A NEW APPROACH FOR SURFACE PROFILE ROUGHNESS CHARACTERIZATION IN THE LAMINATED COMPOSITE PLY PLANE

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Abstract

Based on observations, current surface profile roughness parameters have some limitations to describe a surface texture. Characterizing the surface texture of a machined laminated composite is more complex due to its anisotropic and heterogeneous nature at a micrometric scale. In this study, novel roughness parameters are proposed to characterize the surface texture of a composite, based on the fractal analysis and autocorrelation allowing to describe the complexity, the regularity and the autoscale dependency of the profile. The used fractal analysis, which is the regularization analysis, is adapted to the surface texture definition of the profile method. To depict these parameters and their estimation method, experiments of carbon fibre reinforced polymer (CFRP) trimming were conducted and roughness profiles were measured using a contact profilometer. Both up- and down-milling faces were inspected in the feed direction also within the ply plane, for each ply orientation (0°, 90° and ±45°), for different tool wear and also for three cutting parameters.

Résumé

D'après les observations, les paramètres actuels de profil de rugosité de surface présentent certaines limites pour décrire la texture de surfaces. La caractérisation de la texture de surface d'un stratifié composite usiné est plus complexe en raison de sa nature anisotrope et hétérogène à l'échelle micrométrique. Dans cette étude, de nouveaux paramètres de rugosité sont proposés afin de décrire la texture de surface d'un composite, basé sur l'analyse fractale et l'autocorrélation, permettant de décrire la complexité, la régularité et l'autodépendance d'échelle du profil. L'analyse fractale utilisée, qui est l'analyse de régularisation, est adaptée à la définition d'état de surface de la méthode de profil. Pour décrire ces paramètres et leur méthode d'estimation, des essais de détourage de composite carbone-époxy ont été menés et des profils de rugosité ont été relevés en utilisant un profilomètre à contact. Les deux faces de fraisage (en opposition et en concordance) ont été inspectées dans la direction d'avance qui est aussi dans le plan d’un pli, pour chaque orientation de pli (0°, 90° et ±45°), pour des usures différentes d’outils et également pour trois paramètres de coupe.

1. Introduction

Laminated composites, especially carbon fibre reinforced polymer (CFRP), have been gradually used in the aerospace industry thanks to its high strength-to-weight ratio. During the assembly process and during the product lifetime, the integrity of a composite machine surface is crucial. Besides damages occurring during the machining process such as inter- or intra-ply delamination and burnt resin, the surface texture needs to be optimized depending on the use. Before using it as a machining parameter, the surface texture requires to be characterized. The texture of polymer composite machined surface has begun to be investigated in the 1990s. Wern et al. discovered that the roughness average deviation parameter Ra is inaccurate to describe the surface roughness [1]. Years later, Palanikumar et al. investigated possible factors which could influence surface roughness on the machining of glass fiber-reinforced polymer composites [2]. However, they based their study of the surface roughness on the same inadequate parameter Ra.
Ghidossi et al. conclude that roughness criteria is not representative enough of the subsurface damage and so, of the machining quality during the machining of glass/epoxy laminated composite [3]. However, the surface roughness was characterized by one roughness parameter only – $R_a$, which lacks of accuracy to describe the surface roughness of a laminated polymer composite. In the aerospace industry, areal roughness parameters are preferred to profile roughness parameters to describe the surface roughness. Consequently, the roughness check is more complex and more time consuming to generate areal roughness parameters.

Chatelain et al. investigated the effect of ply orientations on surface roughness with roughness parameters ($R_a$, $R_q$, $R_p$, $R_v$, $R_z$) [4]. Roughness parameters were measured and calculated in the ply plane from specific ply orientations ($0^\circ$, $90^\circ$ and $\pm45^\circ$). Relatively high value variations were noticed between the different ply orientations. That is why each ply orientation is treated separately in this study. Due to its anisotropy at a micrometric scale, the surface profile measurements is relatively different depending on the measurement orientation on the trimmed surface and, if applicable, depending on the fibre orientation. This study is limited to the texture description of the trimmed surface in the ply plane – also in the feed direction – for specific fibre orientations ($0^\circ$, $90^\circ$ and $\pm45^\circ$) and for different tool wear. From different cutting conditions, surface profiles which have very noticeable different behaviour can be characterized with similar roughness parameters values. It results in a limit of characterization of composite surfaces using current roughness parameters. In Figure 1, roughness profiles with very similar roughness parameters are presented (profile average deviation $R_a$, profile skewness – asymmetry – $R_{sk}$, kurtosis – flatness – $R_{ku}$).

$$V_{Bavgh} = 0.038 \text{ mm}$$

Although the roughness parameters are similar, roughness profiles behaviours are obviously different. That is why new roughness parameters are proposed in this study. Those parameters are extracted from the autocorrelation function and log-log graph determining the fractal dimension. Introduced by the mathematician Benoit Mandelbrot, fractal theory and fractal analysis concepts have been used for the last twenty years in the metrology area [5, 6]. Even though this technique has an excellent capability of describing the complexity of a surface or a curve, the use of the fractal analysis and its fractal parameters mainly remains at a trial level.

