Effect of machining parameters on the uncut fibers of a unidirectional flax fiber reinforced composite

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Abstract

In recent years, flax fiber-reinforced polymers (FFRP) are being widely used due to their inherent properties comparable to those of glass fiber reinforced polymers (GFRP). They are partially biodegradable and light weight with good intrinsic modulus and strength. However, milling these composites introduces defects like a poor surface quality with a lot of uncut fibers. The main objective of this study is to analyze the effect of machining parameters and fiber orientation on the uncut fibers (characterized by the number and length of the uncut fibers) of unidirectional FFRP. A full Split-Split Plot Block design of experiment approach was conducted for the analysis. It is shown that the uncut fibers extent depends significantly on the feed rate, the fiber orientation and the cutting tool geometry. The cutting speed does not influence the quantity of uncut fibers. A low feed rate (0.05 mm/rev) and a cutting tool geometry which enhances the fibers shear with a zero-helix angle are shown to minimize the delamination during the up-milling process of unidirectional flax/epoxy composite.

1. Introduction

Thanks to their high intrinsic modulus and strength which are comparable to those of glass fiber-reinforced composites (GFRP) (Do Thi, 2011; Shah et al., 2013), their biodegradability, their low weight and low cost (Bogoeva-Gaceva et al., 2007), flax fiber-reinforced plastics (FFRP) are increasingly attracting the interest of all fields (Avril et al., 2012). Furthermore, they have been considered by several researchers and industrials as a substitute for GFRPs since flax fibers have an intrinsic strength similar to glass fibers in addition to a better fatigue strength (Liang et al., 2011; Liang et al., 2012) and lesser abrasiveness towards cutting tools. Thus, they provide a longer tool life which represents a great economic benefit for companies (Bouzouita, 2011).

However, the viscoelastic nature of natural fiber-reinforced plastics (NFRP) generates a poor surface quality when trimming them. A lot of uncut fibers appear during the process which leads to a high delamination factor (Fd). The latter represents the ratio between the nominal dimensions of the cut and the maximum dimensions obtained after cutting. Babu et al. (2013) investigated the machinability of three different unidirectional NFRPs namely banana/polyester (BFRP), hemp/polyester (HFRP) and jute/polyester (JFRP) composites. They highlighted that delamination increases with the feed rate and decreases with the cutting speed. Therefore, cutting at a low feed rate and a high cutting speed improves the surface finish and minimizes the delamination. Azmi et al. (2016) found that the feed rate is the most influencing factor on the surface roughness in milling kenaf fiber reinforced plastic composites. They showed that the cutting speed has no effect on the surface finish quality. In the milling of GFRPs, the feed rate was found to be the most influencing cutting parameter on the delamination followed by the cutting speed (Jenarthanan et al., 2013). Those contradictions in terms of the effect of the cutting speed on the surface finish quality were explained by Chegdani et al. (2015) research who studied the influence of natural fiber types on the tribological behavior during the milling process. They concluded that the natural fiber shearing mechanism depends strongly on the fiber type. Recently, Delahaigue et al. (2017) showed that the fiber orientation greatly influences Fd. In fact, the best surface finish is obtained when the fibers are oriented at 0° and the worst for fibers at -45°. Further, the authors advise against the down-milling mode which produces a poor surface finish.

The delamination factor Fd often characterized the delamination (Davim & Reis, 2003; Erkan et al., 2013; Sreenivasulu, 2013). However, these «one-dimensional» evaluation criteria cannot evaluate the extent of the defect. A two-dimensional evaluation criterion (2D) is then necessary to properly characterize the extent of the delamination. Thus, Wang et al. (2017) proposed a novel approach to evaluate the uncut fibers extent after edge trimming of carbon-fiber-reinforced composites based on an areal factor (Ad) (the ratio between the nominal area of the cut and the actual area after cutting including the size of uncut fibers).

