COMPARISONS OF THE THRUST AND TORQUE DURING DRILLING OF GFRP COMPOSITES USING TREPANNING TOOLS AND TWIST DRILLS

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Abstract: *This paper presents the results of an experimental investigation into the effect of lubrication and the tool type on thrust force and torque during the drilling of unidirectional glass fiber-reinforced plastic (GFRP) laminates. It is well-known that the most effective way of achieving good quality of holes while drilling fiber-reinforced plastics (FRPs) is by reducing the thrust and torque. Therefore, this investigation was aimed at exploring the possibility of reducing the thrust force and torque by using the concept of trepanning. The design considerations and development methodology of trepanning tools and twist drills are discussed. The appropriate tool has been determined by using statistically planned experiments and analysis. Orthogonal arrays with analysis of means as well as analysis of variance have been used to assess individual factor and interaction effects and their significance levels. The investigations have revealed that the performance of the trepanning tool was superior to that of the twist drill in terms of thrust force, torque and hole quality, as well as the influence of lubrication conditions.*

Keywords: *machining, drilling, trepanning, tool geometry, composites, GFRP, twist drill,*

1. INTRODUCTION

This work was motivated by the complexity involved in the junction and mounting process influences by the drilling of GFRP blades of eolic dynamos. These blades are 25 to 50 m long. The screw and bolt joining them to the rotor are very important, as even a lower deviation in fixing condition, caused by a failed drilling process, and therefore a not secure fixing, could generate great over charges on the rotating blades as well as at the rotor. This work shows some preliminary investigation carried out aiming a process optimization using some statistical tools to decide for a optimal tools as well as machining conditions.

2. FIBER REINFORCED MATERIALS AND EOLIC TURBINES BLADES

Composite polymeric materials reinforced with fibers (FRP) as: glass fiber (GFRP), carbon fiber (CFRP) or aramid fiber (AFRP) are characterized by better mechanical properties as high strength / weight ratio and stiffness / weight ratios, a good corrosion resistance and for having a good net shape manufacturability regarding the properties as well as molding in suitable forms.

In this sense, it becomes especially important for applications needing high performance like the aero spatial, naval, automotive, sport utility and military and civil defense. Even presenting all these characteristics of good near net shaping, the GFRP parts needs joining and mounting process, as very often they can be shaped in only one molding operation. In such cases, the joining process becomes the structure weakest link; here the bolting as drilling process becomes a critical step in the product development (Mathews et al, 1999). Typically two types of junction could be used: mechanical junctions and the adhesives. The adhesives junction (by gluing) needs a careful cleaning before applying the adhesives, which can be affected by service environment, and are difficult to disassembling for maintenance and repair works, however, enables a better load distribution trough a greater area compared with mechanical junction. On the other hand, the mechanical junctions need a good quality for the drilling and trepanning operations for screws, pins and bolts. Therefore, the efficiency of the mechanical junctions depends strongly on the drilling quality. It can be verified for drilling of GFRP that the weakest point stays in its susceptibility to machining damage when submitted to not suitable cutting parameters or tooling geometries. Such factors characterizes GFRPs as materials hard to machine and results in a trend to avoid its finishing processing by machining during its manufacture and assembly. However, among the several processes employed in machining GFRP, the drilling as well as the trepanning processes are probably the most frequent finishing operations. For bolted and screwed junctions arises the need of accurate holes and free of damage in order to assure a higher strength and accurate junction.

2.1. GFRP MACHINABILITY

Machining GFRP has some characteristics that contrast it with the traditional metal machining, as for example [Bratukhin, 1995]:

- **Higher anisotropy of the properti**es: this means that the fiber disposition has an essential importance on the obtained surface quality. Therefore, while machining, the cutting direction should selected accounting the fiber directions.
- **Relative complexity to obtain high quality surface**: this is specially relevant when arises high temperature during the machining operation, as cracks can be initiated due to the laminated structure and low adhesion between the binder material and the filling, resulting in delaminating and fracture, thus thermal and mechanical damage.
- **Low conductivity of GFRP** – it is hundredth times lower than those for metals and causes a low heat transfer trough chip, from the machined part and environment. Therefore, a great part of heat generated is dissipated through the tool. This dissipation is distributed: 90 % trough the tool, 5 % trough the chip and 5 % through the machined part, while in conventional metal machining process almost 90 % of heat is dissipated trough the chip (Trent, 1996).
- **Fiber abrasive action -** fibers can be made from glass, carbon, aramid, kevlar or similar material of high hardness and abrasion resistance.
- **Polymeric matrix damaging by the machining process** – this can occur due to high local stress and temperatures. As a result the polymer becomes viscous, i.e. forms an active substance on surface (SAS). The SAE migration over the tool rake surface under stress reduces its metal surface energy (effect Rehbinder), allowing an easy rupture micro and macro particular from the surface, resulting in wear by chemical mechanical adsorption.
- **GFRP low thermal resistance (100 to 300 o C)** – in this range the temperature range it occurs the polymeric matrix burning and the burned surface appears on machined surface. This is intensified by the fact that in some cases the use of coolers is not possible, as the GFRP could absorbs the cooler fluid.

