EXPERIMENTAL STUDY OF THE AXIAL CUTTING FORCES IN THE DRY DRILLING OF CFRP

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Abstract
Carbon Fiber Reinforced Plastic (CFRP) are in widespread use in aerospace industry because they provide structural strength comparable to metallic alloys, but at a lighter weight. This leads to improved fuel efficiency and performance from an aircraft. Therefore CFRP materials are becoming increasingly relevant in major structural elements. Commonly these elements need to be machined (drilling) for subsequent assembly operations thereby it is essential to deepen the understanding of the key parameters of that drilling process. This paper reports on the results of a study on the axial cutting forces in the dry drilling of CFRP and its evolution with the main drilling parameters. So, cutting speed, thickness and feed rate have a strong influence on the F value. First empirical model have been also proposed.

1. Introduction

Weight is everything when it comes to aerospace industry, and designers have striven continuously to improve lift to weight ratios since man first took to the air. Composite materials have played a major part in weight reduction. Since 1987, the use of composites in aerospace has doubled every five years, and new composites regularly appear. Currently there are three main types in use: carbon, glass and aramide fiber reinforced epoxy. All of them have been classified into the so-named Fiber Reinforced Plastics (FRP) [1,2]. Nevertheless carbon fiber is the reinforcement material of choice for "advanced" composites because it exhibits excellent fatigue resistance which do not suffer from stress rupture compared with glass or aramide fibers and it has been gradually replacing metallic alloys in major structural elements. This kind of advanced material is commonly called as Carbon Fiber Reinforced Plastic or Polymer (CFRP) [1,3].

Those structural parts made of CFRP have frequently to be drilled and riveted afterwards during the assembly operations [4]. With an expansion in air travel and commercial airlines looking to replace older, less-energy efficient planes, aero/defense builders seek to speed up manufacturing processes to meet growing order backlogs and critical aerospace-defense program deadlines. As consequence, automation development pace has quickened, attempting to further automate drilling processes. That scenario makes even more crucial to deepen the understanding of the cutting forces involved during dry drilling operations and try to deduce relationships with other key parameters such as feed rate, cutting speed or tool life as well as their influence in quality of the resulting drilled hole (dimensional finished, roughness, break in, break out and/or delaminations) which could lead to enhanced drilling monitoring optimizing the use of consumables and avoiding defects, reducing current inspection ratios at the same time.

One of the physic magnitudes that help to monitor the quality of the drilled holes is cutting force. In the case of drilling processes, the cutting force can be divided into three orthogonal components, F_x, F_y and F_z, Figure 1.

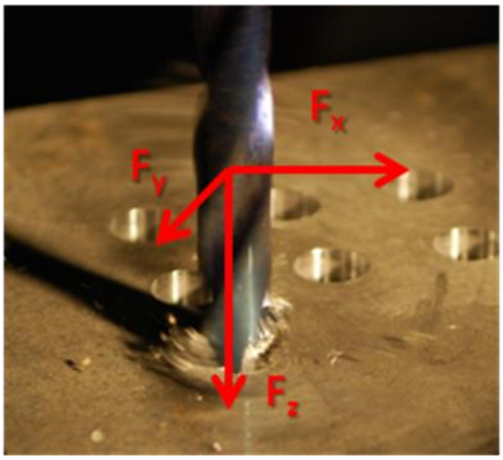

Figure 1. Cutting force orthogonal components in the drilling process

In the drilling process, the value of the force component oriented in the axial -or feedrate- direction or driven force, F_z, is much higher than the values of the rest of components. This force gives rise to the main compressive effects previous to the material cutting process. Because of this, the analysis of this force can provide wide information about the quality of the process. Even, as it has been reported in previous works for other machining processes, the main component of the cutting force can be directly related with quality surface parameters such as average roughness, Ra [5].

This paper reports on the results of an experimental survey about the axial cutting force when drilling CFRP materials without using coolants and its dependence with the cutting speed and feedrate for a given CFRP thickness. And on that point, which may seem the most innovative, obtaining an axial force parametric model.

