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EVALUATION OF CNC MACHINING OF LAMINATED REINFORCED CARBON FIBER COMPOSITE

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***Abstract**: Laminated composite are widely utilized by numerous manufacturers of aerospace, automotive and nautical segments, due to the properties combined in the material being superior to conventional materials (steel, ceramics, etc.). However, the machining of laminated reinforced with carbon fiber composite materials is complex, causing low efficiency in applications of drilling-milling CNC (Computerized Numerical Control) process, because conduces to increased wear of the cutting tool, resulting in serious damage to the composite material, such as type-delamination, grinding and dimensional fiber (roundness) or the separation of the inner layers of the laminate. The quality performance in the holes and surfaces, related to defects caused in the machining process, results in large amounts of waste with very significant economic impacts. In this paper are studied specimens of laminated reinforced with carbon fiber composite materials drilled by dry machining process (without cooling) in order to analyze the defects originated by the process, among which are assessed through SEM/END (Scanning Electron Microscopy/Non-Destructive Testing) techniques, and the visual observation in situ.*

***Keywords:** Drilling of reinforced composite, Damage to laminates, END in thermoset.*

1. INTRODUCTION

A plane has more than 100.000 holes and a large civil plane includes millions of holes that are made for fasteners like rivets and bolts (krishnaraj et al 2005). Composites are used extensively in these structures. Therefore, the drilling operation is often used in the aerospace industry; clearly the quality of these holes is critical to the lives of these joints (Davim and Reis, 2003; krishnaraj et al 2005). Some problems encountered in drilling composites are delamination and removal of fiber. Due to the homogeneity and anisotropy of composites in drilling composites, a surfacing as good as in metals cannot be obtained (Davim and Reis, 2003; krishnaraj et al., 2005; Khashab, 2004). However, a number of studies have been conducted to establish a method for minimizing the delamination and other problems associated with drilling of composites, and improving the quality of holes drilled. This section contains a review of the work that has been carried out on drilling composite materials. (Enemuoh et al., 2001) developed a method for drilling with free damage in carbon reinforced fiber thermosets, as shown in scheme of Fig (1), it is believed that the thickness of the laminate is able to support the drilling forces in an input plane of the tool, but as the tool travels through the depth and approaches of the exit plane, the residual layers may not have sufficient rigidity to support the impulse strength, making the lower layers to bend out, which may lead to propagation of delamination. The experiments were conducted on a computer numerical control (CNC) of the milling machine and laminate and carbon fibers reinforced thermoset were used as the test material. All drilling was done without refrigeration. It is suggested that, in order to achieve the free production of delamination and better surface finish holes, should be used at high rotation speed and low feed rate. (Krishnaraj et al., 2005) performed an experience in a bidirectional reinforced fiberglass plastic using drills of different geometries and, investigated the relationship between the rotation speed and feed rate on the impulse strength and surface roughness, was used a 6 mm drill in a vertical CNC machine equipped with high-speed ACUMAC rotation. (Davim and Reis, 2003) conducted a study and evaluation of epoxy matrix reinforced with 55% carbon fiber machinability. Drilling operations were conducted in a MIKRON VCE500 machining center using hard metal drill, in order to establish a correlation between the cutting parameters and delamination factor, it was found that the delamination factor is higher in the input plane then the output plane, both cutting speed and the feed rate increases the delamination. In other words, the higher delamination occurs at a higher speed of cut and feed. Furthermore, was found that the feed rate has a better influence on the delamination factor in the input plane, and in general, the cutting speed does not change the degree of delamination in the output plane.

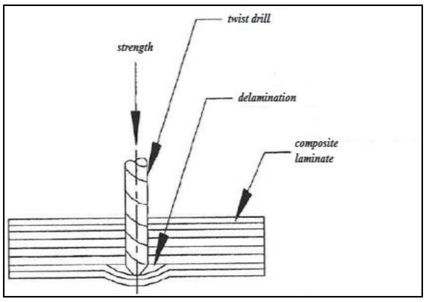

Figure 1. Scheme of delamination in drill output (Source: Enemuoh et al., 2001).

(Latha and Senthilkumar, 2009) performed a series of drills in plastic reinforced with fiberglass (FRP). The experiments were conducted in al ARIX CNC machining center using drills type "impel edge" of 6 mm, 8 mm and 10 mm diameter, at 500, 1500 and 2500 rpm, rotational speed of spindle, and feed rates 100, 300 and 500 mm/min. In all tests no coolant was applied. The study showed that high rotational speed of spindle not affecting the impulse strength, while an increase in the feed rate and/or drill diameter results in increased impulse strength. Figure (2) shows the effect of feed rate on the hole quality.