3. EXPERIMENTAL METHOD AND MATERIAL

A strain gage based transducer was developed, calibrated and used during all the experiments. It is based on one previously proposed by Daar (1967), with improvements on the instrumentation and signal acquisition systems. As operational goal, the developed drilling dynamometer was designed in order to allow for the measurement of the torque and thrust components of the drilling force. A strain gage base sensor was used in the instrumentation of the dynamometer. The dynamometer can be observed in the Fig (2). It consists of a stem to fix in the machine, where the transducer is assembled with the instrumented ribs, with a pin to support the chuck. In this pin there is a cover for protection of the equipment. The ribs were instrumented to form a complete Wheatstone bridge, in such a way that the reading of a channel doesn't affect the other, during the acquisition. The instrument was calibrated, being obtained two curves that were used to transform the values of micro-strains obtained in process as force and torque values.

The data acquisition system is based on hardware **SPIDER** 8. It consists of four digital amplifiers operating in frequency of 4.8 kHz, each channel working with an A/D converter, allowing measurements in frequency range of 1 Hz to 9600 HZ. The A/D converters are synchronized in order to enables simultaneous measurements over all channels.

The software employed for the data acquisition is the **CATMAN** version 2.2 from HBM. It enables receive and processing the data obtained trough the SPIDER, as well as to configure the channels, acquisition time and sampling frequency.

The built drilling dynamometer was fixed in a lathe Romi Tormax 20 TX-8, for the execution of the experiments, and it also can be viewed on the Fig (2).

An experimental plan was developed aiming the quality improvement of an industrial hole making process of GFRP materials. The characteristic properties of GRFP test pieces are listed in Tab. (1). The experiments carried out a statistically aided evaluation of the different tools as well as their machining parameters illustrated in Tab. (2).

It was tested 4 different kinds of tools: HSS twist drill, HSS hole cutter, diamond coated HSS hole cutter, trepanning tool with hard metal inserts, described in the Tab. (2).

Before carrying out the drilling tests, it was prepared a statistical planning aiming to improve experiment results response in order to show the dependence between the output (response variables) and the inputs (controllable variables). It is defined which control factor is to be analyzed and its respective range to be assumed. Keeping in mind that the hole quality depends directly from the torque and thrust force, this two variables are chosen as response variables. In the following sections experimental planning for each one of the four investigated tools are presented and discussed aiming a conclusion of the best choice of tool and parameters fit in order the improve junction performance.

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1 TWIST DRILLS

For the twist drills experiments it was selected as evaluation factors, the values exhibited in Tab. (3), i.e., lubrication (A), cutting speed (B) and feed rate (C) as demonstrated by Tab. (4) and (5) as well as Fig (3), (4) and (5). The plots of the Fig (6) show the interaction between feed rate and cutting speed on the response for the experiments with and without cutting fluid. B1 and B2 are the cutting speed ant lower level (31,9 m/ min) and the higher (50,3 m/ min), respectively. C1 e C2 are the feed rates for the lower level (0.042 mm / rev) and the higher (0.25 mm / rev) , respectively.

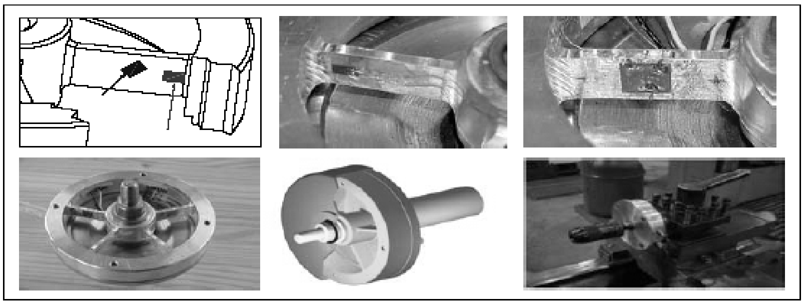


Fig. 2. one strain gage measuring the torque and two strain gages at 45° measuring the thrust force.

Table 1. Characteristic properties for the GFRP test pieces

A. Related to the material system

A.1 Reinforce Characteristics	Glass Fiber
A.1.1 size	Continuous fiber
A.1.2 material	Glass fiber
A.1.3 type	Type “E”
A.1.3.1 fiber	Filament diameter = 17 µm
A.2 Reinforce quantity	64%
A.3 Reinforce orientations (fibers)	0 / +45 / -45 / 90
A.4 Matrix characteristics	
A.4.1 Chemical composition	Epoxi (bisfenol “A” + Epiloridrine + Poliamine)

B. Related to the consolidated material

B.1 Physical properties	Tg = 80 C
B.2 Thermal treatments	Post cure at 60 C for 3 hours
B.3 Obtaining methods	Polymerization with vacuum cure
B.4Reinforce distribution (homogeneous or not)	Orthotropic
B.5 Mechanical Properties	E = 14415 MPa G = 5065 MPa Elongation = 2,12 %

