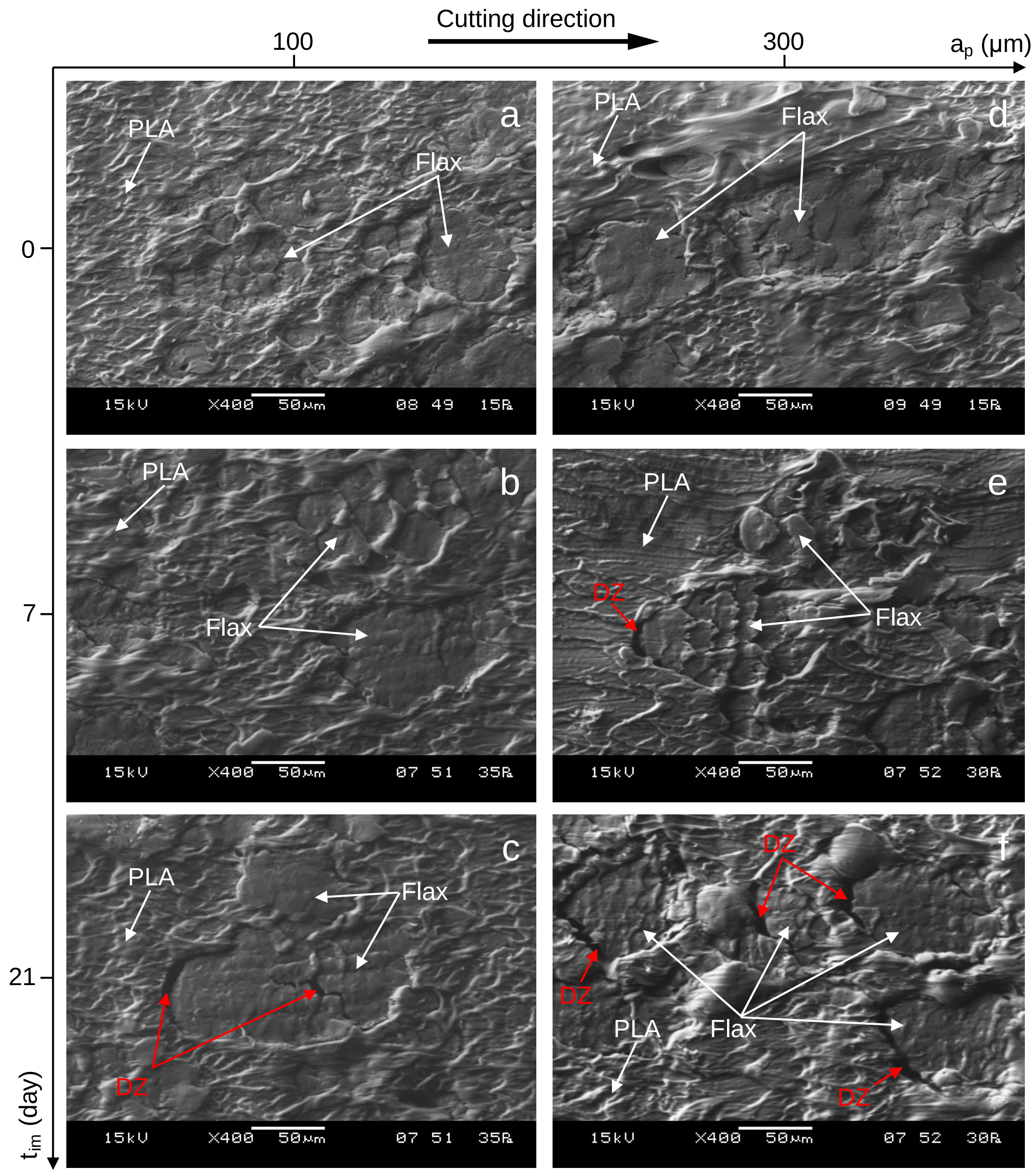

Figure 7: Typical SEM images of machined surfaces of flax/PLA composites in function of cutting depth and water immersion time for the transient hygrometric regime. DZ means debonding zone

