INFLUENCE OF TOOL GEOMETRY AND PROCESS TEMPERATURE ON HOLE QUALITY WHEN DRILLING CARBON FIBER REINFORCED PLASTICS

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Abstract: This paper presents the results of investigations concerning the influence of process temperatures, at the drilling of carbon fiber reinforced composites, on the quality of the drilled hole (roughness, tolerances, burr formation). With the increasing need of lightweight design, carbon fiber reinforced plastics (CFRP) are a feasible alternative to engineering materials. They have excellent properties and are being extensively used in a variety of engineering applications (aerospace industry, automotive and the wind energy industry). Drilling is the most common machining process applied to CFRP, and it is difficult due to the extremely abrasive nature of the carbon fibers and their low thermal conductivity. However, the users of this kind of composites are facing difficulties to machining it, due to its properties. Due to the effects of lubricants on the fiber-reinforced composites, the machining of these materials is performed without coolant. On the other hand dry machining offers the risk of a thermal damage induced by high process temperatures.
The current experimental analysis is focused towards determining process temperatures with different tools and drilling parameters. Infrared Thermography is used to investigate appropriate drilling temperatures based on drill geometry and the ideal drilling parameters were determined. In this paper, an attempt has been made to model the surface roughness through response surface method (RSM) and ANOVA when drilling GFRP composites.
Keywords: ANOVA, IR Thermography, carbon fiber reinforced plastics, CFRP, Drill Hole Quality, RSM.

1. INTRODUCTION

Fiber-reinforced composite materials have become an economic alternative to other materials in highly corrosive industrial applications. In the family of FRP's, carbon fiber reinforced plastics (CFRP) are having a combination of properties such as high specific strength, high specific stiffness and a light weight, that makes it attractive for aircraft and aerospace applications [2-3]. When CFRP composites are machined, it is clearly seen that the fibers are cut across and along their lay direction, leaving deformed projecting and partially disclosed fibers on the machined surface [6]. Conventional machining of fiber-reinforced composites is difficult due to diverse fiber and matrix properties, fiber orientation, inhomogeneous nature of the material, and the presence of high volume fraction (volume of fiber over total volume) of hard abrasive fiber in the matrix.

Previous research show that the thermo physical properties of the fiber reinforced polymers causes high temperatures at the tool tip when machined. Another reason which must be considered is the fact that especially thermoplastic polymers have a glass transition temperature ranging from 150-250°C, meaning that the heat formation during the drilling process can lead to plasticizing of the polymer matrix. In many cases machining of fiber reinforced polymer materials is performed without cooling lubricant. This coolant can imbue the plastic material and it can induce chemical reactions with certain functional groups of the macromolecules [8]. Since the spreading of the coolant cannot be completely avoided the effect can lead to shape and accuracy errors not only of the drilled hole but also of the entire work piece. The later effects are the weakening of the plastic material by reducing is strength, which is a result of lower adhesive forces within the polymer material and the carbon fiber. On the other hand dry machining offers the risk of a thermal damage induced by high process temperatures [7].

In the present work, mathematical models have been developed to predict the surface roughness Ra when drilling CFRP composites using response surface methodology. Analysis of variance (ANOVA) is used to check the validity of the model.

Surface roughness evaluation is very important for many fundamental problems such as friction, contact deformation, heat and electric current conduction, tight-ness of contact joints and positional accuracy. For this reason surface roughness has been the subject of experimental and theoretical investigations for many decades. Also, surface roughness imposes one of the most critical constrains for the selection of machines and cutting parameters in process planning. Although many factors affect the surface condition of a machined part, parameters such as cutting speed, work piece condition, feed rate and depth of cut have more influences on the surface roughness for a given machine tool and work piece set-up [1].

2. EXPERIMENTAL EQUIPMENT

2.1 Roughness measurement device

Fig. 1: Mitutoyo SJ-201

Mitutoyo Sj-201 presented in the above picture is a roughness measurement device, used for the analyze and

interpretation of the different surface roughness parameters (Ra, Ry, Rz, Rq). The obtained results can be shown on the device's display, but they can also be printed on a mini printer or PC. In order to be easily transported this device was designed with a reduced weight. This device has two components: the display unit and the feeler unit. The feeler unit is designed in a way, so that it can be assembled/disassembled from the display unit. The feeler's peak is produced from a special diamond, this being the part that crosses over the measured surface [9]. Technical data's of the roughness device are presented in table 1.

Technical data	Mitutoyo Sj-201
Measuring Domain:	Ra/Rq: 0,01-75 μm; Rz/Ry: 0.02-300 μm
Measuring length:	0,25, 0,8, 2,5mm
Analysed parameters:	Ra, Ry, Rz, Rq
Peak:	Diamond 90°, R5 μm;Carbid (R40 mm)
Display:	(LCD)

Table 1: Technical data roughness device

2.2. Hermle UWF1202 H

Fig. 2: HERMLE UWF 1202 H

The CNC Machine Hermle UWE 1202 H built in 95 is a 4 axis machine with a rotary table with a Heidenhaim TNC 426 CNC control. It has an automatic HTC tool charger with a capacity of 34 tools. Technical data of the CNC machine are presented in table 2.