Table 2 – Evaluated tools and its respective machining parameters

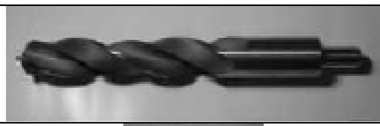
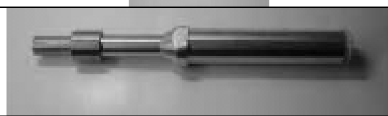
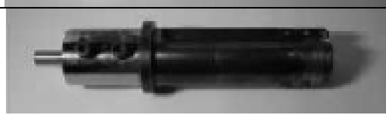
HSS Twist drill – diameter = 25,4 mm	
HSS Hole cutter - diameter = 25,4 mm	
Diamond coated HSS hole cutter – diameter 25,4 mm	
Trepanning tool – hard metal inserts outer diam.= 25,4 mm	

Table 3 – Values for the evaluation factors

	A	**B**	**C**
Level	**Lubrication**	**Cutting speed (m/min)**	**Feed rate (mm/min)**
-1	without	31.9	0.042
1	with	50.3	0.119

Table 4 – Factors effect

	Forces	Torque
A	-24,069	-4,267
B	-18,890	-0,910
C	30,824	12,443
AB	22,399	1,856
AC	-2,776	0,746
BC	-5,283	0,543
ABC	6,574	-1,801

Table 5 – Regression model for the HSS twist drills

A) thrust force

$y = 95,73 + 20,75.x_3$

where x_3 = feed rate

B) torque

$y = 39,71 + 19,63.x_3 + 20,75.x_2.x_3 + 2,88.x_2.x_3\ +$

where x_2 = cutting speed ; x_3 = feed rate

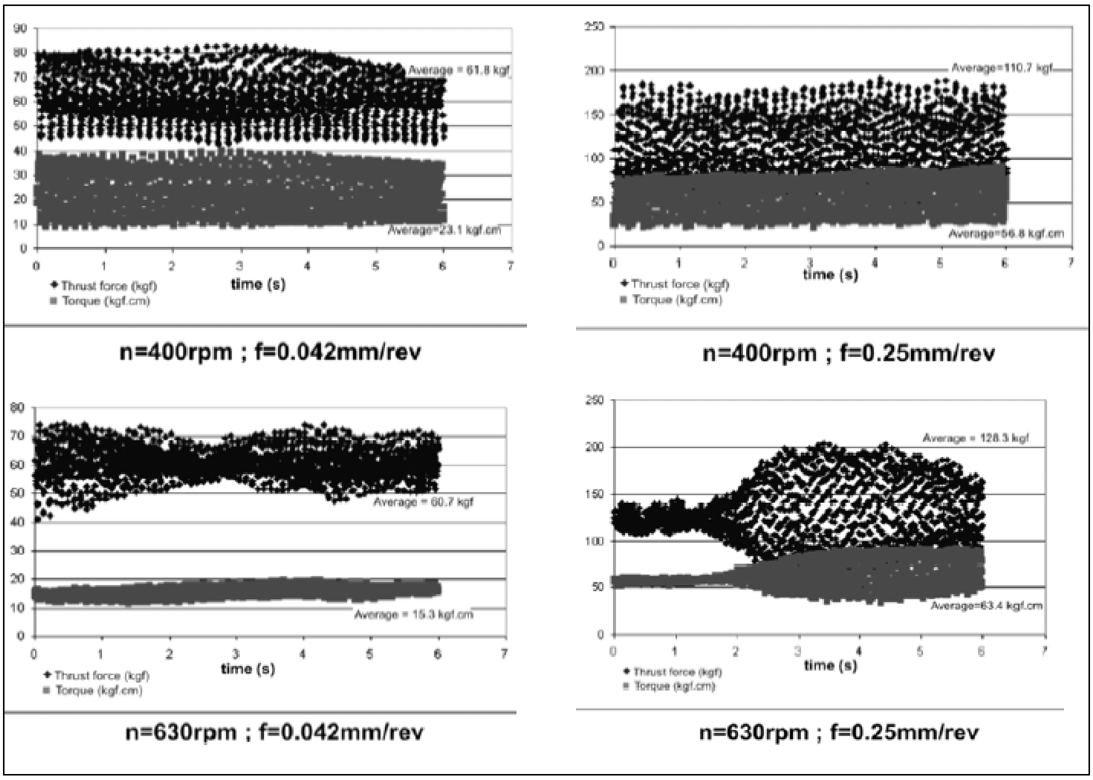


Figure 3. Twist drill without cutting fluid, for different cutting speed and feed rate

