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Fractal analysis of cutting force and acoustic emission signals during CFRP machining

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Abstract

Cutting forces and acoustic emissions signals while machining Fiber Reinforced Plastics (FRP) depends strongly on the tool wear. Fractal analysis can be adapted to those signals to characterize their variations. This tool wear monitoring technique is presented herein for the carbon FRP (CFRP) orbital drilling. Fractal parameters, characterizing the signal complexity and ruggedness, are very efficient for machining quality estimation and to follow the tool wear evolution.

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Keywords: fiber reinforced plastic; orbital drilling; fractal analysis; cutting force; acoustic emission; tool wear

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1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been increasingly used in the aerospace industry over the past decades due to its lightweight vs mechanical properties. CFRP is constituted of two very different materials (carbon fiber and epoxy resin). The CFRP machining usually involves only finishing operations, thanks to its manufacturing, allowing CFRP components to be produced close to their final shape. To evaluate the machining quality, surface integrity is examined. Several problems may occur during fibre reinforced plastic (FRP) machining, e.g. uncut fibres, pulled fibres, delamination and burnt resin [1-4]. Due to the abrasiveness and hardness of the carbon fibres, abrasion is considered as the main tool wear mechanism [5, 6]. With the tool wear increase, keeping sufficient machining quality is challenging, and the surface quality should be examined through the tool life. Hamedanianpour et al. found that, even if the tool wear is still considered as functional, the resin may be burnt during the CFRP machining leading to a lower surface quality [7].

New techniques of tool wear monitoring can emerge due to the FRP heterogeneity. With the tool wear increase, the cutting tool edge radius increases resulting in lower surface quality and the signals' change of cutting forces and acoustic emissions (AEs). In addition to statistical parameters to extract quantitative data from such signals, fractal analysis was used to estimate the complexity of the signal [8, 9]. Therein, cutting force and vibratory signals were analyzed during homogeneous materials machining. However, the changes of the signal complexity through the tool life seem to be relatively low during the machining of homogeneous materials. Nevertheless, the cutting force and AE signals observed while machining CFRP show relatively high signal complexity variations for different tool wear. Thus, performing the fractal analysis of such signals would be relevant. In this study, the orbital drilling of composite/metal stack is investigated. The drilling of such stack is a major concern in the aerospace industry, which is part of the last assembly process of current airplanes' structural parts. In addition to issues specific to each material of the stack, machining stacks constituted of very different characteristics

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materials leads to further problems. So, process monitoring is crucial to maintain sufficient machining quality.

2. Materials and methodology

2.1. Machining setup

The machined part was a stack composed of a quasi-isotropic CFRP, prepared using 24 pre-impregnated plies, with a 3.3 mm thickness, and Ti-6Al-4V titanium alloy, with a 3.0 mm thickness. The K2X10 Huron® high-speed machining center was used to conduct the machining tests. A dust extraction system was mounted onto the machine for health and safety purposes. The stack was machined by orbital drilling with different cutting parameters for each material of the stack. The cutting parameters, used to drill the 5.85 mm diameter holes, are presented in Table 1. The tool was a four flutes uncoated carbide shoulder mill with a 4 mm diameter, 30° helix angle and 11 mm maximum depth of cut. The composite/metal stack was drilled using the same setup until the complete tool failure. A total of 44 holes was achieved even though the tool had already reached the end of its tool life.

Table 1. Cutting parameters

Material	Helix step (mm)	Feed (mm/min)	Speed (RPM)
CFRP	0.7	800	11 000
Titanium	0.35	300	3 200

2.2. Measurements

The cutting force and AE signals were acquired during the tests using a dynamometer table and an AE sensor. The experimental setup is presented in Fig. 1. The input signal from both systems were acquired using the same amplifier and DAQ system at the 48 kHz frequency rate. The cutting force and AE signals from the CFRP machining were analyzed. The machining of titanium allowed generating a faster tool wear.