No previous work has been carried out on optimizing flax fiber composites delamination. This paper aims to investigate the influence of the cutting parameters like the feed rate and cutting speed (f and Vc), the fiber orientation (θ) and the cutting tool geometry on the delamination extent. As recommended by Bradley & Nachtsheim (2009) who argued that the split-plot design of experiment (DOE) are more efficient than completely randomized designs and superior in terms of cost and validity. Dry up-milling experiments were conducted with a full Split-Split Plot Block DOE approach.

2. Methodology and experimental procedure

2.1. Material

The material used during this study consists of an unidirectional 15-ply flax fiber impregnated with epoxy resin. The laminated plates were made using 15 unidirectional long flax fiber plies. They were molded by the vacuum assisted resin transfer molding (VARTM) method to a fiber volume fraction (Vf) of 41.1%. The total thickness of each plate is about 4.597 mm (corresponding to the mold cavity thickness).

The flax plies were first dried in an oven at 80°C for 8 hours in order to reduce their moisture content. The pressure of the resin injection was gradually adjusted to maintain a constant injection rate and a complete impregnation. After the impregnation, the resin was cured in a hot-platen press at 80°C for 3 hours. Figure 1 shows the VARTM setup (the press and the mold installed inside the press on the right and the pressure pot on the left). A total of 4 [0_{15}] composite plates have been molded for the machining experiments. A typical plaque is shown in Figure 2.

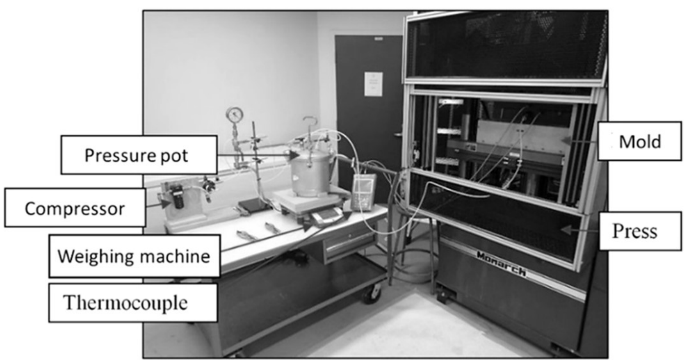

Figure 1. VARTM setup

2.2. Experiment factors

A three-axis numerically controlled machining center, HURON K2X10 (figure 2) was used for the machining operations. To optimize the surface finish quality, the influence of cutting parameters namely cutting speed (Vc), feed rate (f), fiber orientation (θ) and cutting tool geometry on the extent of the delamination was investigated. These parameters were identified in the literature as the most significant for the milling of fiber reinforced composites. A total of three Vc values, six f values, four fiber orientations and two different cutting tools (table 1) were considered in the plan of experiments. Figure 3 defines the convention of fiber orientation while table 1 shows the factor levels of the study.

Tool #1 was a two-flute polycrystalline diamond end mill (PCD) (figure 4.a), as used by Bérubé (2012), while tool #2 was a two-flute uncoated carbide end mill with 70° cutting profiles (figure 4.b). From one flute to the next, tool #2 cutting profiles were inverted to enhance fiber shearing which reduces the risk of delamination. The cutting tools specifications are shown in table 2.

