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Characterization of the area roughness of a GFRP by a 3D profilometer after trimming

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Abstract. The aim of this study is to characterize the link between the cutting conditions used while trimming a composite material glass fiber reinforced polymer (GFRP) and the surface quality by characterizing the area roughness of the machined surfaces. In the experimental evaluation, a central composite design with 20 combinations was used to study cutting parameters (cutting speed (V_c), radial engagement (a_e) and tooth feed (f_z)). The area roughness parameters (S_a , S_q , S_z) were measured by a KEYENCE VHX-6000 3D profilometer. Response Surface Methodology (MSR) were used to determine mathematical models using experimental data.

Keywords: GFRP, Composite Trimming, Area Roughness, 3D Profilometer, Central composite design, MSR

1 Introduction

The composite materials industry is a sector that has made a great deal of progress over many years [1] [2]. Today, the manufacturing of this material is mainly divided between glass fiber reinforced composites (GFRP) and carbon fiber reinforced composites (CFRP). Although they are less efficient, GFRP composites now represent 95% by volume of the composites produced in Europe [3]. The process of obtaining a composite material part involves two stages: a first stage consists of manufacturing and a second stage called finishing. Trimming is one of the most common finishing processes used. Obtaining sufficient quality in terms of dimensional accuracy, surface finish and absence of residual fibers are the main difficulty in machining composites while at the same time assuring a certain productivity: speed of production, tool costs, etc... In view of the difficulties in obtaining finished quality workpieces, various studies are interested in proposing evolutions of the machining finishing process in order to improve

the results [4] [5]. The combined effect of cutting parameters on surface quality or tool degradation in GFRP composite drilling operations has been the subject of extensive study [6] [7] [8] [9]. In the case of milling GFRP composites, the influence on the surface quality of the machining direction in relation to the fiber orientation is known [10]. The same can also be said for the influence of cutting parameters [11]. However, several research works haven't shown a complete and global study on the trimming of GFRP composites combining tool choice and parameters choice and results, both in terms of quality and productivity. The definition of behaviors, generic theoretical principles are studied but the experiments carried out concern carbon fiber reinforced composites [12] [13]. In the present work, the roughness of the machined surface states is investigated. Indeed, we are interested in the use of area roughness parameters to describe the quality of the machined surface.

2 Response Surface Methodology

The principle is to model the experimental response surface. Among the many types of plans to build response surfaces, we will use a central composite design. Indeed, this technique has the advantage of being suitable for the sequential conduct of a study and requiring a relatively few experiments [14]. RSM allows to evaluate not only the linear effects but also quadratic effects as well as the effects of interaction between the different operating variables, the model used is the quadratic model with interactions:

$$Y = a_0 + \sum_i a_i X_i + \sum_{ij} b_{ij} X_i X_j + \sum_j c_j X_j^2 \quad (1)$$

Where a_0 , a_i , b_{ij} and c_j are the regression coefficients of the model and X_i , X_j are the explanatory variables of the model.

3 Material and methods

3.1 Material

The composite material was made with Vetrotex 136 tex continuous glass fibers, reference ZTW EC13 136 tex TD22C with a diameter of 13 μm . The matrix is initially liquid thermoset matrix with two components: epoxy / amine system CY219 and Renlam HY5160 (Huntsmann). The test pieces are made by a method of filament winding to obtain a unidirectional composite. The equipment of the manufacturing composite plates is shown in fig. 1. Indeed, the fiberglass filament is wound on a parallelepiped mold animated by a rotational movement managed by a motor whose speed is controlled. The filament slides in a guiding system whose movement is controlled by the rotation of a worm drive, and is driven by the rotation of the mold. The combination of the rotational speed of the mold and that of the worm drive ensures the implantation of the glass fibers on the mold in the form of parallel lines with two possible orientations:

0 ° and 90 °. The rotation of the worm drive is reversed at each end. At each inversion, the system is stopped manually to reassure manual impregnation with the resin.

