Machinability Study of Unidirectional CFRP Using Central Composite Design of Experiments

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***Abstract*—Thanks to the development of the vehicle and the airplane industries, the usage of polymer composites widely increased. The carbon fibre-reinforced plastics (CFRP) have low density and good mechanical properties, therefore these non-metal materials are the most famous and the most used polymer composites in the world. The primary objective of our study is to make a mathematical model about the changing of cutting forces and the macro-geometrical properties in the unidirectional carbon fibre-reinforced plastics machining with the help of the Central Composite (CC), experimental design method. Drilling experiments for conventional and orbital drilling strategies were designed. A software (DoDEx – Design of Drilling Experiments) for the Windows operating system was developed, which can operate quickly, easily, flexibly and safely and capable of generating NC programs for the drilling experiments. The software can import construction designs from AutoCAD software and the designs of experiments from Minitab. The CC experiments in the BME were performed with a Kondia B640 three axes machine tool with NCT100 control. The cutting forces were measured with a KISTLER 9257BA three directional load cell. We were able to calculate and model the optimization parameters from the measured cutting forces and the macro-geometrical properties.**

I. Introduction

Thanks to the development of the vehicle and the airplane industries, the usage of polymer composites widely increased. The need to optimize their machining progressively increased, in order to minimize the hole errors, delamination, forces and burrs. The carbon fibre-reinforced plastics (CFRP) have low density and good mechanical properties. Therefore, these non-metal materials are the most famous and the most used polymer composites in the world. The machining of CFRP poses several difficulties because of the different machinability of matrix- and fibre materials. The mechanical properties of the defined oriented fibre-reinforced plastics are not the same in every direction, therefore the machinability properties are not isotropic [1-5]. If the cutting direction is changed, the cutting forces and the micro- and macro-properties change as well, even with the same technical parameters [6]. The intent of the airplane industry is to achieve the best quality, the productivity is only a secondary aspect. It is important to pay attention to the machining control because the theory of the polymer composite machining is unfinished.

The first goal of our study is the machinability analysis of one-directional CFRP using Central Composite (CC) Design of Experiments (DOE) method with conventional and orbital drilling strategy. We were able to predict the cutting forces and several micro- and macro- geometrical properties (e.g. delamination) in CFRP machining with conventional and orbital drilling strategy.

II. CFRP Machinability

The CFRP machining is used generally, when the number of products is not enough to create a special tool for it. For this reason, it is relatively often used with expensive technical plastics, but in spite of that only a few things about the CFRP machining's attitude are known. The machinability of plastics is completely different from the one of metals, because plastics are basically viscoelastic materials. Taking into consideration the mechanical properties of plastics, which depend on the time, as well as their viscosity, is crucial [7] [22]. In case of drilling of fibre-reinforced, thermoplastic and thermosetting plastics, the analysis showed that the plastic deformation of the material depends on the number of fibres and the deformability of the matrix material [7]. The edges of the drilled holes are generally sharp except for the cases in which the temperature has risen due to a high cutting speed or the low feed rate. The heat conduction of plastics is worse and the fusion point is lower than the metals, therefore it is very essential to keep the temperature low. Generally the fusion point of the matrix material defines the maximal cutting speed and the number, orientation and tensile strength of the fibres define the maximal feed rate.

A. *Cutting forces and delamination*

The cutting forces in the CFRP are smaller than in metals, therefore it is possible to reduce the fixing forces at the fixture. CFRP has a lower strength and stiffness than the metals, thus it is important to observe the influence of the cutting forces on the dimension tolerances. When the cutting forces are too high and they are coming from wrong directions the laminated layers in CFRP can separate from each other. The most frequent defect in a CFRP machined feature is delamination [2] [5] [8] [9] [24]. The definition of delamination is, the laminated layers separating from each other. The delamination is observable in the entry and the exit of the hole surface [10]. The delamination factor (D) is a one-dimensional factor, which is defined as the ratio of the maximum diameter (D_{max}) of the delamination area to the hole nominal diameter (D_{nom}), as illustrated in Eq. (1) [1] and shown in Fig. 1.

