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COMPARATIVE ANALYSIS OF THE DAMAGE VOLUME AND THE RELATIONSHIP WITH THE MECHANICAL ENERGY OF THE DRILLING PROCESS UNDER DRY CONDITIONS AND WITH CRYOGENIC COOLING IN THE COMPOSITE LAMINATE PPS-C

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Abstract.*In recent decades there has been a considerable increase in the study of drilling, as it involv es many process variables, being considered essential by industries using composite materials. Dry drilling is widely used, however heat generation can lead to the occurrence of defect. In order to minimize these problems, cryogenic cooling drilling has been gaining attention as to its influence on reducing the temperature of the tool and in the literature, there are studies on the drilling process under cooling conditions, evaluating the defects caused by the process of drilling under cooling conditions, evaluating the defects caused by the process, especially along the wall and at the exit of the hole. The objective of this work is to analyze and relate the volume of damage around the hole output, with the mechanical energy of the process under dry conditions and with cryogenic cooling. The values obtained from the volume of damage follow the same trend as other two-dimensional defect valuation methods in the dry condition. The advance has little influence on the ratio between energies in the damage region, in both conditions, indicating that it may be another variable to be studied. The damage stress was also experimentally analyzed aiming to define a level for advancement, to avoid the onset of defects.*

1. INTRODUCTION

In the aeronautical, astronautical and sustainable energy industrial sectors, among others, the use of structural composite laminates of thermoplastic and thermorrigid matrix reinforced with continuous carbon fibers (CFRP) is increasing, highlighting the excellent mechanical properties per unit of mass and good durability. Components and structures designed and manufactured with these laminates are almost entirely subjected to drilling machining processes. In this context, the study of drilling in composite materials has become a promising area for practical application and involving many process variables, is considered essential by the industries. Dry drilling is widely used because it dispenses cutting fluids, however, due to the non-homogeneous structure and strongly anisotropic, its drilling becomes difficult [1]. Combined with this, when subjected to this secondary process these materials present defects such as: torn fibers, fissures in the matrix and delamination in the "peel-up" input and "push-out" of the hole [2]. These defects can cause damage and in order to minimize these problems, drilling with cryogenic cooling has been gaining attention as to its influence on reducing the temperature of the cutting tool and in the literature, there are studies on the drilling process under cooling conditions, proposing methods of evaluation and/or reduction of defects caused by the process, especially on defects along the wall and the exit of the hole [3,4]. Recently, a general review of the methodologies most used to evaluate the extent of delamination, its mechanism and factors applied to direct its control in the industry was presented. They concluded that it is still difficult to have a comprehensive evaluation of the damaged area, delamination cracks, delaminate depth, latch width, et. [5] In this context, understanding and detecting the type, size and location of the defect generated by the drilling process is of paramount importance for production control and assistance in establishing safety factors for the life of the perforated component [6].

2. METHODS OF ANALYSIS OF DEFECTS IN THE DRILLING PROCESS

From the methods of evaluation of the delaminating factor, the dimensional factors of conventional delamination (F_d) [7] and adjusted (F_{ad}) [8], which propose a two-dimensional analysis stand out. Fd is determined according to the ratio between the maximum diameter (D_{max}) of the damaged zone and the nominal diameter of the hole (D_{nom}), as indicated in Equation 01.

$$F_d = \frac{D_{max}}{D_{nom}} \tag{1}$$

The F_{da} is determined by equation 2.

$$F_{da} = F_d + \frac{A_d}{A_{max} - A_o}\left(F_d{}^2 - F_d\right) \tag{2}$$

where A_d is the damaged area in delamination, A_{max} is the area depending on the $_{Dmax}$ of the damaged zone and A_o is the area depending on the diameter of the hole.

Applying the concept of fracture mechanics to isotropic material [9], they defined a mathematical model for the critical feed force depending on the thickness of the unperforated layer and the properties of the composite material, which would eliminate the defect of delamination at the entrance and exit of the hole, as shown in Equation 3.

$$F_{crit} = \pi\left[\frac{8G_{IC}Eh^3}{3(1-\upsilon^2}\right]^{½} \tag{3}$$

where G_{IC} is the tenacity to interlaminar fracture, E it is the modulus of elasticity, h is the thickness of the unperforated layer and represents the Poisson ratio of the composite laminate.

