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METHOD FOR ASSESSING HOLE DAMAGES IN COMPOSITE MATERIALS

Marcelo Ferreira Batista, mfb@usp.br [1]
Alessandro Rodrigues Roger, roger@sc.usp.br [2]
Igor Fernando Basso, igorbasso@usp.br [2]
Francisco de Assis Toti, ftoti@fatecsorocaba.edu.br [3]
Fernando Brandão de Oliveira, fernandobrandao@usp.br [2]

[1] São Paulo Federal Institute of Education, Science and Technology, Dr. Aldo Benedito Pierre St., Araraquara, SP 14801-600, Brazil
[2] University of São Paulo, Trabalhador São-Carlense Avenue, São Carlos, SP 13.566-590, Brazil
[3] Faculty of Technology of Sorocaba, Eng. Carlos Reinaldo Mendes Avenue, SP 18013280, Brazil

Abstract. *This paper proposes a new methodology to assess hole damages in carbon fiber reinforced thermoplastic polymer. Differently from current evaluation methods, Global Damage proposed in this paper considers damages related to material mechanical strength reduction and damages regarded to assembling troubles. Both damage groups are weighted to compound the Global Damage. Cutting speed and feed speed were experimentally carried out in a Romi-D600 machining center using a 6 mm diameter diamond coated carbide drill. Feed force and cutting torsion were measured by using a 9272 4-component Kistler dynamometer. The damages were observed by employing the Axiotech Carl Zeiss and the 3D Olympus OLS4100 microscopes, then they were quantified by a CAD software. The Global Damage showed to be able to evaluate the several types of hole damages and their phenomena. Furthermore, it showed to be more embracing than the habitual delamination factor. The weights balance can be adapted for a given specific application being useful to analyze drilling phenomenon and to improve the machining process.*

Keywords: *Composites drilling, hole quality, delamination*

1. INTRODUCTION

The excellent structural properties with light weight, achieved by a combination of materials acting together as one, have been making the composite materials, like the CFRP (carbon fiber reinforced polymers), a strong substitute for the steel and the aluminum in several applications. Besides the aircraft and automotive industries, their applications are spreading widely, since sporting goods to buildings. Despite being manufactured near net shape, joints still are unavoidable, by either bolts or rivets. Then the drilling operations are required. But differently of the metals, the multilayer laminated polymer composites have not a well-known removal mechanism. Furthermore, the drilling is always carried out at the end of production sequence, so well-done holes become an important economic issue.

The delamination has been considering as the major damage in drilling. According to Daniel and Ishai (2006) the delamination is a interlaminar cracking that occur under the three basic modes of fractures: mode I (opening), mode II (shearing) and mode III (tearing). Some authors (GRILO et al., 2013; JIA et al. 2016; Durão et al. 2013; Hocheng et al., 2005) suggest that the drilling leads the opening or peel mode (mode I), delaminating both the firsts and lasts plies of the composite material, manly in the last layer. The major damages occur on the last layers, and this delamination is considered as a consequence of the thrust force applied for the drill during the operation. The thrust force is intrinsically affected by de feedrate. There is a break point value of feedrate which the thrust force is enough to start the delamination after overpass the interlaminar bonding strength (Hocheng et al., 2005).

However Kakinuma et al. (2015) attained low delaminations and burrs using high feedrates drilling thermoplastic Nylon PA66 reinforced with bidirectional bunches of carbon fiber. In the thermoplastic matrix, the temperature increase the weakness, reduce the viscosity and start to melt it, before the end of drilling. According the author using the high fast drilling there is no time to increase the cutting heat and friction, resulting in good hole qualities. Ben et al. (2012) attained bad quality holes drilling thermoset matrix at high temperature but under the decomposition temperature. Thus, the increase of temperature reduces the matrix stiffness and induce interface failure. If on one side the matrix determines the thermal strength of composites, Merino-Pérez et al. (2015) suggests that the reinforcement has significant influence on heat dissipation, mainly in the fiber direction due the crystalline structure of the carbon fiber.

