UNIVERSIDADE DE ÉVORA

ESCOLA DE CIÊNCIAS E TECNOLOGIA

DEPARTAMENTO DE FISICA

Automatic drilling improvement and standardization by Design-of-Experiments (DOE)

Luís Filipe Costa Guerreiro

Orientadores:
Pedro Miguel de Almeida Areias e
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Mestrado em Engenharia Mecatrónica
Relatório de Estágio

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Internship report
Automatic drilling improvement and standardization by Design-of-Experiments (DOE)

Luís F. C. Guerreiro

July 19, 2019

Resumo

Melhoria e parametrização da furação automática com recurso a Planeamento de Ensaios

Na manufactura aeroespacial, para um dado intervalo de tempo imposto, os requisitos de qualidade têm de ser cumpridos. O custo operacional tem um pesado impacto, especialmente em operações repetidas, como a operação de furação de compósitos na indústria aeroespacial. É realizado um estudo da furação em compósitos, em particular dos bordos de ataque dos Estabilizadores dos jatos executivos Embraer Legacy 450/500 e Praetor 500/600. Este estudo consiste na análise do desempenho das máquinas pneumáticas e introdução de máquinas semi-automáticas com parâmetros programáveis. Os dados recolhidos nas operações de furação com diferentes parâmetros e aplicação do conceito de Planeamento de Ensaios (hipercubos Latinos) para uma análise eficiente, visam incrementar o conhecimento sobre a furação, e determinar os parâmetros mais adequados para cada geometria de ferramenta. Neste contexto, aumentou-se a vida útil da broca.

Abstract

Automatic drilling improvement and standardization by Design-of-Experiments (DOE)

In aerospace manufacturing, for a given imposed time interval, quality requirements must be met. Operating costs have a significant impact, especially on repeated operations, such as the drilling of composites in the aerospace industry. A composite drilling study is carried out, in particular the leading edges of the Embraer Legacy 450/500 and Praetor 500/600 Executive Jet Stabilizers. This study is accomplished by a performance analysis of pneumatic machines and the introduction of semi-automatic machines with programmable parameters. The data collected in drilling operations with different parameters and the application of the concept of Design of Experiments (specifically Latin hypercubes) for an efficient analysis, aim to increase the knowledge about drilling, and to determine the most appropriate parameters for each tool geometry. In this context, the operational life of the drill was increased.

Contents

List of Figures

List of Tables

Chapter 1

Introduction to drilling in Aerospace Industry

1.1 Introduction

Innovation is the key to the industrial development.

In the last decades, there have been significant modifications to the aerospace technology, manufacturing and corresponding requirements. These changes create new requisites and opportunities for in-depth analysis, which are only possible with the symbiosis between experimental equipment, software and advances in the understanding of new materials and their manufacture technologies. Composite materials, due to their versatility, are now the most studied materials in materials science, structural analysis and manufacturing. Our focus is the latter.

Nowadays the Aerospace Industry present the new generation of aircraft's with more composite parts, where Carbon Fiber Reinforced Polymers (CFRP) and Glass Fiber Reinforced Polymers (GFRP) become commonly used materials, mostly due their mechanical properties. The strength-to-density ratio of a composite material is high, so aircraft and automobiles move faster and with better fuel efficiency. Although its high performance and benefits in the final product, composite materials can become a big challenge to the manufacture engineering specially in the machining operations due the abrasive properties and limited plastic deformation.

The Aerospace industry is not only known for the high demand of quality and safety but also for the high technology level, which makes this industry a leader in innovation. It has a significant strategic importance over the companies and economies, having long product development cycles with wide turnover time and involving significant investments. This sector is dominated by global companies which sell high price unit products with a strong innovation component.

According to the Aerospace and Defense Industries Association of Europe (ASD) data from 2017, it shows the strength of this sector and the contribution to the Europe growth as well the cooperation between the Industries, Governments and EU. ASD data shows that in the EU, the Aerospace Industry covers about 543.000 employment positions and a turnover amount over 162×10^9 €.

Portugal keeps its presence inside the global chains of Aerospace Industries, with international acknowledged companies in the fields of maintenance services and engineering and with one of the largest worldwide aircraft manufacture, Embraer. The figure 1.1 shows Praetor 600, a Embraer executive jet.

Figure 1.1: Embraer Praetor 600 model.

Let us take a look at the stabilizers, the theme of this study. A stabilizer is not a unique part, but rather an assembly of a plethora of parts and substructures with their own specifications. If considering the carbon parts, they undergo a lamination process, autoclave process, machining process and only when finish and approved are ready for the assembly. This assembly is made mostly or totally by riveting.

Riveting is the strongest practical way of fastening aircraft skins and substructures together. Although the cost of installing one rivet is small, the large number of rivets used in aircraft manufacture represents a large percentage of the total cost of any aircraft manufacture [1]. During the riveting operation, the stresses in the radial direction are high, causing a tightening due to the rivet swelling. This stress concentration between the rivet and the hole, may create a cracking region of the parts and premature weakening of the assembly mechanical resistance [2], making the hole-drilling operation very important. To ensure that riveting is accomplished with the highest quality, the drilling operation must be as well successfully performed with sufficient precision and quality. Although cost and time of a single drilling hole are small, cumulatively it is one of the most common operations in the Aerospace Industry. With a large number of drills and with tight tolerance, the drilling operation is very important and expensive for the final product quality and cost. Drilling may appear as a simple task, but it requires extensive knowledge about the material, the drilling tool geometry and the drilling parameters to reach the specifications of that task. Reproducibility and consistency of drilling results are the goals to reduce assistant requests. Semi-Automatic drilling plays an important role in this consistency if parameters are solidly established, which is the goal of this work.

Traditionally, for metal drilling, e.g., drilling of aluminum, drilling requires absence of exit burr, scratch-free inner hole and inside tolerance size. With this goal, lubrication and conservative speeds are basic parameters to ensure good results in metal drilling. For composites, lubrication is seldom present and drilling and the operation can incur in problems such as delamination, fiber pull-out or damaged fibers (crazed exit hole ring). These flaws compromise the mechanic ability to withstand the stresses created during the riveting operation and decrease the fastening longevity and quality. On the other hand, wear of the drilling tool causes previously mentioned problems affecting the hole quality with the corresponding cost penalty. For composites, it is suitable a dry drilling and higher speeds, in way to achieve better results.

1.2 Brief overview on engineering materials

Currently, more than 50,000 different materials exist that can be used for design and manufacturing products. These provide the engineers with many different options according their project and manufacturing needs. There are traditional materials that are used for hundreds of years (e.g., brass, cooper, wood, cast iron) and some recent materials such as technical composites. To facilitate the materials selection, it became important to partition the different materials by their properties, e.g., density, strength, stiffness and melting temperature where widely can be included inside four main categories: the metals, plastics, ceramics and composites. The table 1.1 is based on the data from [3]. A systematic approach is described by Ashby [4].

Table 1.1: Material properties

Material	Density ρ, g/cm^3	Tensile modulus E, GPa	Tensile Strength σ, GPa	Specific Modulus ρ/E	Specific Strength σ/E	Max. Service Temp. °C
Metals						
Cast iron, grade 20	7.0	100	0.14	14.3	0.02	230-300
Steel, AISI 1045 hot rolled	7.8	205	0.57	26.3	0.073	500-650
Aluminum 2024-T4	2.7	73	0.45	27.0	0.17	150-250
Aluminum 6061-T6	2.7	69	0.27	25.5	0.10	150-250
Plastics						
Nylon 6/6	1.15	2.9	0.082	2.52	0.071	75-100
Epoxy	1.25	3.5	0.069	2.8	0.055	80-215
Ceramics						
Alumina	3.8	350	0.17	92.1	0.045	1425-1540
MgO	3.6	205	0.06	56.9	0.017	900-1000
Short fiber composites						
Glass-filled epoxy (35%)	1.90	25	0.30	8.26	0.16	80-200
Glass-filled polyester (35%)	2.00	15.7	0.13	7.25	0.065	80-125
Unidirectional composites						
S-glass/epoxy (45%)	1.81	39.5	0.87	21.8	0.48	80-215
Carbon/epoxy (61%)	1.59	142	1.73	89.3	1.08	80-215
Kevlar/epoxy (53%)	1.35	63.6	1.1	47.1	0.81	80-215

Although traditional composite materials have been used since antiquity, it is in the latest decades that these materials gained importance in the industry, mainly in automotive components, sporting goods, aerospace parts, marine and consumer goods. Composite materials challenge traditionally used materials such as steel and aluminum, with same or even better performance with mass savings up to 60 to 80% and 20 to 50%, respectively [3]. Composites are a combination of two or more materials that result in a tailored combination of properties. With efficiency and impending pollution regulations in Aerospace industry, the use of composites is become emergent in the industry. In addition to the aforementioned benefits, composite materials are used in the Aerospace Industry also due to their dimensional stability. Temperature-induced geometry changes are considered null, with low coefficient of thermal expansion.

Aerospace composite materials are typically built by the introduction of reinforcement fibers in a resin matrix, where the function of these fibers is provide strength and stiffness to the composite. The matrix contributes to compression stiffness and environmental resistance. It is very important to note that the functions of the fibers are:

- 70 to 90% of the load is carried by fibers and is greater along its axis;
- Provide stiffness, strength, thermal stability and other structural properties;
- Provide electrical conductivity or isolation.

The main functions of a matrix:

- Bind the fibers together and transfer the load to the fibers;
- Isolation of the fibers, stopping or slow the propagation of a crack;
- Protection to reinforcing fibers chemical or mechanical damage;
- Good surface quality.

On the other hand, the cost of composites is generally high, being 5 to 20 times costlier than aluminum and steel on a weight basis. The high volume of fabrication parts needed, the fabrication time and the hygroscopy can also be drawbacks of composite materials [3].

1.3 Drilling tool

There is a vast range of drilling tools types, all specialized according the drilling conditions and materials to drill. The basic properties are of course the geometry and the tool material. The figures 2.4 and 2.5 show two different samples of twist drill type geometries. It's important to highlight the pilot, whose function is to ensure high precision position accuracy and the point, whose function is to cut the final diameter. The helix angle responsible for the type of shavings.

The drilling tool core material is commonly a metallic alloy. Current requisites of aerospace industry led to the improvement of the tools life by application of CVD technology and coating the drills with more durable materials such as polycrystalline diamond.

Aircraft Part under study: The stabilizers

Figure 1.2 is a diagram of the parts being drilled at the edge, composed of a combination of composites.