Considering the advancing force in delamination [3], they proposed a non-dimensional criterion that relates delamination to a force factor called force-adjusted delamination factor (F_{fa}), which considers three characteristic parameters that affect the delamination globally, as shown in Equation 4.

$$\mathbf{F_{fa} = w_1 \frac{D_{max}}{D_o} + w_2 \frac{A_{max}}{A_o} + w_3 \frac{F_{max}}{F_{crit}}} \tag{4}$$

The impact of each of these factors is controlled by means of wi weighting factors [i = 1.2,3]. The sum of all wi sum must be equal to 1. The first factor (D_{max}/D_o) considers the conventional delaminating factor (F_d). The second factor (A_{max}/A_o) considers the damaged area around the hole. The third factor (F_{max}/F_{crit}) explores the ratio between the maximum feed force achieved and the critical feed force in the delamination factor. The impact of each of these factors on general denunciation is considered equal. As a result, weight factors are distributed equally with a value of 0.33.

Recently, [10] presented a new criterion for assessing defects resulting from the drilling process under dry conditions in the exit plane of holes for CFRP composite, through the C-Scan ultrasound technique called the denunciation factor (F_v), as shown in Equation 5.

$$F_v = \frac{V_d}{V_{nom}} \tag{5}$$

where F_v is the ratio between the accumulated volume of damage in the hole output (V_d) and the nominal volume of the hole (V_{nom}) of the delaminate layers, with this is independent of the thickness of the composite.

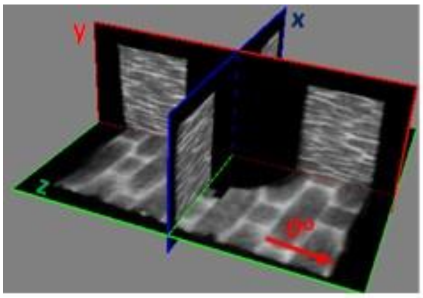
3. EXPERIMENTAL PROCEDURE

3.1. Material, drilling process and tool

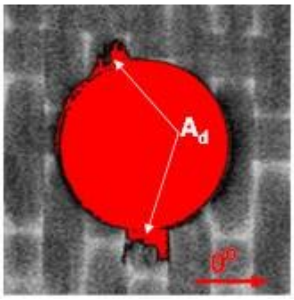
The evaluated material was the Poly-Sulfide Laminate of Phenylene-Carbon (PPS-C) composed of PPS thermoplastic resin, reinforced with continuous fibers of Carbon T300 JB, weight 280 g/m2, 17.8 beams/inch x 17.8 beams/inch, 3,000 filaments per beam supplied by Tencate company. It has a volumetric fraction of 50% fibers, being made by the juxtaposition of 16 blades of 0/90° bidirectional fabric with 5HS weft semi-impregnated with pps polymer, repeating the basic arrangement [(0/90),(+45/-45)2,(0/90)], for a nominal thickness of the laminate of 5 mm. The specimens were extracted from the base laminate according to the orientation of the weft (0°) and warp (90°), with dimensions of 14mmx14mm and integral thickness. The Romi D800 three-axis machining center tool machine with a maximum of 10,000 rpm and power of 20 hp was used for the drilling process, performed under dry conditions and under cryogenic cooling in which the cutting speed (V_c) was fixed at 60 m/me, with four different advances (f) per rotation: 45, 90, 180 and 360 μm/rot. The Seco Tools Industry provided used 6 mm diameter hard metal drill, with two 130° and 60° tip angles, of a1163-6 code diamond coating. The cooling system used to apply liquid nitrogen (LN_2) was the SC18 model supplied by the Semper Crio Industry.

3.2. X-ray computed microtomography

The SKYSCAN 1272 BRUKER microtomographic, conditioned at a voltage of 80 kV, with an electrical current of 125 μA, was used to obtain images of 14 μm thickness, 16 bits, of 24 specimens, from the laboratory of the National Center for Research in Energy and Materials - MR. CNPEN. Subsequently, the image slices were analyzed and treated to obtain both the damaged area (Ad) and the maximum area (Amax) that encompasses the nominal area of the hole (A0) and the damaged area (Ad), as shown in Fig. 1, using DataViewer®, CTAn® and ImageJ, in the public domain, of the National Institutes of Health.



(a)



(b)

Figure 1 – (a) 3D-sectioned images by DataViewer software; (b) 2D image of hole output handled by ImageJ software

With the movement of cursors x, y and z the damaged region is located and defined the cutting plane for analysis and comparison of the depth of damage (h_d) between micro-CT and optical microscopy, as shown in Figure 2.

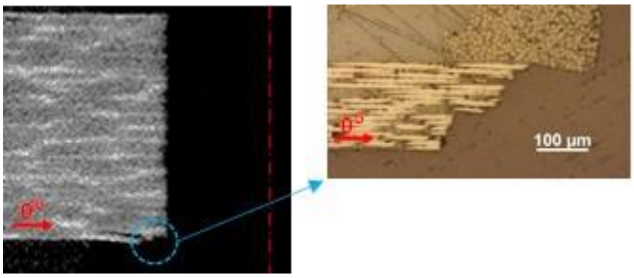


Figure 2 – Image sectioned by micro-Ct presenting enlarged detail of the thickness of the damage (hd) at the exit of the hole, obtained by optical microscopy.