2. Experimental Methodology

Carbon Fiber Reinforced Plastic (CFRP) sheets of 10 mm of thickness have been used in the experimental stage of this work, Figure 2. CFRPs are constituted by 90° interlaced fiber supported by an epoxy resin. This configuration is widely used in different structural elements of the airships.

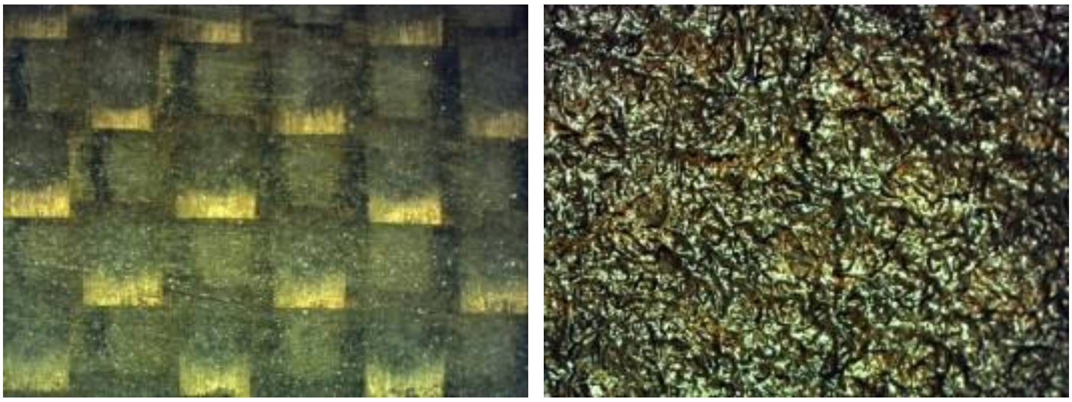

Figure 2. SOM images of CFRP sheets used in the experimental tests (Left) UP/IN (Right) DOWN/OUT

Dry drilling tests were conducted in a High Speed Machining Center Kondia, model Five 400, equipped with a Heidenhain Numerical Control, Figure 3. An air intake system was coupled close to the tool in order to minimize collateral damages by the CFRP dust. CERIN WC-Co drills (6.33 mm diameter) have been used as cutting tool. These tools are specially designed for drilling CFRP.

Figure 3. (a) HSMC Kondia used in the dry drilling tests. (b) CFRP drilling procedure

The dry drilling tests were performed combining different values of cutting speed, V, and feedrate, f. Table 1 includes the values of the cutting parameters used in the tests. So, a total of 12 tests have been conducted, taking into account all the possible combinations V-f. As this is a preliminary study, only a set of ten drills has been carried out in each of the dry drilling tests.

The orthogonal components of the cutting force were acquired on-line during the tests, using a Dynamometric Plate Kistler 9257B coupled with a charge amplifier Kistler 5019B (pC to N), Figure 4 (left). A multiplexor National Instruments BNC-2110 drives the data-signals to a PCMCIA National Instruments DAQCard-6062E acquisition card. Figure 4 (right) shows the acquisition force scheme.

V (m/min)	f (mm/rev)
75	0.20
90	0.25
105	0.30
120	

Table 1. Cutting parameters used in the experimental tests.