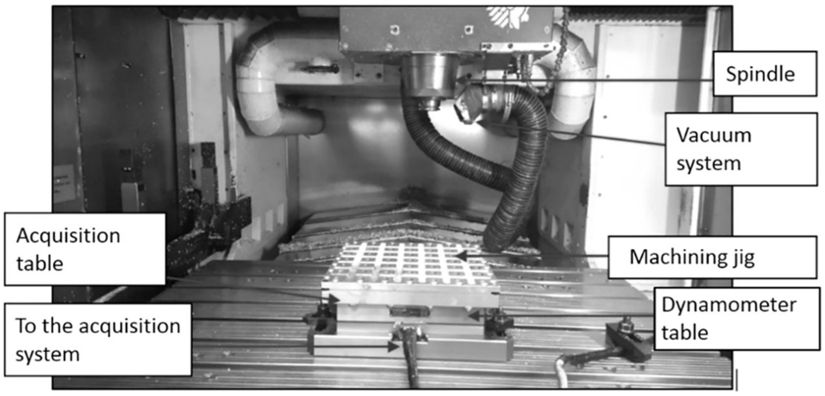

Figure 2. Milling setup

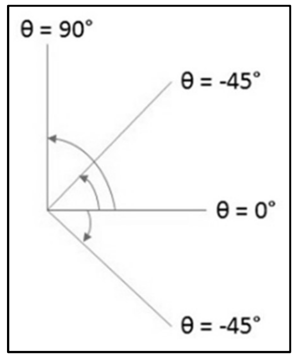

Figure 3. Fiber orientation definition

Table 1. Experimental factor levels

Factors	Factor levels					
Cutting tool	Tool #2	Tool #1				
Cutting angle θ (°)	-45	0	45	90		
Cutting speed Vc (m/min)	200	400	600			
Feed rate f (mm/rev)	0.025	0.050	0.100	0.200	0.300	0.450

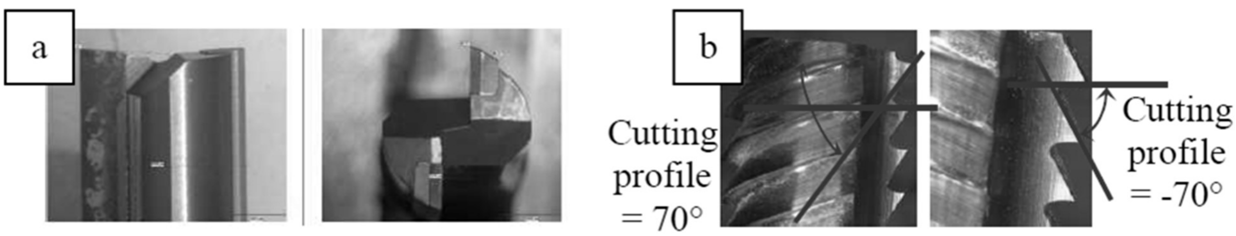

Figure 4. Cutting tools: a) tool#1 and b) tool#2 (Karabibene et al., 2017)

Table 2. Cutting tools specifications

Tool	Diameter	Flutes number	Cutting edge radius	Helix	Coating
#1	9.525 mm	2	5 µm	0°	Diamond PCD
#2	9.525 mm	2	4 µm	0°	Uncoated

The factors levels were chosen following the conclusions of Delahaigue et al. (2017) and based on the technical datasheets of the tools. In fact, Delahaigue et al. (2017) concluded that to minimize cutting forces and roughness when trimming unidirectional flax/epoxy composite, the feed rate should be medium and the cutting speed should be high. They have also defined limits in which Ra and cutting forces remain acceptable. Moreover, preliminary tests were performed to validate and refine the factor levels.

The composite plaques were hold to the machining setup using screws (figure 5) to minimize the vibration effect on the surface finish quality. Therefore, machining vibration effects were neglected in this analysis. Further, the cutting tool was regularly inspected, i.e., after each 7 cutting combinations, to control its wear. A new unaffected area of the cutting tool was systematically selected after every 72 tests (which corresponds to a cutting length of 2.64 m). Consequently, the tool wear effect was also neglected. Thus, dry up-milling tests were carried out.