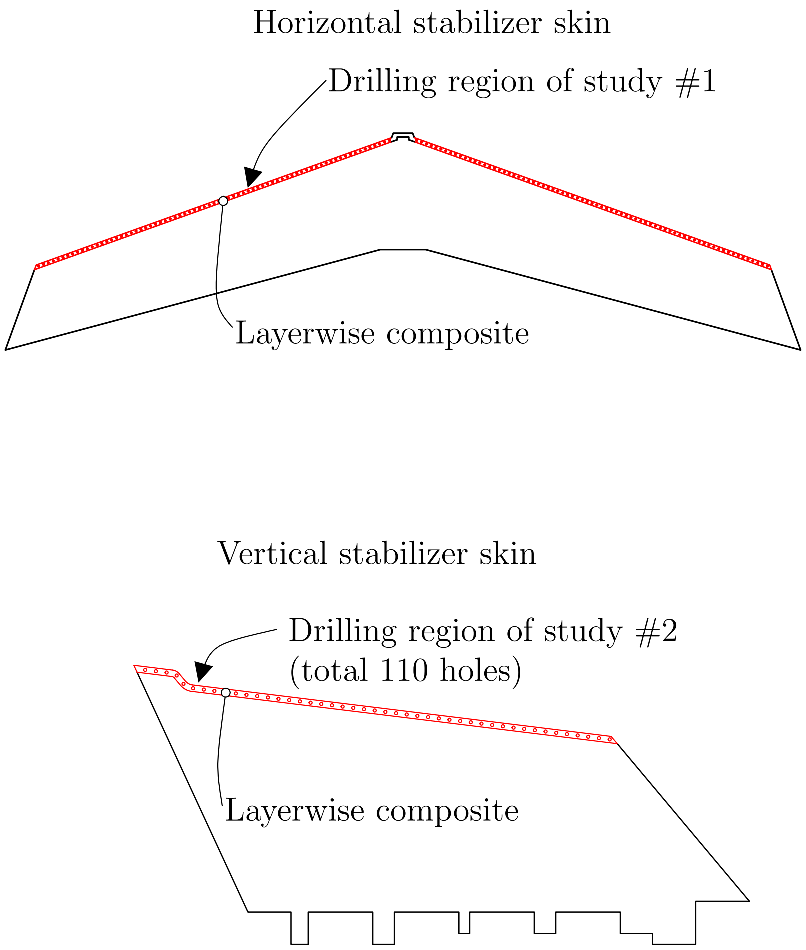


Figure 1.2: Representative Praetor and Legacy Horizontal and Vertical Stabilizers. Drilling region of leading edges.

The Problem

The Embraer manufacturing department set the goal to increase life-expectancy of the drilling tools for the mentioned operation. Specifically, the drilling hole operation in both Vertical and Horizontal Stabilizers leading edges in Legacy 450/500 and Praetor 500/600 models was identified. Preceding the present work, the verified status-quo was:

- 1 drilling tool $\cong$ 110 holes;
- High number of drilling tools discarded;
- Added cost for the final product (tool price and tool changing time);
- Need of internal data about the drilling parameters.

Solution approach

- Summary of findings reported in the literature;
- Reported usage of SETI-TEC semi-automatic machine;
- Collection of test specimen and drilling data with the SETI-TEC semi-automatic machine using the same parameters (speed and feed rate) and drilling tools as the current used pneumatic machine;
- Test specimen and data collection with different drilling parameters;
- Data analysis, torque and thrust force assessment and hole quality result;
- Development of Design of Experiments (DOE), specifically an heuristic version of Latin hypercube sampling for the test program;
- Approval of new drilling parameters for the semi-automatic as a machine for this drilling process.

Chapter 2

Diagnostics, analysis of wear and proposals for CFRP drilling tools

2.1 The current drilling operation with pneumatic machines

To better understand the current drilling process, the drilling of the leading edges was monitored with all steps being registered. The operation is executed using a pneumatic machine, a bayonet, a drilling tool, a leading edge holding drilling template (or mask) and a vacuum device. Retaining the same parameters, each stabilizer has its own pneumatic machine for this operation using distinct bayonets for each drilling diameters. Distinct diameters are employed for the vertical and horizontal stabilizers. These pneumatic machines operating parameters are 4764 rpm of angular velocity and 0.077 mm/rev of feed rate.

The machines are prepared with the respective drilling tool in the set-up room and brought to the line, then the operators place the drilling template over the leading edge of the stabilizer and attach it with holding pins (two pins on middle and two pins on the tips). Both upper and lower face of the drilling template in pre-holes were performed in a previous operation for the vertical stabilizer. While for the horizontal stabilizer there are two drilling templates and each one is attached again with four holding pins on the top face and another four pins in the lower. These pins guarantee the position of the drilling template and preventing it from being displaced during the drilling operation. After this procedure, and since the holding pins are already attached and have a lower diameter, the operator makes one hole beside each pin using the pneumatic machine with its final diameter. In order to replace all this holding pins for final pins and once this is done, the operator can make all the drilling operation in a row.

During the actual operation, a visual assessment is made, mostly on the inner face side (hole exit). We are always concerned with the appearance of a crazed ring around the hole since is the a reason to stop the operation and change tool. After a drilling operation is monitored, and before the drilling tool is discarded, we used the machine to perform drilling tests with a test specimen plate. This allowed some real drilling experience and the detailed observation of the drilling process. In these test specimens it was noted that often a glass-fiber skin would pop out as we can see in the figure 2.1. This raises the following question: why this extra load over the product occurs without the ring being cut? For this question, three possible causes are considered:

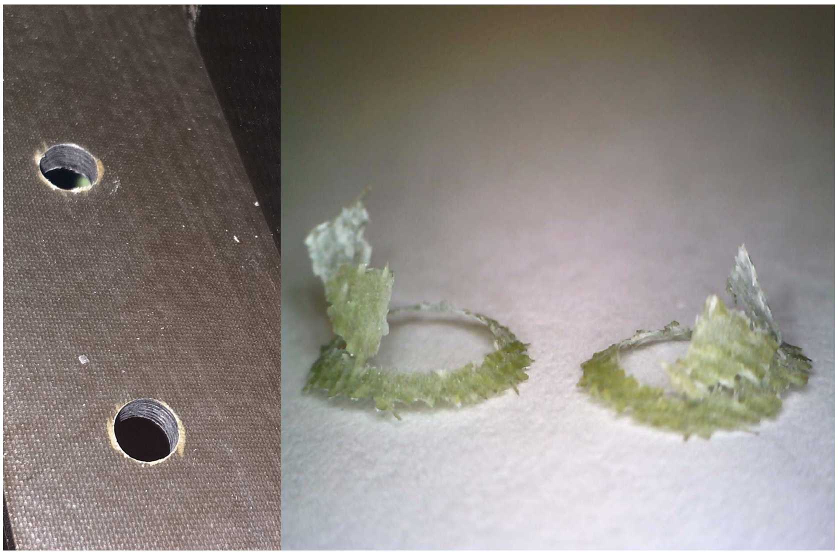


Figure 2.1: Test specimen exit hole with pneumatic machine.

1. Inappropriate drilling parameters (namely the feed rate).
2. Wrong drilling tool geometry namely the pilot and point angles.
3. Significant wear of the drilling tool.

Some of the, otherwise discarded, drilling tools were kept for inspection after use. When the crazed ring around the hole appears, the drilling tool is swapped by a new one. To better understand what is occurring with the drilling tool, a binocular Nikon magnifier and camera were adopted to observe the wear in detail. Specifically, the state of the coating and the structure of the drilling tool were inspected. The responsible regions for the drilling are the pilot angle, but mainly the point angle. In figure 2.2 it is possible to observe with high detail these two regions, identified as A and B, respectively. Furthermore, it is noted that the land (figure 2.4) shows wear as well, which is not normal because this region should not interact directly with the drilling process. It is considered the hypothesis that the bayonet is causing this wear because the bayonet itself lost its initial diameter through the use that the drilling tool performs in each hole. The more pronounced this internal bayonet wear is, the more pronounced the drilling tool land wear was found once the drilling tool concentricity is lost.

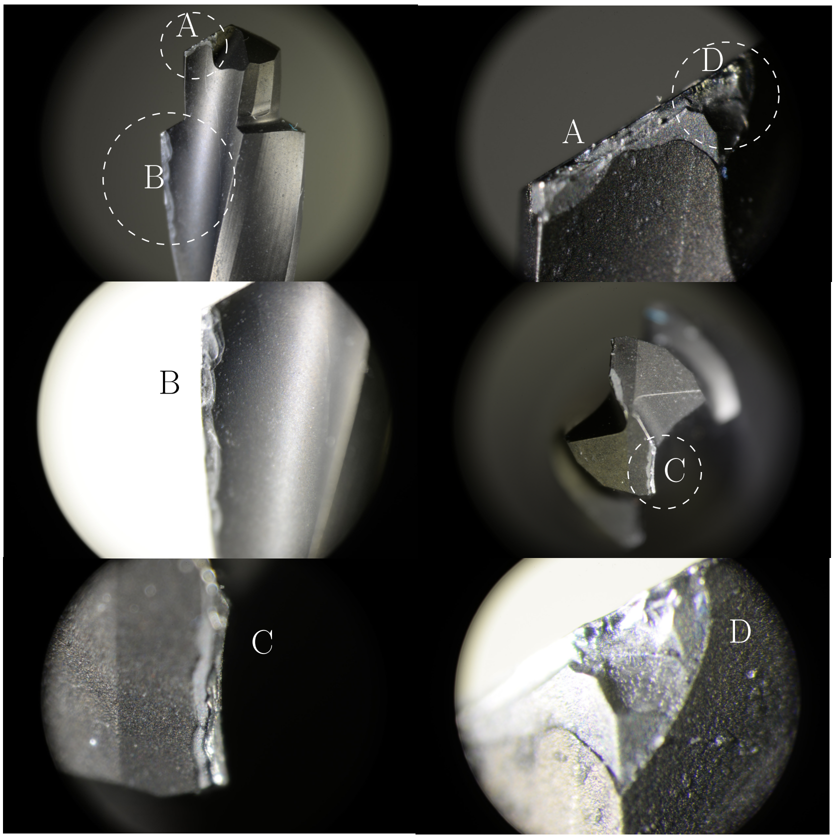


Figure 2.2: Current stepped drill specimen after 110 holes.

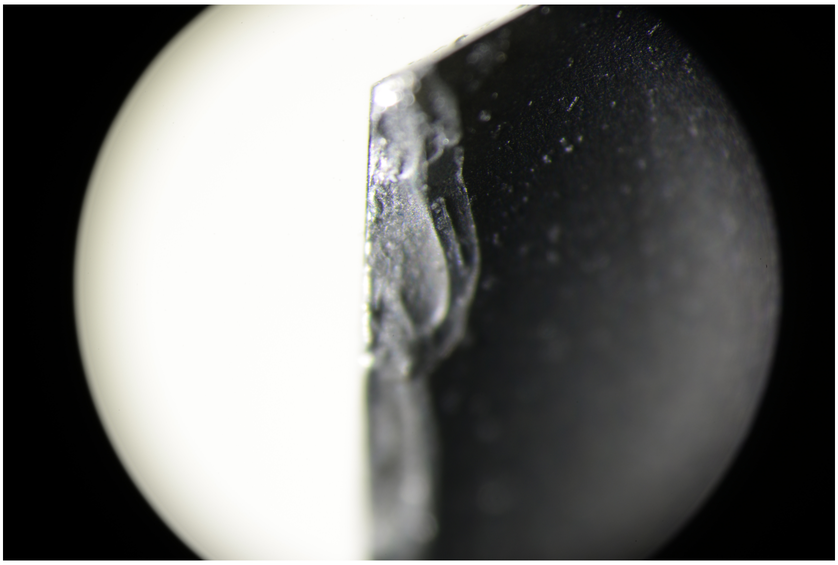


Figure 2.3: Detail of the drill tool guide.

2.2 Previous studies

A summary of the main conclusions found in the literature for CRFP drilling is shown in Table 2.1. We corroborate the conclusions of [5]. Although tool drill geometry was not studied in this work, some consensus exists in the literature with respect to point and helix angles.