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

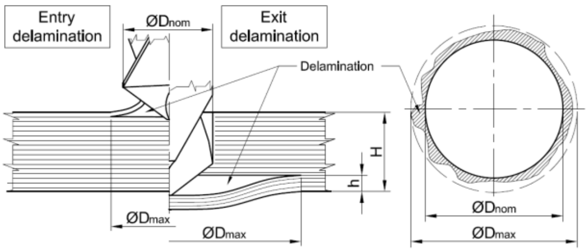


Figure 1. Schematic diagram of delamination at the exit of the hole and delamination factor (D)

B. *Cutting tools and technologies*

The CFRP cutting tool's edges have to be sharp otherwise the effect of the heat generated by the friction on the workpiece becomes higher, therefore the CFRP becomes more flexible and the chips are difficult to remove [11]. In case of CFRP drilling the most noticed hole errors are delamination, fibre pull-out, uncut fibres and the breakout [2] [6].

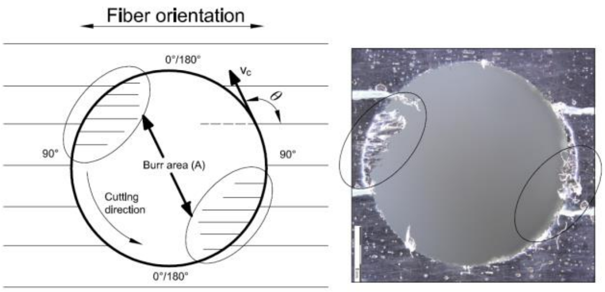


Figure 2. Schematic diagram of burr area (A) and fibre cutting angle

During CFRP cutting the produced exit burr defects usually show certain regional characteristics along the hole circumference, which is high dependent on the fibre cutting angle (θ) as shown in Fig. 2 [1] [12]. In Jinyang Xu et al. investigation [1], a new indicator, namely the burr area (A), was introduced to objectively evaluate the real extent of burr defect in order to exclude the error effect of a single maximum burr length.

It is possible to produce machined holes even with orbital drilling [3] [23] as well as wobble milling [13]. The schematic diagram of orbital drilling using an end mill is shown in Fig. 3. When the machining heat is reduced, a special end mill needs to be used, where the shank diameter is smaller than the working diameter [14] [15].

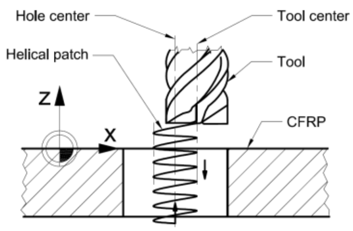


Figure 3. Schematic diagram of orbital drilling with end mill

In case of fibre-reinforced plastics inhomogeneous material construction we have to consider different requirements as shown in Table 1. To machine high-quality holes, it is recommended to use sharp cutting edges [16], small drilling point angle [9], high feed rate [4] [8] [17], usage of coolant, if possible, and chip clearing [11]. Moreover, only the working part of the tool should touch the workpiece.

TABLE I.
REQUIREMENTS OF CFRP CUTTING TOOLS

Reason	Requirement	Positive effect	Negative effect
Matrix smearing and more burr at the hole	Sharp cutting edges	Minimal burr and matrix smearing	Fast wear and cutting edge error
Abrasive wear effect of fibre	Wear resisting coating on the cutting edge	Tool wearing is small	Burr and matrix smearing
Weak matrix material	Little drilling point angle	Small axial forces	More delamination
Delamination at the end of the holes	Big drilling point angle	Less delamination	Big axial forces

III. DESIGN OF EXPERIMENTS

The goal of the design of the experiments is to predict with the minimum number of experimental settings the changing of the optimization parameters over the field of factors [18].