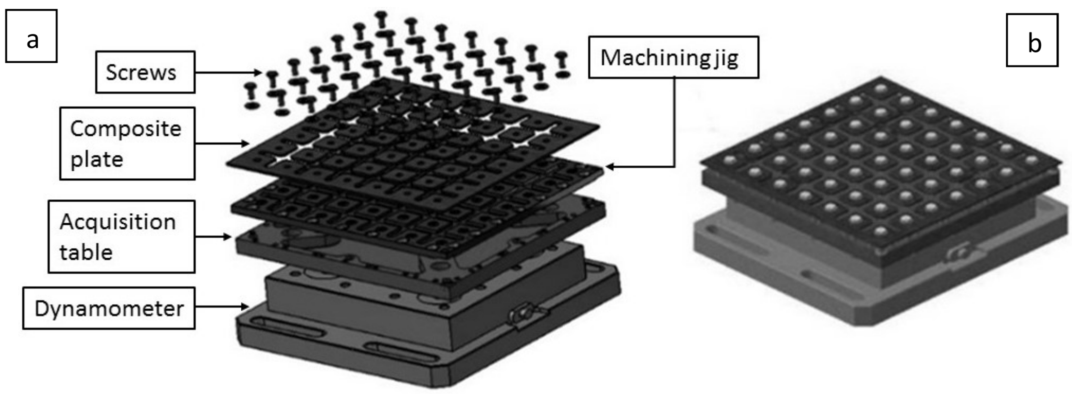

Figure 5. Plates fixation: a) exploded view and b) assembled jig

2.3. Trimming process and design of experiment

A Split-Split Plot randomized complete block design (SSPRCPD) was selected for the present experiment. It allows the minimization of the response variability and reduces the experimental errors. The design was replicated twice for a total of 288 machining combinations ($6\,f\ \times 4\,\theta\ \times 3\,Vc\ \times 2\,tools\ \times 2\,replications$).

2.4. Delamination extent measurement

The delamination was investigated based on Wang et al. (2017) research. They investigated a two-dimensional evaluation approach to characterize the delamination extent (Ad). A MATLAB program, inspired by Wang's was developed for this purpose. Firstly, the coupons obtained after milling were cleaned with compressed air. They were then photographed using a 23 MP resolution camera. The MATLAB processing sequence is organized as follows (figure 6):

- Convert the true color image (figure 6.a) to grayscale intensity image (figure 6.b);
- Select manually the area of interest, i.e. the cutting-induced delamination area, to reduce the computational time (figure 6.c) and extract this area (figure 6.d);
- Binarize the selected area using an Otsu's method combined with the Heaviside step function (a discontinuous function equal to 0 for strictly negative real numbers resulted from the Otsu

segmentation and to 1 for all other values);
- Sum up the black pixels corresponding to uncut fibers. The extent of the affected region is calculated by multiplying the number of pixels by the size of the pixel.

Black pixels that do not correspond to delamination were considered as measurement error and were overwhelmed by the confidence intervals of the delamination measurements.

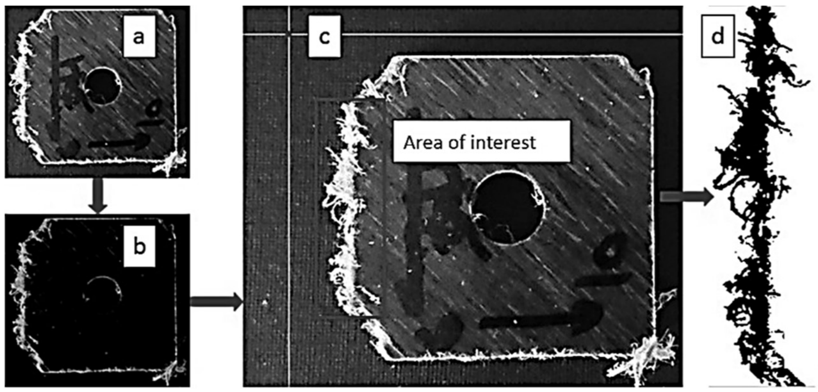

Figure 6. Delamination extent measurement steps

3. Experimental result

The delamination of the upper plie of the composite plates was obtained on samples machined following the up-milling mode. The areal delamination factor (Ad) was taken as the process response. Figure 7a shows the effect of the feed rate on Ad, regardless of the other factors (Vc, θ and the cutting tool). The feed rate has a significant influence on the delamination extent. The latter decreases when f increases from 0.025 to 0.100 mm/rev and then stabilizes when f increases from 0.1 to 0.45 mm/rev (confidence intervals overlap). The worst case (worst surface finish quality) was obtained for a low feed rate. When looking at the main effect on Ad of the cutting speed (figure 7b), the latter does not seem to be significantly influencing. The latter conclusion contrasts with the one in Jonarthanan et al. (2013) and in Babu et al. (2013). This could be explained by the nature of the fibers (Chedgani et al., 2015) and by the experimental factors levels. In fact, Jonarthanan et al. (2013) studied the milling of GFRPs. Flax fibers have a viscoelastic behavior while glass fibers are fragile. Their cutting mechanisms are different. The cutting speed in Babu et al. (2013) study had been selected in the range of 16 to 32 m/min which is much lower compared to the Vc level of this study. The contact time between the cutting edge and the fibers is much longer, the effect of the cutting speed is then more significant.