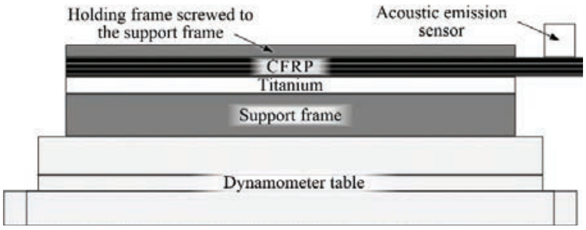

Fig. 1. Experimental setup representation

The tool wear was estimated between each drilling in order to evaluate the fractal parameters along the tool life. The tool wear was estimated using VHC 600+500F Keyence® optical microscope pictures which were taken on the clearance face of the tool tip edges. The maximum tool wear $VBmax$ was estimated according to ISO standard recommendations [10]. The tool wear VB is introduced as the $VBmax$ average of the four tool cutting edges.

Fig. 2 depicts the acquired signals (the cutting forces signals, the total cutting force signal and the AE signal) during the first drilling. The signal section analyzed corresponds to the area between the dash lines (Fig. 2), which is the relatively stable part of the CFRP machining using CFRP cutting parameters.

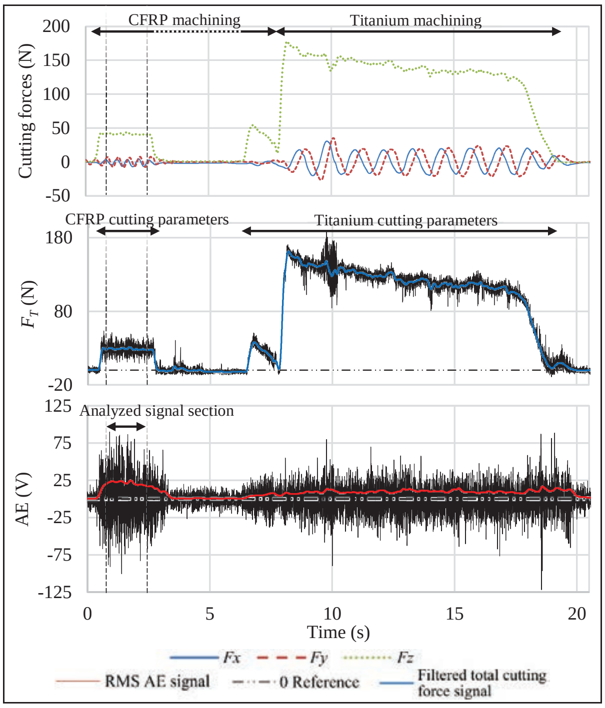

Fig. 2. Filtered cutting forces (top), total cutting force (center) and filtered and root mean square (RMS) acoustic emission (AE – bottom) signals

To highlight the changes of the signals' shape through the tool life, Fig. 3 show magnified signal samples from the analyzed section for different tool wear. In Fig. 3, the signal sample of the total cutting force F_T is relatively steady for a new tool. Then, the passes due to the cutting edges, can be identified on the cutting force signal with higher tool wear.

The signal samples from the AE sensor acquisition for different tool wear show similar trends (Fig. 3), in comparison with the cutting force signal samples. However, the periodic oscillation in those samples is more distinct with the tool wear increase.

From the signals observation of the AE and the cutting force, two outlines can be identified. At high frequency (so at low scale) the signal seems affected with noise for the first holes and becomes sharper with the tool wear increase. At a higher scale (around the tool rotation frequency), both signal types turns from a steady signal for the first holes, to increasingly clearer periodic oscillations for higher tool wear. The period corresponds to the tool rotation time per tooth.

2.3. Fractal analysis

Fractal analysis allows quantifying the signal complexity by a single value, the fractal dimension. Adapted to the