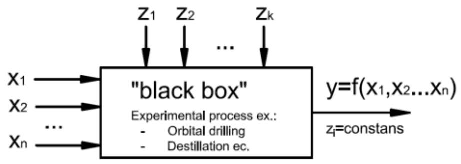


Figure 4. Schematic diagram of the „black box" process

The schematic diagram of the experimental object is shown in Fig. 4. The object of the experiments (y) depends on the noises (z_i) and the x_1, $x_2 \ldots x_n$ factors. Scope is the definition of the "f" function, which is able to predict the changing of the optimization parameter (y) in case of different factor values, as illustrated in Eq. (2).

$$y = f(x_{1,} x_2 \ldots x_n) \quad (2)$$

In contrast to the conventional experiment designs (only one factor is changed at a time), in some cases it would be better to have the possibility to change more factors simultaneously (with a design of experiment method). This way we are able to minimize the number of experimental properties.

A. *The Central Composite method*

One of the most used design of experiments strategy is the Central Composite (CC) method. With the CC design method some special experimental points from the field of the factors are chosen, as shown for a three-factor case in Fig. 5.

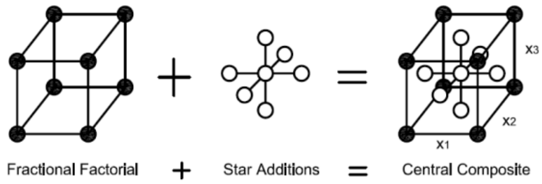


Figure 5. Schematic diagram of Central Composite design in case of 3 factors

In the case of designs with more dimensions, the experimental points are pitch points and axial points of a hyper cube. It is not possible to plot these hyper points, only to operate them with matrix algebra. For a statistical analysis (in order to define the reproducibility variance) it is necessary to measure the reference point several times (3-4x) [18]. This is usually the middle point on the field of the factors, as point 1 in Fig. 6. There are different geometrical versions of the CC method as shown in Fig. 6.

We used the CCI geometrical construction of CC design of experiments method.

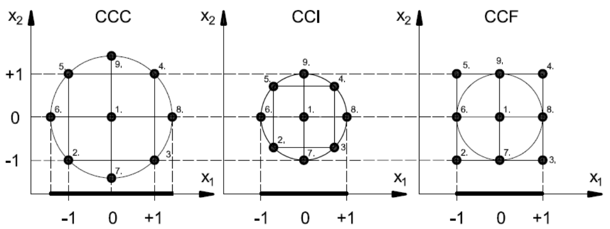


Figure 6. Schematic diagram of several Central Composite designs

B. Design of experiments to CFRP machinability analysis

1) Goal of the experiments

The goal of the experiments conducted in the present work is to model one-directional CFRP machining processes. The study of these processes is crucial in order to predict which micro- and macro-features can be produced through the chosen technical parameters (feed rate, cutting speed, tool, tool patch etc.). Inverse definition: The modeling is necessary, because only with the help of the model it is possible to define by means of which technological parameters, surfaces with the prescribed micro- and macro-geometrical properties can be produced. It is important to underline that when designing the experiments, the analyzed processes considered are the ones available within the industry.

2) Factors

The factors are input parameters that influence the result of the experiments, so the optimization parameters depend on the factor levels. Parameters (mentioned in the industrial and international researches), that have an impact on the quality of the machined holes are: cutting speed, feed rate, cutting depth, geometry of the cutting edge, coolant, tool lifts, machining tool, environment, and the lead of thread and the direction of the milling (in case of orbital drilling). The machinability analysis of conventional and orbital drilling strategy is dependent on 8-10 different factors. Using all of them is not relevant, because our analysis has a higher error scale like the influence of some factors. Therefore, because of technological and economical reasons the number of the factors was reduced. The influence of cutting speed, feed rate and lead of thread on the different optimization parameters was analyzed with a special drill and an end mill. The field of the factors has different limits because of technological and economical reasons. The chosen tools and their technological limits are shown in Table 2, where h (mm) is the thread pitch of the helical tool patch using end mill.

