OPTIMIZATION OF MACHINING PARAMETERS FOR THE TRIMMING PROCESS OF UNIDIRECTIONAL FLAX FIBER COMPOSITES

Karabibene, N[1]*, Chatelain, J-F[1], Beauchamp, Y[1], and Lebrun, G[2]
[1] Department of Mechanical Engineering, École de technologie supérieure Montreal, Canada
[2] Department of Mechanical Engineering, Université du Québec à Trois-Rivières, Trois-Rivières, Canada
*Corresponding author (nouha.karabibene.1@ens.etsmtl.ca)

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ABSTRACT

Flax fibers have been identified by several researchers as a potential substitute for glass fibers in composite materials, considering their high intrinsic modulus and strength, their biodegradability, their low weight and low cost. However, due to the nonhomogeneous nature of natural fibers, defects such as edge delamination and high surface roughness (Ra) appear when milling composites made with these fibers. Their machining thus represents a significant challenge. The main objective of this study is to characterize the machinability of unidirectional flax fiber-reinforced epoxy resin (UDF/Epoxy). The second objective is to identify the optimum cutting conditions within the limits of the experimental work (cutting speed, feed rate, fiber orientation and cutting tool characteristics), using surface roughness and cutting force as quality criteria. Dry up-milling experiments were conducted with a full Split-Split-Plot Block design and the aforementioned inputs. Two different tools (two-flute uncoated carbide end mill and a two-flute polycrystalline Diamond (PCD) end mill) were used. This study showed that fiber orientation, cutting speed, feed rate and cutting tool geometry significantly influence both surface roughness and cutting forces. Depending on the response studied, every factor reacts differently. A general optimization of the up-milling process was proposed. The best parameters found were a low feed rate (0.025 mm/rev), a high cutting speed (600 m/min) and a PCD tool with a zero-helix angle.

1 INTRODUCTION

The lightness and highly interesting mechanical properties of unidirectional natural fiber composites, and particularly, bast fiber-reinforced polymers such as those using flax fibers, are increasingly attracting the interest of the aeronautic, automobile, construction, naval and railway industries [1, 2]. Unlike synthetic fibers, natural fibers are abundant and renewable. Furthermore, their extraction is non-energy-consuming, which makes them inexpensive [3]. Additionally, Natural fiber-reinforced plastics (NFRP) are partly biodegradable, more eco-friendly than synthetic fibers, and recyclable. They are particularly, interesting considering their inherent mechanical properties, which are comparable to those of glass fiber-reinforced polymers (GFRP); that is especially the case with their intrinsic modulus and strength (ratio of the modulus or strength over fiber density) [4, 5]. They are also likely to be less abrasive in manufacturing processes using cutting tools, making them undoubtedly more economical; this assumption though, is yet to be confirmed. Indeed, the anisotropic nature and the non-homogeneous internal structure of NFRPs complicate the understanding of cutting mechanisms [6].

Long (continuous) fiber-reinforced composite components can be produced using a liquid composite molding (LCM) process, such as resin transfer molding (RTM), to increase component quality and fiber content and reduce raw material loss. The molded components are obtained in a quasi-finished near net shape, but finishing to high accuracy using machining operations, particularly drilling and trimming, is required to reach a cutting edge finish quality and the dimensional specifications. Nevertheless, these operations introduce machining defects such as delamination, failure of the matrix, micro cracking and a poor surface roughness of the machined components.

The machining of NFRPs differs significantly from that of metals. Although trimming methods generally used for metal are adapted to composites, determining optimal cutting conditions requires a deeper investigation. Actually, the optimal cutting parameters and the prediction models for machining quality criteria are valid only for the same material. They are also limited to the same experiment conditions used for a same preparation method of the composite [7]. These limitations are due to the non-reproducibility of the sample properties. Previous works dedicated to the machining of NFRPs focused only on identifying factors influencing the quality and the productivity of the drilling operation especially.

Several research works have investigated the cutting forces and the quality of the machined surfaces resulting from the trimming of natural fiber/epoxy laminates. Babu et al. [8] compared the machinability of three unidirectional laminates made of natural fibers and one made of glass fibers, namely, jute/polyester (JFRP), hemp/polyester (HFRP), banana/polyester (BFRP) and glass/polyester (GFRP), with all the laminates having the same fiber volume fraction of 52%. The authors concluded that the delamination factor (Fd) and the arithmetic roughness (Ra) of the machined part increase with the feed rate and decrease when the cutting speed increases. These two cutting parameters are most influential on Fd and Ra. Among the 4 materials, the HFRP produced a smaller Fd and Ra as compared to the NFRPs and the GFRP. That suggests that NFRPs can potentially replace GFRPs for applications requiring a good surface finish.