The delamination decrease significantly the tensile strength (Berger et al., 2017; Turki et al., 2014 and Campbell 2004). Turki et al (2014) verified that the delamination in stitched and unstitched specimens. After drilling the specimens were carried out in cyclic tensile tests. The results showed that there is a slight reduction of fracture stress with the raising of feed in the unstitched specimen.

There are several types of the delamination measure on the literature (Chen et al., 1997; Sonbaty et al., 2004 and Davim et al., 2007). Babu et al (2015) reviewed the proposed methodologies and summarizes then. First one, these methodologies only consider the damages in the material side, either the first or last layers. They do not consider the damages in the inner surface of hole. Second one, they do not consider other damages as uncut fibers or burrs. Each one has advantages and limitations, but no one is totally able to assess all the damages. Vos et al. (2016) proposed a model that is weighted average of some of the current measures of delamination. This model was named as damage value (Qd). The Qd suits better than the previous measures to express the hole quality and the weights can be adjusted according to the application, but still not considering all types of defects.

In other hand Konig (1989) had defined the typical features of the damage in the drilled parts, regarded more than the delamination factor, roughness and dimensional/geometrical accuracy. Konig specified each type of damage owing the fiber orientation, matrix, tool geometry and drilling parameters. Konig takes account the internal damages as roughness, circularity error and dimensional error.

This work aims to discern the different types of damage that occurs during the drilling and proposes an equation that consider all damages called Globa Damages. Furthermore, the Global Damage intent be helpful to understand and find the most appropriated parameters of drilling and then be used on quality control process.

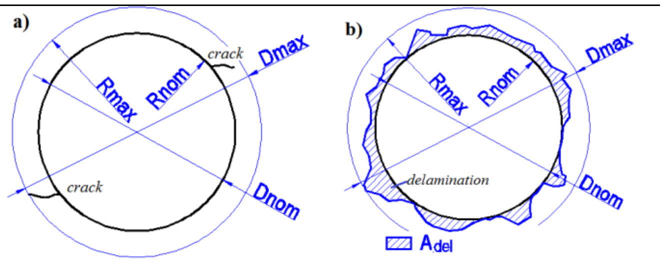
2. METHODOLOGY

2.1. Current and proposed models for measurement

There are several models for the delamination measure on the literature, summarized by Babu et al. (2015). These measures express either the size of the delamination or crack, or in the best case both. Three of the most used measures and their expressions and authors are showed on the Table 02. These measures take account the maximun diameter (Dmax) or radius (Rmax) over the damages and compares these to the nominal diameter (Do) or radius (Rnom) of the drilled hole, or the respective areas (Adel, Amax and Anom). Observing the figure a) and b) in the Table 02, the disadvantage of either Fd (delamination factor) or Dsize (delamination size) is express the same value for different quantity of damage. The Fda (adjusted delamination factor) express the sum of both damage (spalling and chipping) but do not include others possible damages on drilling composite operations.

Table 2. Actual Measures of the Delamination

Delamination Factor Chen (1997)	$Fd = \frac{Dmáx}{Dnom}$
Delamination Size Sonbaty, et al. (2004)	$Dsize = Rmáx - Rnom$
Adjusted Delamination Factor Davim et al. (2007)	$Fda = Fd + \frac{Ad(Fd^2 - Fd)}{Amáx - Anom}$



Adapted: BABU et al. (2015)

More the delamination, several damages appears during the drilling operation on composites materials, like chipping, burrs, fuzzing, roughness, circularity errors, etc (KÖNIG, 1989). These damages can affect the mechanical proprieties and assembly operations. Besides of roughness, diameter error and circularity error, in drilled composites materials some damages could happen.

At this point it is important to define the types of damages for this proposed method. The follow three first damages are relative to the assembly proprieties. The last two affect the resistance of the part.

1) UCF - Uncut fibers (Figure 1a) can be defined as a part of the fiber bunch that was not cut;
2) BUR – Burrs (Figure 1b) is a matrix melting in the edge of the hole;
3) MOW – Mowing (Figure 1c), during the chisel moving, part of the fiber bunch is bent and presents a slight slippering into the matrix and the cut fibers present chopped formation. This damage is being propose in this work, its affect the circular form of the hole, then reduce the assembly feasibility. However, it can affect the mechanical behavior due the slippery, but needs more investigation;
4) CHP – Chipping (Figure 1d) or cracking formation from the edge of the hole, this damage probably will propagate after drilling, during the part duty;
5) DEL – Delamination (Figure 1e) is a pullout of the part of last plies.