TABLE II.
THE CUTTING TOOLS WITH THEIR INTERVAL OF THE TECHNOLOGICAL PARAMETERS

Tool	D_{nom} (mm)	n (rev/min)	v_c (m/min)	f (mm/rev)	h (mm)
Drilling tool: SECO SD205A-11.138-53-12R1-C1 /400€	Ø11,138	1430-4260	50-150	0,035-0,093	-
End mill: PERFOR 82366511000 8	Ø10	1590-4770	50-150	0,02-0,06	0,1-3,0

3) Optimization parameters

The optimization parameter (OP) is a dependent variable that is a means of which it is possible to optimize the analyzed process [18]. In the technical practice there has to be a relationship between the optimization parameters and the prescribed geometrical designs. In our studies specific parameters were chosen, such as: cutting forces (F_z and F_x), main cutting force derivative maximum (FEVIM) [19] and circularity error (H_c).

4) Mathematical model

The mathematical model is a mathematical representation or simplified version of a concept, relationship, structure, system, or an aspect of the real world [18]. Eq. (2) represents the model of the process analyzed in the present research. It is possible to continue the design of the experiments, only provided that the type of function is defined in advance. Generally the unknown "f" function is approximated with a polynomial, because polynomials have a lot of favourable properties [18]. In this particular study, the estimated surfaces (mathematical models) were approximated with quadratic polynomials.

5) The design of experiments to CFRP machinability analysis

The flow diagram of the designed experiments is shown in Fig. 7. The present paper deals only with the first part of the created design of experiments (Fig. 7A), through the second part of the research, further investigations and optimization of the models will be carried out. The design table of conventional and orbital drilling is presented in Table 3, and the percentage error between the measured and predicted values are shown in Table 4.

TABLE III.
THE DESIGN TABLE OF CONVENTIONAL DRILLING AND ORBITAL DRILLING

	Drilling tool		End mill		
Sn. (-)	n_i (rev/min)	f_i (mm/rev)	n_i (rev/min)	f_i (mm/rev)	h_i (mm)
1	2845	0,064	1590	0,040	1,55
2	1844	0,043	2234	0,051	2,41
3	1844	0,084	3180	0,040	1,55
4	3845	0,084	3180	0,040	1,55
5	1430	0,064	4125	0,028	0,68
6	2845	0,064	3180	0,040	3,00
7	2845	0,035	4125	0,051	0,68
8	3845	0,043	3180	0,040	0,10
9	4260	0,064	3180	0,040	1,55
10	2845	0,064	3180	0,060	1,55
11	2845	0,064	2234	0,028	2,41
12	2845	0,064	3180	0,040	1,55
13	2845	0,093	3180	0,020	1,55
14			4125	0,028	2,41
15			4770	0,040	1,55
16			4125	0,051	2,41
17			3180	0,040	1,55
18			2234	0,028	0,68
19			2234	0,051	0,68
20			3180	0,040	1,55

TABLE IV.
THE DIFFERENCES BETWEEN THE MEASURED AND PREDICTED VALUES

Tool	Model	Average percentage error	Deviation of the percentage error
Drilling tool	$F_{z,max}$ (N)	-0,16	2,83
	FEVIM (N)	-3,09	18,67
	Hc (mm)	-7,13	28,46
End mill	$F_{x,max}$ (N)	-1,35	11,95
	Hc (mm)	-18,43	102,13