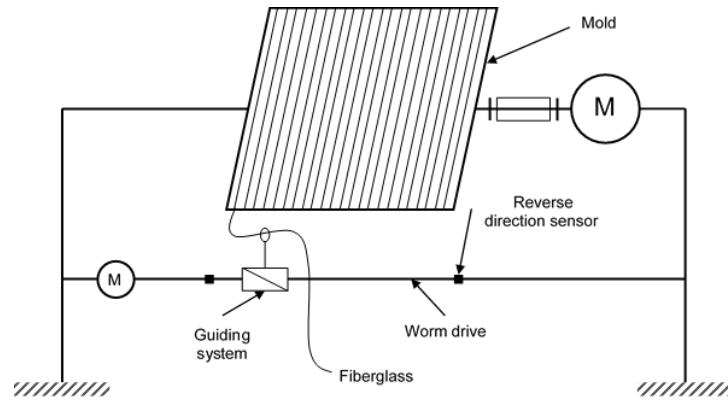


Fig. 1. Device for manufacturing composite plates

3.2 Machine and tool used

The machining tests were carried out on a Charly 2U machine equipped with a spindle turning up to 24000 *tr / min*, allowing feed rates up to 100 *mm / s* and with a maximum spindle power of 1,1 *kW*. For the cutting tool (Fig. 2), our choice fell on a one-piece SECO carbide milling cutter with a diameter $d = 6\text{ mm}$ whose main characteristics are shown in table 1.

Table 1. Characteristics of the tool used

Manufacturer's reference	Teeth number	Coating	Specifications
840060R050Z4.0-DURA	4	DURA	Double helix to avoid delamination



Fig. 2. Cutting tool

3.3 Machining strategy

During machining the composite plate is mounted between two flanges tightened by 8 screws (Fig. 3). During the trimming operation, the machining strategy adopted is climb milling. Indeed, the tool is driven by a translational movement with a feedrate V_f (mm

/ min) and a rotation speed N (tr/min). As part of this work, all the tests were carried out with a tool overhang $D_{ep} = 1\text{ mm}$ and a width of plate $a_p = 4\text{ mm}$. The milling cutter goes out of the spindle about 25 mm.

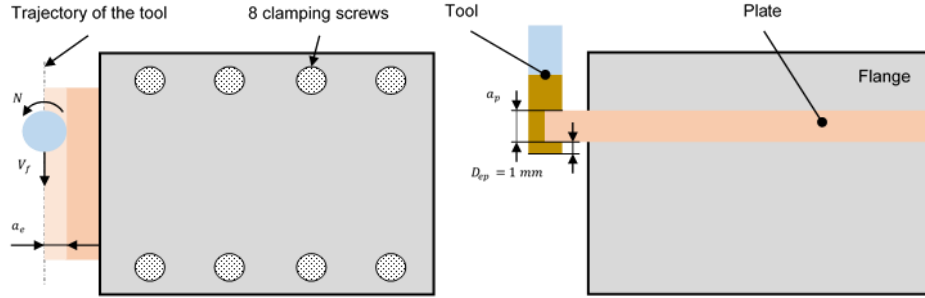


Fig. 3. Trimming strategy

4 Design of experiments

A central composite design with 20 combinations (Fig. 4) was chosen to study the influence of the three selected cutting parameters (cutting speed V_c , radial engagement a_e and tooth feed f_z). The values of parameters were established in accordance with the recommendations provided by the SECO cutting tool manufacturer.