Table 2.1: Main conclusions of seminal works on CFRP drilling

Source	Conclusions
Chen [6]	1) Delamination factor increases with thrust force 2) Thrust force increases with point angle 3) Torque decreases with point angle 4) Thrust force decreases with helix angle 5) Torque decreases with helix angle
Qiu *et al.* [7]	1) Stepped drill is better for quality and smaller force 2) $\alpha_p = 110°$ and $\alpha_h = 28°$ 3) Smaller pilot diameter reduces thrust force
Shyha *et al.* [8]	1) Stepped drill much better than twist drill 2) Best point angle: $\alpha_p = 140°$ and helix angle $\alpha_h = 30°$ 3) Drill type and feed rate are main factors for tool life and thrust force 4) Cutting speed and feed rate are main factors for torque. 5) Uncoated tools found better in terms life expectancy
Kim *et al.* [9]	1) Successful results with $\alpha_p = 135°$ and $\alpha_h = 28°$ 2) Tungsten carbide (WC) more resistant to wear than polycrystalline diamond (PCD)
Al-Wandi *et al.* [5]	1) Thrust force correlates with delamination factor 2) Used PCD twist $\alpha_p = 135°$ and $\alpha_h = 28°$ and PCD stepped
Iliescu *et al.* [10]	1) Optimal solution determined: $\alpha_p = 125° - 130°$, $\alpha_h = 35 - 40°$ 2) Cemecon type diamond coating

2.3 Proposal for drills

A detailed nomenclature of the drills is shown in figure 2.4 and, for a stepped drill, in figure 2.5. We propose 7 prototype drills shown in Table 2.2. Prototype #1 is adopted in the drill parameter study.

Table 2.2: Proposed test drills

Prototype	**Coating**	α_t	α_p	α_h	d_p
#1	Uncoated	118°	120°	18°	3 mm
#2	Uncoated	120°	140°	30°	3 mm
#3	Uncoated	140°	120°	30°	3 mm
#4	Uncoated	100°	140°	30°	3 mm
#5	Uncoated	140°	100°	30°	3 mm
#6	Uncoated	100°	100°	30°	3 mm
#7	PCD tip	140°	140°	30°	3 mm

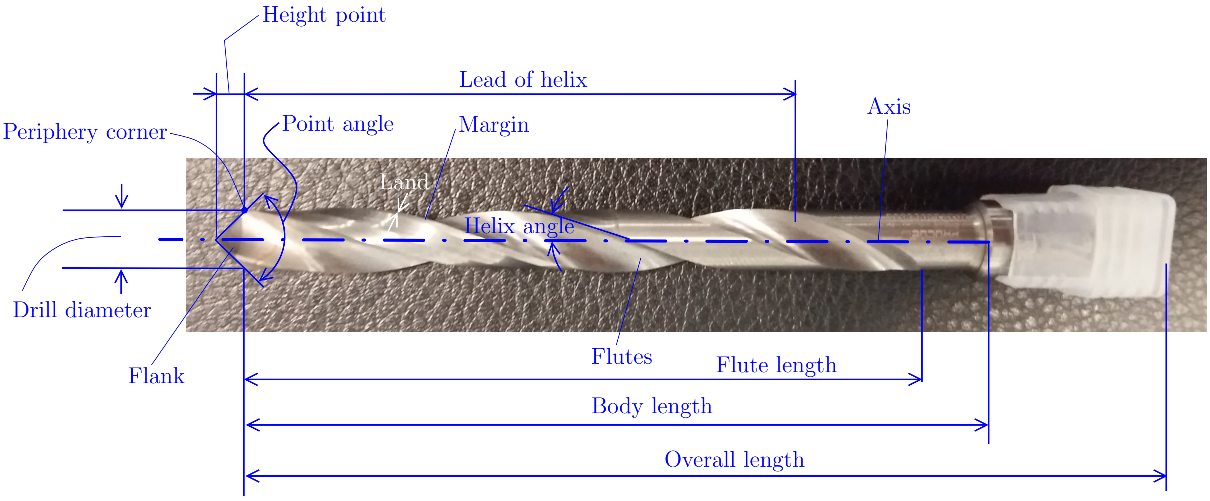


Figure 2.4: General twist drill **type** nomenclature.

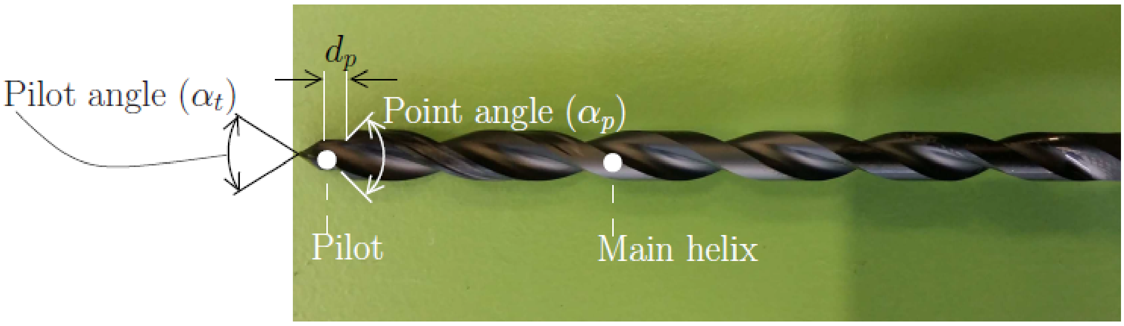


Figure 2.5: Stepped drill type features.

Chapter 3

First test specimen and new Bayonet design

After monitoring of the drilling operation of the leading edges, the work started with the SETI-TEC semi-automatic machine and it respective software. A trial was made with different test specimens and a detailed operation procedure was initiated to connect, configure and work with the machine.

After researching the layers and composition of the stabilizers, it was found that the region of some access windows (which were previously machined) are similar to the leading edges composition and thickness, so this wasted parts can be used as test specimen for this study. Due to its small size, this test specimen can only be clamped and fixed to the product drilling template to perform the drilling tests. After this, we connected the head, bayonet (specially designed for this project) and the current drilling tool to the machine, and set up the parameters. While performing the first drilling hole test, a crash noise was detected and immediately stopped the process. It was pulled out the machine from the drilling template and repeated the drilling step and verified the same event and it was stopped immediately. This strong noise and shaking from machine gives the indication that something serious occurred when the drilling tool reach a specific distance.

To inspect what occurred, the bayonet was unscrewed and we found that the drilling tool shank part is hitting the inner part of the bayonet itself, not allowing the drilling tool advance further than 11 mm (figure 3.1) from the exit of the bayonet, which is not even sufficient to complete the drilling hole in the thinner region.

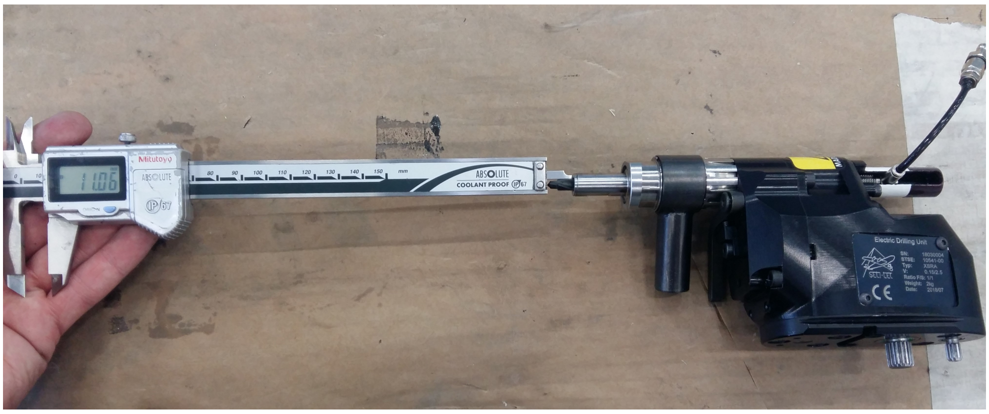


Figure 3.1: Drilling tool clash inside bayonet.

This problem led to a contact with the supplier (PROCUT) of this bayonet to propose a solution. We proposed a solution with small increasing of internal diameter and move the inside part of the bayonet further allowing the drilling tool to move and reach at least 17.5 mm out of the bayonet to face the distance between the drilling template and the product (5.5 mm), plus the thickness of the product (5.5 mm) and plus the drilling tool pilot (5.5 mm). After another meeting the supplier suggest a minor change in the bayonet and decrease of the shank region in new drilling tools. Finally, the first proposal was the one accepted plus the fabrication of a couple test drilling tools uncoated with smaller shank region. A representative draft of the drilling hole process is shown in the figure 3.2 where is possible to see the different parts used on it:

1. Bayonet;
2. Drilling tool;
3. Drilling template;
4. Product.

In addition, the importance of the internal channels of the drilling tools and coating was extensively discussed [11].

When the new bayonet was delivered by the supplier PROCUT, two uncoated drilling tools were was also delivered. A preliminary check of the bayonet was performed. First, it was checked how much the drilling tool was allowed to move in this new bayonet and noted that now the drilling tool can move out approximately 17.5 mm, which is a acceptable value to complete this drilling hole. Second, the compatibility between the bayonet and the drilling template was checked. The bayonet did not satisfy this requirement due the key part not matching the drilling template key hole. The bayonet key required further milling.

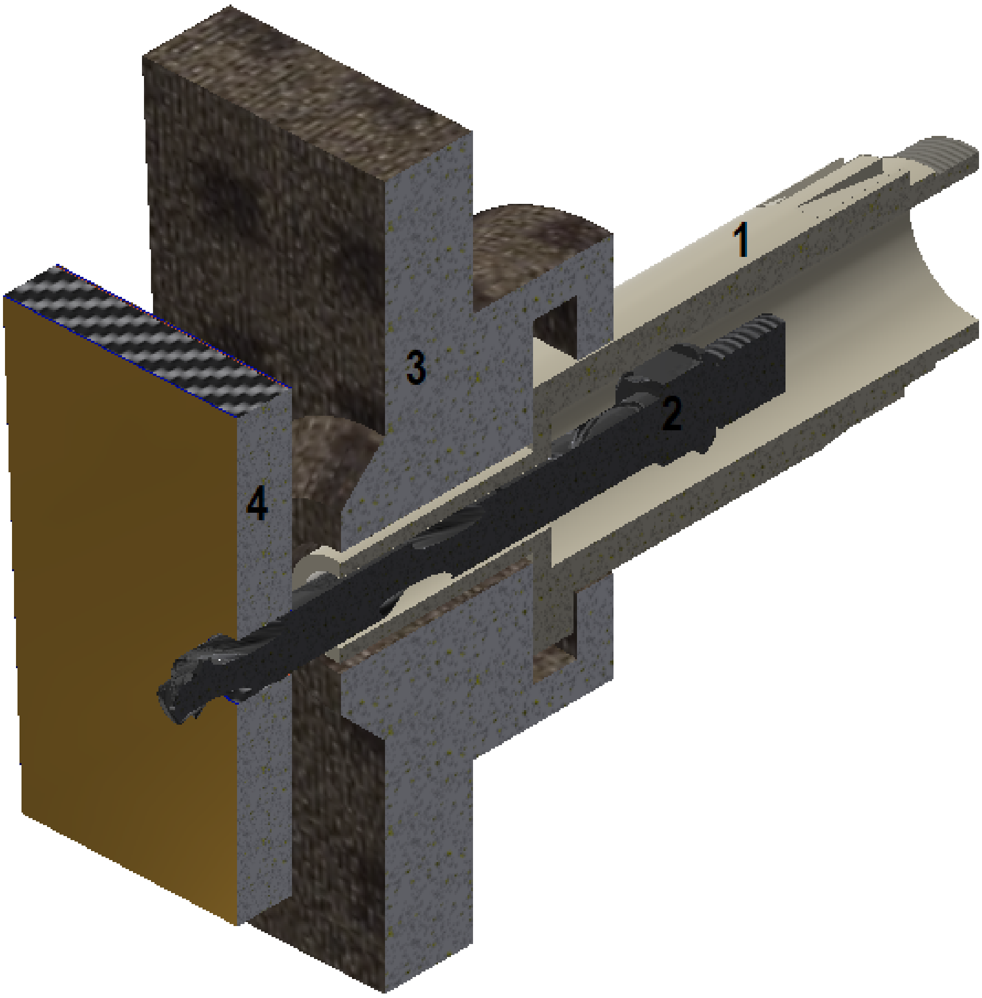


Figure 3.2: Representative cut view of bayonet, drill tool, drilling template and product.