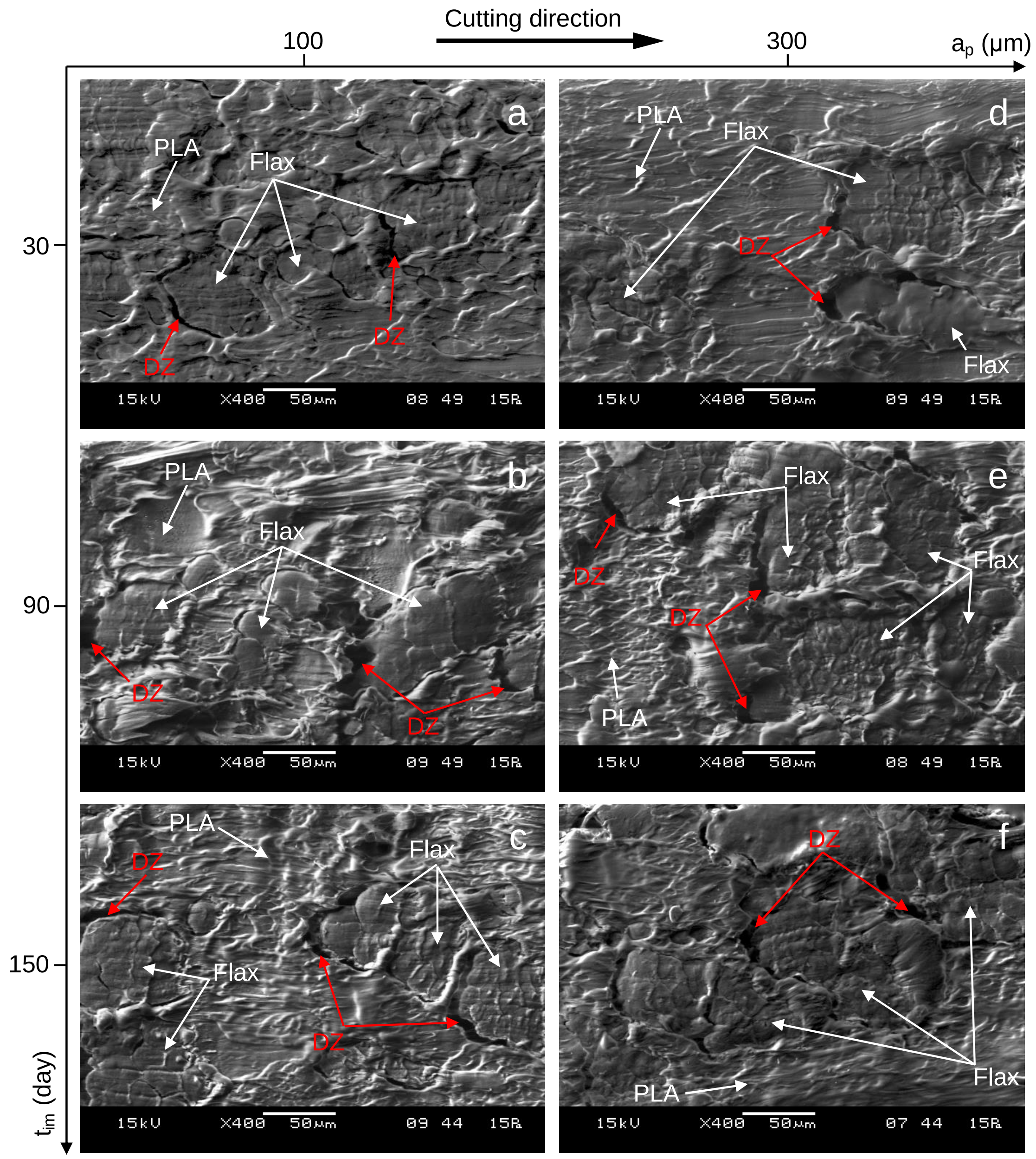

Figure 8: Typical SEM images of machined surfaces of flax/PLA composites in function of cutting depth and water immersion time for the saturated hygrometric regime. DZ means debonding zone

4.5 Hygrometric effect on the machined surface roughness

To qualify the hygrometric effect on the machined surface roughness of flax/PLA composites, the topographic image size should correspond to the considered fibrous structure size in order to be on the relevant scale for an efficient topographic analysis of natural fiber composites [58]. The fibrous structure size in the case of the considered flax/PLA composites are continuous unidirectional bundles of flax fibers. The average diameter of the flax fiber bundles in flax/PLA composites is about $150^{\pm 50}$ µm. The objective of the interferometer has been adapted to be as close as possible to this scale range. Therefore, an objective with a magnification of ×20 is used to get topographic images of 153×204 μm^2. The quantification of these measurements with the arithmetic mean of the surface roughness (R_a) is given in Figure 9.