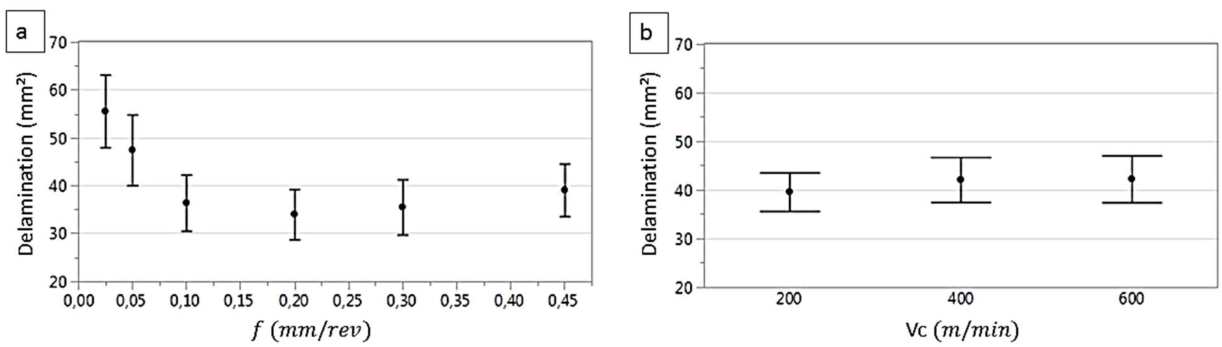

Figure 7. Evolution of the delamination extent with a) f and b) Vc (main effect, regardless the other parameters)

The evolution of Ad with the type of cutting tool and the fiber orientation is shown in figure 8. Tool #2 generates far lower damages on surface integrity (lower delamination). The uncut fibers size and quantity are lesser when using tool #2 whatever the fiber orientation. This can be explained by its special geometry which enhances the shear of fibers in the composites. Moreover, its low value of cutting edge radius (4 µm, lower than that of tool #1) facilitates the cutting of fibers. The worst surface integrity is obtained for fibers at -45° regardless of the tool used while the best surface quality occurs with a fiber orientation of 0°. The finish of the samples reinforced with fibers at 45° is shown to be better than that of samples with fibers at 90°. The fiber cutting mode causes this phenomenon. In fact, at -45° and 90°, the fibers are compressed under the contact tool/laminate, they bend instead of being cut by shear. Figure 9 compares the delamination in terms of uncut fibers quantity for coupons with fibers at 0° and -45° machined with both tool #1 and tool #2, considering a feed of $0.05\ mm/rev$ and a cutting speed of $200\ m/min$.

