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PROCESS ANALYSIS IN THE DRILLING OF CARBON FIBER REINFORCED COMPOSITE USING DIFFERENT POINT ANGLES OF TWISTED DRILLS

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Abstract. Carbon fiber reinforced polymers (CFRP) are widely used in several industrial areas, due to the countless possibilities of matrix-reinforcement combinations, which allow a wide range of customization of the material properties. However, the manufacturing of these composites faces some challenges such as the occurrence of damages during the drilling process. Thus, the evaluation of the drilling conditions is necessary to guarantee the dimensional accuracy and the surface quality of the holes. In this work the analysis of the influence of tool point angle in the drilling of CFRP is approached with the objective of determining the best conditions for the machining considering the power rating as the response of the process. To evaluate impact in the machining, three twist drills were used with different point angles of 90º, 120º and 140º. The cutting parameters of feed rate (0.02, 0.04 and 0.06 mm/rev) and cutting speed of 6000 rpm were set to the experimental testing. The experimental design applied was the full factorial design to verify the influence of each input variable (factors). The analyzed output variable was the power consumption during the machining. Results indicate that point angle of 120º is recommended to reduce the power consumption.

Keywords: CFRP, Drilling, Machining, Power Consumption

1. INTRODUCTION

Composites have already demonstrated their importance in different sectors, being essential for specific applications due to the combination of physical and mechanical properties that could not be obtained using conventional materials. However, as they have only been on the market for a short time and due to their high manufacturing complexity, it remains a major challenge for the industry to obtain high quality holes and low rejection rates (Gao et al., 2022).

There are few studies in the literature addressing the topic of the influence of the drill point angle in CFRP drilling to reduce or minimize the delamination defect, which is the main problem in the machining of these composites today.

The properties of fiber-reinforced composites are directly associated with the properties of the constituent elements of the materials, such as fiber and matrix properties, concentration or volumetric fractions, fiber/matrix interface and adhesion, layer arrangement and orientation, as well as by the geometry of the filament, such as shape and size (Santos and Sales, 2016). Some examples of sectors in which this class of materials has been gaining a lot of space are the sports industry, automobile, bioengineering, aerospace, among others.

According to Kersting (2004), epoxy resins that can be used as a thermoset matrix, have some outstanding properties, such as good adhesion to various substrates, relatively high tenacity, high electrical resistance, weather resistance, etc. Another important feature of this thermoset polymer is its excellent adaptation to different types of industrial processes, making it very interesting for certain applications, being used as an adhesive, molding component and as a matrix for composites used in structural applications.

According to Gutiérrez et al. (2014), replacing steel with CFRP in the automotive industry leads to a series of advantages such as: decrease in the total weight of the car, increased safety, reduced maintenance, in addition to cost reduction due to savings generated in the stages of the production process of this material. The authors also state that the reduction in vehicle weight generates a reduction in costs that is easier to achieve than looking for alternative forms of engines and fuels, so that the continuous increase in demand for these composites is predicted in the coming years (Poór et al., 2021).

Despite the growing popularity of composite materials, challenges arise from CFRP drilling as a result of heterogeneity, anisotropy and the abrasiveness and hardness intrinsic to the fibers, causing defects in machining processes, such as fiber-matrix detachment, fiber pullout, fiber breakage, fiber loss of resin and delamination (Aamir et al., 2019).

Among the defects generated during the drilling process, the most critical is delamination, which, according to Gao et al. (2022), represents up to 60% of all rejections of parts in the manufacturing process of CFRP components. In addition, the authors comment that about 70% of fatigue failure accidents involve problems in riveted joints and 80% of fatigue cracks are generated in rivet holes.

The point angle of the drill corresponds to the angle between the two main cutting edges of the tool. In their study on the influence of tool geometry on the drilling of laminated composites, Durão et al. (2010) used two carbide twist drills with 6 mm in diameter and 85° and 120° of tip angle. The results indicate that the smallest delamination defects were obtained using the 120° drill, with excellent results when combined with the feed of 0.06 mm/rev. The delamination factor (Fd) found by the authors was approximately 1.12 and the 85° angle showed delaminations 12% greater than the drill with the highest angle.

The power consumption is directly linked to energy consumption during machining. Manufacturing processes involve large expenditures of energy and other resources, impacting the environment as a result. Decreasing the energy consumed by machine tools can substantially improve the damage to the environment and contribute to more sustainable processes (Vijayaraghavan and Dornfeld, 2010).