The surface roughness behavior of Figure 9 reproduces the similar cutting behavior shown in section 4.4. In general, the machined surface roughness increases by increasing the cutting depth in the two hygrometric regimes. In the transient hygrometric regime, the surface roughness increases by increasing the water immersion time until reaching the critical threshold of 7 days. Then, the surface roughness decreases by increasing the water immersion time. This result corresponds to the microscopic observation of Figure 7 where the increase of the surface roughness is due to the uncut fiber extremities caused by the poor fiber shearing efficiency. After the water immersion threshold time of 7 days, the surface roughness decreases due to the improvement of the fiber shearing but does not reach the initial surface roughness values (without water immersion) because of the induced debonding zones that contribute to the increase of the machined surface roughness. On the other side, the saturated hygrometric regime shows an increase of the surface roughness when increasing the water immersion time which is mainly due to the expansion of the debonding zones on the machined surfaces because of the interfaces' damage. It can be concluded that the cutting mechanisms induced by the hygrometric effect are well reproduced with the topographic analysis of machined surfaces at the relevant scale of the flax fibrous reinforcement.

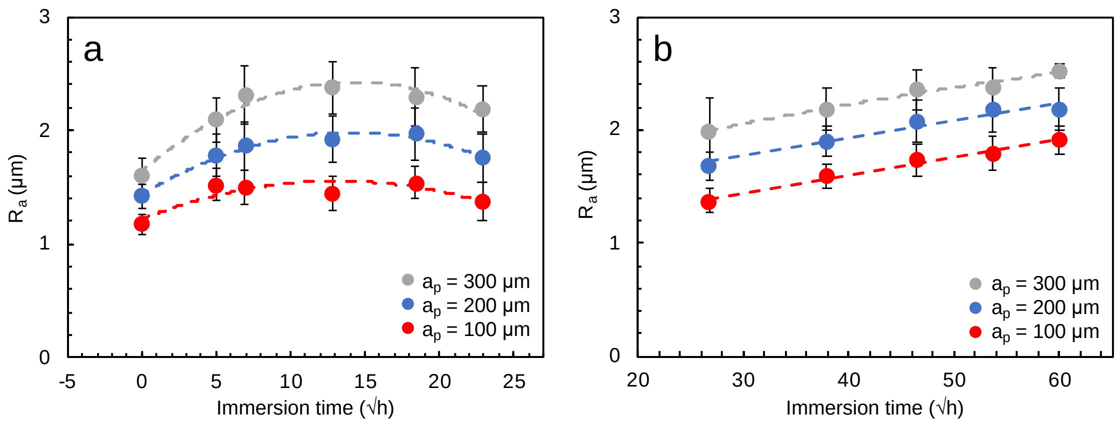

Figure 9: Arithmetic mean values of the machined surface roughness (R_a) for flax/PLA composites in function of cutting depth and water immersion time. (a) the transient hygrometric regime, (b) the saturated hygrometric regime

5 Conclusions

The hygrometric effect on the machinability of biocomposite materials is investigated in this paper by performing orthogonal cutting experiments on flax fibers reinforced PLA composites that were subjected to different water immersion times. The following conclusions can be drawn:

- Flax/PLA composites reached hygrometric saturation after 21 days of water immersion which corresponds to approximately 8% of water content.
- Water content affects differently the chip formation of flax/PLA composites at transient and saturated hygrometric regimes in terms of chip curling. The transient regime favors the chip curling due to the plastic bending moment and

the water-induced bending, while the saturated regime reduces the chip curling because of the interfaces' damage.