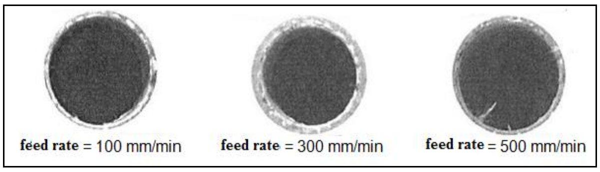

Figure 2. Effect of feed rate on the quality of the holes (Source: Latha and Senthilkumar, 2009)

(Khashaba, 2004) conducted experiments with five different types of thermoset composites reinforced with E-glass fiber, and with different thicknesses and fiber fractions. Polyester and epoxy were used as thermosetting resins. Drilling tests were performed with a conventional radial drilling machine without cutting fluid or backward plan, and the variable feed technique was carried out on a CNC milling/ drilling machine. To perform the test was selected a standard drill of speed steel (HSS) of 8 mm diameter at a rotational speed of the spindle: 455; 875 and 1850 rpm; feed rates of: 0.03; 0.08; 0.15; 0.23 and 0.3 mm/rev. Turned out that the impulse strength increases with increasing feed rate, and the impulse peak decreases with increasing of cutting speed. Composites have low thermal conductivity and low plastic transition temperature, therefore at high cutting speeds the generated heat accumulates around the edge of the tool, and the tool top temperature increases to over 200 °C, where the transition temperature glass-rubber of epoxy and polyester are 130 °C and 150 °C respectively. Thus, the polymer matrix begins to soften, and the softened material acts as a lubricant material, which reduces the impulse strength (Khashaba, 2004). Introduced into two mechanisms of delamination caused by drilling in FRP composites, known as descaling at the entrance and push last layers out at the output (Khashaba, 2004), as schematically shown in Figure (3). After the drill cutting edge enters the laminate, the cutting strength acts in a peripheral direction through the slope of the parallel drill generating a descaling strength in the axial direction, which makes the laminate to separate from each other on the upper surface of the material. This is known as descaling delamination mechanism. As the drill approaches the exit side of the material, the rigidity of the remaining layers is not sufficient to resist the cutting strength, to the extent that the cutting strength exceeds the inter-laminar bond strength and delamination starts before the drill exit completely of the material. (Khashaba, 2004) found that for composite braided/epoxy the descaling delamination and "push out" were reduced with increasing cutting speed, whereas the cutting speed has the opposite effect on descaling delaminations and "push out" for the polyester base composite. An increase in the feed rate results in increased size of delamination. It was concluded that the descaling delamination is less severe than the "push out" (Khashaba, 2004).

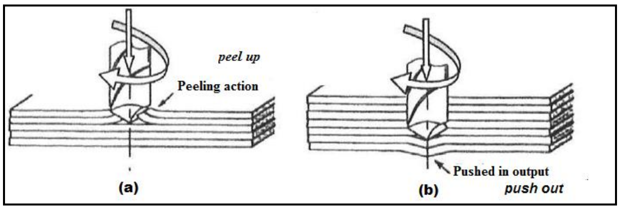

Figure 3. Delamination mechanisms; (a) descaling delamination at the input (b) "push out" Delamination in the output (Source: Khashaba, 2004).