Longitudinal travel	(X-axis) 850 mm
Transversal travel	(y axis) 630 mm
Vertical travel	(z axis) 500 mm
Table load max.	700 kg
Spindle speeds:	up to 5000 rpm
Tool changer:	HTC
Number of tools	34
Machine's weight	about 6500 kg

Overall dimensions machine:	
Length	3700 mm
Width	2400 mm
Height	2400 mm

Table 2: Technical data CNC Machine

3. SCHEME OF INVESTIGATION

In order to achieve the desired goal, the investigations were planned as following:
- Identifying the machining parameters, which are having influence on surface roughness of the machined CFRP composites, and finding the upper and lower limits for the chosen factors.
- Developing the experimental planning and proceeding with the experimental measurements according to the design matrix generated using the design expert software.
- Developing the mathematical model and checking the adequacy of the developed model by ANOVA method.
- Validating the model by compeering the calculated values, using the developed equations, with the measured values obtained by experimental measurements.

3.1. Identification of predominant factors that have an influence on the roughness parameter

Surface finish of the work piece is an important attribute of quality in any machining operation. During the drilling process of carbon fiber reinforced composites many factors affect the surface roughness. Feed rate is an important factor. In practice the cutting speed has been found to be an important factor, however, many theoretical models have concluded that the effect of cutting speed on surface roughness is minimal [1]. A part of the experimental analysis is focused towards determining process temperatures with two different tools. Infrared Thermography was used to investigate drilling temperatures and afterwards the ideal drilling parameters were determined.

Based on the thermal analysis the best-fitted drills were chosen, being the drills that registered the lowest temperatures. Afterwards the research was carried out using two different tools having different point angles, T1 having a point angle of 118° and T2 with a point angle of 155°. Bought of the drilling tools have a diameter of 6.8 mm. A detailed analysis has been carried out to fix the lower and upper limits of the factors.

Based on the analysis, the upper and lower limits of the factors were also set as following:
- the feed rate was selected between 0.1 and 0.2 mm/rev;
- the cutting speed was selected between 1000 and 3000 rev/min.

3.2. Developing the experimental design matrix using design expert

3.2.1 Experimental Measurements

The material used for the experiments is formed in plates 150x150mm having a thickness of 5mm, produced by IFB Stuttgart, containing: 55-60% carbon fibers, a hardener and an epoxy from Hexion, formed in 14 layers at 0°/90°. For the planning of the experiments the upper and lower limits of the variable parameters, that influence the surface quality, were introduced in the software. Design expert generates then the planning of the experiments as shown in the following tables (table 3 and 4). Further we proceeded to processing the material using the process parameters generated by the software and presented in the design matrix. The drilling was performed without coolant. The roughnesses, being the response parameter, was measured for each processed hole, and than the values were introduced in the design matrix.

No.	Speed n [rev/min]	Feed s [mm/rev]	Roughness Ra [μm]
1	2000	0.15	11.68
2	1000	0.15	10.49
3	1000	0.2	19.85
4	2000	0.2	19.12
5	3000	0.15	9
6	2000	0.15	8.64
7	2000	0.15	11.29
8	1000	0.15	13.51
9	1000	0.1	11.84
10	3000	0.2	15.66
11	2000	0.1	12.75
12	3000	0.1	12.35
13	2000	0.1	12.47

Table 3: Design matrix for T1

No.	Speed n [rev/min]	Feed s [mm/rev]	Roughness Ra [μm]
1	2000	0.15	2.15
2	1000	0.15	1.88
3	1000	0.2	2.6
4	2000	0.2	2.7
5	3000	0.15	2.4
6	2000	0.15	2.26
7	2000	0.15	2.23
8	1000	0.15	1.95
9	1000	0.1	1.9
10	3000	0.2	3.19
11	2000	0.1	1.83
12	3000	0.1	2.3
13	2000	0.1	2.16

Table 4: Design matrix for T2

3.3. Developing The Mathematical Model

Representing the surface roughness of the processed CFRP composite ''Ra'', the response function can be expressed as: Ra=f(A, B).

Afterwards the adequacy of the developed model was checked using the ANOVA methodology as shown in tables 5 and 6. The determination coefficients, R^2=0.91, obtained with the process parameters at the drilling with tool T1, and R^2=0.94, obtained with the process parameters at the drilling with tool T2, indicating that the model is significant. The analysis shows that the Quadratic model is the best fitted for the prediction of the response parameter when processing with the two drills [9-10].