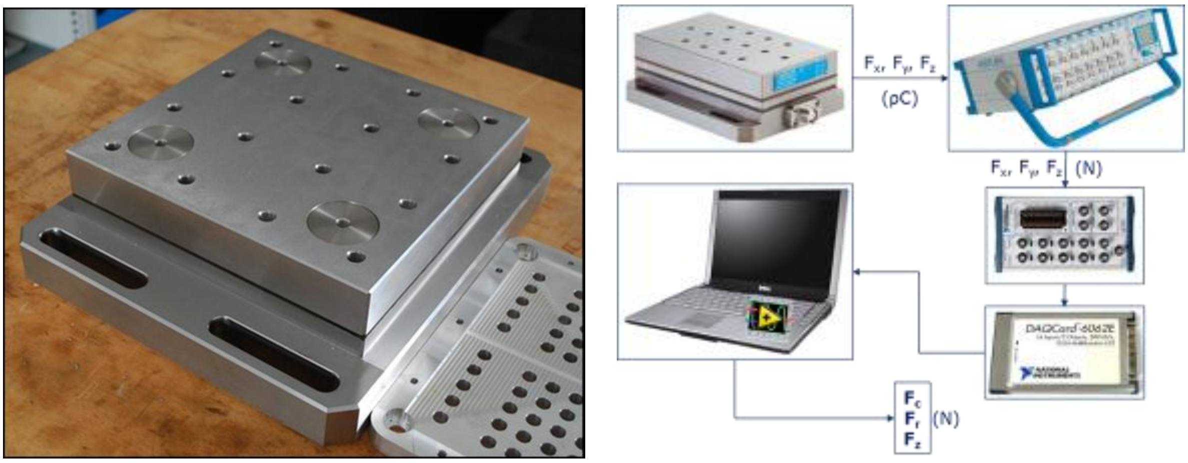

Figure 4. (Left) Dynamometric plate Kistler used for the forces acquisition. (Right) Acquisition system

In order to guarantee the correct forces acquisition and to avoid sheet instabilities during the machining process, a special tooling for the plate-sheet coupling was designed, Figure 5. This design involves a drilled lost-sheet for improving the tool output, and a metallic frame for a peripheral clamping. On the other hand, the tests automation was conducted by using ten-drills cycles, which were programmed using the CAD-CAM module of CATIA V5 with a specially designed postprocessor for the code translation, Figure 6. Force data were treated by using commercial mathematical software. Parametric models were tested using this software.

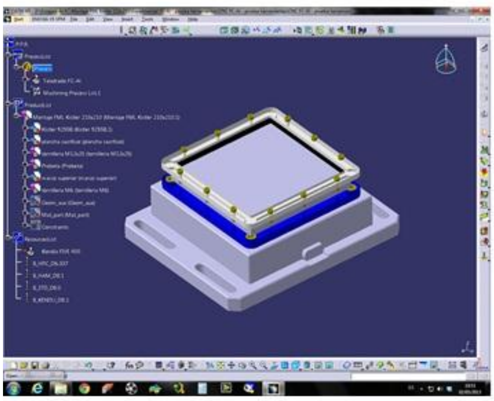

Figure 5. Tooling for the experimental dry drilling tests

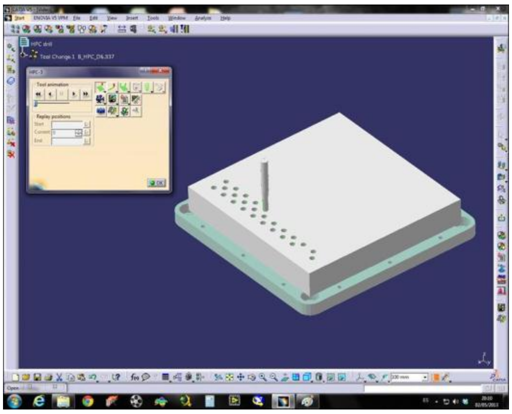

Figure 6. Previous simulation to the drilling tests using the CAD-CAM tools.

3. Results and Discussion

Figure 7 shows a typical force-time spectrum acquired during the one-hole dry drilling of a CFRP sheet.

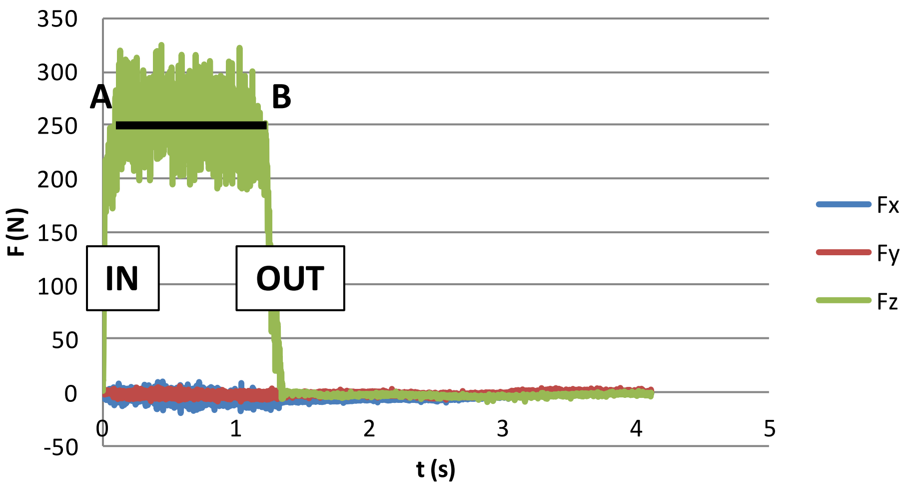

Figure 7. Typical F(t) diagram in the drilling process of a hole.