(Won and Dharan, 2002) conducted drilling tests on two types of fiber reinforced composites, aramid fiber reinforced with epoxy and epoxy reinforced with carbon fiber. The experiments were performed on a machining center with three axle system. Carbide helical drills were used to 6.35mm, 9.53 mm and 7.94mm. The feed rate was held constant for each test, and varied from 100 to 1000 mm/min for the carbon/epoxy composite and from 10 to 300 mm/min to aramid/epoxy composite. The drilling was made without using any coolant. The study indicated that the cutting speed has an insignificant influence on the impulse strength. It has been shown that for a given material and drill diameter, the maximum allowable feed rate to free drilling damage can be determined. It is recommended that, for a diameter of 6.35 mm drill, and carbon/epoxy, to achieve a free damage manufacture the maximum feed rate is 0.145 mm/ ev, and 00.045 mm/rev in aramid/epoxy fibers. (Singh et al., 2008) conducted drilling experiments in four layers of unidirectional GFRP test pieces of 3 mm thickness. It used unidirectional fiberglass-E strip and the reinforcement of epoxy as a matrix. Drilling tests were conducted on a numerically controlled machining center (NC) using a standard helical drill HSS 6 mm diameter. The results suggest that the impulse straight is highly dependent upon the point angle of the drill and the feed rate, which increases with an increase in both parameters. Therefore, the point angle of the drill and the feed rate, and their interactions, affect considerably the cutting straights. Presented a study of drilling in composites using HSS and HSS-Co drills. It has been found that high cutting speeds and low feed rates generate more heat during drilling. High speeds cause higher burrs on both entry and exit, which also increases the wear of the tool and consequently reduces the number of drilled holes. It was observed that increasing the feed rate results in high impulse strength, smaller barbs on input and output, and increases the number of drilled holes. (Chen, 1997) investigated the machinability of CFRP composite. Experiments were conducted in a drill without using coolant. The test material was the multidirectional CFRP laminate composite, which has been drilled with a HSS drill of 5 mm in diameter. Drilling was performed at a speed of 1370 rpm, and feed rate (f): 137; 205.5; 342.5; 438.4 and 548 mm/min. In conclusion, low feed rates generate lower cutting straights, therefore less delamination. Then it is suggested that in order to produce better quality holes, the feed rate of exit must be reduced during the drilling process.

2. QUALITIES EVALUATION IN DRILLING ON THE COMPOSITE LAMINATES

(Colt-Stoica et al., 2013) used non-destructive testing (NDT) in the evaluation of defects and damages resulting from machining by drilling in polymeric laminate composites, particularly the roughness, the micro-cracks and delaminations. In drilling, was used a 5 axis machining center with the basic process parameters "v_a" = 375 mm/min and "v_c" = 150 m/min. Among the NDT techniques in development, the sonic thermography, or vibrational (Vibro/Sonic Thermography) showed potential significant for the inspection of composite laminates, nevertheless demands greater skills than the more common thermographic techniques (optical and lock-in, by example). The others NDT methods used by the authors include: acoustic emission, laser stereograph, ultrasound scans in categories A & C of signals attenuation, as well as depth ultrasonic scanning (wherein, in 2D mapping of reviewed structure, the coloring represents the depth of damage, rather than the attenuation caused by it to the ultrasonic signals), X-rays and γ-rays (gammagraphy), optical holography and finally X-ray refractometry. The researchers conclude that not only the accuracy and speed in achieving of the results affect the choice of the most suitable technique in the inspection task, but also, as previously mentioned the necessary expertise of the operator to reach such high accuracy results in an appropriate time. In addition, issues such as repeatability, reproducibility and probability of detection (POD - Probability of Detection) of END techniques are important in the selection process. (Khashaba, 2013) cites the valuable use of NDT testing inspection of fibrous polymeric composite laminates in order to determine the size, shape and location of delamination. The techniques reviewed by the author include: microscopic tool markers with different magnifications, visual scanner via CCD camera with the aid of scanning program and image processing, Autocad method (Figure 4a), and ultrasound scan. As the last END technique, the author emphasizes that due to the natural heterogeneity of composite materials, the ultrasonic waves tend to suffer great acoustic attenuation and scattering of sound waves, making data interpretation usually a very difficult task. He also emphasizes that the ultrasonic evaluation of delamination requires knowledge and experience of the composite laminated structure, and these difficulties found in inspection of this class of materials are sometimes resolved by the proper selection of settings sounders (transducers) and process parameters such as the width, the amplitude and pulse repetition rate as well as the appropriate processing of the data obtained. In this article, the holographic technique using He-Ne laser source for the formation of interference fringes and image capture via CCD camera is also evaluated. The images obtained are filtered to create more clear and well-defined edges for each generated fringe pattern. The order of the interference fringe is at any moment proportional to the deformation outside the plane at the inspected point. The phase shift program digitally converts the data to recreate contouring three dimensional (3D) of the object, and can also be used to compare the 3D contour of the object before and after applying deflection required to generate the fringe (Figure 4b). This deformation out of the plane corresponds to delamination which occurred in machining. Image scanning electron microscopy - SEM (Figure 4c) of a drilled sample is accompanied by the roughness profile of the inner surface of the hole, where it is observed (Figure 4c) that the position occupied by delamination, the profiler indicates the presence of a deep valley. This technique is used to indicate the presence of delamination, as well as the positioning start sites of this type of laminate manufacturing defect or damage created in the secondary step processing (machining) Khashaba, 2013.

