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Monitoring of trimming operation for lightweight composite structure

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Abstract

Carbon or glass fibre reinforced polymer composites are widely used, notably for lightweight structures, due to their interesting material properties. However, the machining of composites represents a challenge. Their excessive abrasiveness leads to tool wear, which can put workpiece material integrity at risk. In the case of lightweight structure, the monitoring of trimming operation is difficult due to vibrations of the flexible workpiece and scrap offcut. This paper presents a monitoring approach based on vibration and power signals that is compatible with the machining of lightweight composite structure. Tap tests are performed to analyze the experimental set-up and the machining tests. Experiments validate the approach with detections of tool breakage and chatter occurrence.

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Keywords: monitoring, machining, composite material.

1. Introduction

Glass Fibre Reinforced Polymer (GFRP) is a composite material widely used in many industrial applications such as the aeronautical or naval fields. In the naval field, GFRP is chosen for the manufacturing of hulls of boat which are large dimension parts. Lightweight and high strength, compared to metallic materials, justify this choice for the realization of structure workpieces [1].

The manufacturing process of composite part requires a finishing operation of trimming, which is a contour milling operation. Indeed, the contour of the manufactured part is of poor quality and need to be removed. Besides, holes and some internal contours need to be drilled or machined, for e.g. windows, the assembly with other parts, the fixture of equipment [2].

Another characteristic of those workpieces is their flexibility, which is due to the low thickness and large size of the part. During the machining operations, this kind of part is usually not clamped properly, resulting in vibration issues like chatter (instability during machining).

In this case, the monitoring of the tool condition and chatter is necessary because chatter is an important factor in deterioration of tool conditions or surface roughness. Besides, the tool condition can affect the mechanical properties of machined workpieces because of delamination problems [3, 4].

GFRP are also special materials because of several mechanical characteristics such as anisotropy of the material [5], abrasiveness of the glass fibres [6] and flammability. In the literature, the machining of GFRP is shown as particularly complicated. The state of the art is mainly focussed on the machinability issues of GFRP. This subject tries to determine the best machining conditions [7]. Many results have been acquired. A review of the subject [1] shows some good research results. For example, a Desirable Function Analysis (DFA) is used based on a machining Taguchi experimental setup to determine the best cutting conditions in terms of surface roughness, cutting forces and tool wear minimization [8]. Another example deals with a Finite Element model of GFRP cutting taking into account the three phases (fibres, matrix and the interface between them) characteristics of the material. With this model, they can optimize the cutting parameters to decrease the delamination taking into account the fibre orientation [9]. Artificial Intelligence (AI) technics have also been used to predict the surface roughness, knowing the process parameters and the tool design. To do

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that, a Neural Network with a back-propagation error has been used [10]. Regarding all the literature on the subject, it is shown that the machining of GFRP, even in laboratory use-cases, presents some problems. However, some conclusions have emerged linking the machining parameters, tool design and fibre orientation with the surface roughness and tool wear. All those research works have improved the machining conditions. However, Teti et al. [11] highly recommend the sensor-based process monitoring, for composite materials too, for on-line and real time control of the tool conditions in order to pursue zero defect manufacturing.

Other works deal with the online monitoring of tool condition in order to improve the quality of machined component. Online cutting force measurements coupled with an adaptive network-based fuzzy inference algorithm have been used to predict tool wear [12]. This study is a first interesting step but it cannot be generalized to the variety of the cutting conditions encountered in the industry. Another work has been done linking the tool life with cutting parameters, taking into account a delamination criterion as end of life limit [13]. Note that, if the tool wear can be anticipated due to their slow evolution, the tool failures that are stochastic events cannot be anticipated. Therefore, there is a need for online tool failure detection. Concerning the issue of online monitoring of chatter in GFRP, as far as we know, no work was carried out.

On the other side, lot of work has been done on the monitoring of machining for metallic materials. For example, tool failure [14] or chatter detection [15, 16] criteria have been developed with good results. Some issues about vibration of thin wall during machining have also been well studied [17]. Also, several works deal with the prediction of tool wear/failure for metallic materials. For example, analytical model for tool wear prediction [18] has been developed with good results. Those studies cannot be used without modifications in the machining of GFRP because the anisotropy of the material makes difficult the transfer of this knowledge [5]. However, some ideas can be adapted to this use-case.