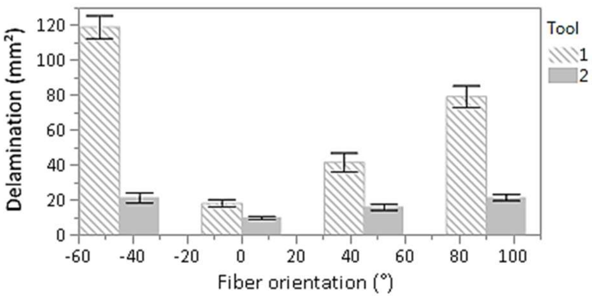

Figure 8. Evolution of the delamination extent with θ and the cutting tool

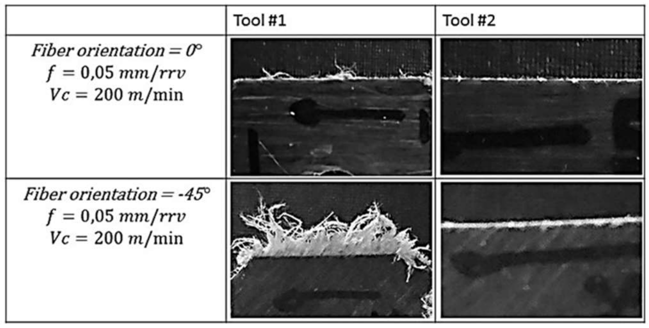

Figure 9. Comparison of delamination extent for particular cutting conditions

If we analyze the effect of the interaction between the fiber orientation and the feed rate regardless of the cutting speed and the cutting tool type (figure 10), the delamination behavior differs depending on f and θ. When the feed is minimum ($0.025\ mm/rev$), the worst delamination is generated when the fibers are oriented at $\pm 45°$ and 90° while the best surface finish is obtained at 0° fiber orientation. For the $f2$ feed rate ($0.05\ mm/rev$), the coupons with fibers oriented at -45° and 90° produce an equivalent delamination. Once again, the lowest delamination level is obtained when the fibers are oriented at 0°. The 45° orientation generates medium delamination for this feed rate. For $f3$ ($0.1\ mm/rev$) and $f4$ ($0.2\ mm/rev$), all different ply angles θ produce significantly different delamination levels. For samples milled at $0.3\ mm/rev$, the delamination of surfaces with fibers at 45° and 90° are similar. When the feed is maximum ($0.45\ mm/rev$), the 0° and 45° fiber orientation are equivalent. It is interesting to note that regardless of the feed rate, the samples with fibers at -45° undergo an almost constant Ad (confidence intervals overlap). To summarize, whatever the feed rate, the worst delamination is obtained for a fiber orientation of -45° while the lowest delamination is obtained for a θ of 0°. For fibers oriented at -45 °, the feed has no influence on Ad and the results are very dispersed (large confidence intervals). As for the other angles, Ad decreases when f increases from $f1$ to $f3$ and then stabilizes. Cutting with tool #2 is cleaner and sharper. Therefore, the best surface finish is obtained for fibers at 0°, a $0.1\ mm/rev$ feed rate and tool #2.

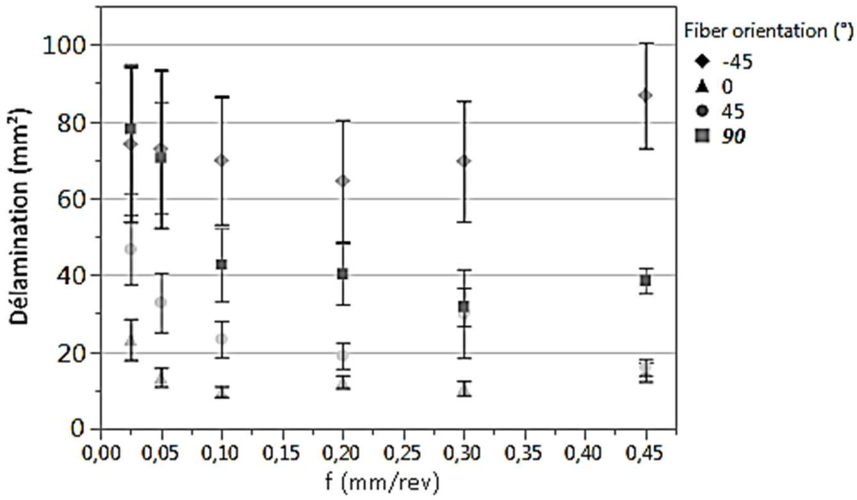

Figure 10. Evolution of the delamination extent with f and θ

The Pareto chart of Ad is represented in table 3. Only significant factors are represented. The feed rate is shown to have the greatest influence on the uncut fibers extent The cutting tool seems also to be significant with respect to Ad even though its effect may remain low (high P-value compared to that of the feed rate). However, its influence strongly depends on the feed rate level, i.e. the interaction between the cutting tool and the feed rate comes second. The fiber orientation, its interaction with the cutting tool and with f also affect delamination (table 3).