Chapter 4

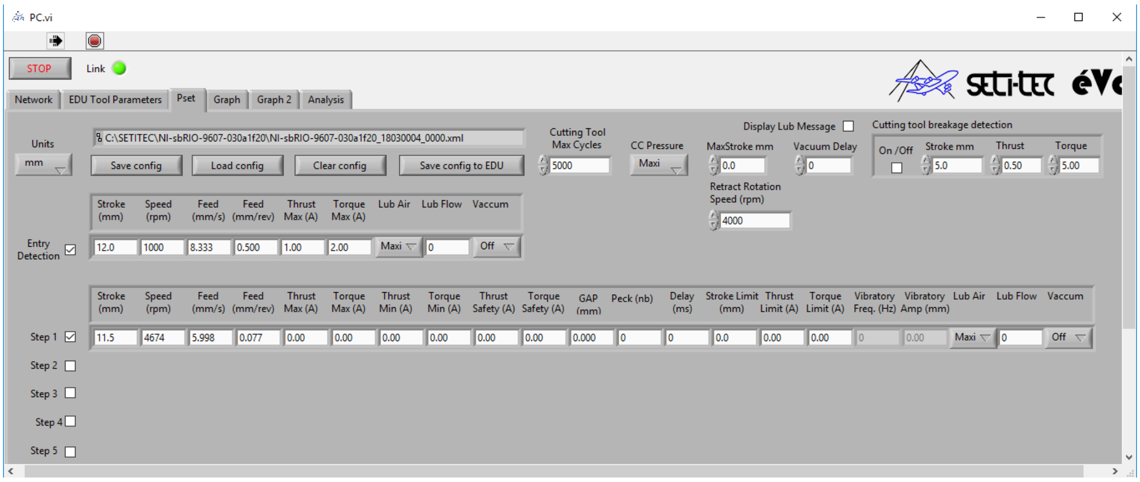
Drilling operation with SETI-TEC semi-automatic machine

The vertical stabilizer was first drilled. The machine head was prepared with an uncoated drilling tool, placed in the machine and programmed with a short stroke for a safety trial. After checking that the set works properly, the stroke was increased enough to drill the thicker region of the stabilizer leading edge but less than the allowed by the inside geometry of the bayonet to avoid the clash between the bayonet and the drilling tool. For the test specimen, we replicated the drilling performed in the real product, by using the same drilling template and the thickest region sample. Beyond that, a program with the exact same parameters as the current pneumatic machine was created. Table 4.1 summarizes the conditions applied to this first drilling tests and figure 4.1 shows the software screen layout with all input parameters.

Since these parameters correspond to the values of the current pneumatic machine and the test specimen complied with the specifications, it was approved by the manufacture engineering department of Embraer to use the semi-automatic machine with the uncoated drilling tool in the vertical stabilizer. The process is still subjected to strict visual assessment, diameter measurement with micrometer clock precision in each hole and also monitoring and collecting data through the computer software. Since the drilling tool is now uncoated, it was performed with caution.

Table 4.1: Experimental conditions

Machine	SETI-TEC semi-automatic
Drilling tool	Table 2.2 #1
Material to drill	CFRP
Material thickness	$\cong 5$ [mm]
Drilling speed	**4674 [rpm]**
Drilling feed	**0.077 [mm/rev] ; 5.998 [mm/s]**
Environment	Dry



C:\SETITEC\NI-sbRIO-9607-030a1f20\NI-sbRIO-9607-030a1f20_18030004_0000.xml

Units: mm

Cutting Tool Max Cycles: 5000

CC Pressure: Maxi

Display Lub Message ☐

MaxStroke mm: 0.0

Vacuum Delay: 0

Retract Rotation Speed (rpm): 4000

Cutting tool breakage detection

On /Off	Stroke mm	Thrust	Torque
☐	5.0	0.50	5.00

	Stroke (mm)	Speed (rpm)	Feed (mm/s)	Feed (mm/rev)	Thrust Max (A)	Torque Max (A)	Lub Air	Lub Flow	Vaccum
Entry Detection ☑	12.0	1000	8.333	0.500	1.00	2.00	Maxi	0	Off

	Stroke (mm)	Speed (rpm)	Feed (mm/s)	Feed (mm/rev)	Thrust Max (A)	Torque Max (A)	Thrust Min (A)	Torque Min (A)	Thrust Safety (A)	Torque Safety (A)	GAP (mm)	Peck (nb)	Delay (ms)	Stroke Limit (mm)	Thrust Limit (A)	Torque Limit (A)	Vibratory Freq. (Hz)	Vibratory Amp (mm)	Lub Air	Lub Flow	Vaccum
Step 1 ☑	11.5	4674	5.998	0.077	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0	0	0.0	0.00	0.00	0	0.00	Maxi	0	Off
Step 2 ☐																					
Step 3 ☐																					
Step 4 ☐																					
Step 5 ☐																					

Figure 4.1: Program layout parameters.

Although all the drilled holes were according the specifications, it was noted a tiny crazed region around the latter holes, so it was decided to change the uncoated drilling tool for a coated drilling tool to make all the lower face of the vertical stabilizer and keep the high quality of the holes. The second part of operation proceeded according to specifications and without variations in the visual assessment providing high quality in all the remain holes.

After this first drilling with the semi-automatic machine, we established a new set of parameters to use in the next product. According to the bibliography and some knowledge collected during the internship, it was noted that for composites, the drilling operation may have higher speeds and lower feed rates. Having this information, a large of possible combinations can still be done and the use of Design of Experiments (DOE) is a necessity.

Chapter 5

Design of Experiments and *Latin* Hypercube

The knowledge about products and processes in the engineering and science are often derived from experimentation. An experiment is a series of tests conducted in a systematic manner to increase the understanding of an existing process or create a new product or process. While working on a experiment, the following question needs to be answered: *Which process inputs have a significant impact on the process output, and what the target level of those inputs should be to achieve a desired result (output)*?

Design of Experiments (DOE), is a useful tool to develop an experimentation strategy that maximizes the knowledge using a minimum of resources. Design of Experiments can be used in many fields and it is widely used by engineers and scientists involved in the improvement of manufacturing processes to maximize yield and decrease variability [12]. Engineers also work on products or processes where no scientific theory or principles are directly applicable or even no previous tries were made. Experimental design techniques become extremely important in such situations to develop new products and processes over the view of cost-effective and confident results.

5.1 Essentials on LHS

Latin hypercube sampling (LHS) is a technique for generating samples in a hypercube corresponding to a parameter domain. This technique is here used to obtain the drilling parameters. LHS was introduced in by McKay, Beckman, and Conover [13].

A square containing sample positions is *Latin* iff there is one sample in each row and each column. A Latin hypercube is a generalization of the square. This introduces a sparse, space filling sample distribution which is adequate when cost of experiments is high. When sampling M variables, the range of each variable is divided into N intervals (here taken as uniform). N random sample points are then placed to satisfy the Latin hypercube definition.

Table 5.1 shows a Latin cube for $M = 3$ and $N = 5$. In our implementation, the Fisher–Yates shuffle permutation from 0 up to $M - 1$ is adopted [14] for each row of this table. Each rank (value) in Table 5.1 R is obtained by identifying $i_N = 0, \ldots, N - 1$ and $i_M = 0, \ldots, M - 1$: $R \equiv R_{i_M i_N}$. For example, for $i_N = 1$ and $i_M = 0$ $R_{01} = 3$. For future reference, Latin hypercube tables are here denoted as L.

After an experiment is established, the value for variable i_M is given by a uniform distribution,

Table 5.1: Example Latin cube $N = 3$ and $M = 5$

	Experiment:				
Variable:	#0	#1	#2	#3	#4
#0	2	3	0	1	4
#1	0	3	1	4	2
#2	4	2	0	1	3

$$v_{i_M i_N} = m_{i_M} d_{i_M i_N} + M_{i_M} \left(1 - d_{i_M i_N}\right) \tag{5.1}$$

where $d_{i_M i_N} = \frac{R_{i_M i_N} + u}{N}$ where $u \in [0, 1]$ is a random value obtained from a uniform distribution. In (5.1), m_{i_M} and M_{i_M} are the minimum and maximum values for variable i_M, respectively. We have, of course, $v_{i_M i_N} \in [m_{i_M}, M_{i_M}]$.

5.2 Spearman correlation

It is now clear that, since rows of L are obtained independent of each other, correlations can emerge. This has created an interest in orthogonalization of this matrix. To calculate the correlation between two rows of L, the Spearman rank correlation coefficient [15] is adopted.

For N distinct samples, this correlation is given by:

$$r_{i_1 i_2} = 1 - \frac{6 \sum_{i=1}^{N} d^2_{i(i_1 i_2)}}{N(N^2 - 1)} \tag{5.2}$$

where $d_{i(i_1 i_2)} = R_{i i_1} - R_{i i_2}$ where $R_{i i_1}$ and $R_{i i_2}$ are the ranks for rows i_1 and i_2 and column i. By applying (5.2) to the complete matrix L we obtain matrix S which is of course M^2.