In this paper, the objective is to develop new online criteria to detect tools failure and chatter during the machining of GFRP materials. To do that, experiments have been done to acquire signals of vibrations and spindle power, during occurrences of tool failure and thin wall chatter. Also tap test have been done on tool and workpiece to diagnose the measured vibration. Based on those experiments, the two needed criteria have been developed, by physic model-based approach of the cut. Both of the criteria are experimentally validated with trial cuts.

2. Experimental setup and measurements

2.1. Experimental setup

For this experimental study a GFRP workpiece was used. This workpiece represents the offcut scrap which was obtained by trimming of a window of a ship. An example of a similar ship is presented on the Fig. 1. The dimensions of this workpiece are L = 1430 mm, B = 465 mm, h = 12 mm. Two trimming PCD tools (d = 16 mm, z = 2, AOB Ecospark), were used in the study (Fig. 2)

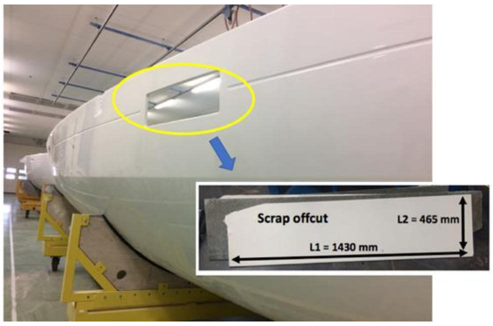
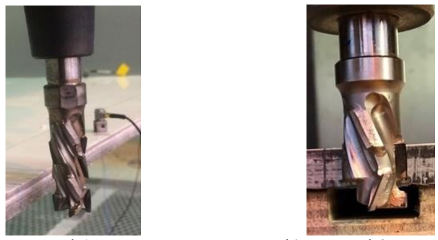


Fig. 1. Example of ship hull and trimming operation



a) Tool 1 b) Tool 2

Fig. 2. PCD tools for trimming

The trimming tests were carried out on a Belotti CNC machine tool, equipped with a 30kRPM – 15kW HSD spindle. Industrial cutting conditions were used: ap = 5 or 12 mm; ae = 18 mm; N = 13500 rpm; Vf = 4 m/min. Four different experimental setups were used to test the criteria of chatter and tool wear.

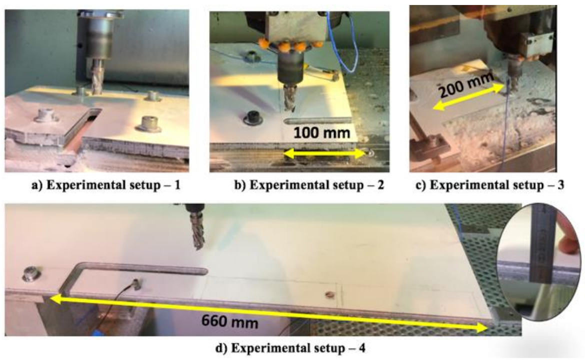


Fig. 3. Experimental setups

The workpiece is firmly fixed on the first experimental setup (Fig. 3a). On the following experimental setups (Fig. 3b, 3c, 3d) the workpiece goes out of 100 mm, 200 mm and 660 mm respectively. The aim of these different experimental setups is to study the impact the flexibility of the workpiece on the chatter vibrations issues.

2.2. Measurements

The monitoring data set during process is composed of two sources of data. The first source is composed of two accelerometers measuring the vibrations of the system (Fig.

4), one of them (3-axes) is on the spindle housing and another on the workpiece (one axis). Vibration signals are measured with a National Instrument 9233 acquisition card at a sampling frequency of 24 kHz.

The second source records information related to power consumption of the cutting process. The power being used can be calculated by continuously sensing the current and voltage of the motor. Power signal are measured by Zimmer LMG 450 with a National Instrument 9215 acquisition card at a sampling frequency of 24 kHz (Fig. 4). The Zimmer was connected to the motor of spindle and measures its current and voltage to computes the power consumption at any instant.