- The shearing of flax fibers is weakened at the beginning of the transient hygrometric regime until reaching a water immersion time threshold of 7 days. Then, the shearing efficiency of flax fibers is improved by increasing the water immersion time. This cutting behavior is attributed to the effect of water uptake on the microstructure of flax fibers that hence impact the flax fiber stiffness. This effect differs before and after the critical threshold of 7 days in the transient hygrometric regime.
- The cutting behavior of flax/PLA composites in the saturated hygrometric regime is characterized by the interfaces' damage, inducing debonding zones between fibers and matrix on the machined surfaces. This interfaces' failure is attributed to the hydrolysis of the polymer at the interfaces by water aging.
- Cutting forces are reduced by increasing the water immersion time in both the transient and saturated hygrometric regimes. This behavior is due to the hygrometric aging of the biocomposite that leads to reduce its mechanical properties.
- Thrust forces do not behave similarly in the transient and saturated hygrometric regimes. Thrust forces are reduced by increasing the water immersion time in the saturated hygrometric regime. However, thrust forces behavior shows a fluctuation after the water immersion time threshold of 7 days in the transient hygrometric regime. This behavior is attributed to the fiber spring-back that is monitored by the fiber stiffness.
- The machined surface roughness at the relevant analysis scale of flax/PLA composite structure can quantify the hygrometric effect on the machined

surfaces by capturing the different cutting mechanisms that occurred in each hygrometric regime.

6 References

[1] Pil L, Bensadoun F, Pariset J, Verpoest I. Why are designers fascinated by flax and hemp fibre composites? Compos Part A Appl Sci Manuf 2016;83:193–205. https://doi.org/10.1016/j.compositesa.2015.11.004.

[2] Lau K, Hung P, Zhu M-H, Hui D. Properties of natural fibre composites for structural engineering applications. Compos Part B Eng 2018;136:222–33. https://doi.org/10.1016/J.COMPOSITESB.2017.10.038.

[3] Cheung H, Ho M, Cardona F. Natural fibre-reinforced composites for bioengineering and environmental engineering applications. Compos Part B Eng 2009;40:655–63. https://doi.org/10.1016/J.COMPOSITESB.2009.04.014.

[4] Hallak Panzera T, Jeannin T, Gabrion X, Placet V, Remillat C, Farrow I, et al. Static, fatigue and impact behaviour of an autoclaved flax fibre reinforced composite for aerospace engineering. Compos Part B Eng 2020;197:108049. https://doi.org/10.1016/J.COMPOSITESB.2020.108049.

[5] Kumar N, Das D. Fibrous biocomposites from nettle (Girardinia diversifolia) and poly(lactic acid) fibers for automotive dashboard panel application. Compos Part B Eng 2017;130:54–63. https://doi.org/10.1016/J.COMPOSITESB.2017.07.059.

[6] Yan L, Chouw N, Jayaraman K. Flax fibre and its composites – A review. Compos Part B Eng 2014;56:296–317. https://doi.org/10.1016/J.COMPOSITESB.2013.08.014.

[7] Nassar MMA, Arunachalam R, Alzebdeh KI. Machinability of natural fiber reinforced composites: a review. Int J Adv Manuf Technol 2017;88:2985–3004. https://doi.org/10.1007/s00170-016-9010-9.

[8] Ho M, Wang H, Lee J-H, Ho C, Lau K, Leng J, et al. Critical factors on manufacturing processes of natural fibre composites. Compos Part B Eng 2012;43:3549–62. https://doi.org/10.1016/J.COMPOSITESB.2011.10.001.

[9] Wang D, Onawumi PY, Ismail SO, Dhakal HN, Popov I, Silberschmidt VV, et al. Machinability of natural-fibre-reinforced polymer composites: Conventional

vs ultrasonically-assisted machining. Compos Part A Appl Sci Manuf 2019;119:188–95. https://doi.org/10.1016/J.COMPOSITESA.2019.01.028.

[10] Debnath K, Singh I, Dvivedi A. Drilling characteristics of sisal fiber-reinforced epoxy and polypropylene composites. Mater Manuf Process 2014;29:1401–9. https://doi.org/10.1080/10426914.2014.941870.