5.3 Decreasing the correlation

We follow the study by Iman and Conover [16] to reduce the correlations between rows of L. First, we start by decomposing S using the Cholesky decomposition:

$$\boldsymbol{S} = \boldsymbol{Q}\boldsymbol{Q}^T \tag{5.3}$$

where $\boldsymbol{Q}$ is lower-triangular. Then, a real ranking matrix is obtained:

$$\boldsymbol{R} = \boldsymbol{Q}^{-1}\boldsymbol{L} \tag{5.4}$$

With (5.4), we introduce an index-ordering of each row of $\boldsymbol{R}$ to obtain an improved hypercube matrix $\boldsymbol{L}^\star$:

$$\boldsymbol{L}^\star = \text{rowrank}\left[\boldsymbol{R}\right] \tag{5.5}$$

We use n_{it} cycles of this Iman-Conover correlation reduction to decrease the norm $E = \|\boldsymbol{S} - \boldsymbol{I}\|_\infty$. Figure 5.1 shows the results. As the number of variables increase, the

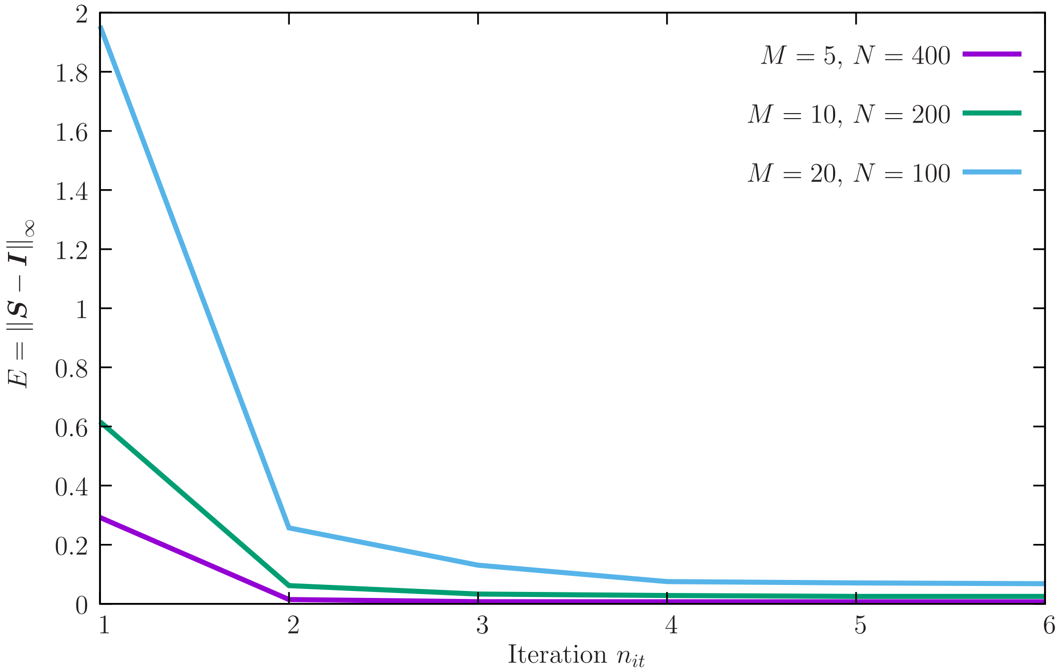


Figure 5.1: Reduction of the correlation norm as a function of n_{it}.

effect of iteration is more pronounced. It can be observed that even two iterations of the reduction process have considerable effect on E.

Chapter 6

Data processing and analysis

6.1 The torque and thrust force vs drilling tool wear

The drilling tool wear and the critical (delamination) crazed circle around the hole are of difficult measurement and need a very high precision and specific tools otherwise it would be misleading. In order to estimate and understand the evolution of drilling tool quality, a direct relation between output data (torque and thrust force) and quality was established. Since the torque and thrust force data change according to the drilling tool performance and this is related to the drilling tool wear, it was simply applied the Pythagorean Theorem as a relation between the two variables "*torque*" (M) and thrust "*force*" (T) to obtain the inverse-quality (Q_1) along the drilling process:

$$||Q_1|| = \sqrt{T^2 + M^2} \tag{6.1}$$

where both T and M are converted by the software to Ampere units [A]. The drilling tool pilot and point angles regions are responsible for the cutting process. The higher wear of this region, the higher thrust force and torque are. During the drilling process the latter layers are more weakness once they have no more supporting layers after it. Cutting this layers is easier and with better results while the drilling tool still new, but when the drilling tool wear increase the cutting effect decrease which lead to a higher thrust force and torques. For this reason, the collected data analysis is focused on the latter values of each drilling process. It is important to note that for example, a 3 seconds drilling process extract approximately 300 values for each parameter, i.e., stroke, thrust force and torque.

For this reason and also considering that the collected data is very extensive, for the quality calculation only the last values of each hole between -22.6 to -23.5 of stroke are considered. For better understanding of the drilling tool quality evolution it was made a ratio between the first and the current hole:

$$Q = \frac{||Q_{1\text{initial}}||}{||Q_{1\text{current}}||} \tag{6.2}$$

The result graphs of this quality *ratio* in each drilling operation made during this study will be shown below. All pictures in the following section were shot using a Dino-Lite Digital Microscope.

6.2 A new drilling tool

The figure 6.1 shows the top part of a currently used drilling tool the operation studied on this work. This stepped drilling main geometries are described in 2.2 1#, plus the material is Tungsten Carbide with CVD diamond coating.

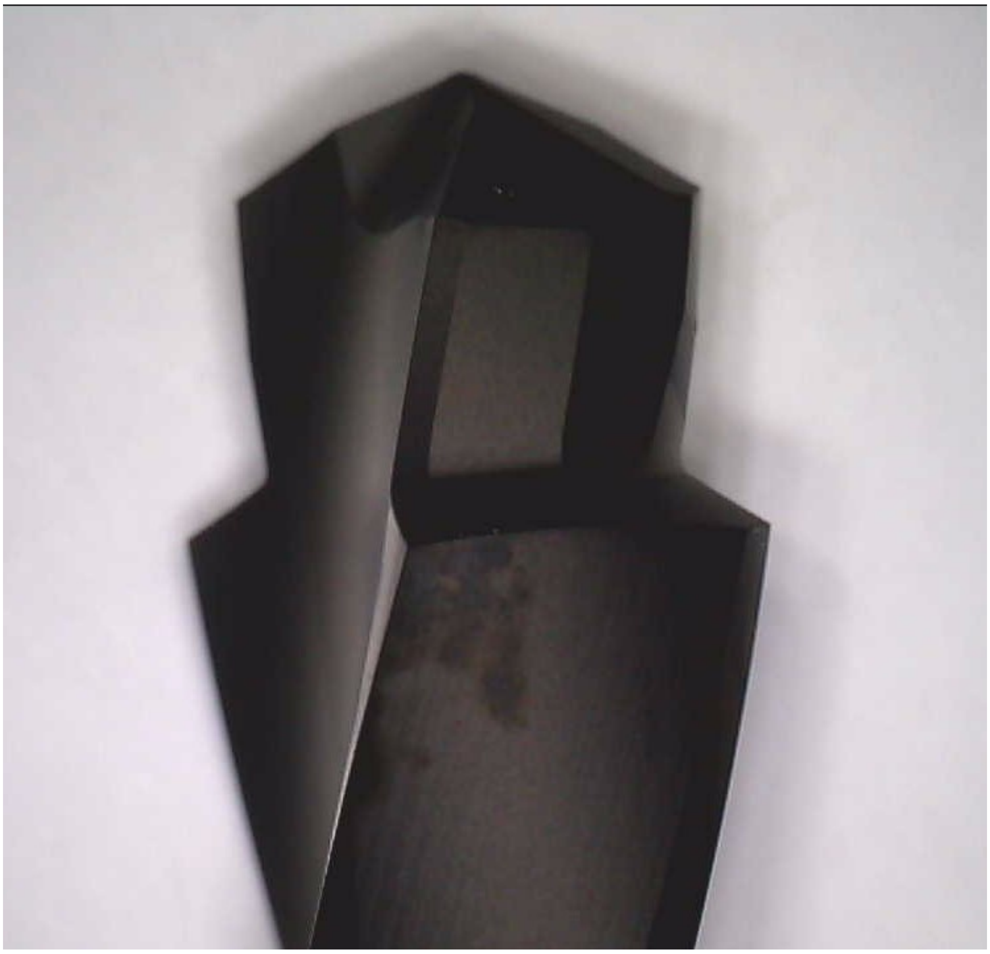


Figure 6.1: Current unused coated drilling tool.

6.3 Case 1 - Pneumatic machine

While monitoring the drilling operation of the stabilizers with the pneumatic machines, it were kept some used drilling tools for the wear analysis. In the table 6.1 are shown the conditions used on this drilling operation. The figures 6.2 and 6.3 are two samples of drilling tools wear result after performing the current vertical stabilizer drilling operation.

Table 6.1: Drilling conditions with SETI-TEC machine

Machine	SETI-TEC pneumatic
Drilling tool	Table 2.2 #1
Material to drill	CFRP
Material thickness	$\cong 5$ [mm]
Drilling speed	**4674 [rpm]**
Drilling feed	**0.077 [mm/rev] ; 5.998 [mm/s]**
Environment	Dry

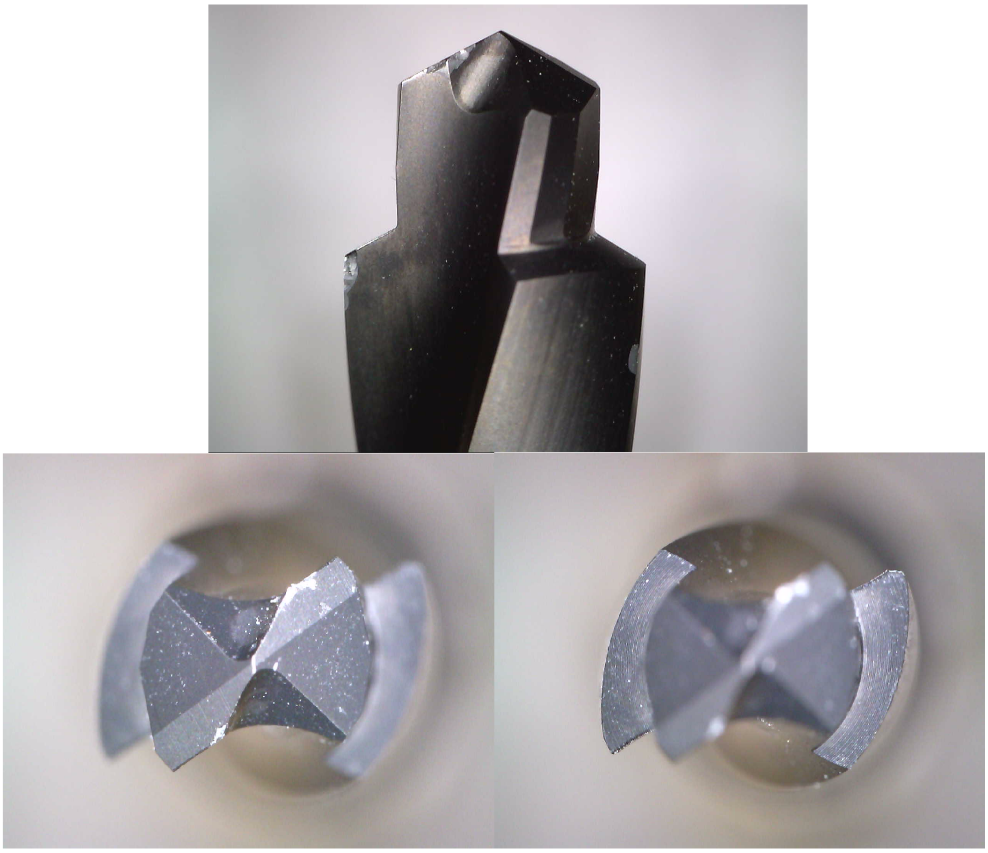


Figure 6.2: Tool wear after 110 holes (pneumatic machine) - Tool sample 1.