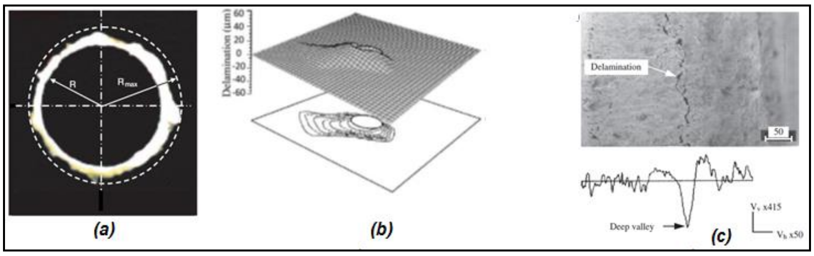

Figure 4. Different techniques from inspection of drilled composite laminates: (a) Definition of delamination size (R_{max}-R); (b) 3D representation of delamination; (c) Delamination and related roughness profile (Source: Khashaba).

3. EXPERIMENTAL PROCEDURE

Table (1) lists the parameters of the machining tests. The algorithm of the testing drilling activities manifests itself in Fig. (5a), that demand quality checks in 40 printed holes in specimens of structural laminates of thermo-rigid matrix, epoxy reinforced with high-strength carbon fibers. Specimens are taken from original plates Inatura in prismatic shape with size (5x29x150mm) provided by the Embraer SA/EESC-USP Company according to a simulation in Fig. (5b) and the pre-set in the used dimensions, tolerances and finished surfacing is shown in Figure (5c). The circularity measurements are compared to obtain better control of dimensional quality of the holes, for this purpose three machines are used, one three-dimensional optical Mitutoyo Quick Scope of the VMM in Fig. (6a) is the CMC/IFAM metrology laboratory. Other two are Mitutoyo Crysta C equipped with granite table shown in Fig. (6b) also computed three dimensional Starrett® Kinemetric in Fig. (6c), where both are available on the Metrological measurement room of the company "BIC of Amazonia SA". The CNC drilling/milling tests in the dry mode consume high speed steel/HSS and and carbide/WC-Co helical drills of diameter (Ø = 8 and 7 mm), and the tests conducted on CNC drilling/milling in ROMI® 3D Vertical Machining Center named Discovery 1000 brings 10.000 RPM exposed in Fig. (6d), available in Tooling Sector of the company "BIC Amazonia SA" localizes PIM (Industrial Pole of Manaus-AM).

Table 1. CNC drilling cutting parameters in composite laminates employing the dry mode.

Cutting Speed v_c **(rev/min)**	**Feed Rate** v_a **(mm/min)**																			
2500	090	110	130	150	170	190	210	230	250	270	290	310	330	350	370	390	410	430	450	470

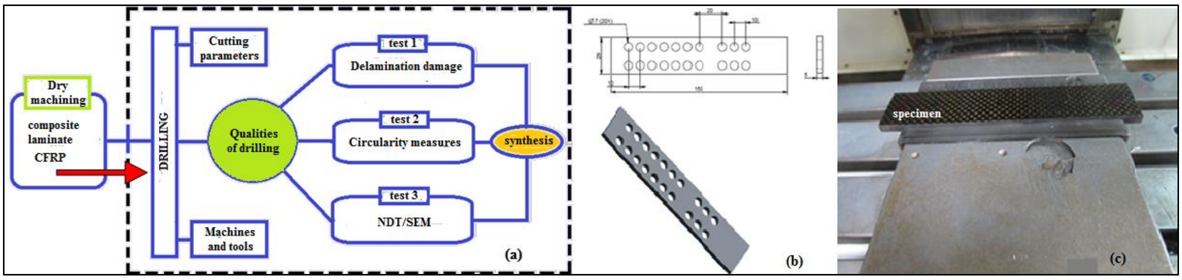

Figure 5. Strategy for machining specimen: (a) algorithm of the tests for checking the quality of the drillings; (b) Simulation of geometry; (c) Pre-set of drilling.