The left side of the Figure 1 show some of the consequence of the assembly damages as location errors, bad plate laying and accomplishing, gaps formation, interference during the assembly process that make impossible to fit the rivets or screws. These problems increase in automatic riveting and screwing process (Campbell, 2004). The right side of the Figure 1 show some of consequences of the structural damages as cracking appearance and growth, exposes the carbon fibers that will galvanic corrode in contact with some metal, and until leakage depending of the delamination extension.

Some of these damages could occur at the same area. In the Figure 1a could be realized the occurrence of the uncut fibers and the chipping. In the Figure 1-c there are an occurrence of mowing and the uncut fibers. Actually, during the drilling, there is a macro process of cutting. The thrust force and torque act together pushing down and twisting the fibers.

Part of them are mowing and the inner material undergo start a cracking or be ripped out (delamination), mainly due the low coupling force between matrix and fibers at each layer.

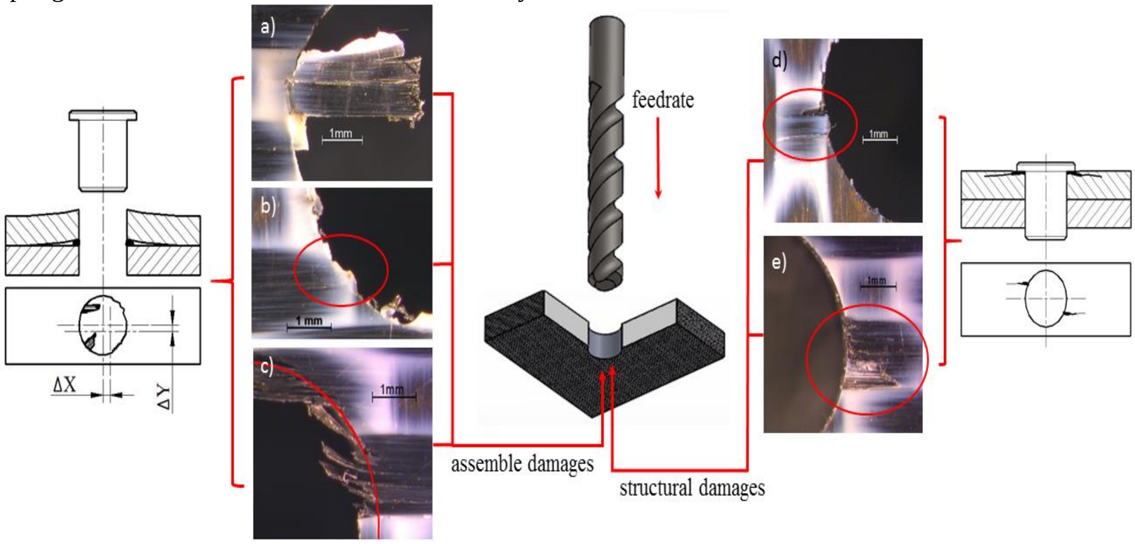


Figure 1. Types of damage at hole exit a) uncut fibers, b) burr, c) mow, d) chipping and e) spalling

The proposed model consists by a weighted average, that takes account more the delamination. The damages were separated in two vectors. The first vector is group of the damages that reduces the feasibility of assembly operations, like uncut fibers, burrs and mowing. The second vector is a group of damages that reduces the strength of the part, the "chipping" and the "delamination". This work did not include neither the roughness nor circularity, but is easy to include on the equation 01:

$$AS_{dam} = (k_1.UCF) + (k_2.BUR) + (k_3.MOW) \quad (1)$$

and

$$ST_{dam} = (k_4.DEL) + (k_5.CHP) \quad (2)$$

For each one type of damage there is a weight named k_1 to k_5. These constants enable each type of damage be adjusted according to the application and/or the manufacturing features. Depending of the material been drilling or the mechanical behavior of the part these weights must be set to aim the best quality as possible, concern the manufacturing parameters and limitation.