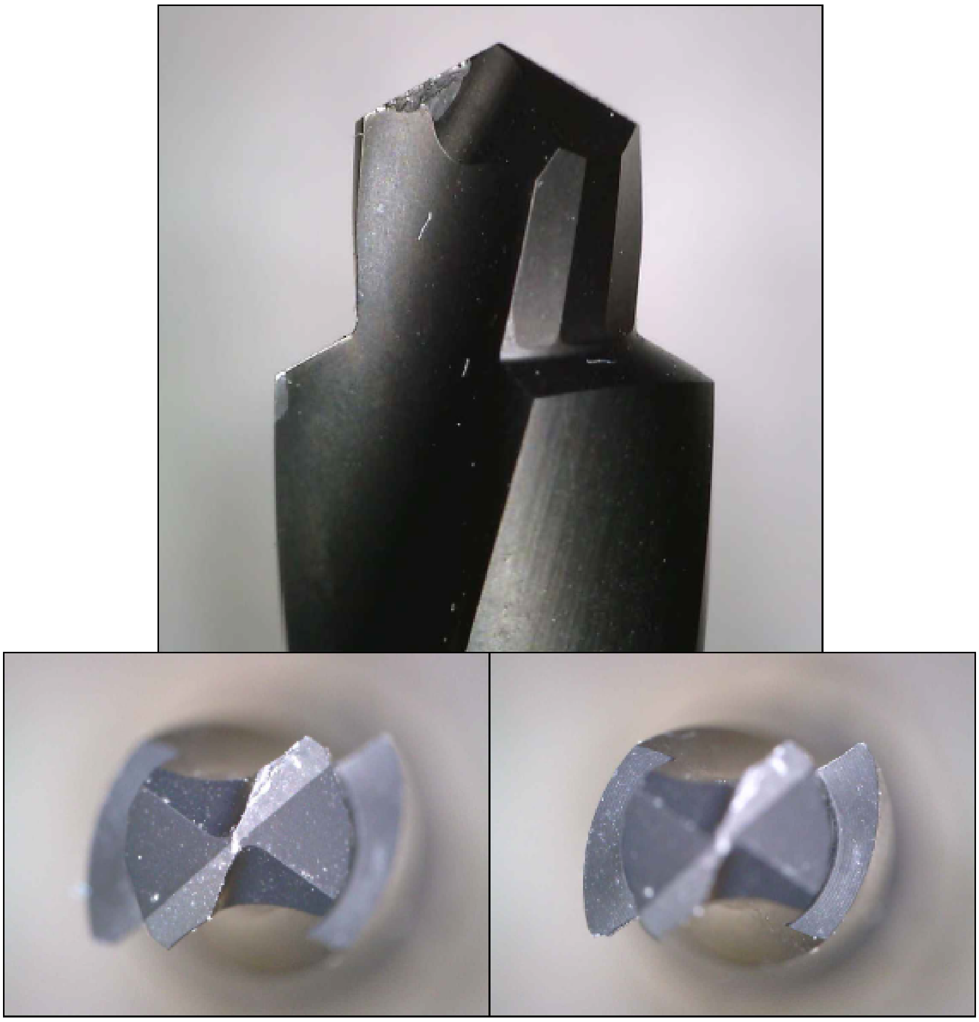


Figure 6.3: Tool wear after 110 holes (pneumatic machine) - Tool sample 2.

6.4 Case 2 - Semi-Automatic machine with pneumatic machine parameters

This drilling operation was divided in an upper face with uncoated drilling tool and a lower face with coated drilling tool. In table 6.1 the conditions used on this drilling operation are shown. Figure 6.4 shows the graph with the quality ratio evolution as well its tendency line along the upper face drilling operation. The drilling tool wear visual analysis is shown in the figure 6.5.

Table 6.2: Drilling conditions with semi-automatic machine

Machine	Semi-Automatic
Drilling tool	Uncoated and coated Table 2.2 #1
Material to drill	CFRP
Material thickness	≅ 5 [mm]
Drilling speed	**4674 [rpm]**
Drilling feed	**0.077 [mm/rev] ; 5.998 [mm/s]**
Environment	Dry

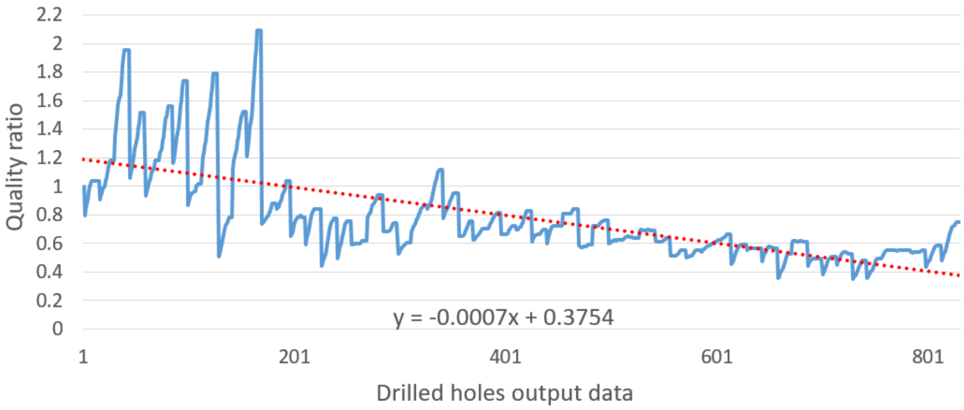


Figure 6.4: Uncoated drilling tool quality during the drilling of 58 holes.

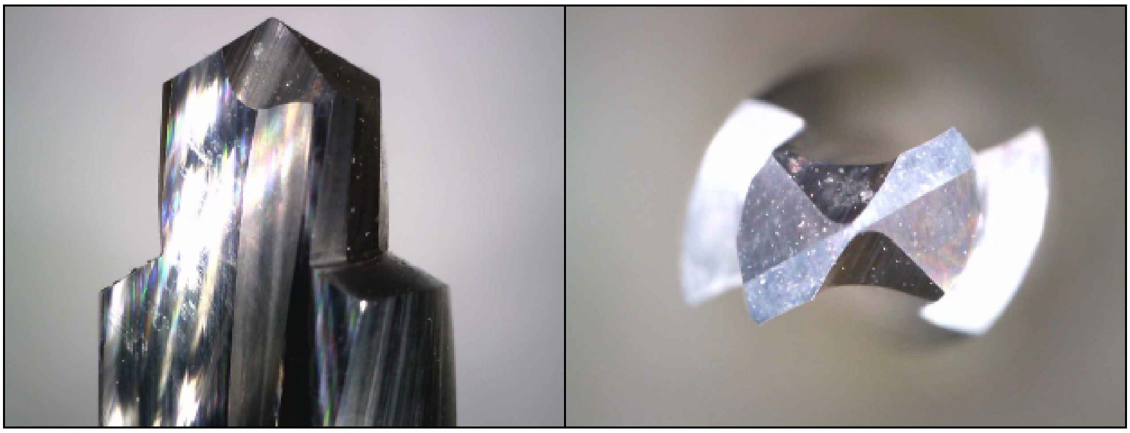


Figure 6.5: Uncoated drilling tool appearance after 58 holes using semi-automatic machine with pneumatic machine parameters.

After the stabilizer upper face is drilled with the uncoated drilling tool, the emergence of the crazed circle around the hole is pronounced. This led to the change to a coated drilling tool for the drilling of a lower face. The lower face is drilled in a row without any visual or measured flaw. Figure 6.6 shows the quality evolution along this lower face drilling and figure 6.7 shows the tool wear.

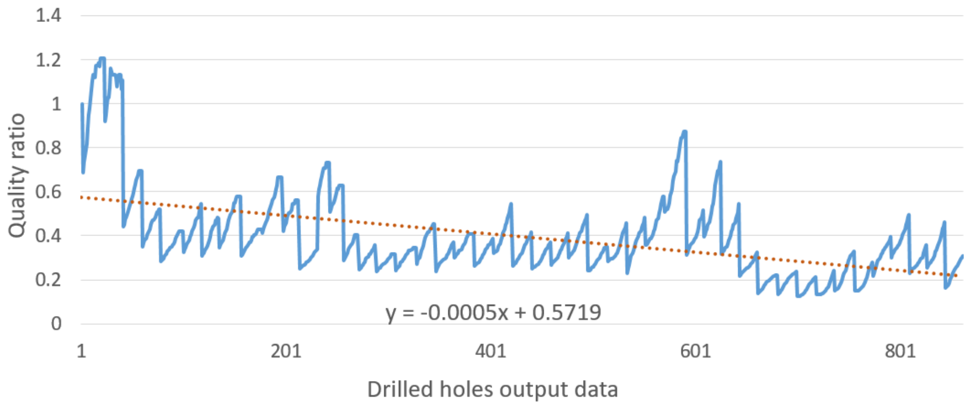


Figure 6.6: Evolution of drilling tool quality in 52 holes.

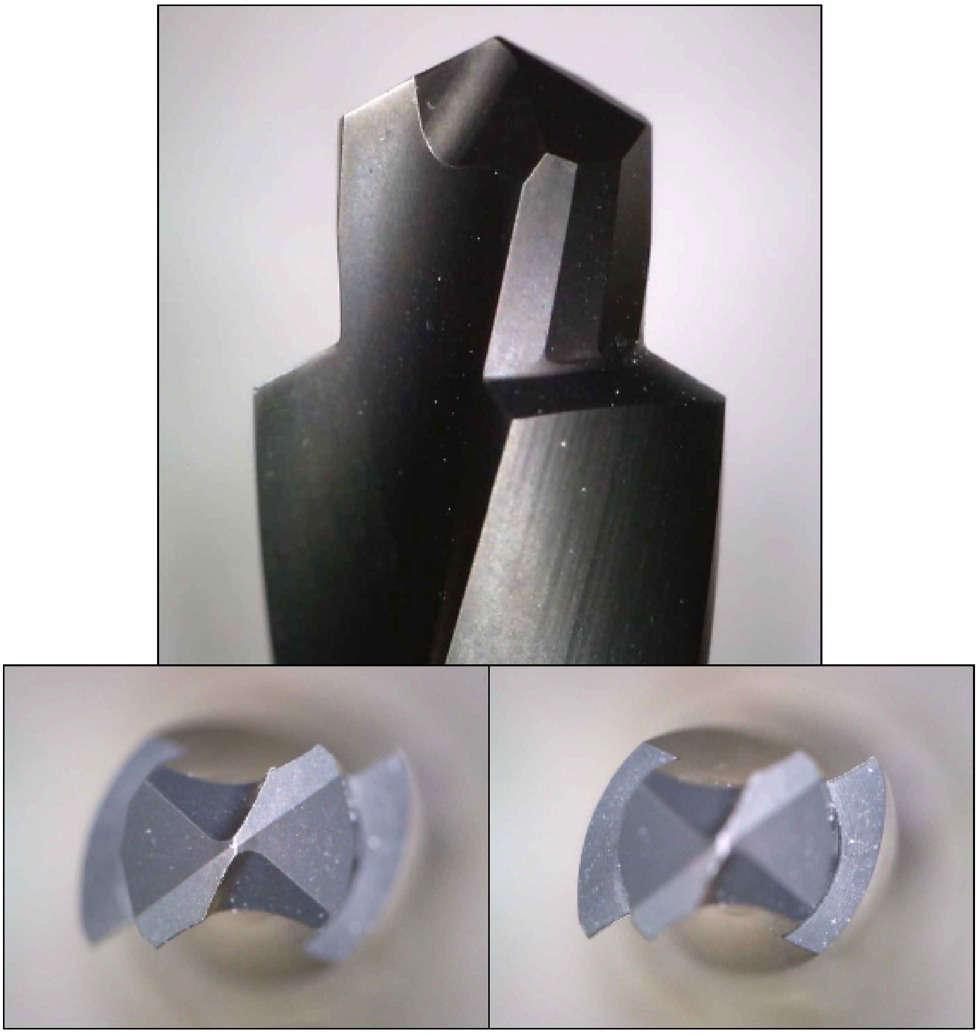


Figure 6.7: Tool wear after 52 holes using the semi-automatic machine with the parameters of the pneumatic machine.