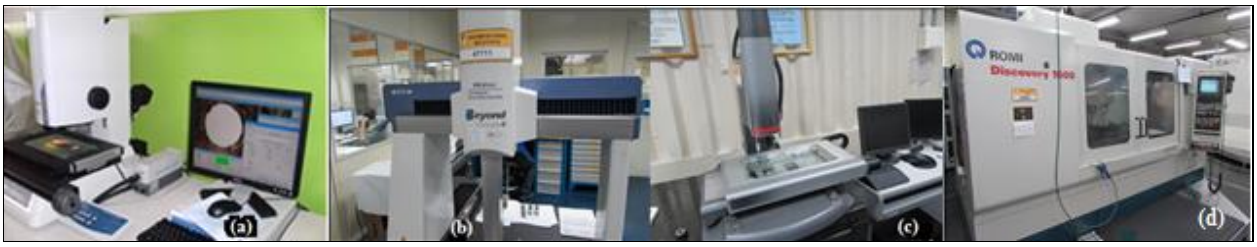

Figure 6. Equipment of cirularity and machining measures: (a) Mitutoyo Quick Scope VMM; (b) Three-dimensional Mitutoyo Beyond Crysta C; (c) Starrett® Kinemetric; (d) CNC machining centers (Source: CMC/IFAM Equipments and BIC/PIM, 2014).

Figure (7) shows systematic of the tests by scanning electron microscopy - SEM run on the perimeter (edges + walls) of the specimen holes, apply the EDAX/QUANTA 250-Centaurus Detector Unit from Technique mineralogical/Geosciences Lab of course "Geology "of the Federal University of Amazonas/UFAM.

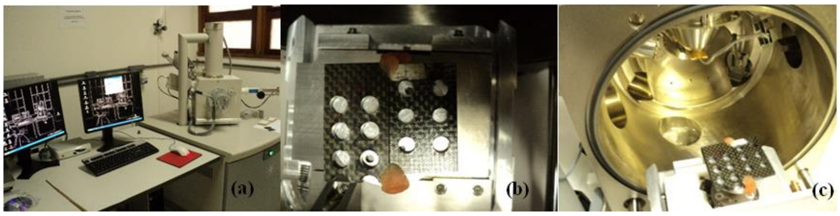

Figure 7. Systematic of images tests by SEM: (a) SEM apparatus; (b) Assembly of specimen; (c) scanning tunneling preparation (Source: UFAM equipments, 2014).

4. RESULTS AND DISCUSSION

In the visual aspect led to a predominant event of "pell up" delamination in the drilled holes with WC-Co, to know about, this is far less harmful in the drilling, it is evaluated by (Khashaba, 2004). Figure (8) exemplifies the result of type-delamination damages common in 40 drillings using cutting data seen in Tab. (1) in the dry mode, and the use of WC-Co drill with performance, to know about, 30% of the holes had burr in entry of the drill (peel up) and only 15% of the holes were checked burr in output of the drill (push out), while 55% of the holes were not checked any burr, however drilling with HSS drill entails 55% of burr damages in holes in the drill output (push out). Therefore, in Figure (9) compares damage (delamination) post machining in the holes applying drills with differents Ø, the drilling/milling brings cutting speed (v_c) sets at 2500 rev/min and its feed rate (v_a) being progressive in range of 90 to 470 mm/min, with an increment of 20 mm/min. In that event the v_c assume higher values, so the effects paired well the result bases of studies of (Enemuoh et al, 2001; Won & Dharan, 2002; Venugopal et al, 2007 and Khashaba, 2004 and 2013), and about the damage severity of drilling, where at the same time correlated input burrs and drill output, as well as the control of the cutting parameters also drill diameters in the quality of drilling in CFRP. The balance of the drilling, checking the quality of the holes results of Fig. (9) leads to compare that WC-Co drill with higher v_a and with smaller diameter brings better performance and aligns the result of (Latha & Senthilkumar, 2009). Figure (10) shows sequence of circularity measurements in the holes using three disparate metrological devices, but the holes that were used WC-Co drill the optical appearance of images generated in the implement conditioning, the holes of Ø = 7mm performed better on inference of the amplitude (circularities $Ø_{broca}$ = 7 and 8 mm) brings average M = 6.9795/8.045; Standard Deviation SD = 0.0119/0.0237 and Coefficient of Variation CV = 0.17%/0.29%.