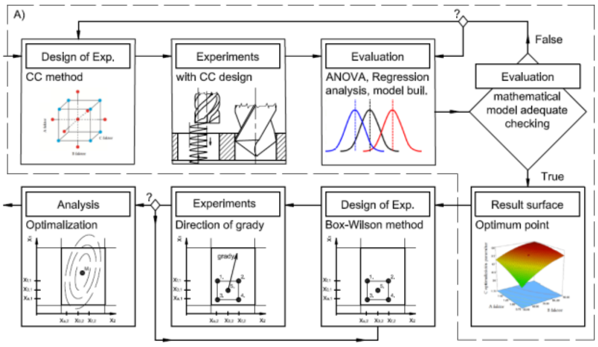


Figure 7. Schematic diagram of the experiments and processes

IV. SOFTWARE DEVELOPMENT FOR EXPERIMENTAL DRILLING CNC PROGRAMMING

In case of experimental drilling the technical parameters are usually obtained from a mathematical software (e.g. Minitab) and the geometrical parameters from a CAD software (e.g. AutoCAD). Additionally, the experiments are conducted by a CNC controlled cutting tool. There are many well-known methods to generate a CNC program, such as:

- Conventional CNC program with manual programming
- Conventional CNC program with CAM software
- Parametric program system generating with manual programming

With all of the methods it is necessary to write step by step all parameters obtained from a CAD and a DOE software applications. These procedures require several time and it can imply many possibilities of error. A software (DoDEx – Design of Drilling Experiments) for the Windows operating system was developed, which can operate quickly, easily, flexibly and safely and is capable of generating NC programs for the drilling experiments (for conventional and orbital strategy as well). The software can import construction designs from AutoCAD and the designs of the experiments from Minitab. The programming time with the DoDEx is around 1-3 minutes, in contrast with the one of the methods previously mentioned (30-60 min) [19]. The schematic diagram of the DoDEx is shown in Fig. 8.

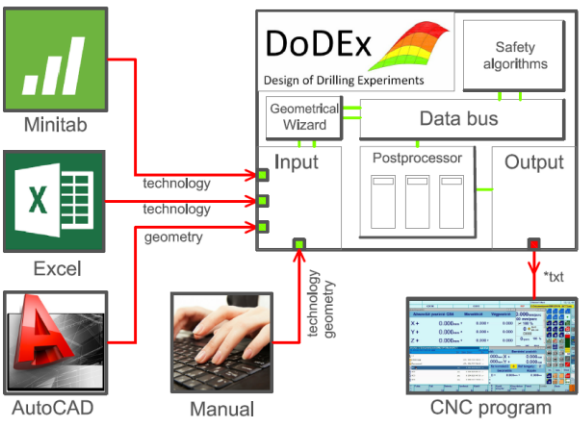


Figure 8. Schematic diagram of DoDEx 2015 v1.0

V. THE EXPERIMENTS

A. *Machine tool, cutting tools and instruments*

The CC experiments in the BME with a Kondia B640 three-ax machine tool were conducted as shown in Fig. 9: a vacuum pump was located next to the machine tool, in order to clear the chips off the workpiece to avoid the influence of the carbon chips on the parts of the machine tool. The cutting forces were measured with a KISTLER 9257BA three-directional load cell with 1000 Hz sampled signal. The data were collected by the Dyno Ware software. The macro- geometrical properties of the holes were measured by a Mitutoyo Crysta Plus coordinate measurement.

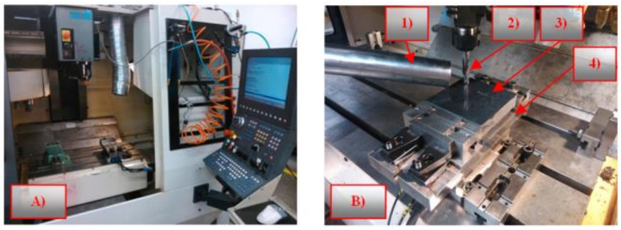


Figure 9. A) The cutting machine tool; B) the CFRP with the drilling cutting tool 1) Vacuum cleaner; 2) Drilling tool; 3) CFRP; 4) Fixture

The conventional drilling experiments were carried out by a special SECO drill (400€) as shown in Fig. 10A and the orbital experiments by a PERFOR end mill (35€) as shown in Fig. 10B. During the experiments the tool wear was measured and found to be low, it was therefore not necessary to compensate the measured OP values.