Table 6.3: Drilling conditions with new parameters (#6)

Machine	Semi-Automatic
Drilling tool	Table 2.2 #1
Material to drill	CFRP
Material thickness	≅ 5 [mm]
Drilling speed	**4991 [rpm]**
Drilling feed	**0.049 [mm/rev] ; 4.076 [mm/s]**
Environment	Dry

6.5 Case 3 - Semi-Automatic machine with new parameters

The developed program which generates a set of parameters was used for the next experiment. This set is defined from the number of parameters in use, the number of specimens and the ranges for each parameter.

As shown in the figure 6.8, the inputs generated different test specimens with a Spearman correlation of 0.042(42), which is satisfactory from a DOE perspective. The ranges were based on the current pneumatic parameters. In this case we selected the test specimens number #6 and #7, with the parameters listed in the tables 6.3 and 6.4 respectively. As standard procedure, after the results were approved by the specifications and quality department, these parameters are now in use for CFRP the drilling operations.

The upper face of the product was drilled using the parameters from the test specimen #6 listed in the figure 6.3. Figure 6.9 shows the calculated drilling tool quality evolution using these parameters.

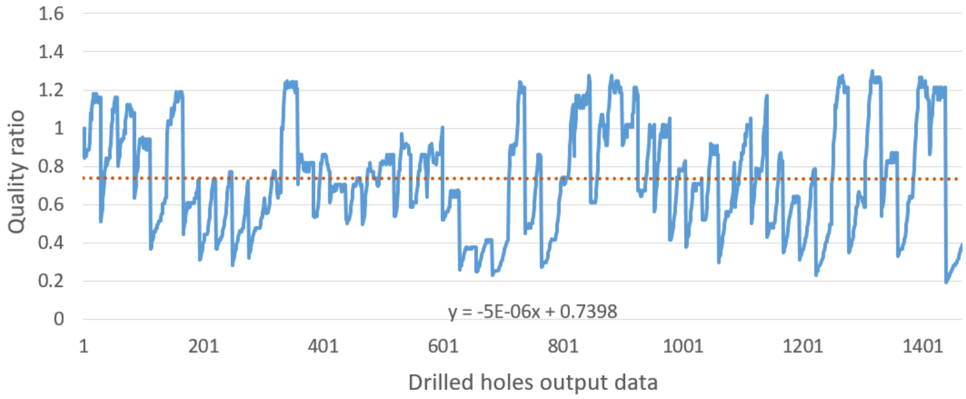


Figure 6.9: Coated drilling tool quality during the drilling of 55 holes.

For the lower face parameters were changed to test specimen #7. In table 6.4, these parameters are listed. Figure 6.10 shows the calculated drilling tool quality evolution using this parameters.

Table 6.4: Drilling conditions with new parameters (#7)

Machine	Semi-Automatic
Drilling tool	Table 2.2 #1
Material to drill	CFRP
Material thickness	≅ 5 [mm]
Drilling speed	**5441 [rpm]**
Drilling feed	**0.058 [mm/rev] ; 5.260 [mm/s]**
Environment	Dry

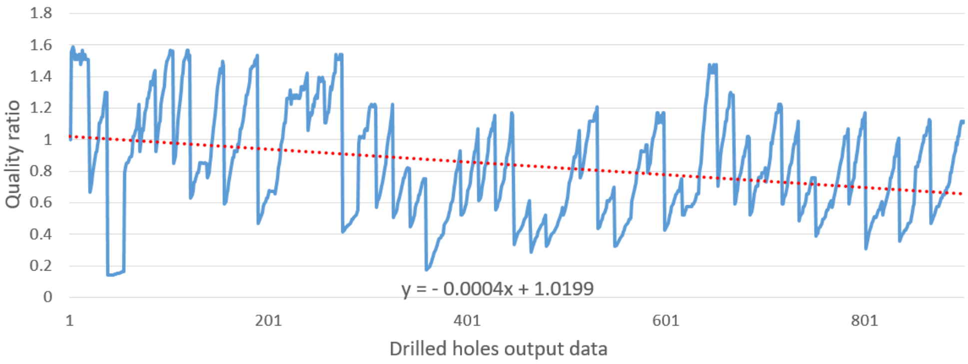
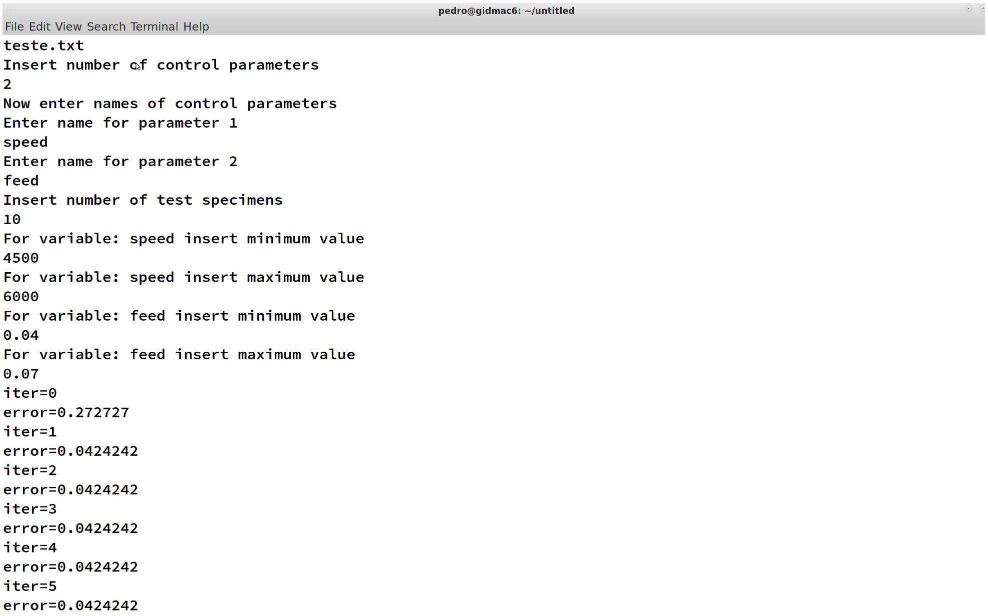
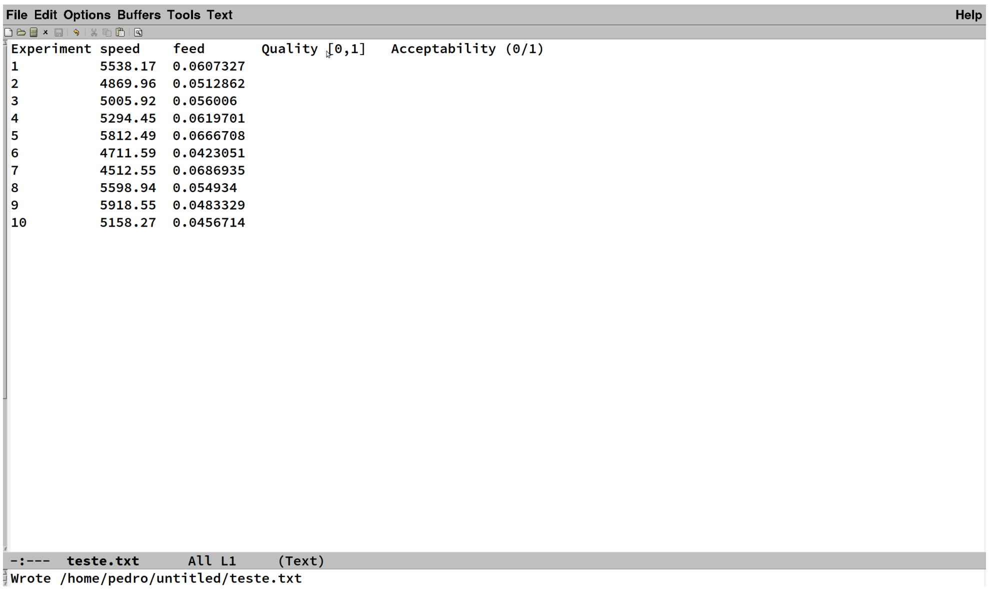


Figure 6.10: Coated drilling tool quality during the drilling of 55 holes.



```
teste.txt
Insert number of control parameters
2
Now enter names of control parameters
Enter name for parameter 1
speed
Enter name for parameter 2
feed
Insert number of test specimens
10
For variable: speed insert minimum value
4500
For variable: speed insert maximum value
6000
For variable: feed insert minimum value
0.04
For variable: feed insert maximum value
0.07
iter=0
error=0.272727
iter=1
error=0.0424242
iter=2
error=0.0424242
iter=3
error=0.0424242
iter=4
error=0.0424242
iter=5
error=0.0424242
```

(a) Problem definition



```
Experiment speed    feed       Quality [0,1]   Acceptability (0/1)
1          5538.17  0.0607327
2          4869.96  0.0512862
3          5005.92  0.056006
4          5294.45  0.0619701
5          5812.49  0.0666708
6          4711.59  0.0423051
7          4512.55  0.0686935
8          5598.94  0.054934
9          5918.55  0.0483329
10         5158.27  0.0456714
```

```
-:---  teste.txt      All L1     (Text)
Wrote /home/pedro/untitled/teste.txt
```

(b) Generated experiment parameters

Figure 6.8: Specimen generator input conditions and outputs.

Figure 6.11 shows the wear of the tool after $55 + 55$ holes are drilled with both programs and the figure 6.12 shows the test specimen exit hole made with the different parameters.

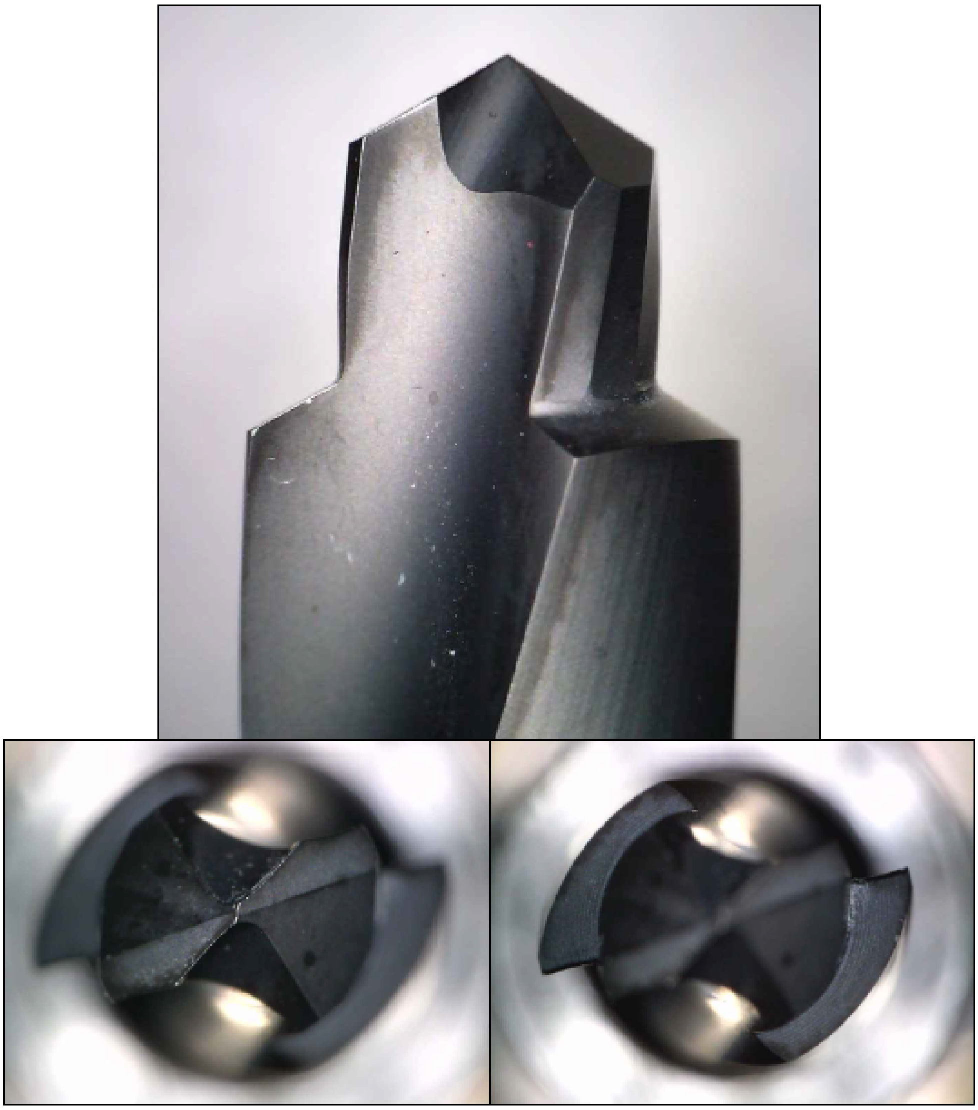


Figure 6.11: Coated tool after $55 + 55$ drills using semi-automatic machine with new parameters.