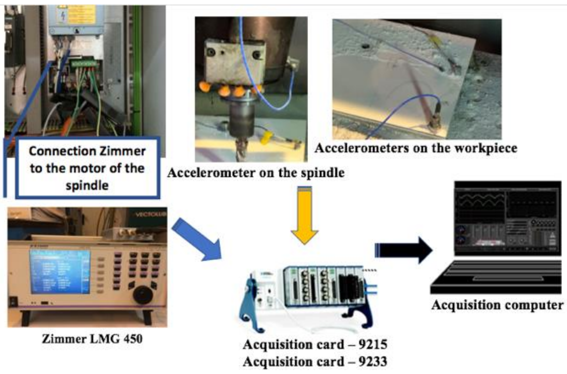


Fig. 4. – Schema of acquisition of the data

In order to analyze the natural frequencies of the system, the tap tests were performed. The Frequency Response Functions, resulting from tap test for third experimental setup, are shown in Fig 5.

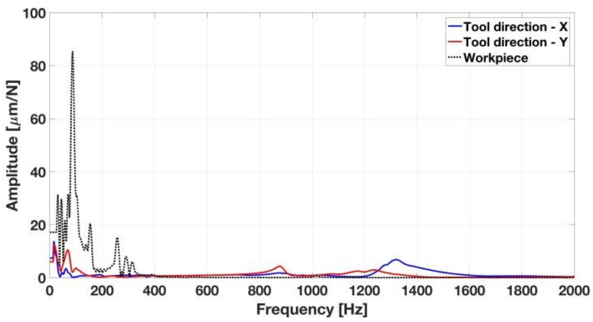


Fig. 5. FRF of the workpiece and of the tool

It can be seen that the workpiece is very flexible in the system, compared to the tool in the spindle. It will contribute to the analysis of the reason of appearance of chatter vibration.

3. Detection of tool breakage

Four parameters: Cutting power (P), specific cutting energy (Esp), Unbalance (Ub) and Vrms were proposed and tested to find a criterion that detects tool wear. The criteria result from cutting mechanics model.

To distinguish different possible situations in machining, four types of tool condition were studied: new cutting tool (Fig. 6a), tool presenting some light chippings (Fig. 6b), tool with a damaged insert (Fig. 6c) and tool with one brazed insert totally removed (Fig. 6d).

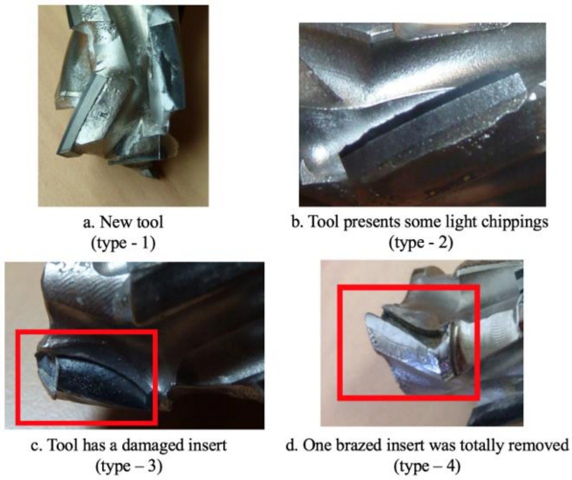


Fig. 6. Four types of the tool condition

3.1. Proposition of criteria

Cutting power and specific cutting energy: In order to find the relationship between cutting power and tool wear, the results of power consumption for different types of tool condition, depth of cut ap and the types of tool are presented on the Fig. 7. As shown by Fig. 7, for the same tool and with the same ap, with help of power consumption, an important tool wear can be detected (types 3 and 4) with the monitoring of power consumption. Nevertheless, this criterion is not universal since the values of the power vary with the depth of cut ap.

So, in this case, a specific cutting energy (Esp) can be calculated:

$$Esp = \frac{P}{ae \times ap \times Vf} \tag{1}$$

where P is the cutting power (W), Esp the specific cutting energy (W/mm3/min), ap and ae the depth and width of cut (mm), Vf the feedrate (mm/min).