Table 3. Pareto chart of the delamination analysis

Factors		P-value
f (mm/rev)		0.00000
Tool × f (mm/rev)		0.00000
Tool × Fiber orientation (°)		0.00001
Fiber orientation (°)		0.00120
Fiber orientation (°) × f (mm/rev)		0.00496
Tool		0.00665

The Pearson-correlation coefficient (R^2) was found to be equal to 80.2%. The variation of the factors considered as influential explains the 80.2% of the variation of Ad. This coefficient is not sufficient to validate the model (the standard of significance is 85%). This can be explained by the locally non-homogeneous mechanical properties of the machined plaques because of non-similar fibers distribution in the matrix. The intrinsic error of the imaging measurement method could also explain this low coefficient. Nevertheless, the degree of liberty (DDL) of the model error is very high (246 DDL excluding the outliers) compared to the model DDL (6 DDL corresponding to the number of the model factors). In addition, the mean square error (MSE) is small compared to the mean delamination value (the MSE represents 10% of the delamination average). Finally, the Watson-Durbin coefficient (this coefficient detects the presence of autocorrelation in the residuals i.e. the presence of noise factor) is 1.92 ($\approx$ 2 i.e. the significance level) which validates that the model residual is not auto-correlated (absence of noise factor). These criteria validate the delamination prediction model below within the limits of the experimental work.

$$\mathrm{Ad} = \begin{cases} 94.603 - 0.039 \times \theta - 33.072 \times f - 50.157 \times Tool \quad (f - 0.1875) - \\ \quad 0.838 \times (\theta - 22.5) \times (f - 0.1875) - 0.078 \times Tool \quad (\theta - 22.5) & \text{For tool\#1} \\ \\ 21.733 - 0.039 \times \theta - 33.072 \times f - 50.157 \times Tool \quad (f - 0.1875) - \\ \quad 0.838 \times (\theta - 22.5) \times (f - 0.1875) - 0.078 \times Too \quad (\theta - 22.5) & \text{For tool\#2} \end{cases}$$

Here θ is in degree, f in mm/rev, Vc in m/min.

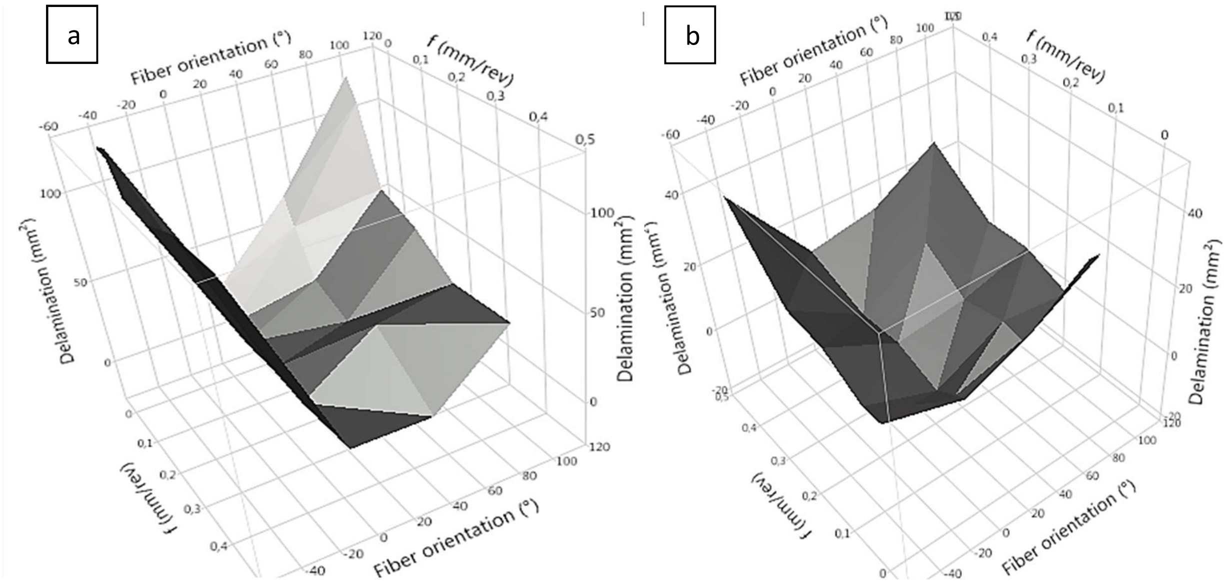

Figure 11. Response surface of the evolution of Ad with f and θ for a) tool #1 and b) tool #2