The volume of damage in the hole output is calculated by the images obtained by the micro-CT, depending on the image with damaged area (A_d), the thickness of the image slice (h) and the number of slices (n_{fi}), as shown in Equation 6.

$$V_{ds} = \sum A_d \,.\, h \,.\, n_{fi} \tag{6}$$

To experimentally evaluate the damage tension (σ_d), obtained through mechanical damage energy (E_{ds}) by the volume machined with damage (V_{ud}), considering the maximum area (A_{max}), as shown in Equation 7.

$$V_{ud} = A_{max} \,.h\,.n_{fi} \tag{7}$$

3.3. Mechanical energy of the drilling process

The data obtained from the force drilling test versus tool displacement were processed by a computational program developed, using the Matlab *software* platform® to generate the mechanical energy versus displacement and force graphs of advanced versus displacement, with reference to three stages as proposed [11]. With the micro-CT technique, it was possible to evaluate the thickness of the damage (h_d) [6], defining the interval (mm) between the positioning of the drill tip at the beginning of the damage, obtaining the damage force (F_{id}) until touching the exit surface of the hole (boundary between stages II and III) to determine the mechanical energy of damage to the hole output (E_{ds}). The energies in the three stages were also evaluated and Fig. 3 presents the graphs.

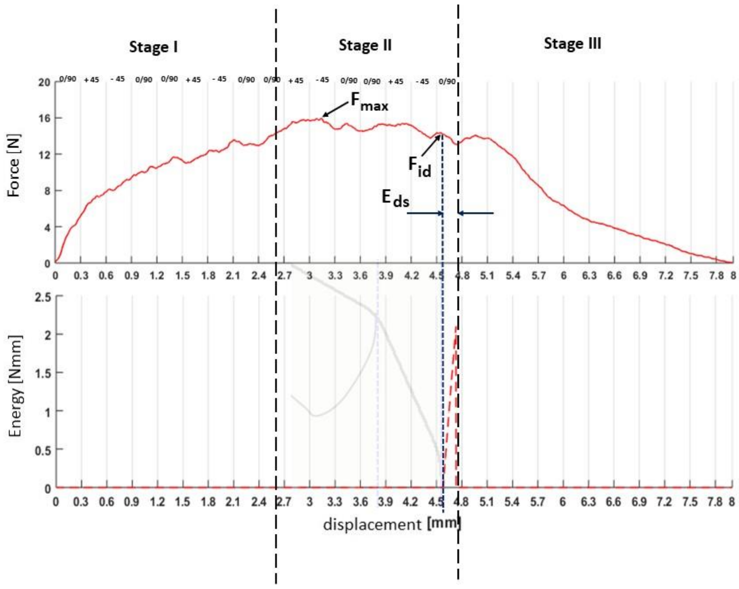


Figure 3 - Graphs of feed force and mechanical energy versus tool displacement (mm), under cryogenic cooling, in the advancement (f) of 90 µm/rot, with cutting speed of 60 m/min.

4. RESULTS AND DISCUSSION

The values obtained from the volume of damage in the hole output (V_{ds}) under dry conditions and with cryogenic cooling according to the advances (f), are displayed in Fig. 4. It is observed that the values in cryogenic condition are higher in the four advances compared to dry condition. This is due to the effective cooling of liquid nitrogen, which increases the stiffness of the polymer matrix and consequently increases the opposition of tool penetration [12]. The advance of 90 µm/rot presents the lowest result of V_{ds} in both conditions, indicating that it is the best advance for the drilling process for the material of the present study. The three-dimensional delamination factor (F_v) was also evaluated, according to E_q. (5), in which the values obtained presented the same trend for the four advances, in both conditions.

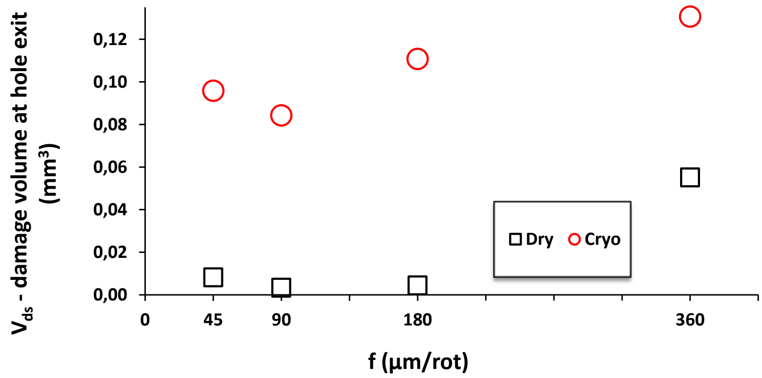


Figure 4 – Volume values of damage at the exit of the hole, under dry conditions and with cryogenic cooling as a function of feed (f), with cutting speed of 60 m/min.