The results of specific cutting energy for different types of tool condition, ap and types of tool are presented on the Fig. 8. As can be seen on Fig. 8, the values of specific cutting energy do not depend on value of ap. Nevertheless, for two different tools the values can change.

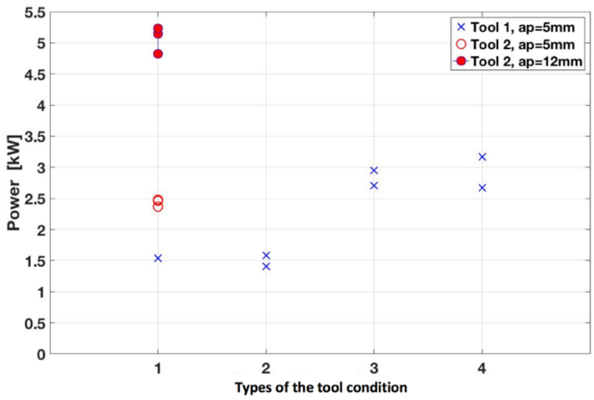


Fig. 7. Detection of the tool breakage by power

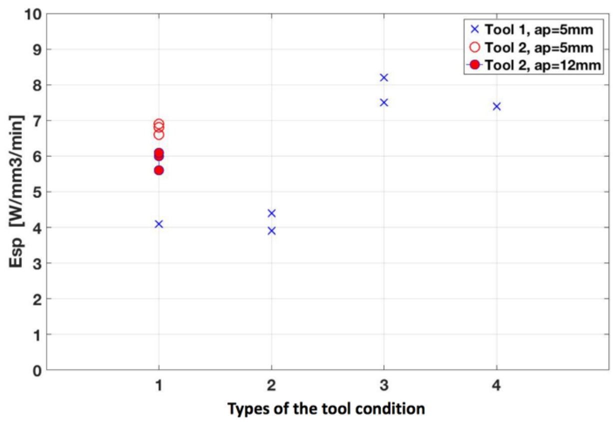


Fig. 8. Detection of the tool breakage by Esp

Unbalance (Ub): It is proposed to detect tool breakage through the increase of tool unbalance. Unbalance *Ub* is defined as the amplitude of the contribution at the spindle frequency, in the vibration frequency spectrum. *Ub* criterion is evaluated when the spindle is rotating and cutting. The data for vibration spectrum result from the signals of the accelerometer on the spindle housing.

Vrms: The Vrms criterion is commonly used for the monitoring of rotating machine. It is proposed to detect tool breakage through the increase of vibrations of the cutting system. The calculation of *Vrms* is realized in three steps:

- a band-pass filter (50 Hz – 3500Hz) is applied to the signal to eliminate effects that are not related to the machining (vibratory modes of the machine or of faulty spindle bearings).
- Digital integration is realized to convert acceleration in vibration velocity.
- Computation of root mean square of the velocity.

The results of Ub and Vrms for different types of tool condition are presented in Fig. 9. As can be seen the criterion Vrms can detect the important types of the tool damage (3,4). On the other side the criterion of Ub allows us to discern the difference between all types of tool condition (especially the difference between the first and second types of tool condition, i.e. between new and early damage).

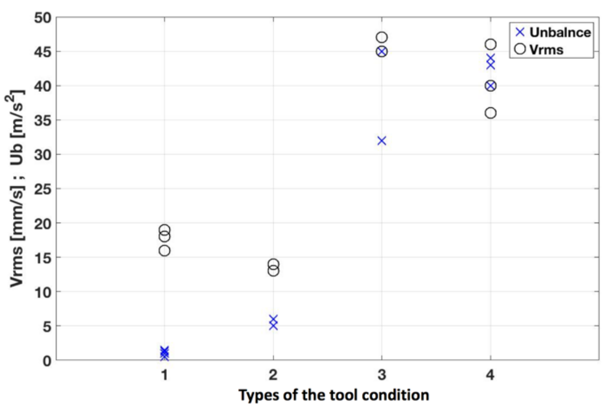


Fig. 9. Detection of the tool breakage by Unbalance and Vrms

3.2. Application of the criteria

The results which are presented above were obtained by post-processing of signals. Nevertheless, it needs the detection of tool wear in a real time to prevent negative consequences. Online signal processing is carried out, every 0.1s on samples of 7000 points. The root mean square of the vibration velocity (Vrms) is calculated, the frequency spectrum is computed by Fast Fourier Transform (FFT) and order tracking is performed (since spindle speed is measured). Online signal processing of Vrms and Ub for two different types of tool condition (2,4) are presented on the Fig.10 (Cutting conditions: ap=5mm, ae = 18, N = 13500 rpm, Vf = 4 m/min).