### 2. Methodology

#### 2.1. Design of experiments

The machining tests were performed with the parameters listed in Table I using three tools. The cutting parameters were selected according to the best operational cutting conditions for similar tool and CFRP
material in the literature [7]. One tool was used for each test. The tools were used until the tool life criterion was reached. The limit was determined as the 0.3 mm maximum average wear $V_B$, as described in ISO 8688-2:1989 standard [8].

### Table I. Chosen cutting parameters for the machining tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Tool</th>
<th>Feed (mm/min)</th>
<th>Speed (m/min)</th>
<th>Feed (mm/rev)</th>
<th>Feed (µm/rev/tooth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>1524</td>
<td>400</td>
<td>0.114</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2794</td>
<td>300</td>
<td>0.279</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>4064</td>
<td>200</td>
<td>0.608</td>
<td>101</td>
</tr>
</tbody>
</table>

2.2. Experimental setup

The machining experiments were performed with the 3-axis Huron® K2X10 computerized numerical control (CNC) machine-tool. This high speed machining center, allowing a 28 000 RPM maximum spindle speed at 30 kW, was geared up with a dust extraction device for health and safety purposes. The setup mounted inside the CNC machine allows to machine short and long cuts: the long cut setup was used to generate tool wear only, the short cut setup was used to machine coupons in order to fully inspect them. Short and long cuts were performed alternatively until the tool life criterion was reached.

To conduct the machining tests, an end mill router with six flutes was selected. This tool has a 3/8’’ diameter, a 10° relief and helix angle and a 8° rake angle as geometrical properties and a diamond chemical vapour deposition as coating property.

The laminated composite is a quasi-isotropic CFRP composite, prepared using pre-impregnated plies with the (90°,-45°,+45°,0°,+45°,-45°,+45°,-45°,0°,-45°,+45°,90°) stacking sequence. This autoclave-cured composite has a 4.44 mm thickness with a 64 % fibre volume fraction.

2.3. Measurements

The CFRP coupons were inspected using the Keyence® VHC-600+500F optical microscope and Hitachi® S-3600N scanning electron microscope (SEM).

The cutting tool was observed with the Keyence® optical microscope allowing to give an estimation of the tool wear $V_{Bmax}$. The tool wear $V_B$ was then calculated as the average of the tool wear $V_{Bmax}$ estimated for each of the six faces of the tool.

The surface texture of the coupon was examined using the SV-CS3200 Mitutoyo® profilometer. In order to compare all the measurements with each other, a common sampling length was selected, as shown in Table II. The measurements were performed for both up- and down-milling coupon faces, in the feed direction, which is also oriented in the ply plane. Figure 2 depicts the measurement area where the measurements were conducted. For each face, only the eight central plies were inspected and four measurements were realized by ply orientation. The stylus used was the 12AAC731 standard stylus with a 2 µm tip radius and a 60° tip angle.

### Table II. Profile length datasheet

| Roughness sampling length or cut-off length | 2.5 mm |
| Evaluation length                        | 12.5 mm |
| Waviness sampling length                 | 25 mm  |
| Lowest roughness sampling length         | 0.008 mm |
To insure the stylus to remain probing one ply only during the measurement of one whole profile, the CFRP coupon was gripped into a vice which was mounted on a compact compound cross table. This cross table allow to orientate and to position the coupon towards the stylus trajectory with micrometric screws.

![Measurement area](image)

*Figure 2. Measurement area on the machined coupon face*

The primary profiles measured were filtered using the phase correct function filter based on the Gaussian probability density function as described in the ISO 11562:1996 standard [9] and for a 2.5 mm cut-off length as presented in Table II. This filter was selected because it is currently the most commonly used filter nowadays even though it may be affected by outliers and induce profile edge distortion. To evaluate the negative impacts of this filtering, other filters were used such as the robust Gaussian filter but no major impact was identified on the roughness parameters values.