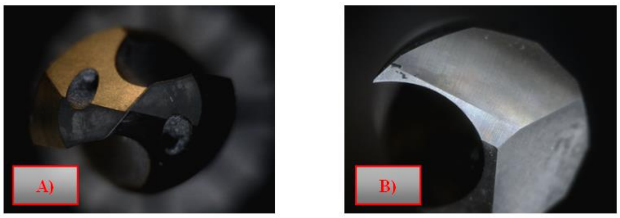


Figure 10. A) Drilling cutting tool; B) End mill

VI. RESULTS AND DISCUSSION

The changing of the several measured and calculated optimization parameters and their optimum points was analyzed. Several factors affect the optimization parameters, but only the cutting speed, feed rate and the thread pitch were chosen to be analyzed. The other factors (e.g. vibrations, temperature) we attempted to maintain at constant level in order to make their effect negligible. The measured and calculated values were analyzed by means of Microsoft Excel 2007 and Minitab 17. It was possible to calculate the reproducibility variance from several optimization parameters obtained considering the same technical properties. In addition, the confidence intervals of the optimization parameters were estimated. Over the measured and calculated points we were able to design "n"-degree regression polynomials. The algorithm to define "n" is shown in Fig. 11.

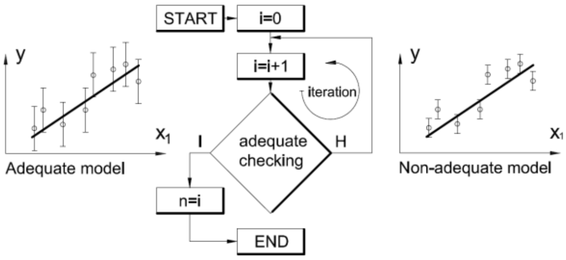


Figure 11. Schematic diagram of definition of „*n*"

With an adequate analysis it was observed that the designed regression polynomials were in the reproducibility variance field, because the mathematical model has to be more exact than the confidence intervals of the optimization parameters. With the help of Minitab it was possible to analyze the two factors CC experiments and design 3D-s surfaces, with the ANOVA (Analysis of variance) and the significant effects were evaluated.

A. Cutting forces

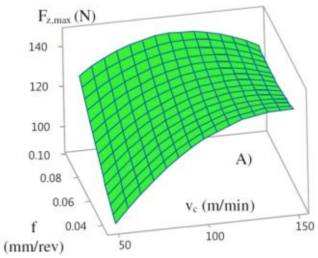
The effect of the cutting speed, feed rate and the thread pitch (in orbital drilling) on the axial force (F_z) for the conventional drilling and on the radial force (F_x) for the orbital drilling was analyzed. The FEVIM (the main cutting force derivative maximum) [19] was evaluated for the conventional drilling. The designed mathematical models are valid for the analyzed field of the factors with the estimated confidence intervals and the used cutting tools.

1) Conventional drilling

The quadratic regression polynomials of the maximal axial force and the FEVIM were estimated with the help of Minitab as shown in Fig. 12 and expressed in Eq. (3) and (4). Results showed that both cutting speed (v_c) and feed rate (f) are significant factors to both maximal axial force and FEVIM. In case of increasing of the feed rate both the maximal axial force and the FEVIM increase as well, as shown in Fig. 12. The influence of the feed rate on the maximal axial force was measured by Jinyang Xu et al. [1] as well, but with fewer experiments. In case of increasing of the cutting speed, both the maximal axial force and the FEVIM behave hyperbolically, as shown in Fig. 12. The influence of the cutting speed on the maximal axial force was measured by M. Rahman et al. [2] as well, but with fewer experiments. The maximum of the function (with respect to the cutting speed) is found not to be at the edge of the field of the factors (Fig. 12), but inside: the explanation of this phenomenon is yet unknown, it is therefore, important to analyze it by means of further experiments, as shown in Fig. 7.