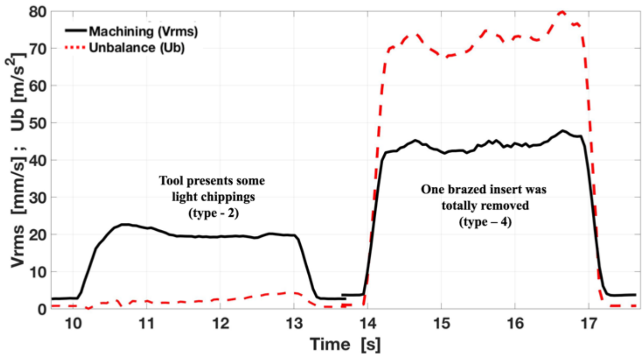
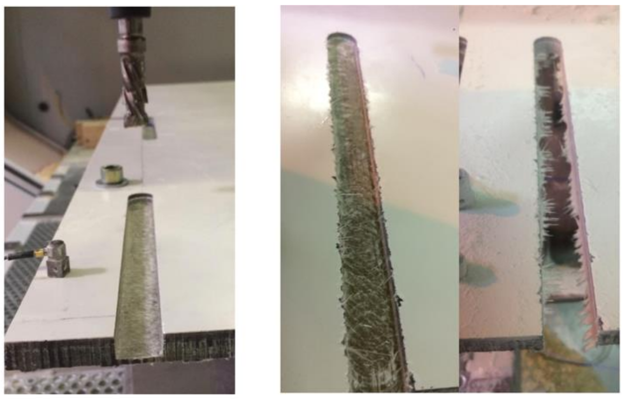


Fig. 10. Test of tool wear criteria by online signal processing

As shown by Fig. 10, the criteria of Ub and Vrms enable the online detections of tool wear. The consequence on the quality of the final surface by two types of tool condition is presented on the Fig. 11.



a) The path with new tool (type of the tool condition - 1)

b) The path with damaged tool (type of the tool condition - 4)

Fig. 11. Consequence of tool condition on GFRP delamination

As shown by Fig. 11, machining with damaged tool lead to delamination of the workpiece surface, chippings at the top surface and uncut fibers at the bottom (Fig. 11b).

4. Detection of chatter vibrations

Two parameters: Nh and Vrms were proposed and tested to find a criterion that detects chatter vibrations.

4.1. Proposition of criteria

In order to develop a new criterion to detect chatter the cutting tests were performed at different setups (Fig. 3). Analysis of the vibration spectrum for each setup was carried out. The analysis of the vibration spectrum reveals that, in presence of chatter, new contributions appear at non-harmonic frequencies (of the spindle speed).

Examples of the vibration spectrum are presented on the Fig. 12.

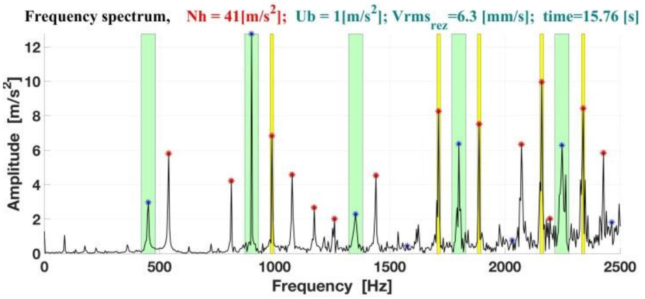


Fig. 12. Examples of the vibration spectrum

On the vibration spectrum (Fig. 12), blue stars with green columns represent harmonic frequencies which related to the frequency of rotation of the spindle. Non-harmonic frequencies are marked by red stars. The yellow columns represent 5 dominant non-harmonic frequencies.