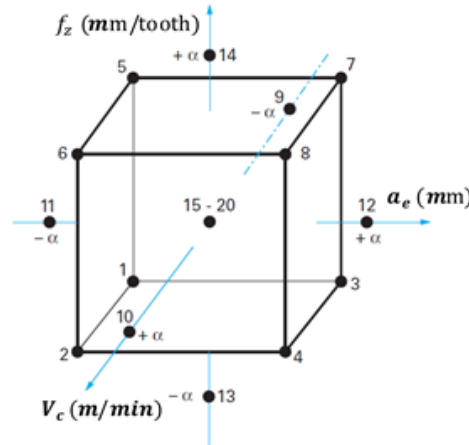


Fig. 4. Central composite design

The experimental design consists of 20 tests: 8 tests corresponding to the orthogonal plane, 6 tests for the axial points and 6 tests at the central point (0, 0, 0) to check the repeatability. The domain of variation of the coded factors is brought back to the interval [Min; Max] divided into 5 levels: $-\delta$, -1 , 0 , 1 , $+\delta$ which are calculated according to

the expressions given in table 2, where: $\delta = \sqrt[4]{N}$ and N is the number of fractional plan tests. Here N = 8, so: $\delta = \sqrt[4]{8} = 1,68$.

Table 2. Variation of the cutting parameters and their levels

Levels	Real variables	V _c (m/min)	a _e (mm)	f _z (mm/tooth)
- δ (-1,68)	Min	130	0,1	0,04
-1	$\frac{Min+Max}{2} - \frac{1}{\delta}(Max - \frac{Min+Max}{2})$	146	0,26	0,05
0	$\frac{Min+Max}{2}$	170	0,5	0,06
1	$\frac{Min+Max}{2} + \frac{1}{\delta}(Max - \frac{Min+Max}{2})$	194	0,74	0,07
+ δ (1,68)	Max	210	0,9	0,08

5 Analysis method of area roughness

We have at our disposal a 3D KEYENCE VHX-6000 digital microscope that will allow us to measure area roughness parameters. This microscope is essentially characterized by: advanced lighting and focus, multiple illumination and direct depth composition. With digital microscope, the operator can tilt the lens and camera at a maximum angle of 90 degrees, eliminating the need to manipulate the object by hand and thus facilitate control. The XY stage allows a displacement range of $100 \times 100 \text{ mm}$ so observation and image assembly are faster. For magnification we can go from $20 \times$ to $2000 \times$ with one lens. The aim is to characterize the machined surface with area roughness parameters. The microscope used allows us to scan the entire machined surface to calculate the desired parameters. The scanning operation of the entire surface to do the 3D reconstruction is only done if the lens and the camera are perpendicular. In our case we cannot satisfy this condition because of the length of the machined samples. For this reason, we have designed a support inclined at 60° to the vertical to measure all the machined plates. In order to properly characterize the machined surface, we chose to use a $1000 \times$ magnification and to average 8 evenly distributed measurement points (Fig. 5). For each "point" we defined a square measurement zone of $250 \mu\text{m}$ of side and recorded the values of Sa, Sq and Sz by setting the filters to the following values: S-Filter = $2 \mu\text{m}$, L-Filter = $0,25 \text{ mm}$. This strategy is based on the instructions in ISO 25178-2.

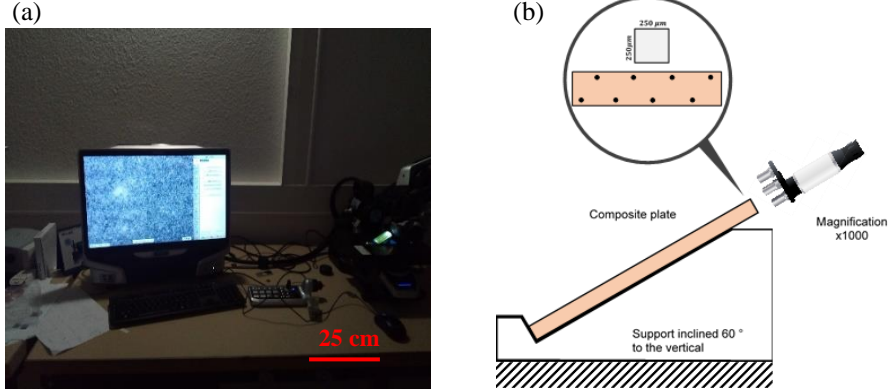


Fig. 5. (a) Area roughness measurement instrument, (b) Area roughness measurement strategy