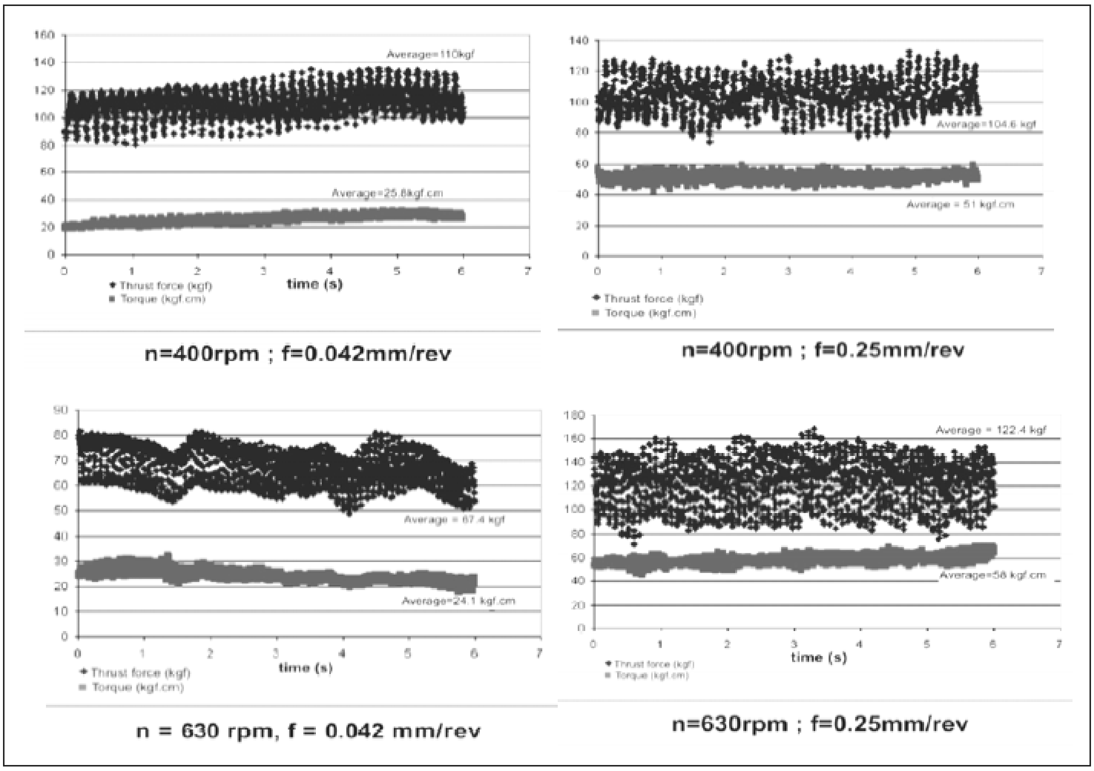


Figure 4. Twist drill with cutting fluid, for different cutting speed and feed rate