Then the Global Damage "G_{dam}" is a sum of the Assembly Damages "AS_{dam}" and Structural Damages "ST_{dam}" with the respective weight k_{as} and k_{st} and, the k_{as} and k_{st} constants enable each damage group be emphasized according to the their constrains.

$$G_{dam} = k_{as}.AS_{dam} + k_{st}.ST_{dam} \quad (3)$$

The measurement process consists in recognize the damages on the loaded image on the CAD software and then delimit them using a different color for each one. The damage size is a perimeter, which are in millimeters, of each one on the hole edge, as showing on the Figure 2, except the delamination, that was considered the major damage due its extension means a lack of material affects the part properties. Then the delamination size is its extension (Figure 2). After obtain these measures they are input on the equations (1) and (2) at their correspondent parameter. Follow the G_{dam} is calculated with the equation (3). All the constants "*k*" values used on the equations below were set as "*1*" in this work, i.e., all the damages were the same weight and importance. These constants "*k*" were designed to be set according to specific industrial situation.

According to Mallick (1997) the matrix plays important roles as hold the fibers in the right place and protect them agaist the adverse environment. After drilling, the cutting forces affect these important roles because of the mow effect (Figure 1c) moving the fibers into the matrix. The delamination and chipping exposes the fibers and open the fiber bundle (Figure 1d and Figure 1e) respectively. Otherwise the matrix works a path to conduced the stress transfer as said by Mallick (1997) as showing in the Figure 1d.

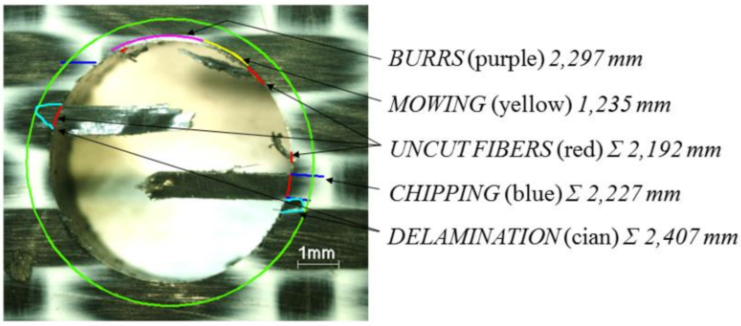


Figure 2. An example of Global Damage measurement.

2.2. Experimental procedures

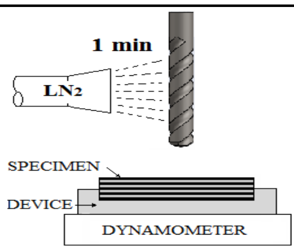
The material for the drilling tests was Carbon Phenylene PolySulfide (PPS-C) made with thermoplastic resin PPS and reinforced with T300 JB continuous carbon fibers, 280 g/m2 of grammage, 17,8 beams/inch x 17,8 beams/inch, 3.000 filaments/beams and 50% of fraction volume. The laminate PPS-C is manufactured by 16 overlap laminae tissue of bidirectional 0/90°, forming a board with 5mm of thickness. The 5HS (harness satin) prepreg with Phenylene Sulfyde resin (PPS), was stacking in [(0/90), (+ 45 / -45) 2, (0/90)] layers.

The three axis Romi D600 machine center with 10,000 max rotation, 20m/min max federate and 20cv of power was used for drilling tests. The drilling was done in dry and cryogenic conditions. Two cutting speeds and three feed per rotation were tested. One reply was conducted, totalizing 24 holes. The Table 01 shows all the parameter values of the experiment sets and the responses aimed.

Two 6mm diameter carbide drill, which diamond coat, code A1163-6 provided by Seco Tools, were used. These drills have two angle points. The first one with 130 degrees follow the second one with 60 degrees.

Table 1. Experimental matrix

Control factor (input)	Levels	Response (output)
Cutting speed [m/min]	50; 100	Global quality
Feed [mm/rot]	0.07; 0.20; 0.40	Thrust force [N]
Cooling	dry; cryogenic	Torque [N.cm]



The set of the experiment is showed into the Table 01. On the 12 tests, the cryogenic system model SC-18, provided by Semper Crio Industry, was used to apply the liquid nitrogenous during one minute, enough to freeze the drill before the drilling. The specimen was fixed by a device that enable made a through hole. In all the tests the thrust force and torque were measured by a 9272 4-component Kistler dynamometer.