6 Results and discussion

The analysis of the machined surface state according to the experimental procedure detailed above, allowed us to recover several area roughness parameters. Among these parameters, the choice was fixed on two parameters which have a mean of measurement which are S_a and S_q and a parameter which describes a maximum height which is S_z . Indeed, these parameters are defined as follows:

$$S_a = \frac{1}{A} \iint_A |Z(x, y)| dx dy \quad (2) ; \quad S_q = \sqrt{\frac{1}{A} \iint_A Z^2(x, y) dx dy} \quad (3) ; \quad S_z = \max_A Z(x, y) + \left| \min_A Z(x, y) \right| \quad (4)$$

6.1 Results

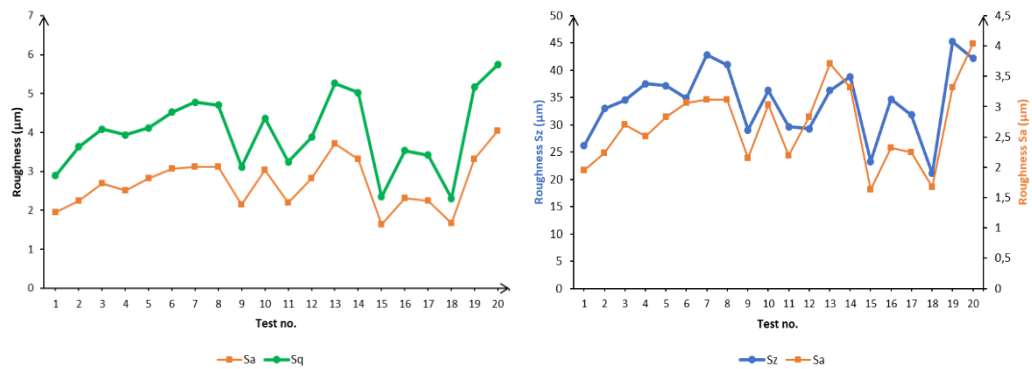
The different results of the area roughness parameters are presented in the following table (Table 3).

The recovered results show a coincidence at the level of the trend of evolution for the S_a and S_q responses and this one is entirely logical considering the similarity of these two parameters. The found values of the area roughness are in line with the recommendations of the manufacturer VHX.

For the area roughness response S_z , it has the same trend of evolution as the area roughness response S_a with a difference in values as shown in fig. 6.

Table 3. Experimental matrix and area roughness responses

Test no.	V_c (m/min)	a_e (mm)	f_z (mm/tooth)	S_a (μm)	S_q (μm)	S_z (μm)
1	146	0,26	0,05	1,9	2,9	26,2
2	194	0,26	0,05	2,2	3,6	33,0
3	146	0,74	0,05	2,7	4,1	34,5
4	194	0,74	0,05	2,5	3,9	37,5
5	146	0,26	0,07	2,8	4,1	37,2
6	194	0,26	0,07	3,1	4,5	34,9
7	146	0,74	0,07	3,1	4,8	42,8
8	194	0,74	0,07	3,1	4,7	41,0
9	130	0,5	0,06	2,2	3,1	29,1
10	210	0,5	0,06	3,0	4,4	36,3
11	170	0,1	0,06	2,2	3,2	29,6
12	170	0,9	0,06	2,8	3,9	29,3
13	170	0,5	0,04	3,7	5,3	36,3
14	170	0,5	0,08	3,3	5,0	38,8
15	170	0,5	0,06	1,6	2,4	23,3
16	170	0,5	0,06	2,3	3,5	34,7
17	170	0,5	0,06	2,3	3,4	31,8
18	170	0,5	0,06	1,7	2,3	21,1
19	170	0,5	0,06	3,3	5,2	45,2
20	170	0,5	0,06	4,0	5,7	42,1

**Fig. 6.** Variation of the area roughness parameters S_a , S_q and S_z

6.2 Results study with “Minitab”

For the study of surface roughness results with Minitab, we will limit ourselves only to the study of the area roughness response S_a .