Figure 5 displays the values of the ratio between the mechanical energy of each stage (E_{stage}) and the total mechanical energy (E_{Total}), under dry conditions and with cryogenic cooling as a function of advances (f). It is noted that the values of the ratio in stage I increase as the advance in both conditions increases, this is because as the tip of the tool penetrates the specimen, there is a progressive increase in the cutting area, consuming more energy. In stage II, the values decrease little with the increase in the advance due to the tip of the tool being engaged in the specimen and maintaining a constant cutting area [11]. They also show that the advance has little influence, indicating that mechanical energy can be another variable to be studied in the cutting parameters. In stage III, the tip of the tool is coming out of the specimen that does not offer resistance, becoming dependent on the greater the advance the lower the energy consumed.

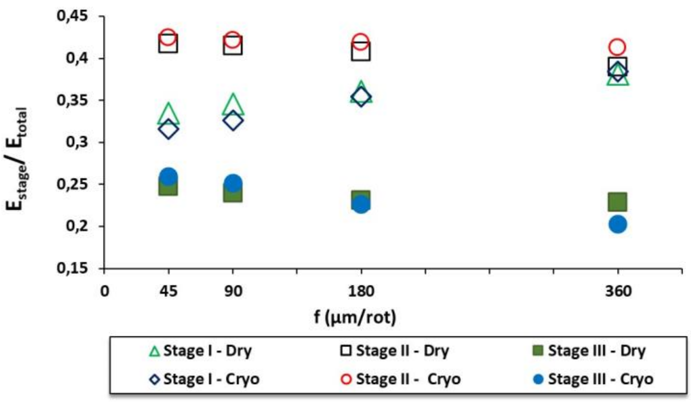


Figure 5 – Ratio values between s_{tage} and E_{total}, under dry conditions and with cryogenic cooling as a function of feed (f), with cutting speed of 60 m/min.

With the identification of the positioning of the beginning of the defect in the axial direction of the hole output in the force versus displacement graph, damage start strength (F_{id}), mechanical energy of damage at the hole output (E_{ds}) and the volume machined with damage (V_{ud}), in which through the energy and volume ratio can be experimentally defined the damage tension (σ_d) so that a level for the advance can be evaluated so that this voltage cannot be achieved, thus avoiding the onset of the defect. The values of the damage stress (σ_d), under dry conditions and with cryogenic cooling as a function of advances (f), are shown in Figure 6. It is noted that in the advance of 45 µm/rot presents lower values of σ_d, both in the dry condition and with cryogenic cooling. The 90 µm/rot advance that presented lower E_{ds} and V_{ud} values, σ_d was slightly higher compared to the advance of 45 a/rot in the dry condition and advances of 45 and 180 µm/rot with cryogenic cooling. The trend of σ_d as a function of the feed is noted in the dry condition at 45, 90 and 180 µm/rot.

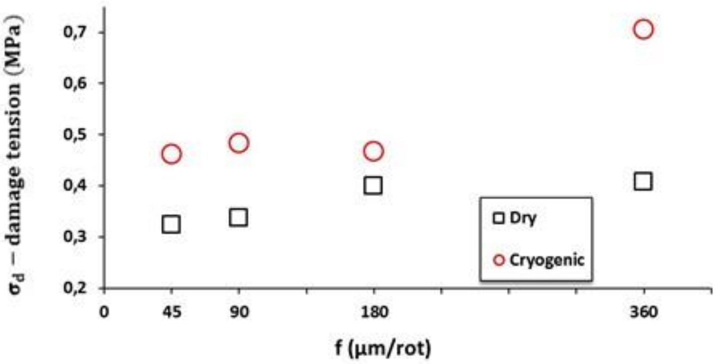


Figure 6 – Values of σ_d, under dry conditions and with cryogenic cooling as a function of feed (f), with cutting speed of 60 m / min.

5. CONCLUSION

With the micro-CT technique, the volume of damage can be evaluated, and the results indicated that the values obtained follow the same trend as the two-dimensional factors for the material of the present study. However, the two-dimensional factors evaluate the delamination defect and the volume of damage encompasses delamination and other defects that by the scanning electron microscopy technique may be exemplified. From the analysis of the mechanical energy of the process with the volume of damage, experimental values of damage stress were obtained, but their study should be deepened and applied in other composites to obtain a deeper view of its foundation and applicability. The ratio of energies in stage II of the drilling process is presented as a variable that depends on the advance.

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