Monitoring the power consumed during the machining processes allows the evaluation and choice of cutting conditions that generate less energy demand, consequently lower costs and lower impacts on the environment (Callisaya et al., 2023). According to Yan and Li (2013), relevant studies were conducted in the area of machining aimed at optimizing cutting parameters and reducing machining costs, however, few studies have a critical view on the issue of sustainability. Reducing the energy consumed can significantly improve the environmental performance of machining processes.

2. MATERIALS AND METHODOLOGY

An epoxy matrix composite reinforced with carbon fiber was used to perform the drilling tests. The material consisted in a laminate with 8 crossed layers at 0°, 45° and 90°, with final dimensions of 250 x 20 mm. For the drilling machining tests, three helical drills with 6 mm in diameter were used, with different tip angles (90°, 120° and 140°).

The 90° and 120° cutting tools are made of high speed steel with titanium nitride (TiN) coating and have a length of 35 mm, from the Ganren brand. The 140° cutting tool with model KC7325 is made of hard metal with TiN coating and is 60 mm long, from the Kennametal brand. The applied drills are shown in Figure 1.

Figure 1. Twisted drills used in the drilling tests.

2.1 Drilling tests

The machining tests were carried out at the Laboratory for the Study of Machining of the Department of Materials and Technology of the Sao Paulo State University (UNESP), on the Guaratinguetá campus, using a 5-axis CNC vertical machining center with a power of 18 kW, from the DMG brand, DMU 50 ECO model, DMG Ecoline series (Figure 2-a).

To the data acquisition, a National Instruments terminal block, model BNC-2120 (Figure 2-b) was connected to a computer based acquisition system. The system registered the output variables during the machining using the LabVIEW graphical programming language software. The program also allowed to capture the real-time variations in the power consumption during the tests. The data capture rate was 4000 points per second.

To capture the power consumption, an AT-B10 AC current transducer was used, with a current amplitude of 100 A, from the LEM brand, model AT 100 B10 (Figure 2-c). The sensor was positioned next to the machining center motor and generates a voltage value that varies from 0 to 10 V.
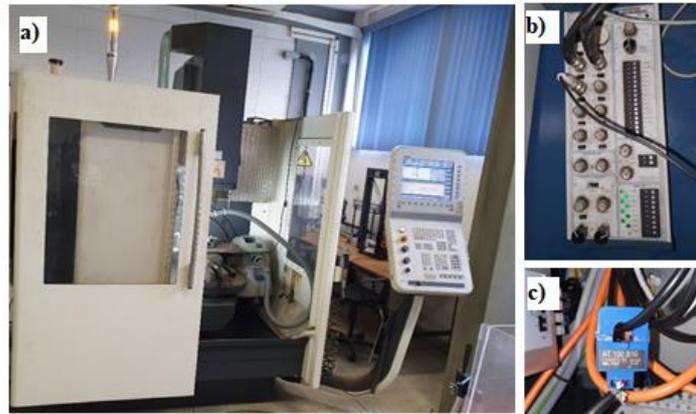
Figure 2. Experimental testing. a) Machining center; b) Acquisition system PCI BNC-2120 and c) Power consumption sensor.

2.2 Experimental planing and statistical treatment

To the experimental planning a full factorial design method was applied, due to the reduced number of factors and applied levels, allowing verification of the dependence and interaction between all factors (cutting parameters) considered. Regarding to the tool geometry, the drill point angle was varied at three different levels: 90º, 120º and 140º.

The cutting parameters considered the rotation and feeds. The rotation was stabilized at 6000 rpm and three feeds (f) were varied: 0.02, 0.04 and 0.06 mm/rev. Two repetitions were performed, totaling 18 trials of drilling.

All holes occurred in a single test specimen, respecting a distance of 7 mm between each hole.

From the signals captured by the sensor and recorded in LabVIEW, the next step was the processing and treatment of data in the mathematical software MATLAB®, from MathWorks Inc, version R2022b were three treatments (code programs) were used. The LabVIEW generated a file for each output variable and test performed, totaling 54 different files, composed of several decimal numerical values that represent the results of each variable. The first code converts commas to points in all files, as LabVIEW separates the decimal places with commas, while MATLAB® reads these numbers in points.