[11] Rezghi Maleki H, Hamedi M, Kubouchi M, Arao Y. Experimental investigation on drilling of natural flax fiber-reinforced composites. Mater Manuf Process 2019;34:283–92. https://doi.org/10.1080/10426914.2018.1532584.

[12] Abdul Nasir AA, Azmi AI, Lih TC, Abdul Majid MS. Critical thrust force and critical feed rate in drilling flax fibre composites: A comparative study of various thrust force models. Compos Part B Eng 2019;165:222–32. https://doi.org/10.1016/J.COMPOSITESB.2018.11.134.

[13] Babu GD, Babu KS, Gowd BUM. Effect of Machining Parameters on Milled Natural Fiber-Reinforced Plastic Composites. J Adv Mech Eng 2013:1–12. https://doi.org/10.7726/jame.2013.1001.

[14] Çelik YH, Kilickap E, Kilickap Aİ. An experimental study on milling of natural fiber (jute)- reinforced polymer composites. J Compos Mater 2019;53:3127–37. https://doi.org/10.1177/0021998319826373.

[15] Chegdani F, Mansori M El. Mechanics of material removal when cutting natural fiber reinforced thermoplastic composites. Polym Test 2018;67:275–83. https://doi.org/10.1016/j.polymertesting.2018.03.016.

[16] Chegdani F, Takabi B, El Mansori M, Tai BL, Bukkapatnam STS. Effect of flax fiber orientation on machining behavior and surface finish of natural fiber reinforced polymer composites. J Manuf Process 2020;54:337–46. https://doi.org/10.1016/j.jmapro.2020.03.025.

[17] Díaz-Álvarez A, Díaz-Álvarez J, Cantero JL, Santiuste C. Analysis of orthogonal cutting of biocomposites. Compos Struct 2020;234:111734. https://doi.org/10.1016/j.compstruct.2019.111734.

[18] Quadrini F, Squeo EA, Tagliaferri V. Machining of glass fiber reinforced polyamide. Express Polym Lett 2007;1:810–6. https://doi.org/10.3144/expresspolymlett.2007.112.

[19] Sheikh-Ahmad J. Machining of Polymer Composites. Boston, MA: Springer US; 2009. https://doi.org/10.1007/978-0-387-68619-6.

[20] Sheikh-Ahmad J, Davim JP. Cutting and Machining of Polymer Composites. Wiley Encycl. Compos., Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2012, p. 648–58. https://doi.org/10.1002/9781118097298.weoc061.

[21] Feih S, Manatpon K, Mathys Z, Gibson AG, Mouritz AP. Strength degradation of glass fibers at high temperatures. J Mater Sci 2009;44:392–400. https://doi.org/10.1007/s10853-008-3140-x.

[22] Marrot L, Lefeuvre A, Pontoire B, Bourmaud A, Baley C. Analysis of the hemp fiber mechanical properties and their scattering (Fedora 17). Ind Crops Prod 2013;51:317–27. https://doi.org/10.1016/j.indcrop.2013.09.026.

[23] Chegdani F, El Mansori M, Chebbi AA. Numerical modeling of micro-friction and fiber orientation effects on the machinability of green composites. Tribol Int 2020;150:106380. https://doi.org/10.1016/j.triboint.2020.106380.

[24] Chegdani F, Mezghani S, El Mansori M, Mkaddem A. Fiber type effect on tribological behavior when cutting natural fiber reinforced plastics. Wear 2015;332–333:772–9. https://doi.org/10.1016/j.wear.2014.12.039.

[25] Chegdani F, Takabi B, Tai BL, Mansori M El, Bukkapatnam STS. Thermal Effects on Tribological Behavior in Machining Natural Fiber Composites. Procedia Manuf 2018;26:305–16. https://doi.org/10.1016/j.promfg.2018.07.039.

[26] Dittenber DB, GangaRao HVS. Critical review of recent publications on use of natural composites in infrastructure. Compos Part A Appl Sci Manuf 2012;43:1419–29. https://doi.org/10.1016/j.compositesa.2011.11.019.

[27] le Duigou A, Merotte J, Bourmaud A, Davies P, Belhouli K, Baley C. Hygroscopic expansion: A key point to describe natural fibre/polymer matrix interface bond strength. Compos Sci Technol 2017;151:228–33. https://doi.org/10.1016/j.compscitech.2017.08.028.