Chegdani et al. [7] investigated the effect of 3 different coated tools on the surface finish when dry milling a unidirectional flax fiber-reinforced polypropylene composite (UDF/PP). The authors paid special attention to the tool wear and the fiber cutting parameters. They concluded that up-milling provides the best surface integrity and surface roughness [2, 7]. The optimum cutting condition was obtained with the tool having the smallest cutting edge radius used with a high feed rate. Teti [9] highlighted that the cutting parameters most influential on the finishing quality of the milling process are primarily the feed rate and the cutting depth, and secondly, the cutting speed. A combination of low depth of cut, low to medium feed rate and high cutting speed optimizes the surface integrity and the surface roughness for the up-milling of fiber-reinforced polymers (FRPs). The feed force and the surface roughness increase with the feed rate and depth of cut, while they decrease when increasing the cutting speed [7].

Recently, Delahaigue et al [2] carried out a study on the dry up-milling of a unidirectional flax/epoxy composite using two cutting tools. The authors investigated the influence of cutting speed, feed rate, tool geometry and fiber orientation on surface integrity, surface roughness and cutting forces. The good machinability of flax/epoxy composites was confirmed. However, a poor surface roughness was generated. According to the orientation of fibers and the tool type, different trends for the surface roughness parameter were observed. In short, the best responses were observed with a medium feed rate, and the cutting efforts were correlated with the feed rate. Further, the worst case in terms of machining response was observed on laminate plies oriented at -45°, while the best result was obtained with 0° plies.

Different statistical approaches have been investigated to optimize the cutting parameters, but none has investigated the robustness of prediction models developed or focused on reducing errors in models in order to overcome the non-homogeneity of the responses studied. Therefore, models developed in the literature are not generalizable [7]. To validate this review, this paper aims to identify the optimum cutting conditions within the limits of our experimental work (cutting speed, feed rate, fiber orientation and cutting tool characteristics) using surface roughness and cutting force as quality criteria. Dry up-milling experiments were conducted with a full Split-Split Plot Block design and the aforementioned inputs.

2 METHODOLOGY AND DESIGN OF EXPERIMENT (DOE)

2.1 Material preparation

Six laminated composites plates (including one for preliminary tests and one for the validation of the models) were investigated. The laminates were fabricated through the vacuum assisted resin transfer molding (VARTM) method. They were made using epoxy resin Marine 820, delivered by Adtech Company, and having a density of 1.09 g/cm^3, once premixed to Marine 824 hardener at a ratio of 18% by weight. The test laminate consisted of a stack of 15 unidirectional long flax fiber plies (Flaxtape 200 delivered by LINEO, France) having a surface density of 194 g/m^2 (measured experimentally by weighing known surfaces of the reinforcement), with a fiber density of 1.54 g/cm^3. 15 layers were required to reach a fiber volume fraction (V_f) of 41.1 ± 0.589 % in a mold cavity thickness of 4.597 mm.

Figure 1 shows the three steps involved in the molding of composite plates. The fabrication process begins with the preparation of a stack of unidirectional plies (Figure 1.a). The injection process comes next (Figure 1.b shows the pressure pot aside the press inside which the flat mold is installed), and after the final cure, the composite plate is obtained, as shown in Figure 1.c. The plies were cut to 304.8 mm x 330.2 mm sizes. They were then dried in an oven at 80 °C for 8 hours to minimize the humidity level in the molded plate. The injection pressure was initially set to 30 psi, and was gradually increased during resin injection to allow a constant injection rate to complete the impregnation. The resin cure was obtained in a hot-platen press, under a 20 ton closing pressure at 80 °C, for 3 hours. A [0_{15}] unidirectional flax-epoxy composite was then obtained for the machining tests.