Looking at this figure, it can be made the following observations:

- Driven (axial) force, F_z, is much higher than the radial, F_y, and tangential, F_x, forces. Because of this, F_z can be considered as the principal component of the cutting force.
- F_z shows three well-defined zones. Two high slope branches corresponding to the drill-IN and drill-OUT, and an intermediate zone that can be associated with the mechanically stable coupling tool-workpiece during the hole making. This can be assimilated as a pseudo stationary state. In this zone, the average cutting force has been calculated. To another scale, similar observations have been made for F_x and F_y.

Because of this, in this study, only F_z has been analyzed. Figure 8 shows the evolution of Fz as function of the number of drills for different cutting conditions.

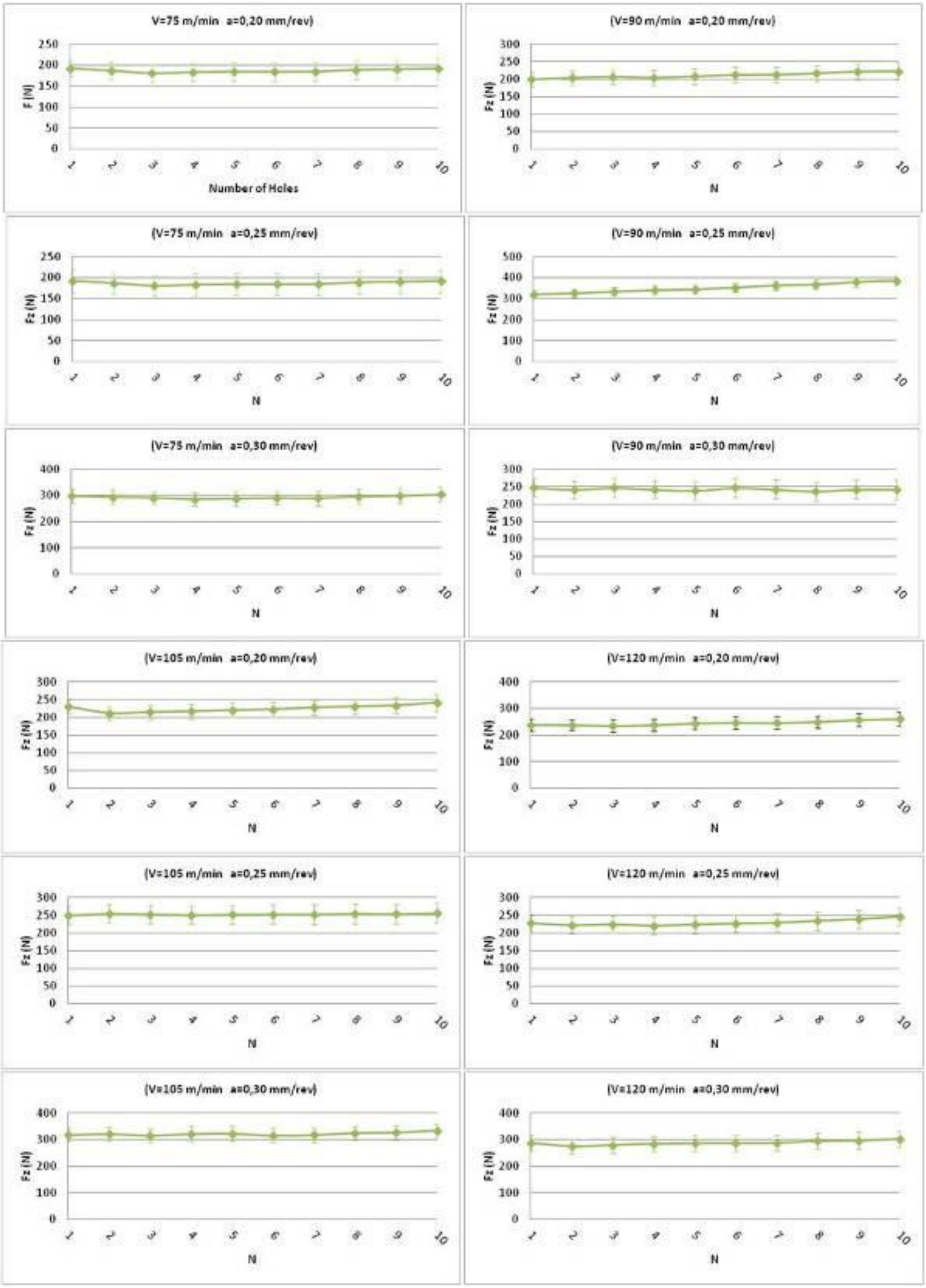

Figure 8. Evolution of the cutting force components as a function of the number of holes.

Looking at the Figure 8, it can be observed as the evolution of F_z is different depending on the cutting parameter increased. In effect, driven force shows a certain tendency to increase with feedrate. This is expected because the driven force is oriented in the same direction that feedrate. On the other hand, in this direction, the tool-material surface contact is maximum and so the force required is higher. Notwithstanding, it must be noticed that there are singular combinations cutting speed-feedrate where F_z has not evident changes when feedrate is increased.

Relating to cutting speed, the evolution of driven force with this parameter is lighter. Even, in some cases, F_z shows imperceptible variations when cutting speed is increased.

According to the analysis recorded in previous studies [5,6], a potential model has been proposed for F_z as a function of cutting speed (V) and feedrate (f)

$$F_z = F_M \cdot V^x \cdot f^y \tag{1}$$

In this equation F_M is the force module coefficient and it represents approximately the normalized average value of the cutting force. Exponents x and y show the influence of cutting speed and feedrate, respectively, on the driven force, F_z. This empirical potential model has been calculated applying multilineal regression to the logarithmic form of the Equation (1)