The second code handled the output variables, applying equations and adapting data for later analysis. In order to work in the International System of Units (SI), the program applies Equation (1) to the values generated by the power sensor, where: 10 V corresponds to the nominal voltage range of the transducer (DC RMS 0-10 V); 100 A is the measuring range of the sensor; 220 is the electrical voltage of the machining center motor in Volts; 0.9 is the motor multiplication factor and $\sqrt{3}$ due to the three-phase motor.

$$\text{Power consumption [W]} = (\text{output voltage}/10 \text{ [V]}) \times 100 \text{ [A]} \times 220 \text{ [V]} \times 0.9 \times \sqrt{3} \tag{1}$$

To analyze the power consumption data, a statistical analysis was performed using the Minitab® software (version 17.1.0). The objective of the analysis is to investigate the dependence between the factors (point angle and feed), the contribution of each variation within the factor on the power consumption, as well as to determine the best cutting conditions, considering the statistical interest "lower is better" for all responses and to avoid and reduce the occurrence of failures (delamination process).

For this purpose, the Analysis of Variance (ANOVA) method was used, adopting a significance level (α) of 5%. First, data normality was checked using the Kolmogorov-Smirnov test. Then, the P values and the F values were analyzed in order to verify the significance of the factors. Finally, graphs of the main effects, interactions and contour were plotted, making it possible to determine the best angle and the best feed for machining, according to the established statistical interest.

3. RESULTS AND DISCUSSION

For the analysis of the power consumption in the drilling tests, the average power values were acquired and evaluated. The first step was the application of the Kolmogorov-Smirnov normality test, in order to verify whether the variable follows a normal distribution (Figure 3). The P value obtained in the normality test was greater than the significance level of 5% adopted, proving the normality of the data. The average power variation throughout the composite drilling process can be seen in Figure 4.
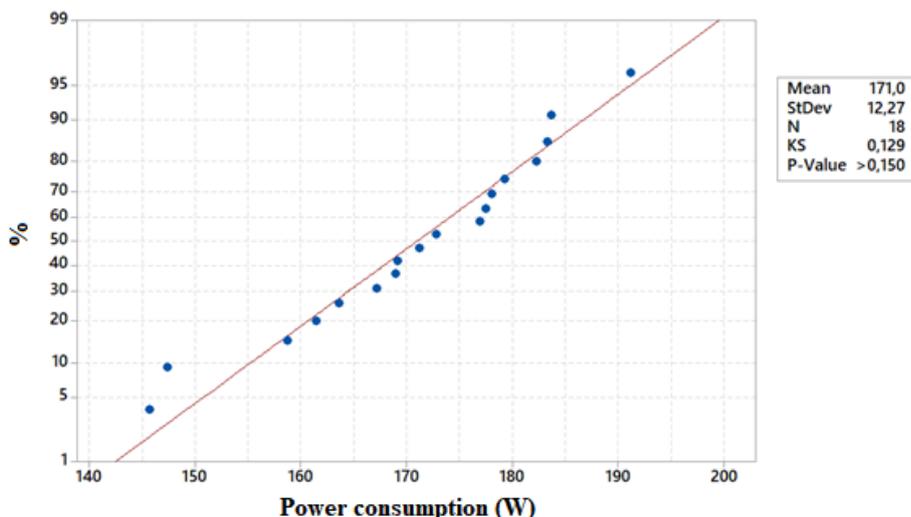
Figure 3. Kolmogorov-Smirnov normality test for the power consumption during drilling.
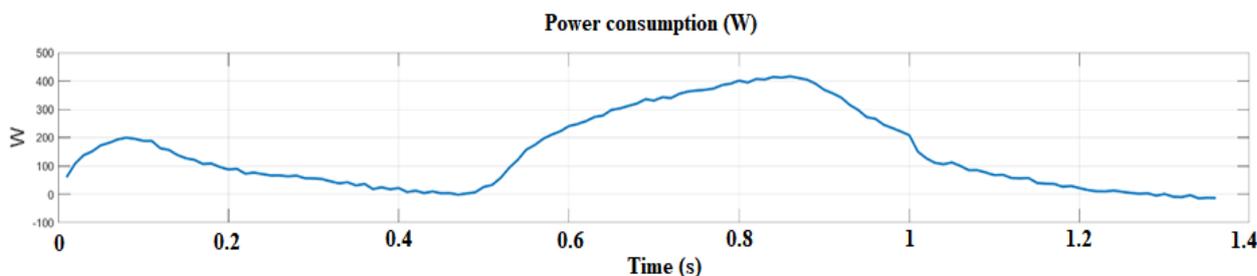

Figure 4. Fluctuation of power consumption during the composite drilling using the 120º drill and 0.06 mm/rev feed.