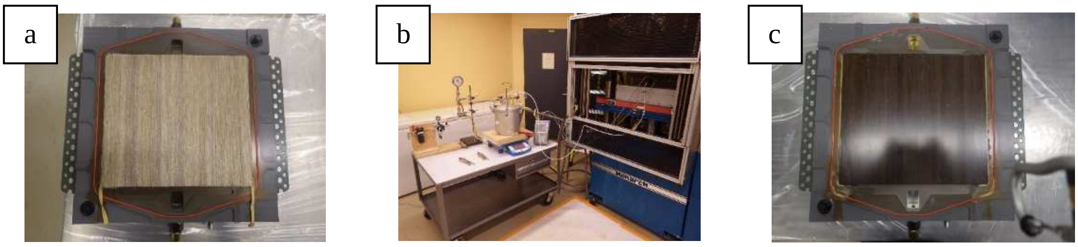

Figure 1. Plaques processing: a) plies stacking b) VARTM setup c) Molded plaque

2.2 Experimental set-up and machining

2.2.1 Experiment factors and responses

Two cutting tools were selected for this study. The first one was a two-flute polycrystalline Diamond end mill (PCD) with a zero-helix angle, as utilized in the Bérubé study [10] (Figure 2.a). The second was selected based on Chegdani's study [7], and was a two-flute uncoated carbide end mill with a smaller cutting edge than the PCD tool.

It had a zero-helix angle and, from one flute to the next, the cutting profiles of 70° were inverted, thus enhancing fiber shearing and reducing the risk of delamination (Figure 2.b). The cutting tools specifications are presented in Table 1.

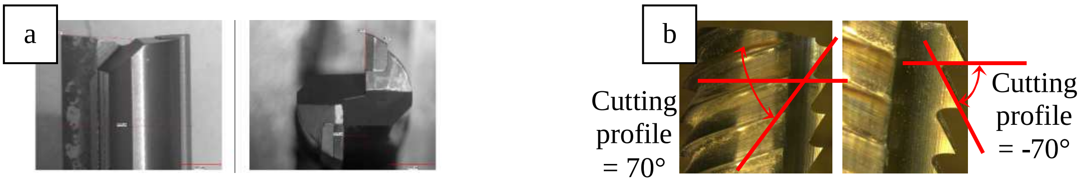

Figure 2. Cutting tools: a) tool#1 [10] and b) tool#2

Tool	Diameter (mm)	Flutes number	LOC (mm)	Rake (°)	Relief angle (°)	Cutting edge radius (µm)	Helix angle (°)	Coating Material
Tool #1	9.525	2	25.4	10	20	5	0	Diamond PCD
Tool #2	9.525	2	25			4	0	Carbide 28072

Table 1. Specifications of cutting tools

This paper investigates the influence of the parameters that were identified in the literature as potentially the most significant for the dry up-milling process. These parameters (named "design factors" below) are the feed rate (f), the cutting speed (Vc), the fiber orientation (θ) and the cutting tool geometry. Four fiber orientations, three cutting speeds, six feed rates and 2 cutting tools were selected (Table 2). Two tests were run to provide a measure of process stability and inherent variability. For these tests, the cutting speed and feed rate had, respectively, a value of 400 m/min and 0.2375 mm/rev (which is the average between their low and high level) per fiber orientation and cutting tool. The design was replicated twice to minimize dispersion effects and measurement errors, for a total of 304 machining combinations.

The levels of the design factors were selected based on the conclusions of Delahaigue [2] and the results of the preliminary tests performed on plates with fibers oriented at -45°. These tests showed that a high Vc produces high cutting forces while a low Vc leads to a high surface roughness. It was also found that high feed rates also caused high cutting forces. Moreover, the technical datasheet of tool#2 limits its operating range from 200 m/min to 500 m/min. Thus, based on previous works, the proposed responses of interest in the present study are the cutting forces (i.e., the feed force (Ff), the normal force (Fn) and the passive Z-component force (Fp)) and the surface roughness (i.e., the arithmetic mean roughness (Ra) and the total height of roughness profile (Rt)). Table 2 shows the different parameters evaluated with the different levels considered for the analysis.

	1	2	3	4	5	6
Cutting tool	Tool#1	Tool#2	-	-	-	-
Plate configuration (°)	0	- 45	-	-	-	-
Cutting angle (°)	0 (along X-axis)	90 (along Y-axis)	-	-	-	-
Vc (m/min)	200	400	600	-	-	-
f (mm/rev)	0.025	0.05	0.1	0.2	0.3	0.45
Responses	**Ra**	**Rt**	**Ff**	**Fn**	**Fp**	

Table 2. Experiment factor levels and responses

2.2.2 *Milling and design of experiment*

The milling operations were conducted using a three-axis numerically controlled machining (CNC) center, HURON K2X10 (Figure 3). The plate was affixed to a three-axis dynamometer table, type Kistler 9255, allowing the measurement of the cutting force components in three directions, i.e., X, Y and Z.