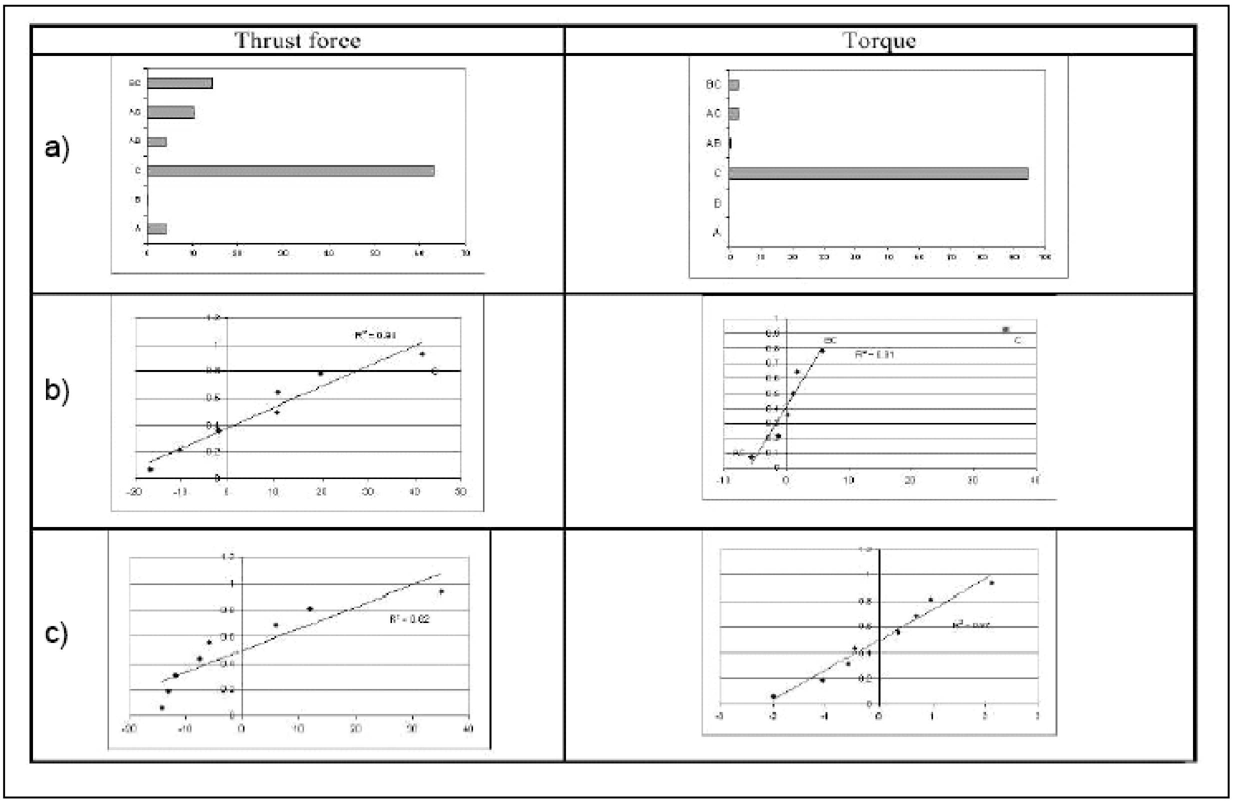


Figure 5 – Interaction evaluation between factors and the responses of torque and thrust force – a) Pareto diagram – b) normal probability for the effects – c) normal probability for the residue

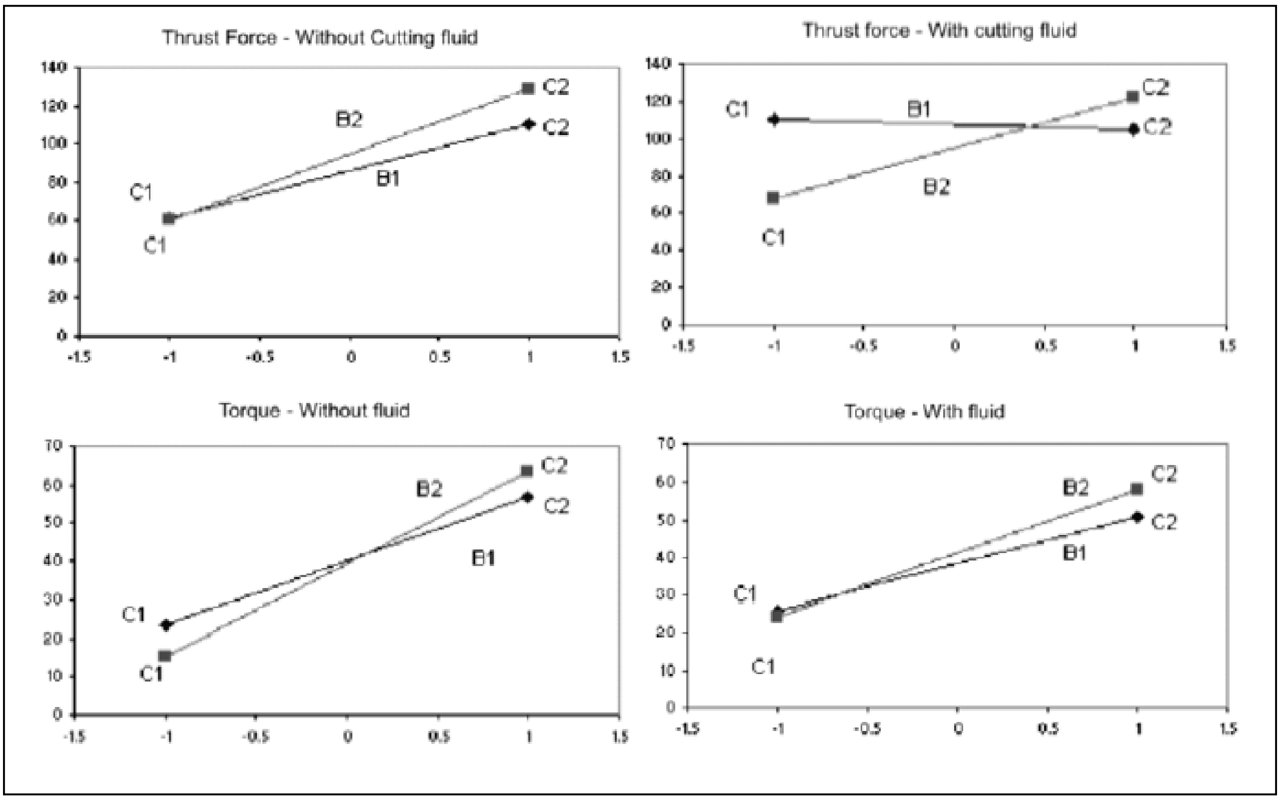


Figure 6 – Graphic representation for the interaction between thrust force and torque for twist drills

4.2 – COMMON HOLE CUTTER

The results for the common hole cutter are presented on the Fig (7) and (8). The evaluation factors are presented in Tab. (6), the factors effect in Tab. (7) and the regression model in Tab. (8).