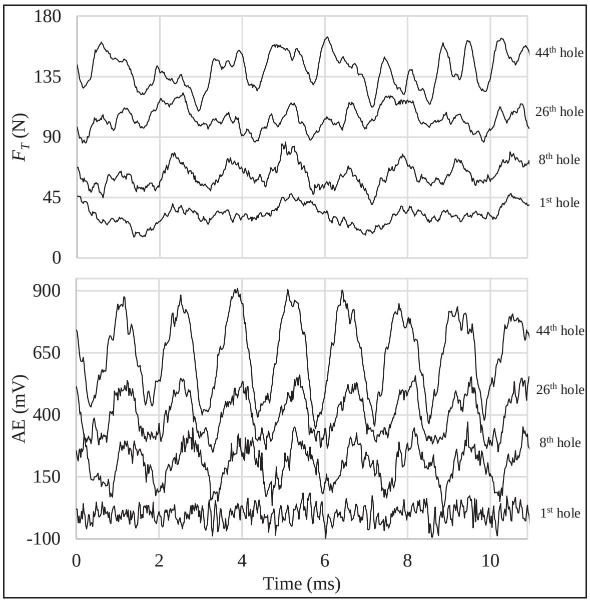

Fig. 3. Zoom samples, from the analyzed section presented in Fig. 2, of the total cutting force (F_T) signals – up – and of the acoustic emission (AE) signals – down – over two tool rotation periods for different holes

cutting force and AE signal, several signal features changes (e.g. complexity, shape) can be tracked along the tool life.

Various fractal analysis emerged such as box-counting but have some constraints e.g. relatively low robustness. The regularization fractal analysis, selected herein, was used to assess gear damage using accelerometer signals [11] and showed relatively good repeatability rates. This regularization dimension is estimated from the convolutions of the signal 's' with different kernels g_a with a width of 'a' [12, 13]. Each convolution product s_a is written:

$$s_a = s * g_a \tag{1}$$

The kernels g_a are based on a rectangle kernel which is an affine function. Then, the hypothesis that s_a has a finite length called l_a, for the size of 'a', is set. The regularization dimension D_R is calculated using:

$$D_R = 1 - \lim_{a \to 0} \frac{\log l_a}{\log a} \tag{2}$$

The limit, in the equation 2, is usually estimated as the slope estimation, where the 'a' values are the smallest and the coefficient of determination, R^2, of the linear regression of a part of the curve ($log\ l_a$ vs $log\ a$) is close to 1. From preliminary analyses, the range of the slope determination was selected for the low scale (from 2 kHz to 6 kHz so between eight and 23 sampling points). In the case where the cutting parameters would change, the range determination could be selected accordingly, and adapted depending on the cutting speed.

Samples of curves ($log\ l_a$ vs $log\ a$) determining the fractal dimension and fractal parameters are shown in Fig. 4. For both, cutting forces and AEs, the tool wear influence is easily identified from the fractal dimension determination curve characteristics. The curve is relatively straight for the first holes. With higher tool wear, the curves becomes bumpy with higher and more distinct arches. Those periodic arches illustrate the tool tooth rotations observable in the AE and cutting force signals (Fig. 3).

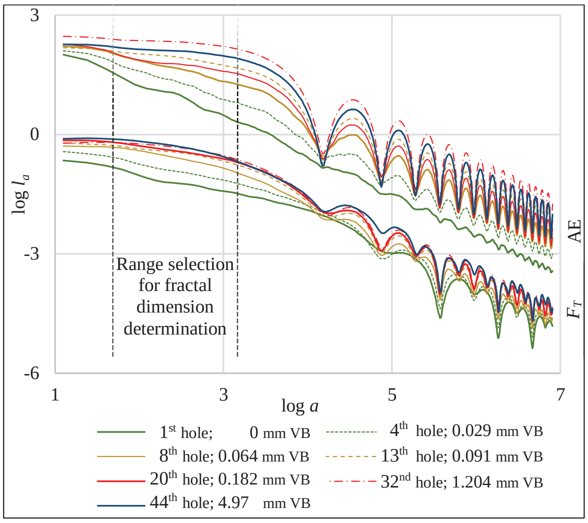

Fig. 4. Graph of curve samples for the fractal dimension determination using the rectangular kernel of total cutting force and acoustic emission signals