Figure 3. Milling setup

The cutting was performed along two directions, namely the X-axis (0° cutting angle) and the Y-axis (90° cutting angle). Two different fixations of the plate (named "plate configuration" in Table 2 above) were used to study the effect of fiber orientation (Figure 4). First, the plaques were perforated following the square pattern shown in Figure 4, with the perforations used to hold the plate to the setup using screws to minimize the vibration effect on the surface roughness [2, 7].

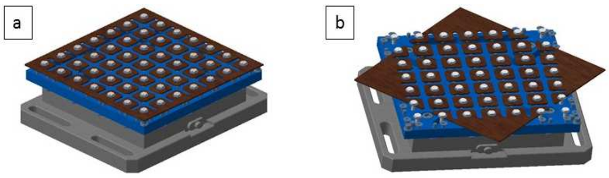

Figure 4. Plate configuration: a) 0° and b) -45°

The interaction between the plate configuration and the cutting angle (plate configuration*cutting angle) is here equivalent to the fiber orientation (θ). When the plate configuration is 0°, the fibers are oriented at 0° with regard to the tool movement direction (Figure 5.a), while for a cutting angle of 90°, the fibers are oriented at 90° with regard to the motion direction. Likewise, when the plate configuration is -45°, for a cutting angle of 0° with regard to the movement direction (Figure 5.b), the fiber orientation is -45°, while for a cutting angle of 90°, the fibers are oriented at 45°.

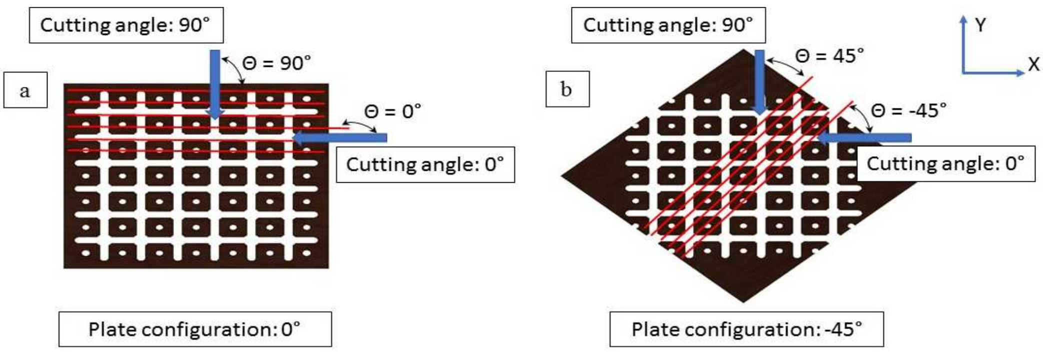

Figure 5. Fiber orientation with: a) 0° plate configuration and b) -45° plate configuration

To minimize the response variability and systematically reduce experimental errors, a Split-Split Plot randomized complete block design (SSPRCPD) was identified as the most suitable for this study. For each plaque, one cutting tool (tool#1 or tool#2) milled the first 38 combinations of 3 levels of Vc, 6 levels of feed and two cutting angles, randomly. Then the second tool milled the last 38 combinations. The cutting tool was regularly inspected, i.e., after each cutting of 4 coupons, to control its wear. A new unaffected region of the cutting tool was chosen after a cutting length of 2.64 m (which corresponds to cutting 92 coupons). Consequently, the tool wear can be neglected in this study. Figure 6 shows an example of randomization of the first two cutting operations when cutting at -45° (Figure 6.a) and at 0° (Figure 6.b).