The criterion, noted *Nh*, is therefore defined as the sum of the amplitudes of the five dominant non-harmonic contributions of the vibration spectrum (yellow columns).

4.2. Application of the criteria

Online signal processing is carried out, every 0.1s on samples of 7000 points. The root mean square of the vibration velocity (Vrms) is calculated, the frequency spectrum is computed by Fast Fourier Transform (FFT) for calculation of Nh.

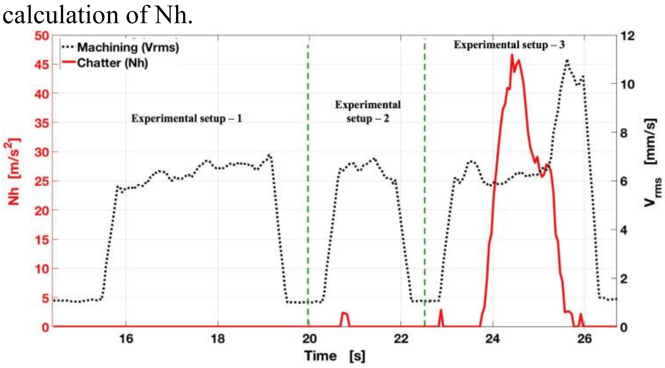


Fig. 13. Test of chatter detection for different setups

The results of chatter detection for setups Fig. 3a, Fig. 3b, Fig. 3c are presented on the Fig. 13. As can be seen, there was no chatter vibration for the setups 1 and 2 (Fig. 3a, Fig. 3b) because the workpiece is stiff enough. Nevertheless, our criterion Nh detected the chatter vibration for setup 3 (Fig. 3c), where the workpiece is more flexible.

The results of chatter detection for setups – 4 (Fig. 3d) is presented on the Fig. 14.

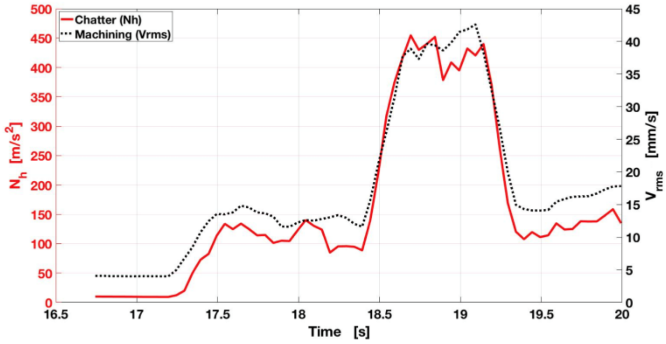


Fig. 14. Test of chatter detection (setup – 4)

As shown by Fig. 14, the criterion (Nh) well detects the high chatter vibrations due to flexibility of the workpiece. These chatter vibrations led to degradation of the tool, from tool condition 1 to 3 (Fig. 6) after 5s of the machining. This degradation confirmed again the importance of detection of chatter vibrations along the machining.

Conclusions

The importance of online detection of tool wear and chatter vibration during machining was confirmed by the cutting tests. It was shown that damaged tool (type 3 and 4) can lead to important surface delamination of the workpiece and high chatter vibrations can lead to tool breakage, within 5s of machining. So, to tackle this problem, online criteria were proposed to detect tools failure and chatter vibrations during the machining of GFRP. The criteria are experimentally validated with trial cuts.

Concerning tool wear four parameters, based on cutting mechanics model (P, Esp, Vrms, Ub), were tested. It was shown that all parameters enable the detection of the tool wear, but not with the same sensibility. Also, the criteria Ub and Vrms lead to better results, since they do not depend on depth of cut ap and on the type of tool. Also, it is interesting to note that the unbalance criterion Ub is more precise to detect light chippings of the tool (like type 2).

For the detection of chatter vibrations, the new criteria Nh was proposed. It was shown that criterion Nh enable us to detect the sum level of chatter vibration and notify appearance of high chatter vibrations.

The next step of this study is to implement these criteria on the real industrial database. This analysis will enables us to determine critical thresholds of the monitoring criteria through the statistical modeling and data aggregation.

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