2.4. Calculated roughness parameters

Before parametrizing the surface roughness using the autocorrelation function and the fractal analysis, observations were made with the roughness profiles. Some examples of the roughness profiles are presented in Table III. Surface profiles vary depending on the tool wear, the cutting parameters and the ply orientation. The main pattern in the roughness profiles is close to periodic oscillation but the period is not related to the tool tooth feed and the period value is different depending on the face milling type. Concerning the tool condition, the most observable variation with the tool wear increase is both a decrease of the oscillation amplitude and an increase of the oscillation period. With a highly worn tool, the roughness profile seems more erratic and affected with noise.

Due to the so-called noise in the measured roughness profiles, the power spectral density function was not selected to determine this main periodic pattern. Instead, on the one hand, the autocorrelation function is able to detect at the same time the profile amplitude decrease and the period increase if there is one. On the other hand, the fractal analysis is able to quantify the profile complexity and regularity.

From the roughness surface profiles, the current surface profile roughness parameters were calculated based on the standard recommendations of ISO 4287:1997 [10], 13565-2:1996 [11].

Besides those roughness parameter calculation, the autocorrelation function was computed giving the normalized autocorrelation function $acf$ (Figure 3). Six roughness parameters were calculated from the $acf$ presented in Figure 3: the abscissae and ordinates of the first local minimum and maximum reached (black squares in Figure 3), the first abscissa when the $acf$ curve reaches the y-axis (grey rhombus in Figure 3) and the average deviation of the $acf$ curve (dash-dot line in Figure 3).

The abscissae are correlated with the repetitive pattern period and the ordinates reflect the impact of those patterns. The average deviation of the $acf$ curve provides information about the autocorrelative profile behaviour.
Table III. Roughness profile samples for the four ply orientations and both face milling types and machined with different tool wear (first, ninth and twentieth passes respectively a, b and c) of tool 1

![Roughness profile samples](image)

Figure 3. Roughness parameters associated to the normalized autocorrelation function $acf$

For this study, the regularization analysis was selected from numerous existing fractal analyses, due to its relative robustness. For example, this technique has already been used to assess any gear damage with the use of accelerometer signals [12].

The regularization analysis consists in the estimation of fractal parameters such as fractal dimension using convolutions of the signal $s$ with different kernels $g_α$ with a width of $α$ [13, 14]. Each convolution product $s_α$ can be written:

$$s_α = s * g_α$$

(1)
The kernel $g_\alpha$ which was used in our calculation with a width of $\alpha$ was the rectangle kernel which is an affine function. Then, the hypothesis that $s_\alpha$ has a finite length called $l_\alpha$, for the size of $\alpha$, is set. The regularization dimension $D_R$ can be calculated by:

$$D_R = 1 - \lim_{\alpha \to 0} \frac{\log l_\alpha}{\log \alpha}$$

The limit, in the equation 2, is usually estimated as the slope value when $\alpha$ values are close to 0 and when the coefficient of determination $R$-squared of the linear regression of a part of the curve is close to 1. Figure 4 depicts the fractal dimensions determination graphs for different tool wear of tool 1.

From preliminary analyses, two ranges of the slope determination were selected. One was chosen between one and two cut-off lengths (section between dot lines in Figure 4) and the second one was selected across four and twelve lowest roughness sampling lengths (section between dash lines in Figure 4). Although other selections can be done, from preliminary analysis and observations, the choice of these two ranges is particularly fitting to the tool wear evolution whatever the selected cutting parameters are. For each range of slope approximation, fractal dimensions $D_{Range}$ were estimated as the slope estimation the rectangular kernel within the designated graph section. The topothesy $G_{Range}$ was the intercept calculated from the same slope estimation. $D_{Range}$ is a parameter which is the fractal dimension, characterizing the regularity or autoscale behaviour of the profile. $G_{Range}$ is a parameter characterizing the ruggedness of the roughness profile at the range scale selected. An additional fractal parameter $R^2_{Range}$ was the coefficient of determination of the linear regression from the same slope estimation of the graph section. This additional fractal parameter was also introduced due to observations of the log-log curve. The curve seem strongly impacted by the behaviour change of the profile roughness with the tool wear: with a new tool, the curve is bumpy, and with a worn tool, the curve is smoother. This last parameter $R^2_{Range}$ can be the representation of the roughness profile complexity at the range scale selected.