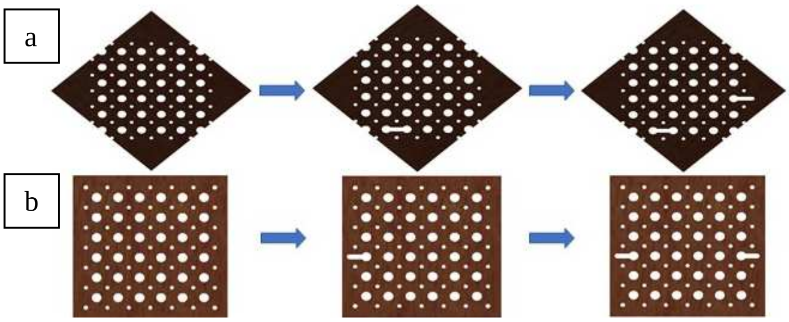

Figure 6. First two cutting operations when cutting at: a) -45° plate configuration, and b) 0° plate configuration

2.3 Roughness measurement

The surface roughness was investigated using a Mitutoyo profilometer surftest SJ-400. This equipment possesses a 2 µm radius diamond tip with a 90° angle. It was linked to a SURFPAK-SJ acquisition software application to enable data processing. An optical microscope, Keyence VHX-500FE helped to detect any deviation of the profilometer trajectory and outliers caused by the presence of any residual chip at the machined surface (Figure 7).

Figure 7. Roughness measurement setup

To proceed with the surface roughness measurements, the coupons were first cleaned with compressed air, and then preliminary tests were carried out to identify the best profilometer cut-off. The specifications of the cut-off, selected according to ISO 4287-1997, are shown in Table 3. Five random measurements were carried out for each up-milled coupon edge, for a total of 1440 measurements.

Ra measurement (µm)	Basic length (mm) λs	Evaluation length (mm) L	Sampling number N
$2 < Ra \leq 10$	2.5	12.5	19

Table 3. Specification of the profilometer cut-off

3 EXPERIMENTAL RESULT

The flax/epoxy composite was easily machined an no tool wear was observed during the machining operation. Figure 8 shows the tool#1 and tool#2 at the start of the milling of the second plaque (Figure 8.a) and after the milling is completed (Figure 8.b) i.e., after a cutting length of 2.64 m. It is shown that no modification in cutting edge occurs during the milling process. This confirms that flax/epoxy composites are not abrasive, and thus ensure a long tool life.

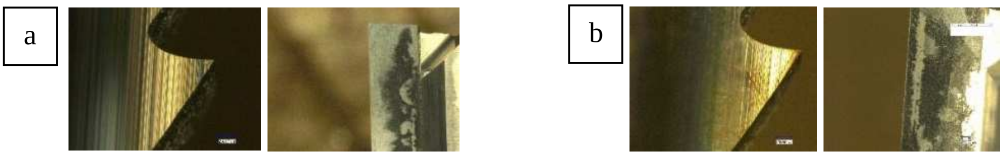

Figure 8. Cutting tools a) before and b) after the milling operation

The correlation between the responses obtained from the milling operation was firstly studied to reduce the number of the responses to analyze and to better understand the relationship between them. The analysis was run using MINITAB 17. It showed that the cutting forces i.e., Ff, Fn and Fp, were correlated with Ra and Rt (Table 4). This conclusion agrees with Wang's study [11]. This was explained in [7] by the fact that the cutting forces create vibrations which affect the cutting mechanism of the fibers. In fact, the fiber bends instead of being cut by shear, thus affecting the surface roughness. The Rt parameter was also correlated with Ra. Consequently, only the surface roughness Ra and the cutting forces are investigated in this paper.

	Ra	Rt	Ff	Fn
Rt	0.000			
Ff	0.049	0.000		
Fn	0.001	0.011	0.995	
Fp	0.001	0.002	0.134	0.925

Cell content: P-value

Table 4. Correlation matrix

An analysis of variance (ANOVA) was performed in order to identify the factors which significantly influence, the cutting forces, on the one hand, and the surface roughness, on the other.

3.1 Surface roughness Ra

The Pareto chart of Ra is shown in Table 5. The significant factors here are those possessing a P-value higher than 5%, i.e., the standard of significance (the dashed line in Table 5). The feed rate (f) is shown to be the most influential factor on the roughness, and the cutting angle comes next. The cutting speed (Vc), the tool type and the fiber orientation (the item Plate config*Cutting angle) also have a significant effect, even though their influence may remain low (high P-value compared to that of the feed).