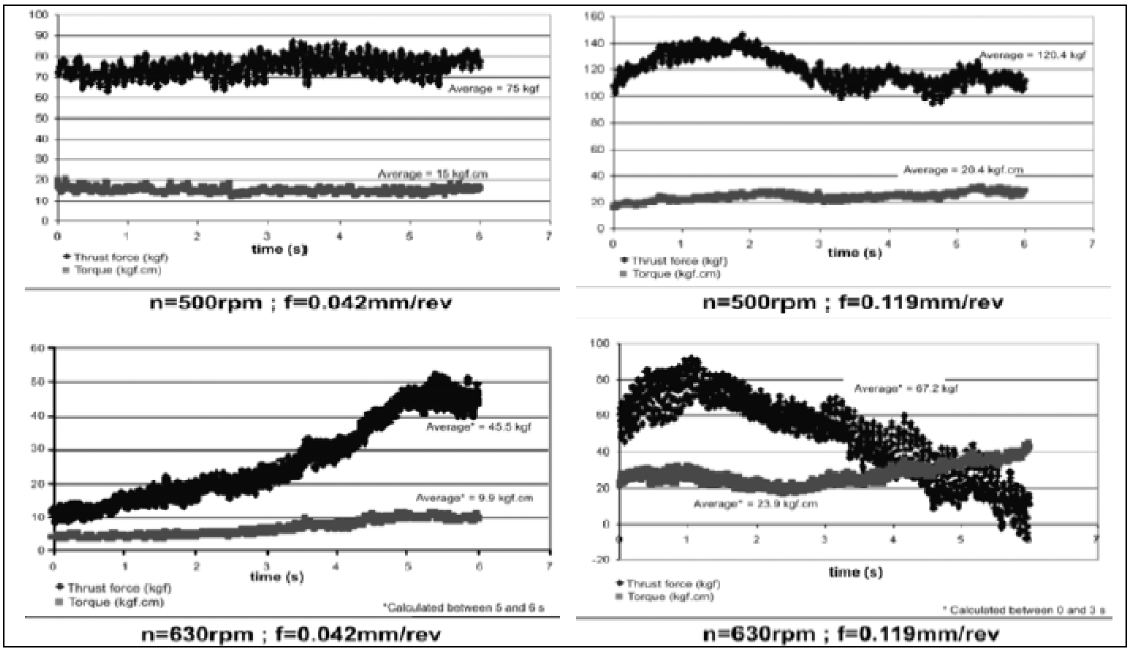


Figure 7. Common hole cutter without fluid, for different cutting speed and feed rate

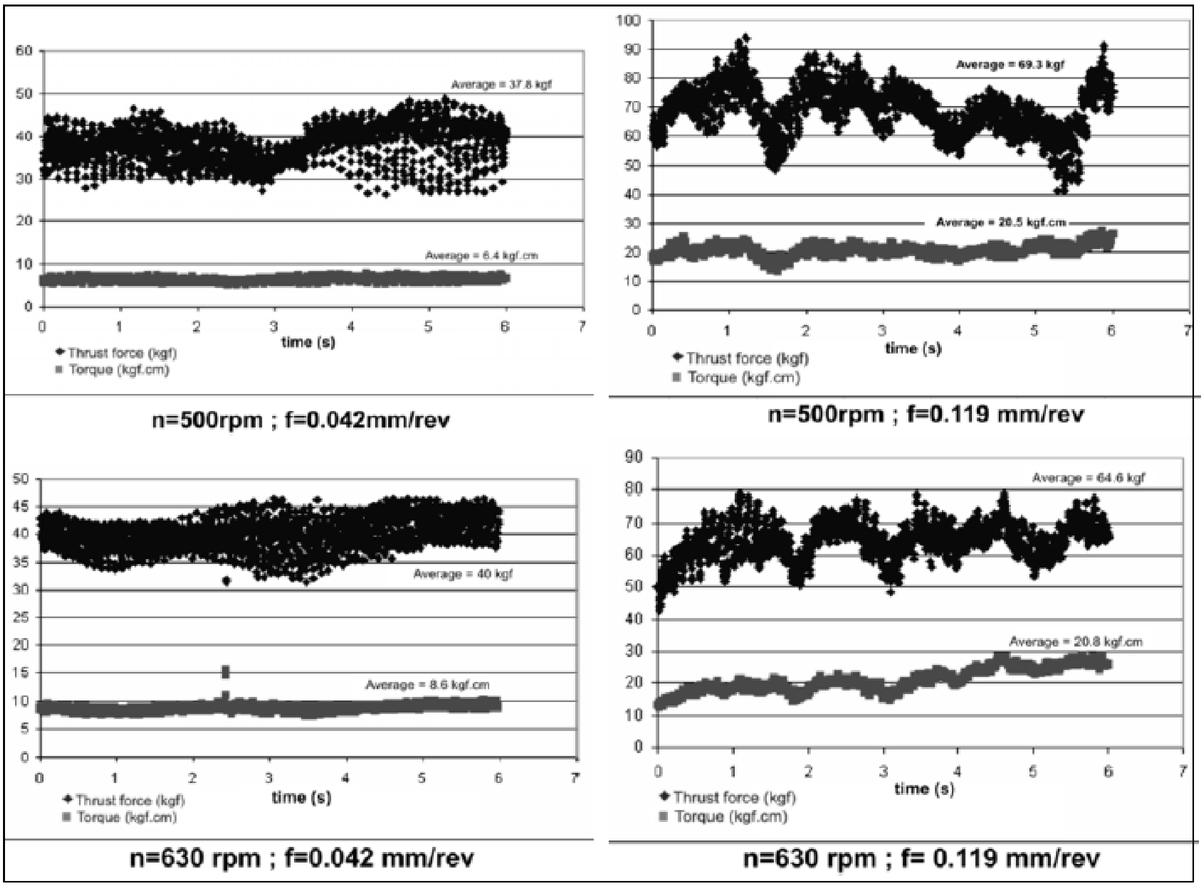


Figure 8. Common hole cutter with fluid, for different cutting speed and feed rate