The hole exits were observed by employing the Axiotech Carl Zeiss and the 3D Olympus OLS4100 microscopes. The pictures were loaded into a CAD software, then the damages were quantified by marking lines over each damage, as showed on the Figure 02. This work only considers the quality on the hole exit, this due this be the most damaged region by drilling and by consider the hole exit suitable to apply the suggested method named Global Quality.

2.2. Experiments and Results

The Figure 03 shows how the drilling process occurs and compares with the force and torque at each step. In this specific case the cutting speed was 50m/min and the feed was 0,2mm/min. At the step I, the drill tip entries on the specimen and the thrust force raise sharply, due the chisel edge imposes a high thrust force (Jia et al. (2016). When the second tip angle engage, the thrust force keeps raising but slightly. At the thirty step, the force raise very slightly because of the engagement of the secondary edge, besides of that when the entire drill was engaged into specimen the torque reached the maximum value. At the IV step the drill point start to exit and the force drops sharply, then the second angle point start to exit the force keeps drops at low tax. At the VI step the drill exit of the specimen, there is a negative force due the traction that drill imply on the material, which reacts compressing the drill due the elastic deformation.

The Table 2 displays the images of the exit surface of the holes for each condition. These images were obtained at Axiotech Carl Zeiss microscope with 10x amplifying. In case of doubt about the damage type, details of the hole edges were scanned at a magnification of 20x at 3D Olympus OLS4100 microscopes.

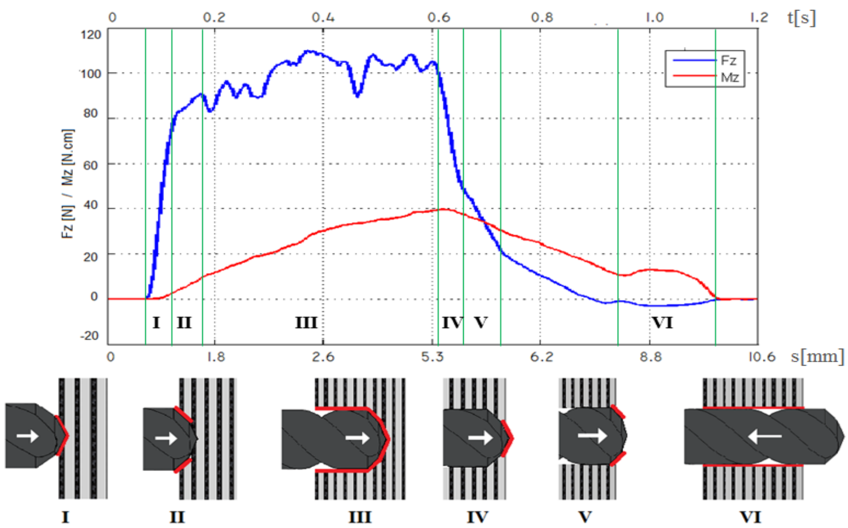
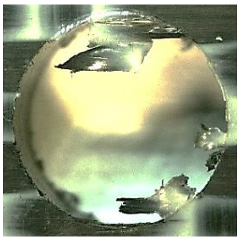
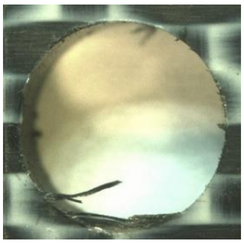
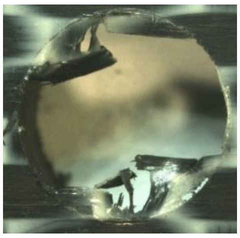
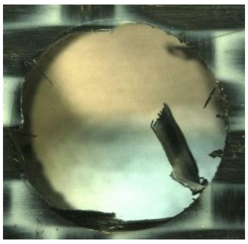
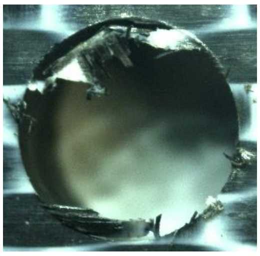
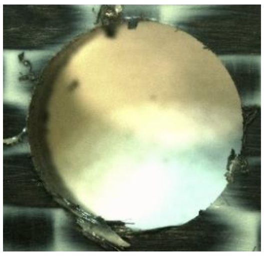
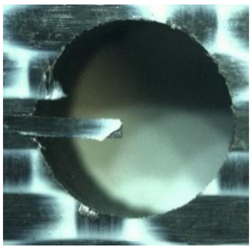
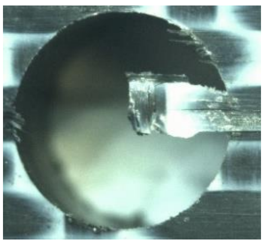
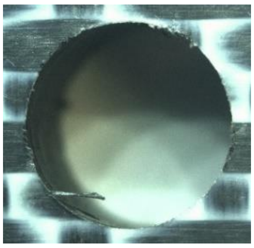
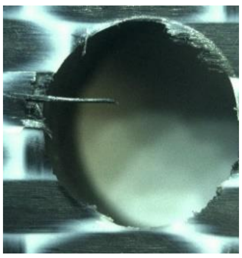
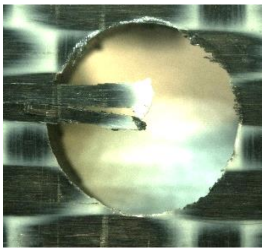