Source	P-value
f	0,00000
Cutting angle	0,00000
Vc	0,00772
tool	0,01009
Plate configuration*Cutting angle	0,01096
Plate configuration	0,10160

Table 5. Pareto chart, Ra analysis

The variation of the factors exposed above explains only 57% ($R^2 = 0.57$) of the variation of Ra within the experiments. This can be explained by the non-reproducibility of the Ra measurements due to the non-reproducibility of the milling of the natural fiber composite samples. It can also be explained by the locally non-homogeneous distribution of the fibers and matrix in the machined plaques. Indeed, a high roughness can result from local fiber pull-out and a low roughness can result from matrix softening and a homogenization of the surface finish. Figure 9 summarizes the influences of the factors studied on the surface roughness. The latter decreases significantly with the feed rate until a value of 0.1 mm/rev is reached, and then stabilizes from 0.1 to 0.45 mm/rev, where the confidence intervals overlap. The best surface roughness is obtained with a fiber orientation of 0°. The cutting tool, cutting angle and cutting speed have a low influence on Ra. Figure 9 shows that to minimize the surface roughness, a fiber orientation of 0° (combination of a plaque configuration of 0° and a cutting angle of 0°), tool#2, a medium feed rate of 0.3 mm/rev and a high cutting speed of 600 RPM are recommended (the level of factors shown in red in Figure 9). Tool#2 is found to be better than tool#1 because of its special geometry which enhances the shear of fibers in FRPs and because of its low value of cutting edge radius, which facilitates the cutting of fibers.

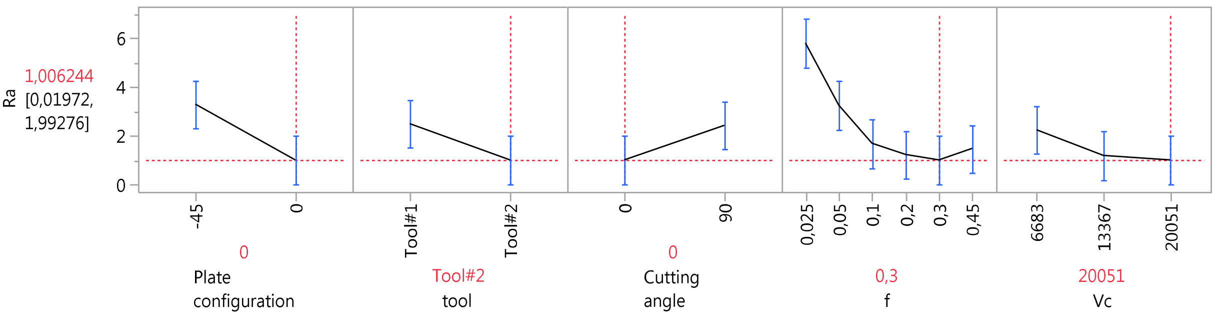

Figure 9. Main effects diagram and optimum cutting condition, Ra analysis

3.2 *Cutting forces*

Table 6 shows the Pareto charts of the different force components, as well as the R^2 associated with each model. The fiber orientation is the most influencing factor on the feed force (Ff), followed by the cutting angle and the feed rate (Table 6.a). The cutting speed and the tool type are weakly significant with respect to Ff. The feed force amplitude increases with the feed rate and decreases with a cutting speed increase (Figure 10). The Pearson-correlation coefficient was found to be equal to 93.7%, which confirms that the factors selected as influential allow a good prediction of the behavior of Ff. The normal force (Fn) is mainly influenced by the cutting angle and the feed rate. The tool type has a little effect on Fn while neither the cutting speed nor the fiber orientation (plate configuration*cutting angle) influence Fn (Table 6.b). Similarly to the feed force, the normal force increases with the feed rate (Figure 10). The passive force (Fp) is correlated with the feed rate, the cutting speed and the tool type (Table 6.c). Fp increases with the feed rate (f) until f= 0.3 mm/rev and then decreases. It has a quadratic behavior with the cutting speed, with a minimum value at an intermediate cutting speed (Figure 10).

a (R^2=94%)

Source	P-value
Plate configuration*Cutting angle	0,00000
Cutting angle	0,00000
f	0,00000
Vc	0,00331
tool	0,01772
Plate configuration	0,19015

b (R^2=99%)

Source	P-value
Cutting angle	0,00000
f	0,00000
tool	0,00168
Plate configuration*Cutting angle	0,09517
Plate configuration	0,12126
Vc	0,43148

c (R^2=86%)

Source	P-value
f	0,00000
Vc	0,00000
tool	0,00000
Cutting angle	0,01868
Plate configuration	0,11580
Plate configuration*Cutting angle	0,70440

Table 6. Pareto chart, a) Ff analysis, b) Fn analysis and c) Fp analysis

Based on these results, a global optimization of surface roughness and cutting forces was proposed. All responses were minimized or targeted to zero. The behavior of the three cutting force components and surface roughness as a function of the input factors is presented in Figure 10. Considering all responses, a compromise was made in identifying the optimum cutting parameters. It results that, a 0° fiber orientation, a low feed rate (0.05 mm/rev), a high cutting speed (600 m/min = 20051 RPM) and tool#2 are the parameters optimizing the cutting forces and surface roughness, and indirectly the up-milling process itself.