Table 6 – Values for the evaluation factors

	A	B	C
Level	**Lubrication**	**Cutting speed (m/min)**	**Feed rate (mm/min)**
-1	without	39.9	0.042
1	with	50.3	0.119

Table 4 – Factors effect

	Forces	Torque
A	-24,07	-4,27
B	-18,98	-0,91
C	30,82	12,44
AB	22,40	1,86
AC	-2,78	0,746
BC	-5,28	0,54
ABC	6,57	-1,80

Table 5 – Regression model for the HSS twist drills

C) thrust force

$y = 64.99 + 12.03.x_3 – 9.49.x_2 + 15,41.x_3 + 11,20.x_1.x_2$

x_1 = cutting fluid (without = -1; with = 1) x_2 = cutting speed - x_3 = feed rate

D) torque

$y = 16.21 – 2.13.x_1 + 6.22.x_3$

where: x_2 = cutting speed ; x_3 = feed rate

4.3 – DIAMOND COATED HOLE CUTTER

The results for the diamond coated hole cutter are presented on the Fig (9) and (10). The evaluation factors are presented in Tab. (9), and the factors effect in Tab. (10).

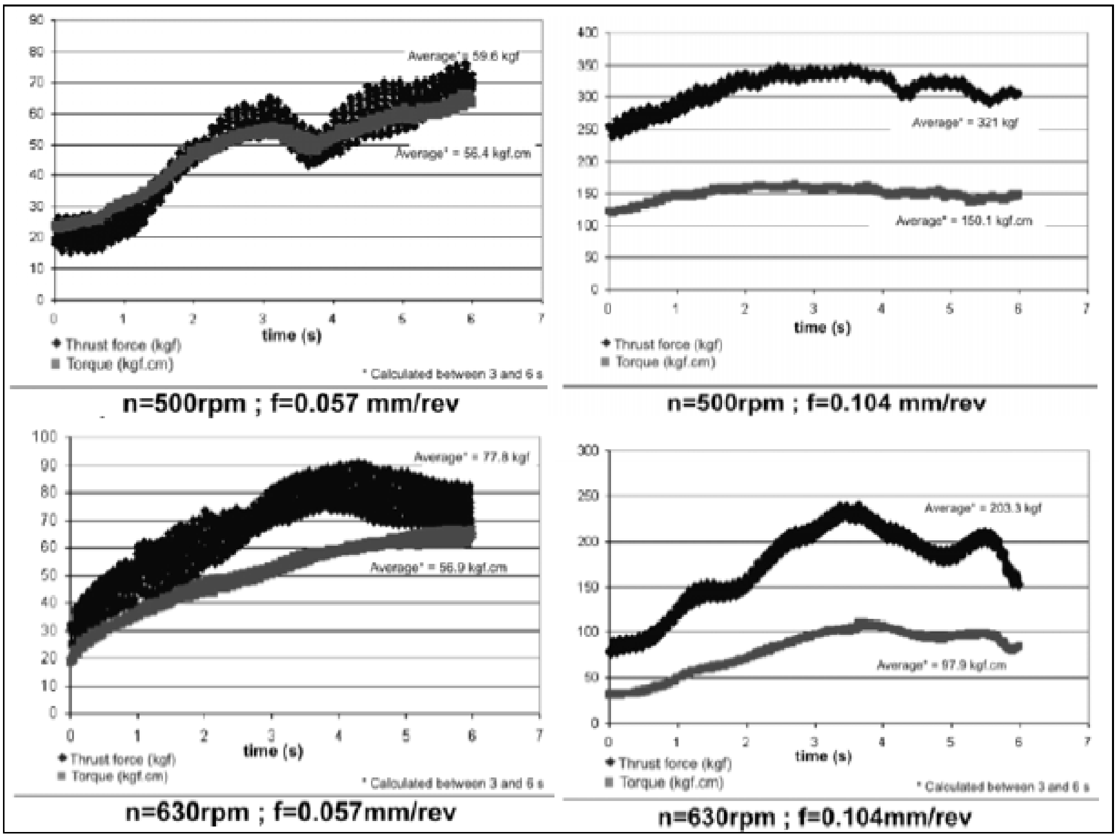


Figure 9. Diamond coated hole cutter, with cutting fluid

Table 9 – Values for the evaluation factors

	B	C
Level	**Cutting speed (m/min)**	**Feed rate (mm/rev)**
-1	39.9	0.057
1	50.3	0.104

Table 10 – Factors effect

	Force	Torque
B	-49.77	-24.33
C	193.43	65.86
BC	-67.996	-27.836

4.4 – TREPANNING TOOL WITH HARD METALS INSERT

The results for the trepanning tool with hard metals insert are presented on the Fig. (10).