Figure 3. Thrust force and torque at each step (I to VI) of drilling

It is possible observe that the f=0,40mm/rot produce less internal defects (assembly damages) but causes more defects at the material side (structural damages) as delamination and chipping. In all the images is possible realize that the angle between the drill edge and the of fibers bunch alignment, at the last layers, plays an important effect on the damage type. The uncut fibers occurs from about 45° at each quadrant. When the drill edge attached the bunch perpendicularly, the high fiber shear modulus difficult the cut and causes a crack or leads to pullout of the part of fibers bunch. Therefore, the material must be considered bi-oriented due the damages occurs mainly at the last layers.

Table 2. Exit hole images for each drilling.

	v_c = 50 [m/min]		v_c = 100 [m/min]	
	cryo	dry	cryo	dry
f = 0,07 [mm/rot]				
f = 0,20 [mm/rot]				
f = 0,40 [mm/rot]				

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The Figure 4a and Figure 4b show the thrust force increase with the feedrate. The structural damages raise very slightly with the increase of thrust force. This agrees with the literature and proves that the delamination and crack are due both the thrust force and probably are developed by the first failure mode one.

Otherwise the feedrate raising reduces slightly the assembly damage until f=0,20mm/rot, then the assembly damages reduce very slightly at v_c=50m/min and keeps practically constant at v_c=100m/min.