[28] N.-S. Hon D, Shiraishi N. Wood and Cellulosic Chemistry. Marcel Dek. New York: 2000.

[29] Saidane EH, Scida D, Assarar M, Ayad R. Assessment of 3D moisture diffusion parameters on flax/epoxy composites. Compos Part A Appl Sci Manuf

2016;80:53–60. https://doi.org/10.1016/J.COMPOSITESA.2015.10.008.

[30] Cheour K, Assarar M, Scida D, Ayad R, Gong XL. Effect of water ageing on the mechanical and damping properties of flax-fibre reinforced composite materials. Compos Struct 2016;152:259–66. https://doi.org/10.1016/j.compstruct.2016.05.045.

[31] Berges M, Léger R, Placet V, Person V, Corn S, Gabrion X, et al. Influence of moisture uptake on the static, cyclic and dynamic behaviour of unidirectional flax fibre-reinforced epoxy laminates. Compos Part A Appl Sci Manuf 2016;88:165–77. https://doi.org/10.1016/j.compositesa.2016.05.029.

[32] Assarar M, Scida D, El Mahi A, Poilâne C, Ayad R. Influence of water ageing on mechanical properties and damage events of two reinforced composite materials: Flax-fibres and glass-fibres. Mater Des 2011;32:788–95. https://doi.org/10.1016/j.matdes.2010.07.024.

[33] Li Y, Xue B. Hydrothermal ageing mechanisms of unidirectional flax fabric reinforced epoxy composites. Polym Degrad Stab 2016;126:144–58. https://doi.org/10.1016/j.polymdegradstab.2016.02.004.

[34] Chilali A, Zouari W, Assarar M, Kebir H, Ayad R. Effect of water ageing on the load-unload cyclic behaviour of flax fibre-reinforced thermoplastic and thermosetting composites. Compos Struct 2018;183:309–19. https://doi.org/10.1016/j.compstruct.2017.03.077.

[35] Moudood A, Rahman A, Khanlou HM, Hall W, Öchsner A, Francucci G. Environmental effects on the durability and the mechanical performance of flax fiber/bio-epoxy composites. Compos Part B Eng 2019;171:284–93. https://doi.org/10.1016/j.compositesb.2019.05.032.

[36] Jeannin T, Berges M, Gabrion X, Léger R, Person V, Corn S, et al. Influence of hydrothermal ageing on the fatigue behaviour of a unidirectional flax-epoxy laminate. Compos Part B Eng 2019;174:107056. https://doi.org/10.1016/J.COMPOSITESB.2019.107056.

[37] Almansour FA, Dhakal HN, Zhang ZY. Effect of water absorption on Mode I interlaminar fracture toughness of flax/basalt reinforced vinyl ester hybrid composites. Compos Struct 2017;168:813–25.

https://doi.org/10.1016/J.COMPSTRUCT.2017.02.081.

[38] Hristozov D, Wroblewski L, Sadeghian P. Long-term tensile properties of natural fibre-reinforced polymer composites: Comparison of flax and glass fibres. Compos Part B Eng 2016;95:82–95. https://doi.org/10.1016/J.COMPOSITESB.2016.03.079.

[39] Regazzi A, Corn S, Ienny P, Bénézet J-CC, Bergeret A. Reversible and irreversible changes in physical and mechanical properties of biocomposites during hydrothermal aging. Ind Crops Prod 2016;84:358–65. https://doi.org/10.1016/j.indcrop.2016.01.052.

[40] Kuciel S, Jakubowska P, Kuźniar P. A study on the mechanical properties and the influence of water uptake and temperature on biocomposites based on polyethylene from renewable sources. Compos Part B Eng 2014;64:72–7. https://doi.org/10.1016/J.COMPOSITESB.2014.03.026.

[41] Stamboulis A, Baillie CA, Peijs T. Effects of environmental conditions on mechanical and physical properties of flax fibers. Compos Part A Appl Sci Manuf 2001;32:1105–15. https://doi.org/10.1016/S1359-835X(01)00032-X.