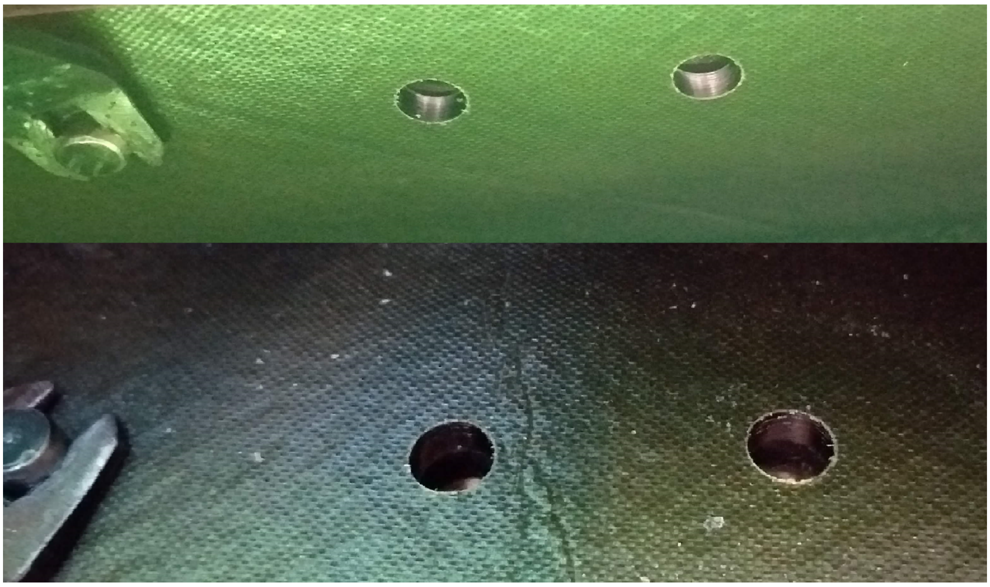


Figure 6.12: Test specimen exit hole with conditions from 6.3 and 6.4.

Chapter 7

Conclusions

Aerospace is considered a specific industry where information is closely controlled. Therefore, information from this internship and work is not made explicitly available, keeping the commitment with the company.

In an effort to characterize the drilling tool life and quality of the hole as well as the influence of drilling parameters and the resulting forces, the experimental investigation on the drilling of composites was conducted using a tungsten carbide diamond coated drilling tool. Based on this experimental investigation the conclusions can be summarized as:

- The current pneumatic machine and drilling parameters are demanding a high force from the drilling tool which lead to a fast and severe wear as shown in 6.2 and 6.3;
- The uncoated drilling tool 6.5 loses the performance quickly and doesn't ensure the good exit hole quality and so it is not considered as a option for a safety drilling operation. Comparing the drilling tool quality ration between the uncoated and coated drilling tool with the pneumatic machine by simply making the difference (uncoated - coated) trend-lines 7.1 it is concluded that the uncoated tool is 20 to 35% worst than the coated one.
- The new drilling parameters produce significant results both from the trend in the quality and wear diagnostics. From figures 6.9 and 6.10 it is possible to observe that both trends are less pronounced when comparing with the previous experiments,

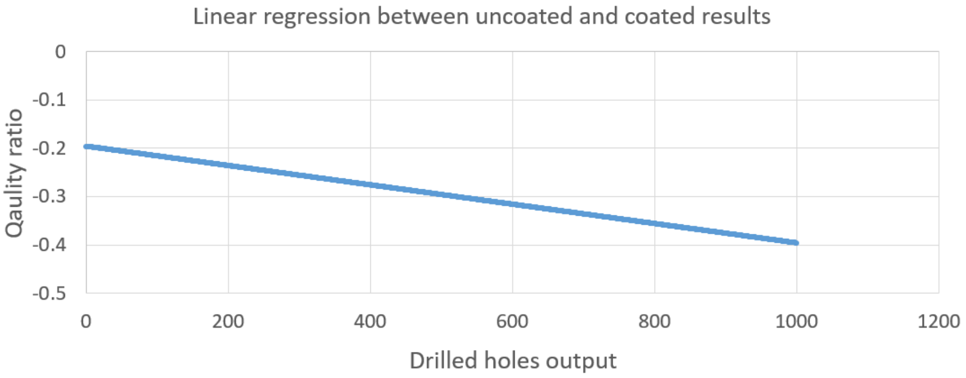


Figure 7.1: Linear regression: uncoated vs coated drilling tool.

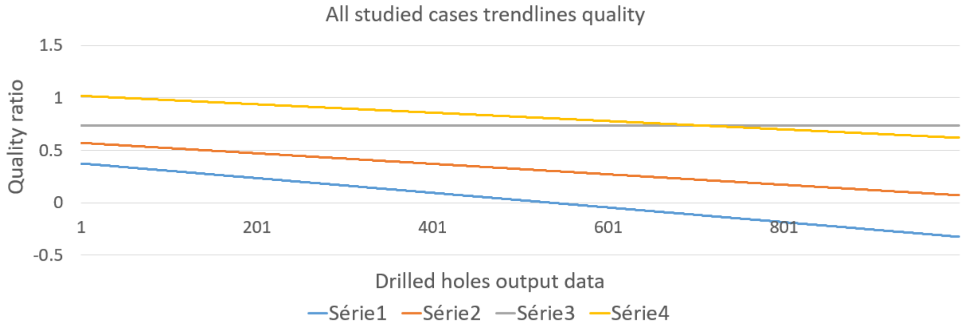


Figure 7.2: All cases trend-lines in order of study.

which show that the thrust force and torque changed less along the drilling operation. Figure 6.11 shows that the drilling tool wear with the new parameters is lower than previous tests. Figure 7.2 shows CASE 2 uncoated (serie1) and coated (serie2) with pneumatic machine drilling parameters, CASE 3 with parameters #6 (serie3) and parameters #7 (serie4) trend-lines. Coated drills with parameters of experiment #6 are shown to perform the best.

- Finally is possible to conclude, that for this specific drilling tool geometry, higher speed and lower feed rate are reference trends to increase tool life and retain the highest hole quality in composite parts.

Deliverable results:

1. *Specimen generator* software,
2. Conclusions with respect to:
   (a) the drilling process knowledge;
   (b) optimal drilling parameters;

Chapter 8

Additional projects support

KC390 LINK drilling Analysis and improvement

All assembly operations have their own specifications and requirements. The Horizontal Stabilizer Link part of the KC390 military aircraft is responsible for the connection between the two stabilizers. This component composed by packages of high thickness titanium alloys with pre-holes. During the internship, it was monitored and given support this drilling process improvement. By increasing one more step in the process, the less amount of material is removed in each step, less load over the machine and less vibrations, thus better drilling stability.

Briefly, the specimens where placed in the worst case scenario positions and was made a series of steps with a small diameter increasing in order to obtain the alignment and concentricity of all holes. In each step were recorded the diameters of each specimen and calculated the amount of material to remove until the final diameter.

After all the specimens made, it was decided to add one more step to the step machine 1.

To check this strategy, it was made one test specimen with this 4 steps and measured the final diameter, reaching a proper result inside the specific diameter tolerance.

Finally, it was given engineering assistance to prepare the the procedure operation standardization.

Flap and Splices drilling holes parameters approval with SETI-TEC Automatic drilling machines

It was realized a series of test specimen with aluminum alloys in order to approve the parameters for the Flap and Splices drilling operation. Meanwhile it was designed with the *Autodesk Inventor student version 2017* software and printed with my home-made 3D printer a prototype model of a diameter reducer for better coupling between the drilling machine and the vacuum cleaner. The results of this reducer were very satisfied, showing improvement of holes quality, so it was kept used in the assembly line.

In figure 8.1 is possible to see the drilling test specimen, the drilling templates and the different machine heads with the respective bayonets.

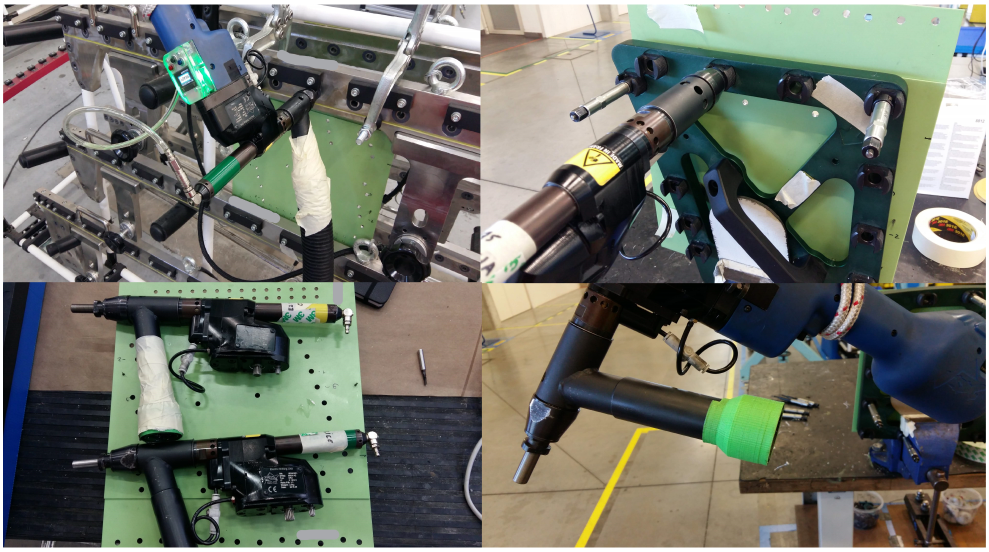


Figure 8.1: Horizontal stabilizer flap and splice test specimen.

Chapter 9

Follow-up studies

The drilling process is complex and depends of many variables. In this work, we focused on the study and analysis of coating importance as well the parameters used in the process, i.e. the speed and feed rate. Yet, to achieve the full understanding and best best drilling process some other variables must be considered.

As a continuation of this project, besides the variables used on this study, subsequent test specimens should also consider the geometry of the drilling tools, e.g. 2.2 and the influence of internal drilling tool cooling.

A series of test specimens and a deep analysis study of its data, considering all the referred variables will be a supplement for this paper and may allow to reach top knowledge and keep the improvement of the drilling process.

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