3. Results and discussion

The fractal analysis results are shown in Fig. 5. The fractal dimension D, the topothesy G and the R^2 calculated for each drilling from the total cutting force and AE signals are presented hereafter. The fractal dimension D (slope value in the selected range) is a factor characterizing the signal complexity, the topothesy G (slope offset) quantifies the signal ruggedness and the R^2 (slope coefficient of determination) stands for the auto-scale regularity of the signal. Results from the AE signals analysis reflect the tool wear evolution more efficiently than for the cutting force signals. A fractal index I_F is introduced in order to propose an efficient machining quality factor improving the monitoring process:

$$I_F = \frac{D \cdot G}{R^2} \tag{3}$$

Fig. 6 depicts this index, and the tool wear, vs the holes drilled, including the three wear stages. Due to the complexity of the tool wear evaluation for such a tool, the stages are fairly an indication of their positions. The primary stage (**I**) is found to end around the third hole and the steady state stage (**II**) to end around the 20th hole with the beginning of the rapid wear stage (**III**). All parameters and so the fractal index vs the holes drilled show humps, during the initial wear stage (A in Fig. 6)and at the beginning of the third stage (B in Fig. 6), characterized by a rapid tool wear increase. Both humps in the fractal index (A and B in Fig. 6) are linked to the changes of the tool wear derivate. This I_F index humps point out high curve variations of the tool wear.

In Fig. 6, the fractal index of AE signals analysis also presents a continuous decrease during the second stage which could be linked to the machining quality decreasing along the tool wear evolution. This stage **II** is crucial due to the critical point presence of machining quality turnaround within this second stage. This abrupt change of surface quality occurs around the 15th hole. So, by setting up an I_F index threshold at 0.5, low machining quality could be avoided.

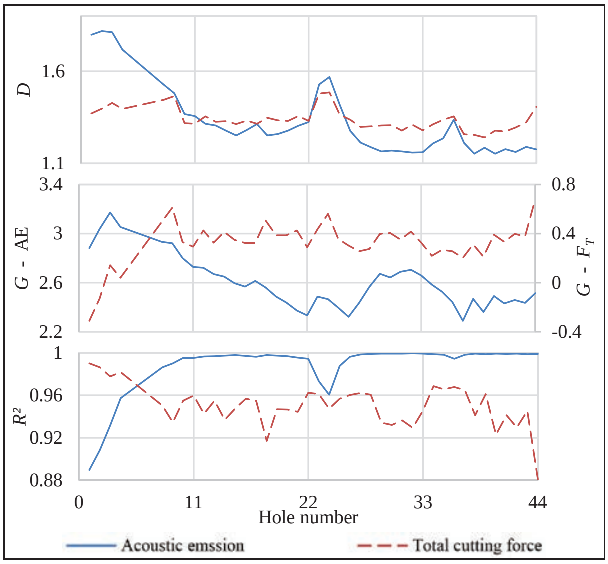

Fig. 5. Results of the fractal dimension D, the topothesy G and the R^2 from the analysis of F_T and AE signals vs the number of holes drilled

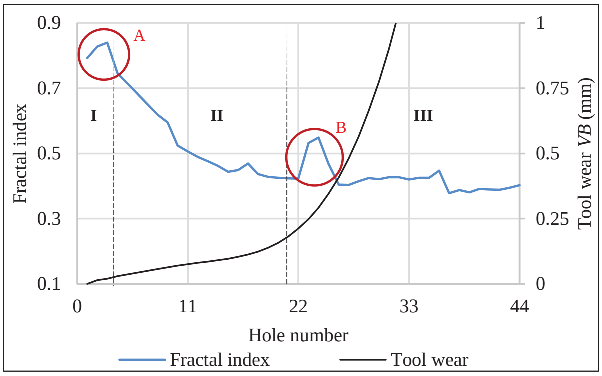

Fig. 6. Fractal index, I_F, results and the tool wear in function of the number of holes drilled

4. Conclusion

A promising online monitoring method of tool wear while machining composite is presented in this study based on fractal analysis of cutting force and AE signals. The fractal parameters and index are found efficient to assess the tool wear during CFRP machining. The fractal analysis used herein admits for only inputs the range of the observation scale for the fractal dimension determination. Adapting this monitoring technique is easy to setup contrary to e.g. statistical parameters which require rather long preliminary machining tests.

Fractal parameters (fractal dimension D, topothesy G and R^2) obtained from AE signal analysis are efficient to describe the tool wear evolution and, to a further extent, the machining quality. In order to improve this technique further, the fractal index I_F can be calculated based on parameters such as fractal dimension and topothesy. In this study, this index is confirmed to be an excellent factor to evaluate the tool wear while drilling CFRP. Further experiments could be performed to investigate the robustness of this method e.g. with the online change of the cutting parameters.

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