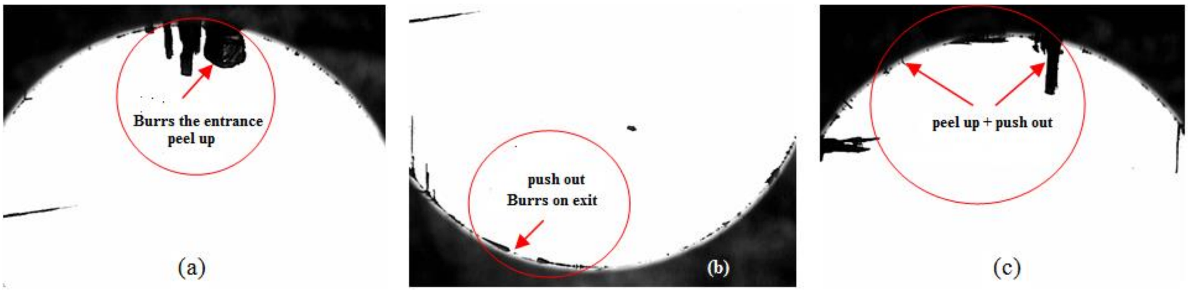

Figure 8. Distinction of type-delamination damages (input and output burrs, for example) in the drilled holes.

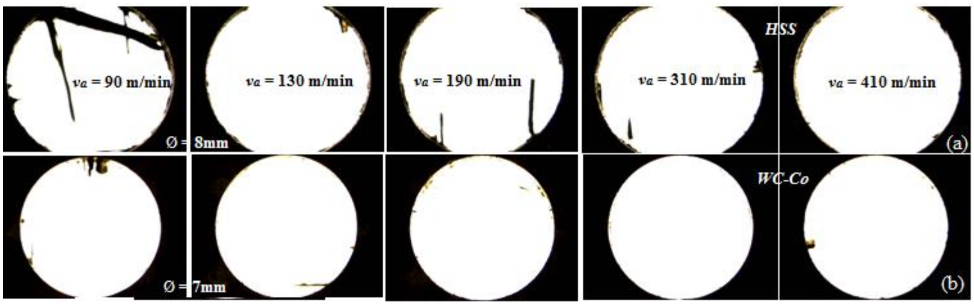

Figure 9. Feed rate effect on the quality of the holes; (a) Damage in the holes with progressive v_a rate and rotation v_c = 2.500 rev/min using HSS drill of Ø = 8mm; (b) Employing WC-Co drill of Ø = 7mm.

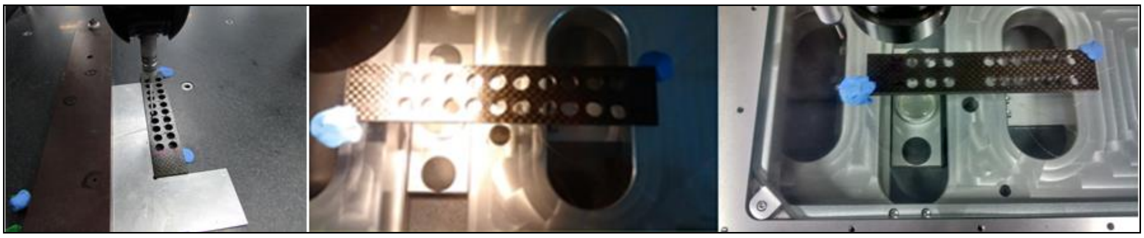

Figure 10. Implementation of the measure of average circularity in the post machining holes using unequal drills.

It is noted that in each hole the cutting data is unique, in other words, 20 series of holes in the strategy were machined, but the method of the drilling combines a cutting speed "v_c" of 20 different feed rates "v_a" incremented from 20 mm/min totaling machining of 40 series of holes testing. The graph in Figure (11) shows the comparative effects between averages of circularities caught of three implement conditioning, it is plotted in the correlation against the feed rate v_a of 20 drills, in which unequal drills of series of holes were used in specimen.

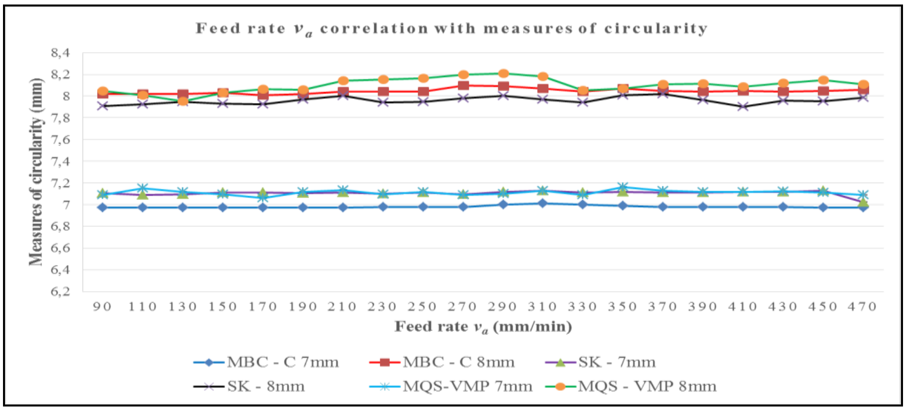

Figure 11. Effects of circularity measurements caught in the holes of the laminated composite.