3. Results and discussion

3.1. Roughness profiles

From the observations of the different roughness profiles, for $0^\circ$ and $45^\circ$ ply orientation with a low tool wear, the main pattern is a periodic oscillation. The period value is different depending on the face milling type, for example it reaches 270 $\mu$m for the up-milling side of the coupon and 670 $\mu$m for the down-milling
side of the coupon for 0° or 45° ply orientation in Table III. Both observed periods are different compared to the tooth cutting feed. For homogeneous material such as aluminium and titanium alloys, the oscillation periods are called tool marks and are strongly correlated to the cutting feed. During the machining, the tool is not fracturing the fibres one by one when the pressure is applied by the tool cutting edge. Because, in this case, the tool mark length would be similar to the observed roughness profile period. Instead, the fibres are fractured by relatively small fibre groups apparently due to bending or shearing. This may be due to the composition of the composite. The inner part of the CFRP used is constituted of resin and threads of carbon fibres. The number of fibres within a thread may influence the size of the fractured fibre group and so on the noticeable period on the roughness profiles.

With the tool wear increase, the observed periods are increasing as well. At the same time, the profiles seem more affected by noise and this oscillation periods tend to be more difficult to detect. Concerning the 90° ply orientation roughness profiles, no main oscillation period is easily observable, especially on the up-milling side of the coupon. The profile behaviour seems erratic. With the tool wear increase, the measured profiles remain similar until reaching a high tool wear generating an apparently more erratic behaviour.

The profiles measured on the down-milling side of the -45° ply orientation does not allow to easily distinguish a periodic pattern. With the tool increase, the surface texture is similar with deeper narrow cavities and then becomes extremely smooth for the highly worn tool. On the up-milling side of the -45° ply orientation, relatively similar observations can be formulated.

Main results obtained with the autocorrelation analysis and the fractal analysis are presented in the following sections. Only one parameter from each is presented to illustrate the new proposed roughness parameters characterization capabilities.

3.2. Autocorrelation

From the autocorrelation analysis, the average deviation of the $acf$ curve was selected to be presented. The lowest value – closest to zero – corresponds to a profile with a very low autocorrelative behaviour. No specific repetitive pattern can be easily identified in this case. Table IV displays autocorrelation functions samples calculated from roughness profiles for up- and down-milling sides, for the four ply orientations and for different tool wear. With this roughness parameter, curves are relatively similar for ply orientations of 0°, 45° and 90° and for each tool and each milling type, as opposed to the results obtained with the -45° orientation ply. Similar variations are also noticeable between the tools e.g. for 0° orientation ply in down-milling.

This parameter allows to identify relatively easily the tool wear and so the surface quality machined, whatever the ply orientation of 0°, 45° or 90°.

3.3. Fractal analysis

From the fractal analysis and so the log-log fractal curves, only the coefficient of determination of the highest range was selected to be presented to illustrate those new roughness parameters characterization capabilities. In Table V, the coefficient of determination of the highest range is displayed with both milling types, the four different ply orientations and different tool wear. In each figure from Table V, the results of the three different cutting parameters from identical tools are presented. Similarly, the results obtained with the average deviation of the $acf$ curve, the fractal parameter curves have comparable variations between ply orientations of 0°, 45° and 90° for each tool and each milling type as opposed to the results obtained with the -45° orientation ply. Similar variations are also noticeable between the tools e.g. for 0° orientation ply in down-milling.
Table IV. Autocorrelation results (normed acf average deviation) vs the averaged tool wear $V_B$ for the four ply orientations and both milling types

<table>
<thead>
<tr>
<th>Orientation/Tool Type</th>
<th>0°</th>
<th>45°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down-milling</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>Up-milling</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
</tbody>
</table>

- **Tool 1**
- **Tool 2**
- **Tool 3**
Table V. Fractal parameter $R^2$ vs the averaged tool wear $VB$ for the four ply orientations and both milling types
4. Conclusion

In this study, new roughness parameters are proposed to characterize the surface texture of CFRP composites. Current roughness parameters have some limitations to describe the surface profiles of machined composites. Those new parameters are based on the autocorrelation function and on the fractal theory using the fractal parameters. Results show their efficiency to describe the regularity and complexity of the profiles. Observations of roughness profiles show surface marks due to the breakage by groups of the fibres. Those marks are relatively similar to tool marks on a homogenous material machined surface but cannot be linked to the feed but seem strongly correlated with the tool wear. Those repetitive profile patterns can also be identified and their period can be estimated using the roughness parameters introduced in this study. However, the presented results of the proposed roughness parameters have some limitations but are accurate for most cases and may be complementary to actual roughness parameters. A combination of those new parameters and the actual ones could be the solution to accurately describe the surface texture of a laminated composite in the ply plane.

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References