5. DISCUSSION

It is identified the factor C (feed rate) as the main factor, as well as the two factor interactions AB (lubrication vs. cutting fluid) and BC (cutting speed vs. feed rate), that shows a F0 value greater than 5.32 in the ANOVA. Therefore these factors affect the torque and trust force as shown by the Pareto Diagram. The factors significance could be also evaluated with the construction of normal probability charts for factors effect. The effects that stay far from the line are those having more pronounced influence on the responses. From the effects values it becomes possible to compute the regression coefficients. The regression equations written related the response variables with the factors with variation significance. The used values for the twist drills are resumed in Tab. (2). Computing the averaged responses in the stabile ranges it is obtained the response values. Only the C factor has a value greater than 5.32. This indicates than it was the main influence factor identified influencing the thrust force with significance of 95 %. Computing the residues through the differences between the experimental values and those predicted by the regression equation, it is possible to construct normal probability chats for the residues. Confirming that the normal probability charts for the residues are close to a linear relationship, it is confirmed the hypothesis of a Gaussian error.

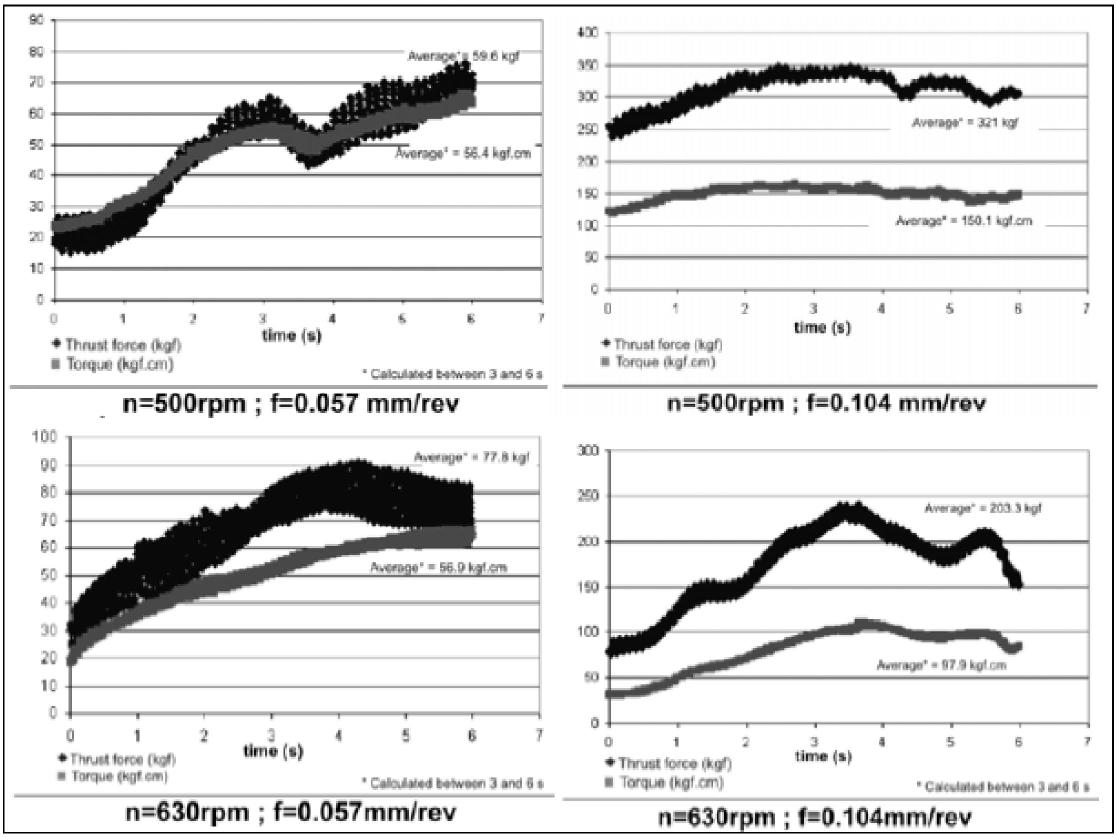


Figure 10. Trepanning tool with hard metals

6. CONCLUSIONS

• The developed dynamometer provided a satisfactory performance in order to evaluate different tools and machining conditions for drilling and trepanning process of GFRP parts;
• For high feed rates, using HSS twist drill, the thrust force was almost the same for the drilling with or without cutting fluid, but for the common hole cutter, the cutting forces increased for high values, when drilling without cutting fluid.
• The diamond coated hole cutter also presented high values of cutting forces, and was almost impossible make the holes using it without cutting fluid. The trepanning tool with hard metals insert, presented the smallest values of cutting forces working without cutting fluids.
• experimental signals for the response variables: torque and thrust force signals allowed for an investigation of the effects of lubrication, cutting speed and feed rate effects following a statistical planned experiment.

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