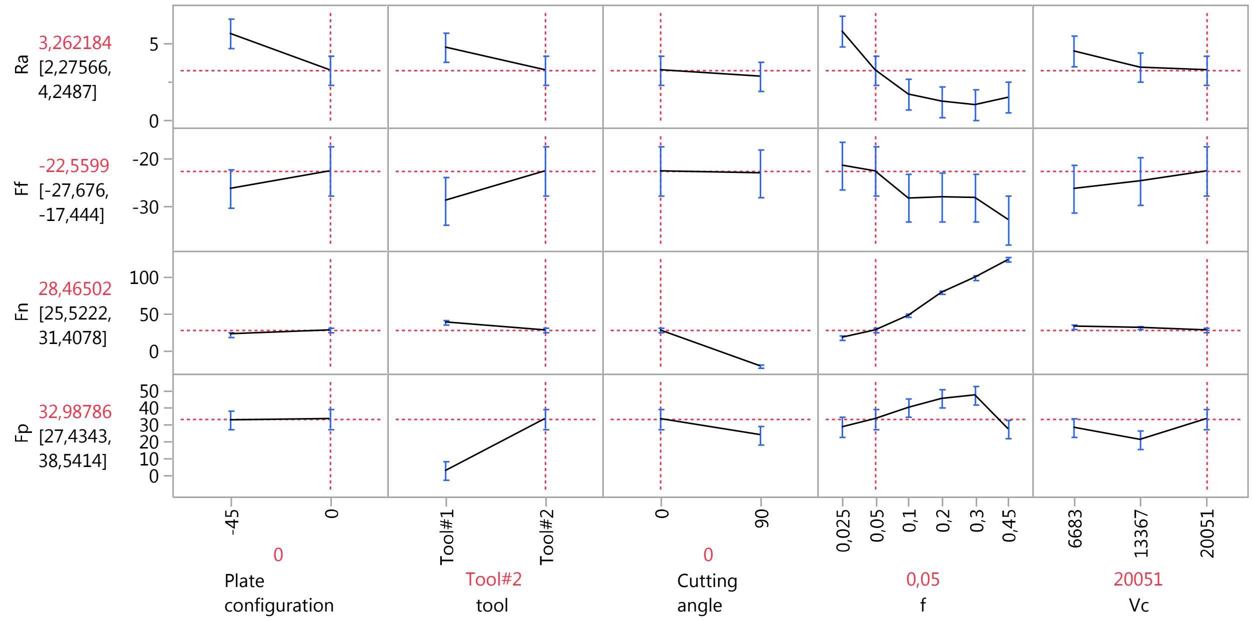

Figure 10. Main effects diagrams and optimum cutting conditions, whole milling process

4 CONCLUSION

The main objective of this study was to characterize the machinability of unidirectional flax fiber-reinforced composites made of epoxy resin as matrix (UDF/Epoxy) and to identify the optimum cutting parameters minimizing the surface roughness and cutting forces, chosen as quality criteria. The results show that:

- Flax/epoxy composites can be easily machined. Flax fibers are not abrasive, since no tool wear was observed after the milling operation.
- The correlation between the cutting forces and surface roughness was confirmed. Consequently, the optimization of one leads undoubtedly to the optimization of the other.
- A correlation exists between the studied factors, i.e., cutting parameters, fiber orientation and cutting tool characteristics, on the one hand, and the cutting forces and surface roughness, on the other.
- The feed rate, fiber orientation, cutting tool geometry and cutting speed significantly influence the surface roughness and the cutting force. The cutting speed has a little effect, but cannot be neglected.
- To optimize the up-milling process, the best parameters found were a low feed rate (0.05 mm/rev), a high cutting speed (600 m/min) and a carbide tool with a zero-helix angle and a low cutting edge radius.

To validate the importance and the potential of flax fiber composites as an alternative to glass fiber composites, a comparison between FFRPs machinability and GFRPs machinability is required.

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