The results of the machining in the circularity measures of the specimen holes are added to further undesirable attributes, once the drilling is very severe in testing with the Dry mode, so it follows the assessment of the results of circularity measures noted in correlation with the feed rate v_a (see Fig. (11)), also makes link with amplitudes of "Average, SD and CV" using the three implement conditioning, they are within the normal range, the findings on the qualities of the holes, with some caution, convince the thermoset composite drilling to deal bases in exposed quote. In drillings with WC-Co drill dominated the appearance of peel up delamination, in which is less harmful to drilling CFRP composite laminates, and there is no occurrence in the "burned" regions, whereas the machining parameters v_c and v_a were adjusted in preliminary step simulation of CNC drilling/milling.

The images of the specimen holes obtained through SEM are shown in Fig. (12) which focuses in multiple types of delamination damages, burrs, cracks, grinding fibers, fiber bending and chipping at the edges, respectively have been transmitted by drilling using carbide drill (Ø = 7mm), in the scheme of SEM image the holes with v_a assuming 90 mm/min and 110 mm/min were opted, they are selected by reason that the visual inspection step of the holes was detected a poor performance in quality of it. And certainly attributes of holes in specimens demand full manufacturing, to know about, first of all the orientation of the fibers in the analyzed holes remain unaffected in the composite, and the selection of the cutting parameters of that event brings the rotation v_c fixed at 2.500 rev/min, the study checked that this range does not influence to increase impulse and increase the defects, the rotation v_c make a relation with 20 progressive feed rate v_a (see Tab. (1)) with very high intensities that accumulate damages, in addition to different diameters of drill, effects focuses in research of (Liu et al, 2012; Davim & Reis, 2003), last of all visual inspection with evaluations of images through SEM with some limitations (ie, roughness instrument profiler and laser are not available in the region, for example) to enrich the results, the analyses were based on the studies of (Dhokia et al, 2012; Durão et al, 2013; Colt-Stoica et al, 2013 and Khashaba, 2013) as the explanation of the damages and about new techniques, in other words, a truly innovation.

However, the images with SEM shown in Fig. (13) the drilling used HSS drill (Ø = 8 mm) can be noted similarity of resulting damages from the machining of holes with WC-Co drill that brings much higher hardness, the holes using HSS accumulated undesirable qualities, since the rate v_a assumed 150 and 170 mm/min for visual inspection, these had a important role in the selection of damages in holes of SEM examination.

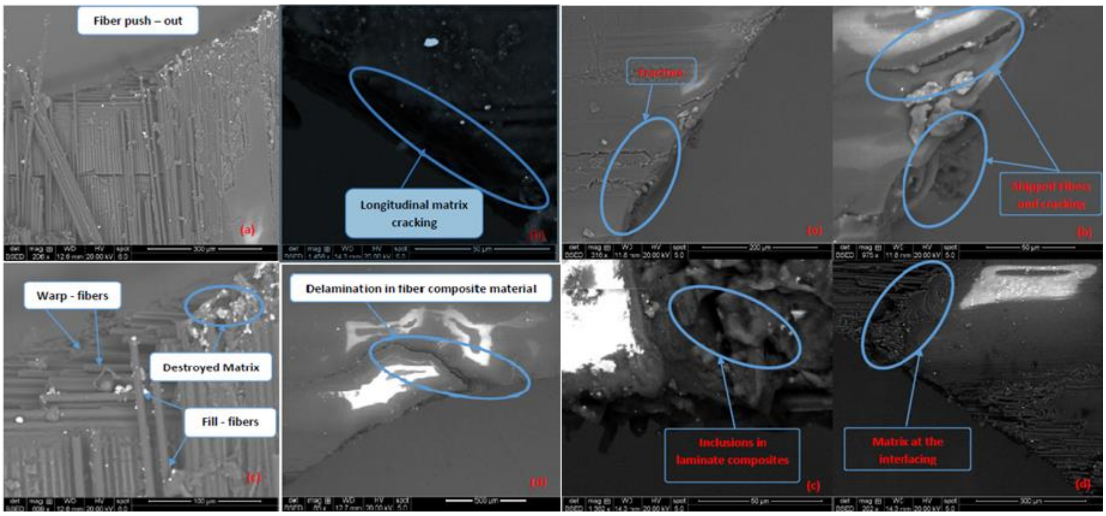

Figure 12. Images obtained by SEM in the holes machined with WC-Co drill (Ø = 7mm).