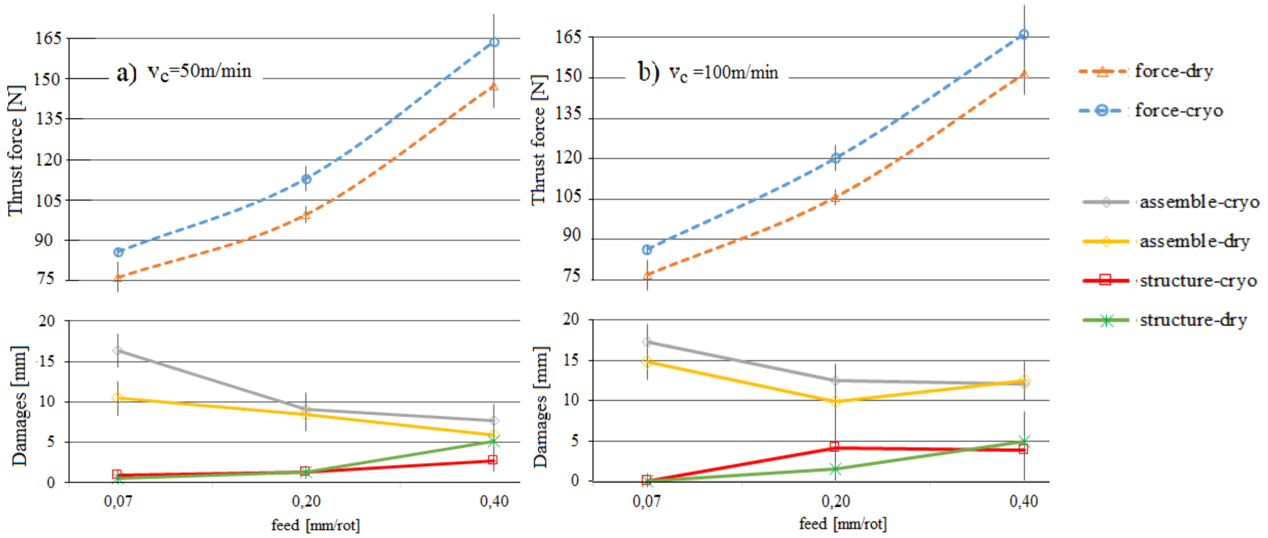

Figure 4. Damages Vs Thrust force a) at v_c=50m/min and b) at v_c=100m/min

The Table 3 and Figure 5 show the Analysis of Variance (assuming the interval of confidence equal to 0,95) and Pearson Correlation for cutting speed (v_c), feedrate (f) and cooling condition input variables vs. structural and assembly damages. The feedrate has straight correlation to the structural damages, which agrees to the behavior showed on the Figure 4. For structural damages, the ANOVA show no correlation for the cutting speed and cooling and in the Pearson Correlation show a very weak relation. Thus, the most suitable feedrate value must be choose if the structural damage is the main aim in the hole quality, regardless the cutting speed and cooling mode. In other hand, the feedrate has an inversely correlation with assembly damages, ie, the increase of feedrate has a slight reduction on the assembly damage. These behaviors over the structural and assembly damage suggest that there is a feedrate break even point.

Table 3. ANOVA (IC=0,95) and Pearson Correlation for structure and assembly damages.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PCC
Structure							
v_c	1	1.072	1.088	1.088	0.210	0.651	0.083
f	2	58.074	57.701	28.851	5.600	0.012	0.607
lub	1	0.018	0.017	0.018	0.000	0.934	0.057
error	19	97.863	97.862	5.151			
total	23	157.026					
Assembly							
v_c	1	40.14	33.570	33.573	7.030	0.016	0.360
f	2	140.1	155.770	77.883	16.300	0.000	-0.579
lub	1	37.95	37.950	37.951	7.940	0.011	0.298
error	19	90.8	90.800	4.779			
total	23	308.99					

DF: degrees of freedom; Seq SS: sequential sum of squares; Adj SS: adjusted sum of squares; Adj MS: adjusted mean square; F: F-test; P: value of probability; PCC: Pearson correlation coefficient.

In opposite of these, the cutting speed and cooling mode have a straight but weak correlation to the assembly damages. Was expected that, with use of cryogenic cooling, the ductile thermoplastic matrix change to a brittle behavior during the drilling. According to ANOVA this hypothesis can be denied, but the cryogenic cooling made the thrust force raise 13% in average, consequently this affected the damages indirectly. Thereby more studies must be conducted using different methods of cooling.

According to ANOVA (Table 3) the cutting speed have no relation to the structural damages. Thus, the spalling and chipping occurs due the thrust force at fracture mode one. For the assembly damages, the ANOVA shows a correlation.

On the Figure 5b shows a correlation to the assembly damages. This can be attributed to the softening followed by melting in some areas of hole that contribute to the burr formation and help the movement of the fiber bunchs that will not cut.