Analysis of the empirical model

The studied model takes into account the linear, interaction and quadratic effects. The regression coefficients of this model make it possible to express the relation of the area roughness S_a according to the three parameters studied:

$$S_a = 6,9 + 0,011V_c + 6,1a_e - 262f_z - 0,000005V_c \times V_c - 0,55a_e \times a_e + 2333f_z \times f_z - 0,0160V_c \times a_e + 0,07V_c \times f_z - 35a_e \times f_z \quad (5)$$

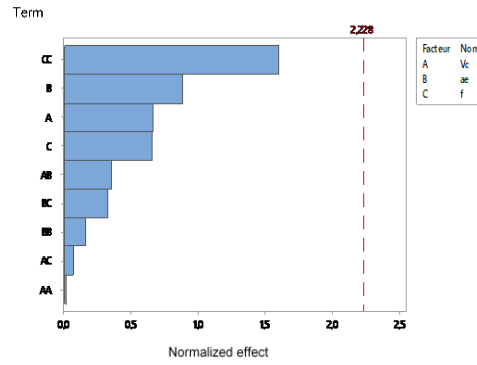


Fig. 7. Pareto diagram of the area roughness response S_a

The fig. 7 shows that the tooth feed-tooth feed interaction is the most influential. It is followed by radial engagement, cutting speed and tooth feed.

Analysis of response surfaces

The relationship between the different operating variables and the response studied is illustrated in the three-dimensional representations of the response surfaces:

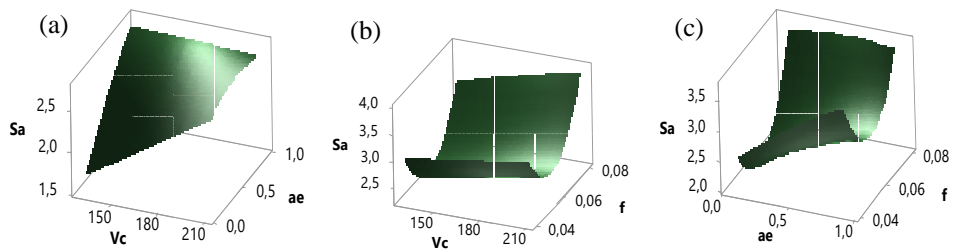


Fig. 8. Response surface results: (a) $f_z=0,006$ mm/tooth, (b) $a_e=0,5$ mm, (c) $V_c=170$ m/min

- The Fig. 8 (a) illustrates the effect of the interaction (V_c , a_e) on the area roughness S_a , more a_e increases more S_a is high.

- The Fig. 8 (b) illustrates the effect of the interaction (V_c , f_z) on the area roughness S_a , the minimum value of S_a corresponds to the central values of V_c and f_z .
- The Fig. 8 (c) illustrates the effect of the interaction (a_e , f_z) on the area roughness S_a , the influence of a_e is more important than f_z .

7 Conclusions and perspectives

In this work, various GFRP composite trimming tests were presented in order to study the influence of the cutting parameters V_c , a_e and f_z on the quality of the surfaces obtained. From the study of the surface quality and the results of the experimental designs we can conclude that the machined surface roughness is highly sensitive to the variation of the cutting parameters.

Many approaches can be considered to progress in this work, such as improving the experimental protocol, testing other tool engagements (small pass depth and high radial engagement), investigating larger variation ranges of f_z and V_c , testing parameter variations to see if the influence is the same, completing the study with work on tool lifespan ...

While the first results are encouraging and the prospects numerous, they highlight the need to quantify vibrations and to have at our disposal a means of characterizing the vibratory behavior of the workpiece during trimming. Vibration measurement will help to better define the operating ranges of a tool in relation to cutting conditions.

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