$$F_{z,\max} = -0{,}5 + 1{,}807 v_c + 655 f - 0{,}00539 v_c^2 + 3025 f^2 - 7{,}26 v_c f \quad (3)$$

$$FEVIM_{64} = -65{,}6 + 0{,}677 v_c + 1327 f - 0{,}00306 v_c^2 - 8063 f^2 + 4{,}25 v_c f \quad (4)$$



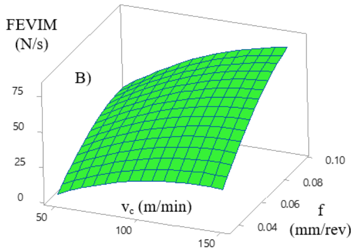


Figure 12. A) Influence of cutting speed (v_c) and feed rate (f) on maximal axial force B) Influence of cutting speed (v_c) and feed rate (f) on FEVIM

In the drilling axial force diagram, the change of the force for the evaluated section is one order of magnitude higher than the change of the axial drilling force for the aluminium alloy 5083 (considering the same cutting machine) [20]. It is essential to look for the reasons of this difference, through the conduction of more experiments, for example: through the measure of tool vibrations and axial accelerations. Most likely the answer will be found in the inhomogeneity and anisotropy of the CFRP.

2) Orbital drilling

The quadratic regression polynomial of the maximal radial force was estimated with the help of Minitab, as shown in Fig. 13 and expressed in Eq. (5). Results showed that both cutting speed (v_c) and feed rate (f) are factors that have a significant impact on the maximal radial force. On the other hand, the ANOVA and the regression analysis showed that the influence of the thread pitch of the end mill on the cutting forces is not a significant factor in the measured field of the factors.

$$F_{x,\max} = 48{,}8 + 0{,}049 v_c - 590 f - 0{,}000002 v_c^2 + 69{,}3 f^2 + 4{,}59 v_c f \quad (5)$$

In case of increasing feed rate, the maximal radial force is monotonically increasing (Fig. 13). The influence of the cutting speed on the radial force is similar to the one on the maximal axial force in conventional drilling.

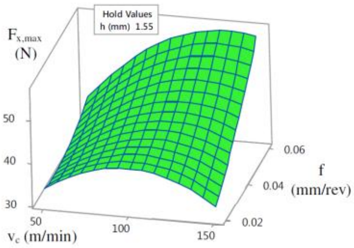


Figure 13. Influence of cutting speed (v_c) and feed (f) on maximal radial force, hold value: h= 1,55 mm

B. Macro geometrical errors

The effect of the cutting speed and the feed rate on the circularity (H_c) in conventional and orbital drilling was analyzed. In case of increasing feed rate the circularity error reduces, as shown in Fig. 14 for both cutting tools. On the other hand, in case of increasing cutting speed the circularity error reduces only when the drilling tool is used, and increases with the end mill. The results presented in Biren Desai et al. [21], show that spindle speed is the most effective parameter during measuring circularity with drilling tool. On the contrary, in the present research the cutting speed (v_c) was not found to be the most effective parameter in case of the drilling tool, but in case of orbital drilling, as illustrated in Fig. 14. The influence of the cutting speed and feed rate on the circularity using the drilling tool is presented in Fig. 15. the ANOVA and the regression analysis showed that the influence of the thread pitch of the end mill on the circularity error is not a significant factor in the measured field of the factors.

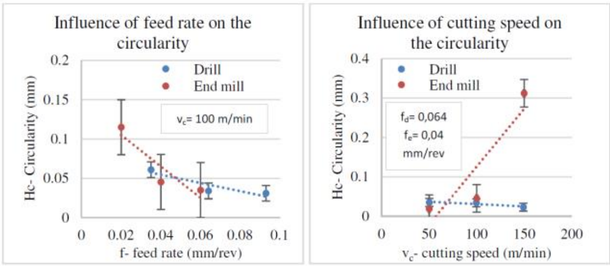


Figure 14. Influence of feed rate and cutting speed on the circularity using drilling tool and end mill