Figure 11 shows the surface response of the Ad evolution with f and θ depending on the tool. These results are consistent with the previous ones. For both tool #1 and #2, the lowest uncut fibers size is obtained with fibers oriented at 0° whatever the feed rate level. The delamination extent increases with the feed rate. Tool #1 generates more uncut fibers. Thus, the delamination extent depends on both f and θ and on their interaction.

Figure 12 summarizes the factors level which minimize the delamination (factors in abscissa in the figure). Globally, a fiber orientation of 0° and a low feed rate of 0.05 mm/rev provide the best surface finish. Better surface finish was obtained with tool #2 thanks to its geometry which enhances the fibers shear in the FRPs. A high cutting speed is recommended to maximize the material removal rate and thus the productivity (Vc has no influence on Ad).

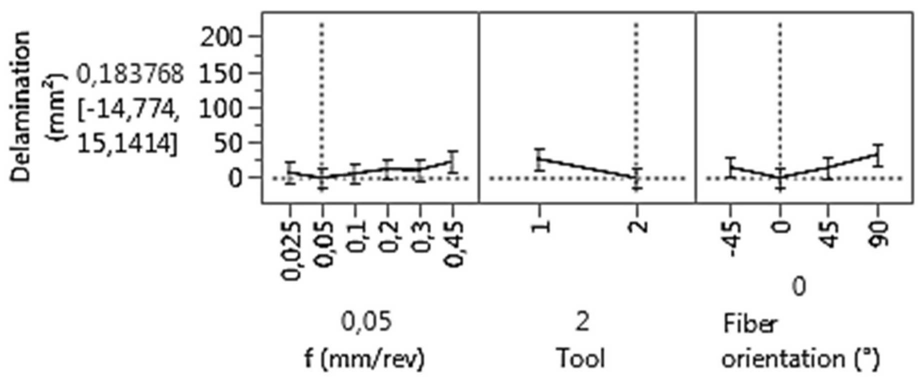

Figure 12. Main effects diagram and optimum cutting condition

To conclude, these results are consistent with the literature since on one hand the feed rate is the most influencing factor on the uncut fibers size. The latter increases with the feed rate and is minimum when the fibers are oriented at 0° which supports the results in Babu et al. (2013), in Azmi et al. (2016) and in Delahaigue et al. (2017). On the other hand, the cutting speed has no significant effect on Ad which supports the results of Azmi et al. (2016). This is in contrast with the results in Babu et al. (2013) that emphasize the importance of the cutting speed on Ad.

4. Conclusion

This paper aims to characterize the effect of machining parameters and fiber orientation on the delamination extent of unidirectional flax fiber-reinforced epoxy resin. It was shown that:

- The studied factors i.e. feed rate, fiber orientation and cutting tool geometry were well correlated with the areal delamination factor Ad.
- The feed rate was the most influential factor on the delamination extent while the cutting speed had no influence on it.
- The lowest quantity and size of the uncut fibers was obtained with fiber oriented at 0° with respect to the cut direction while the highest was generated when fibers are oriented at -45°.
- Tool #2 showed a better performance than tool #1 due to its special geometry which enhances the fibers shear.
- Depending on the factors level and their interactions when trimming, the delamination behaves differently

To reduce the length and quantity of uncut fibers, a low feed rate (0.05 mm/rev) and a carbide tool with a zero-helix angle and a low cutting-edge radius are recommended. This cutting combination leads also to the minimization of the cutting forces and the surface roughness (Karabibene et al., 2017).

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