$$\log F_z = \log F_M + x \cdot \log V + y \cdot \log f \tag{2}$$

As the evolution of F_z as a function of the number of holes, N, has not shown evident increasing or decreasing, the hole number five has been taken as a reference for constructing the potential model. Starting from these considerations, the average empirical potential model that has been obtained is:

$$F_z = 342.91 \cdot V^{0.15} \cdot f^{0.71} \tag{3}$$

Notice as the average axial cutting force module is in the order of 300 N. Exponents x (0.15) and y (0.71) show a higher influence of the feedrate on the driven force, as it has been observed in Figure 8. The values reported from the application of the pairs (V, f) to this model are in good agreement with the experimentally obtained data. This model allows predicting the driven force in the dry drilling of CFRP composites using WC-Co drills.

Currently, the average roughness of the drilled holes is under study. The main objective of this study is focused on the establishment of a relationship Ra (F_z). This relationship would allow monitoring on-line the surface quality of drills through the values of the axial cutting force.

4. Conclusions

An experimental study on the axial cutting force, Fz, when drilling CFRP materials without using coolants has been achieved. In this study, the dependence of this force with the cutting speed and feedrate for a given CFRP thickness has been evaluated. The other two cutting force orthogonal components (F_x, F_y) have been obviated in this study, because their values are so lower than those acquired for F_z.

Cutting force time-spectra have shown three well-defined zones: two transient branches, associated with the drill-IN and drill-OUT processes; and a pseudo-stationary zone, related to the mechanically stable coupling tool-material. F_z average values have been calculated in this last zone.

Driven force experimental data have shown that F_z depends lightly on cutting speed, V. However a stronger -quasy linear- dependence with the feedrate has been observed. From these considerations, a potential model has been developed. This model contains the aforementioned influences of V and f and it has shown a good approximation to the experimental data.

5. Acknowledgements

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