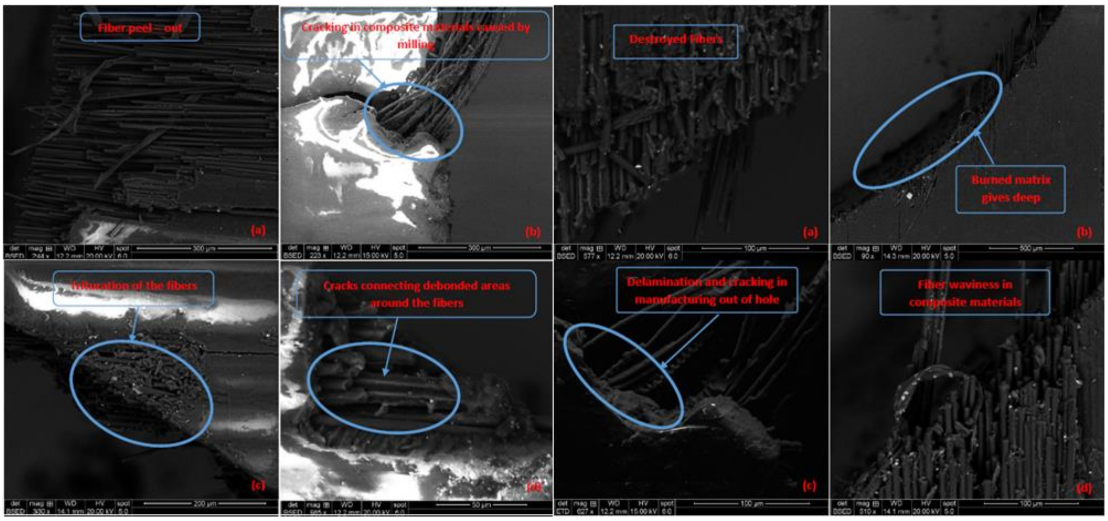

Figure 13. Images obtained by SEM in the holes machined with HSS drill (Ø = 8mm).

5. CONCLUSIONS

The manufacturing time decreases exponentially, besides the trustworthiness. (metrology, for example) and using CNC programming, with rotation v_c more appropriate and, more uniform feed rate, in contrast decreased the number of slots in the drilled region, as showed a less rough surface in relation to the machined specimen with HSS drill. The CNC machining consuming WC-Co standard drills had a better performance compared with HSS drill, since added no degradation in the tool and introduced low degree of deformities in the drilled sample, however, there were rare exception only low number of entry burrs (pell up) in the early holes, there were also little burrs on the exit (push out) of the holes counted at the far end. Analyses using better techniques associate higher proportional costs. Damages (type-delamination) occur due to progressive advance rate, assuming very low or very high values at the extremes of the data list (cutting parameters). The art of drill diameter variation influences the quality of the holes, moreover, the geometry of the cutting edge or even the model of the drill, when are ignored they deliver impulse increase in the cutting step (cutting strength and torque, for example). It is believed the large mode to introduce a rough surface on the drilling site, what was found only obtained by image analysis using SEM on the surfaces, edges, and side inner of the holes, this series of grooves in drilled perimeter (factor of delamination - F_d) is often go through an imaging treatment cited in machining research of high-performance composites (aeronautics). The images obtained by SEM lined up to effects based on this study. Drilling in composite in dry mode is ideal, for ecological reasons, but has their peculiarities relating to the application of the cutting tool (parameters, type, hardness and geometry, for example). In addition to the environmental gains the use of a "clean machining" focuses on vast innovation, and the cutting carbide tool introduced qualities, fewer defects and brings reduction in the volume of waste (chips), it only explained by inspection visual in loco and SEM noticed by the effects in this study.

6. ACKNOWLEDGEMENTS

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