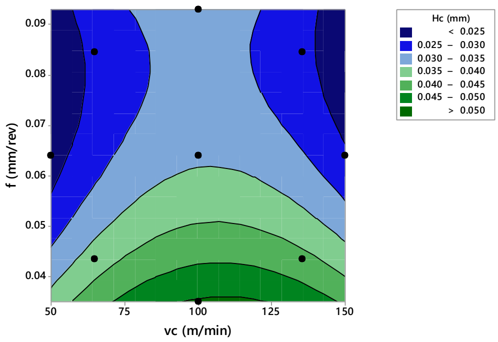


Figure 15. Influence of cutting speed and feed rate on the circularity using drilling tool

VII. Summary and Conclusions

A. Conclusions

In this study, with Central Composite design of experiments the influence of the cutting speed (v_c), the feed rate (f) and the thread pitch (h) on several optimization parameters (F_z, F_x, FEVIM, H_c) was analyzed, using a special SECO drilling tool and a PERFOR end mill in CFRP. It was possible to design regression polynomials (mathematical models) for the analyzed processes and to estimate the confidence intervals.

The influence of the cutting speed on all the analyzed optimization parameters, using a drilling tool, can be predicted with the designed quadratic polynomials, their maximum points lie inside the field of the factors, with fixed feed rate value. In case of increasing feed rate the F_z and FEVIM optimization parameters increase monotonically, but the H_C parameter decreases, the trends are shown in Table 5 for tool a.

The ANOVA and the regression analysis showed that the thread pitch of the end mill does not have an influence on the optimization parameters in the measured field of the factors. In case of increasing cutting speed the H_c optimization parameter increases monotonically, but the F_x parameter behaves like a parabola, as illustrated in Table 5 for tool b. In case of increasing feed rate the F_x optimization parameter increases monotonically, but the H_C parameter decreases, the trends are shown in Table 5 for tool b.

TABLE V.
Summary table: in case of increasing vc, f factors the following changing was noticed

Tool	F_z= f(v_c)	F_z= f(f)	FEVIM= f(v_c)	FEVIM= f(f)	R(F_x)= f(v_c)	R(F_x)= f(f)	H_C= f(v_c)	H_C= f(f)
a)	⌒	↗	⌒	↗	-	-	⌒	↘
b)	-	-	-	-	⌒	↗	↗	↘

Marks comment to the Table 5:

a) SECO SD205A-11.138-53-12R1-C1 drilling tool
b) PERFOR 823665110008 end mill
↗ Increasing trend
↘ Descending trend
⌒ The function has a local maximum point
\- Don’t analyzed

B. Technological suggestions for drilling in large thickness CFRP

Because of the macro-geometrical properties of the drilled holes, and the fast operation element, an analyzed special drilling tool is suggested, for that specific technical and economic environment where the quality of the holes and the operation speed are important requirements.

Because of the analyzed macro-geometrical properties of the drilled holes, the slow operation element and the cheap cutting tool, an orbital drilling strategy is suggested for that technical and economic environment where the quality of the holes is important, but the operation speed is not an important requirement.

C. Plans and goals

In this study the machinability of CFRP with CC method over the whole of the field of the factors was analyzed. Several regressions polynomials present a maximum or minimum inside the field of the factors, it is therefore necessary to analyze the position and the reason of the existence of these notable points. Knowing the position of the minimum is crucial, because these points and their neighbourhood can lead to bad features, when used. These points will be analyzed with the Box-Wilson design of experiments method [19].

In the drilling axial force diagram, the change of the force for the evaluated section is one order of magnitude higher than the change of the axial drilling force for the aluminium alloy 5083 (considering the same cutting machine) [20]. Therefore, it is necessary to look for the reasons of this difference by conducting more experiments.

The goal of future further experiments is to improve our understanding of the analyzed machining processes. It is essential to design models with lower error and higher significant level in order to define and control the CFRP machining processes with the same precision that the advanced industries require.

Acknowledgment

This work was supported by the Department of Manufacturing Science and Engineering of the Budapest University of Technology and Economics.

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