Then, the Analysis of Variance (ANOVA) technique was applied, where it was verified whether the values are statistically significant through the P value and the F value, as well as the contribution of the point angle from the twisted drills, the feed and of the interaction between both factors.

In Table 1 is possible to verify the ANOVA results to the power consumption, the contribution was calculated by the sum of squares of the factor divided by the total sum of squares and provide the amplitude of impact of the factor to the response.

Table 1. ANOVA to the power consumption.

Factors	DF	SS aj.	Contribution	F-value	P- value
Point angle (°)	2	993.6	38.80%	8.51	0.008
f (mm/rot)	2	448.9	17.53%	3.84	0.062
Point angle*f	4	592.9	23.15%	2.54	0.113
Error	9	525.5	20.52%		
Total	17	2560.9			

The ANOVA stated that the twisted drill point angle had a significant influence on the power results, since the P value of 0.008 is lower than the adopted 5% α.

Regarding the feed, it cannot be stated that this factor was statistically significant taking into account the value of P, as it is greater than 0.05. However, according to the F>2 criterion proposed by Phadke, it is possible to confirm the significant relevance of the factor due to the found value of 3.84 (Phadke, 1989), categorizing the feed fact as a secondary impact to the total power consumption. The point angle and feed interaction (point angle*f) is not significant for both the P value and the F value.

Once the significant influence of the two input variables was assured, the main effects graph was plotted (Figure 5), which displays the average of the power consumption for the three levels of the two factors used in the drilling machining.
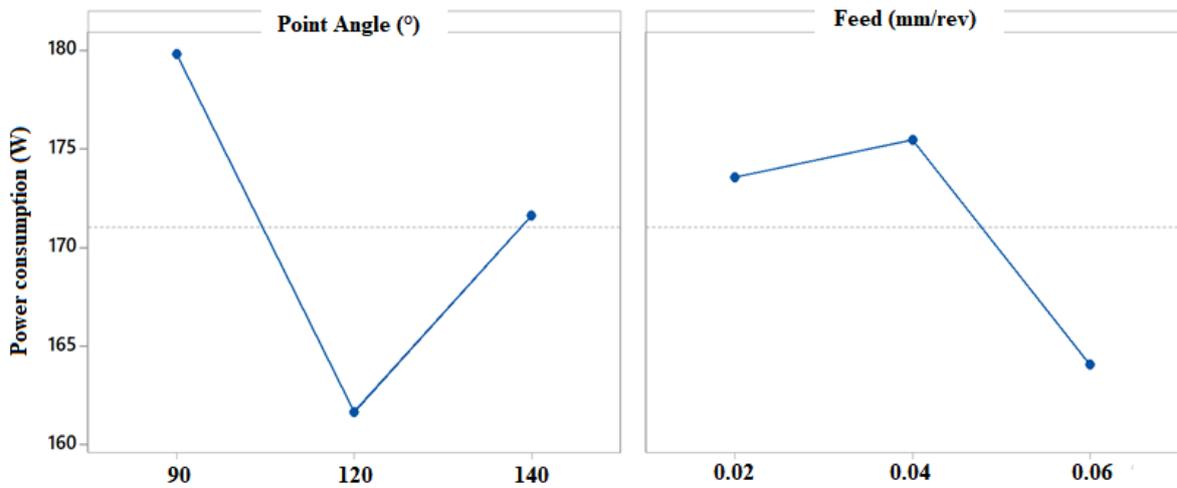
Figure 5. Main effects plot to the power consumption.

In the main effects plot it is not possible to observe a clear trend on the power results with the variation of the point angle. Evaluating the point angle, there was a representative decrease of 10% in the mean power consumption when changing from the 90º to 120º drill, but the value increases when using the 140º drill. As the 140º drill has a different brand and material than the others (made of carbide), other factors may have interfered with the consumed power considering the tool item, in addition to the point angle.

For the feed, a linear behavior was also not obtained, however, the variation was less accentuated between the levels.

In this way, according to the "smaller is better" ratio adopted in this work, it can be concluded by analyzing the graph that the best cutting conditions (taking into account the consumed power) were obtained using the 120º angle drill with Power consumption of 161, 67 W and feed of 0.06 mm/rev (Power average of 164.06 W).