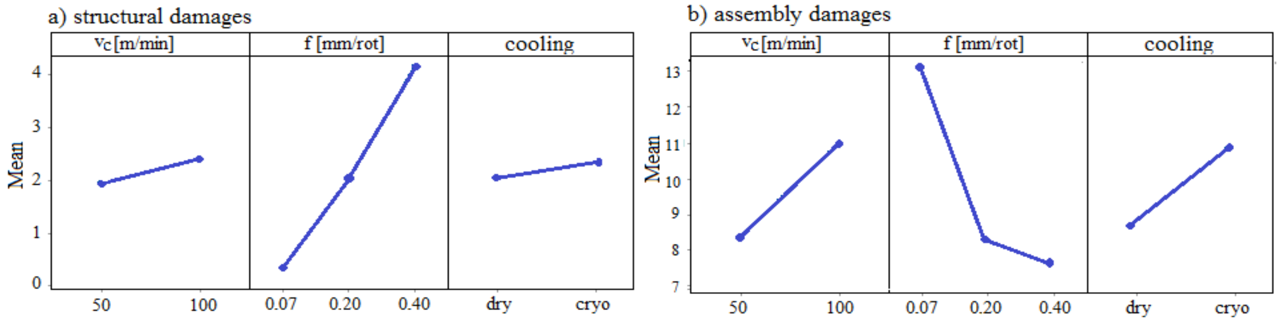

Figure 5. (a) Structural damages and (b) assembly damages a function of rotation, feedrate and cooling type.

The Figure 6 shows the average of Global Damage values for each control factor. The abscises is a vector that plots the assemble damages and the ordinate is a vector that plots the structural damages. A threshold value, St_{adj} and As_{adj} can be set to control the structural and assembly damages respectively. Due this, the Global Damage is suitable to improve drilling processes in industrial applications. This is, the Global Damage values help to find the most appropriated drilling parameters and, once found these parameters, the Global Damage can be used to control the drilling process. But the application of the Global Damage values must be done for specific case, i.e., can not used to compare different process. Besides of these, on the Figure 6, the carbon fiber reinforced thermoplastic polymer exhibit high quantity of assembly damages that is a barrier for automate location assembly process.

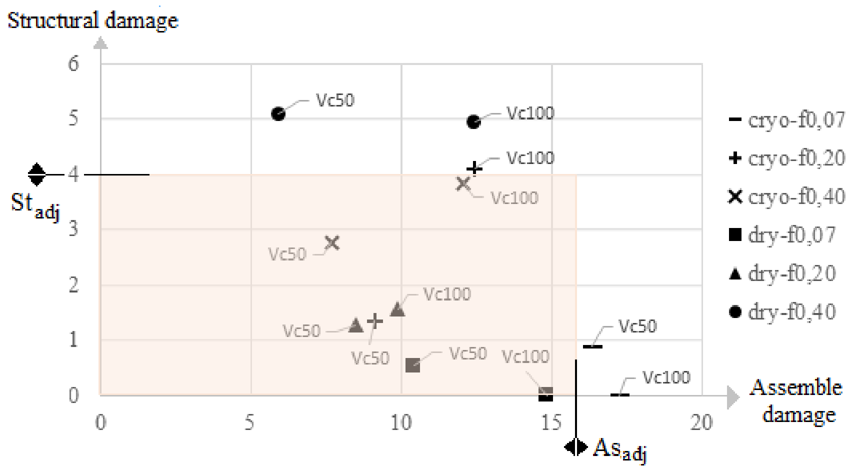

Figure 6. The results of damages and thresholds for Structural (St_{adj}) and Assembly damages (As_{adj}).

Aiming to improve the results, in future works we plan to change the way to apply the nitrogen and measure the temperature. Another improvement would be to automate the recognition and measurement of the different damages. Include the roughness and circularity error at the Global Damage equation is another one improvement.

2.3. Conclusions

The habitual measures of drilled holes in composites as the delamination factor are not helpful to understand the drilling phenomenon and to find the most appropriated drilling parameters.

After applying the Global Damage was possible understand the drilling processes for PPS thermoplastic reinforced material and the consequence of the feedrate, cutting speed and cooling, being that the feedrate governs the structural damage and the cutting speed governs the assemble damages. The cryogenic cooling probably had a slight effect over the thrust force, but need more studies. More experiments applying the Global Damage should be necessary to found the feedrate break even point to either structural and assemble quality.

The Global Damages unveils the different types of damages and theirs causes. From this it is possible to improve the drilling parameters. The reasonable quality can be reached weighting each type of damage. Once found the most appropriated drilling parameters, the Global Damage can be used to control the drilling process.

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4. RESPONSIBILITY NOTICE

The authors declare that there is no conflict of interest.