[42] Placet V, Cisse O, Boubakar ML. Influence of environmental relative humidity on the tensile and rotational behaviour of hemp fibres. J Mater Sci 2012;47:3435–46. https://doi.org/10.1007/s10853-011-6191-3.

[43] Le Duigou A, Davies P, Baley C. Seawater ageing of flax/poly(lactic acid) biocomposites. Polym Degrad Stab 2009;94:1151–62. https://doi.org/10.1016/J.POLYMDEGRADSTAB.2009.03.025.

[44] Dhakal HNN, Zhang ZYY, Richardson MOWOW. Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. Compos Sci Technol 2007;67:1674–83. https://doi.org/10.1016/J.COMPSCITECH.2006.06.019.

[45] Scida D, Assarar M, Poilâne C, Ayad R. Influence of hygrothermal ageing on the damage mechanisms of flax-fibre reinforced epoxy composite. Compos Part B Eng 2013;48:51–8. https://doi.org/10.1016/j.compositesb.2012.12.010.

[46] Muñoz E, García-Manrique JA. Water Absorption Behaviour and Its Effect on the Mechanical Properties of Flax Fibre Reinforced Bioepoxy Composites. Int J

Polym Sci 2015;2015:1–10. https://doi.org/10.1155/2015/390275.

[47] Hu R-H, Sun M, Lim J-K. Moisture absorption, tensile strength and microstructure evolution of short jute fiber/polylactide composite in hygrothermal environment. Mater Des 2010;31:3167–73. https://doi.org/10.1016/J.MATDES.2010.02.030.

[48] Baley C. Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase. Compos - Part A Appl Sci Manuf 2002;33:939–48. https://doi.org/10.1016/S1359-835X(02)00040-4.

[49] Chilali A, Zouari W, Assarar M, Kebir H, Ayad R. Analysis of the mechanical behaviour of flax and glass fabrics-reinforced thermoplastic and thermoset resins. J Reinf Plast Compos 2016;35:1217–32. https://doi.org/10.1177/0731684416645203.

[50] Cook NH, Jhaveri P, Nayak N. The mechanism of chip curl and its importance in metal cutting. J Manuf Sci Eng Trans ASME 1963;85:374–80. https://doi.org/10.1115/1.3669898.

[51] Liu PD, Hu RS, Zhang HT, Wu XS. A Study on Chip Curling and Breaking. In: Atkinson J, Barrow G, Burdekin M, Chitkara NR, Hannam RG, editors. Proc. Twenty-Ninth Int. Matador Conf., London: Macmillan Education UK; 1992, p. 507–12. https://doi.org/10.1007/978-1-349-12433-6_66.

[52] Le Duigou A, Castro M. Hygromorph BioComposites: Effect of fibre content and interfacial strength on the actuation performances. Ind Crops Prod 2017;99:142–9. https://doi.org/10.1016/j.indcrop.2017.02.004.

[53] Le Duigou A, Castro M. Moisture-induced self-shaping flax-reinforced polypropylene biocomposite actuator. Ind Crops Prod 2015;71:1–6. https://doi.org/10.1016/j.indcrop.2015.03.077.

[54] Lasri L, Nouari M, El Mansori M. Modelling of chip separation in machining unidirectional FRP composites by stiffness degradation concept. Compos Sci Technol 2009;69:684–92. https://doi.org/10.1016/J.COMPSCITECH.2009.01.004.

[55] Arola D, Ramulu M. Orthogonal cutting of fiber-reinforced composites: A finite element analysis. Int J Mech Sci 1997;39:597–613.

https://doi.org/10.1016/S0020-7403(96)00061-6.

[56] Keller JB. Surface tension force on a partly submerged body. Phys Fluids 1998;10:3009–10. https://doi.org/10.1063/1.869820.

[57] Carter DL, Draper MC, Peterson RN, Shah DO. Importance of dynamic surface tension to the residual water content of fabrics. Langmuir 2005;21:10106–11. https://doi.org/10.1021/la050583w.

[58] Chegdani F, El Mansori M. New Multiscale Approach for Machining Analysis of Natural Fiber Reinforced Bio-Composites. J Manuf Sci Eng Trans ASME 2019;141:11004. https://doi.org/10.1115/1.4041326.