In addition to the main effects graph, the interactions plot was also evaluated (Figure 6), which allows identifying significant second-order interactions. The crossing of the lines indicates the presence of this interaction, which can be observed between the f of 0.02 mm/rev and the other two curves for angles of 120º and 140º.
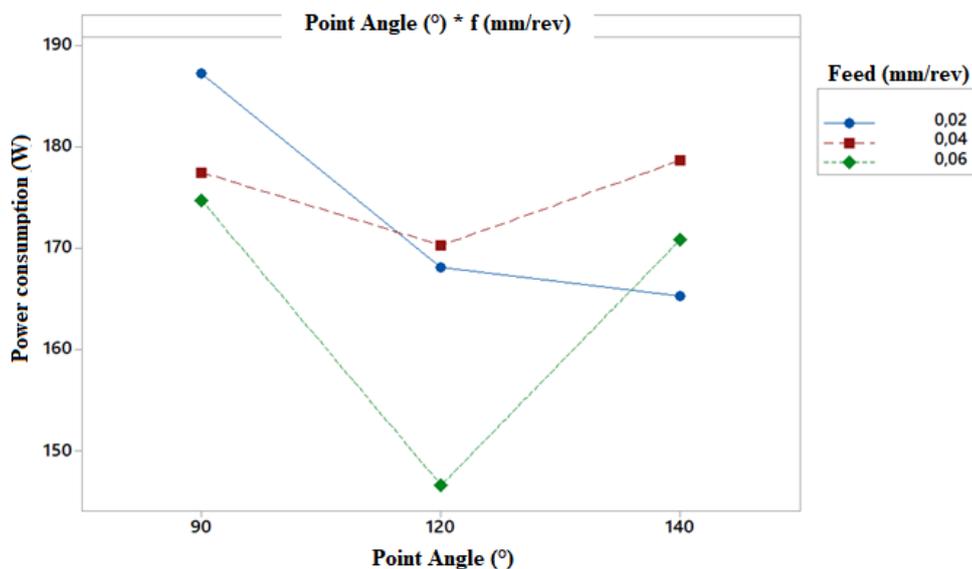

Figure 6. Interaction plot of Point Angle and feed to the applied twisted drills.

Another factor to be highlighted is the similar behavior for the feed curves of levels 0.04 and 0.06 mm/rev. They start with higher power consumption averages for the 90º point angle, which decrease with the 120º drill and increase again with the highest level of point angle.

It is also possible to visualize that, using the combination of a 120º tip angle and a 0.06 mm/rev feed, the lowest power values were obtained with an evident difference in relation to the other arrangements as can be seen in Figure 7.
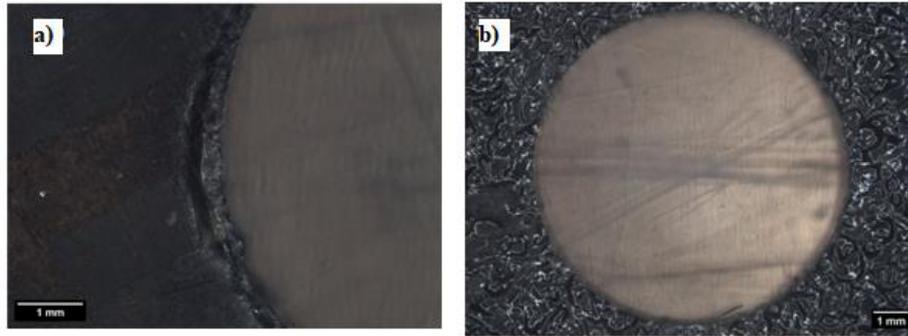
Figure 7a) Hole surface using 90º angle drill and feed 0.06 mm/rev; b) Hole exit surface using 120º drill and f = 0.04 mm/rev.

4. CONCLUSION

According to the statistical analyses, the results indicate that the 120º point angle favored the lowest values for power consumption also favoring circularity stability of machined holes. The difference in tool manufacturers and material may have affected the values, as carbide twisted drills tend to produce better holes compared to high-speed steel drills. However, as it was stated in the statistical analysis the angle has influence on the results and should be considered to reduce the power during tests. In relation to the feed, the feed rate level of 0.02 mm/rev provided lower values of consumed power, deviations and delamination at the entrance of the holes, while the feed of 0.04 mm/rev was more efficient in minimizing delamination in the exit holes. Results consulted in the literature indicate that smaller feeds tend to cause minimal delamination, therefore the use of 0.02 mm/rev is recommended.

5. ACKNOWLEDGEMENTS

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