Model	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS
Linear	2.95	0.37	0.24	-0.06	148.93
2FI	3.01	0.41	0.21	-0.4	196.46
Quadratic	1.28	0.91	0.85	0.78	30.16
Cubic	1.46	0.92	0.81	0.39	84.512

Table 5: Model suggestion for T1

Model	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS
Linear	0.17	0.82	0.78	0.65	0.61
2FI	0.18	0.82	0.77	0.34	1.15
Quadratic	0.11	0.94	0.9	0.81	0.32
Cubic	0.138	0.94	0.87	-0.85	3.28

Table 6: Model suggestion for T2

This determination coefficient R^2, calculates the distance between experimental results and the calculated results. As long as the value of R^2 is wery near to 1, the precision of the chosen mathematical model is good. The "Pred R-Squared" is in reasonable agreement with the "Adj R-Squared", meaning that the model is significant.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F

Model	128.21	5	25.64	15.5	0.0011
A-Speed	9.53	1	9.53	5.76	0.0474
B-Feed	59.32	1	59.32	35.86	0.0005
AB	5.52	1	5.52	3.33	0.1104
A^2	0.54	1	0.54	0.33	0.5831
B^2	70.49	1	70.49	42.61	0.0003
Residual	11.57	7	1.65		
Lack of Fit	1.5	3	0.5	0.199	0.8917
Pure Error	10.07	4	2.51		
Cor Total	139.79	12			

Table 7: Analysis of variance for surface roughness obtained with T1

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1.67	5	0.33	24.28	0.0003
A-Speed	0.43	1	0.43	31.38	0.0008
B-Feed	1.01	1	1.01	73.4	0.0001
AB	0.009	1	0.009	0.653	0.4451
A^2	0.007	1	0.007	0.555	0.4806
B^2	0.19	1	0.19	13.89	0.0074
Residual	0.0965	7	0.013		
Lack of Fit	0.033	3	0.011	0.697	0.6003
Pure Error	0.0633	4	0.015		
Cor Total	1.77	12			

Table 8: Analysis of variance for surface roughness obtained with T2

Fig. 3. Correlation chart for T1

Fig. 4. Correlation chart for T2

The adequacy of the model is checked using the analysis of variance (ANOVA) technique; the test results are presented in the Table 7 and 8. The lack of fit was found to be less than 0.199, for drill T1, and 0.697 for T2, meaning that the developed models may be accepted. Further, the experimental data and the predicted data, using the mathematical models were plotted as shown in figure 3 and 4, indicating a good correlation, as the determination factor, R^2, also shows.
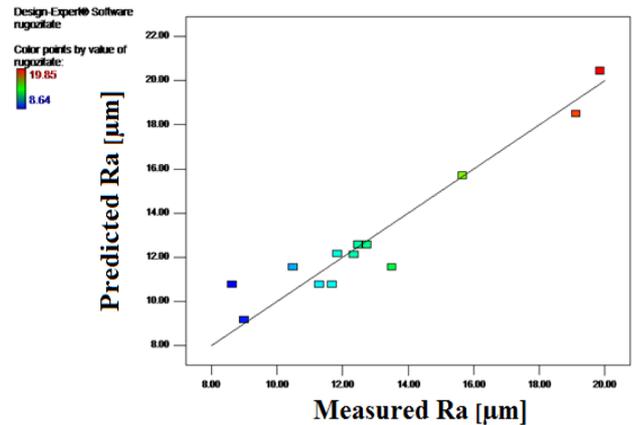
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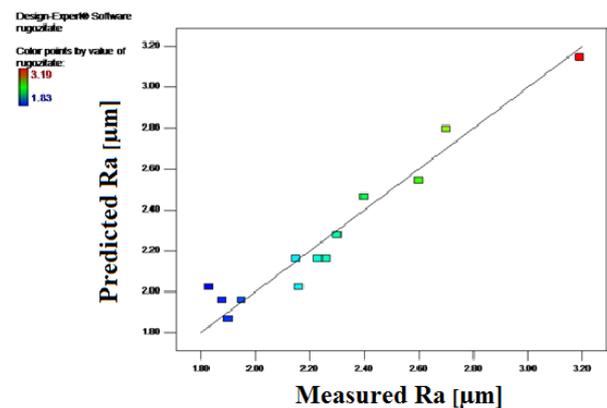
After the ANOVA analysis, the mathematical equation in terms of actual factors was determined as following:

The final equations in coded factors are:

$$Ra = 10.78 - 1.19 \times A + 2.96 \times B - 1.17 \times A \times B - 0.42 \times A^2 + 4.75 \times B^2 \text{ [µm] for T1} \tag{1}$$

$$Ra = 2.16 + 0.25 \times A + 0.39 \times B + 0.048 \times A \times B + 0.049 \times A^2 + 0.25 \times B^2 \text{[µm] for T2} \tag{2}$$

Where: A represents the coded factor for speed, and B being the coded factor for feed;

The final equations are:

$$Ra = 38.25517 + 4.0092E - 003 \times n - 63.22779 \times s - 0.0235 \times n \times s - 4.18169E - 007 \times n^2 + 1898.33247 \times s^2 \text{ [°µm] for T1} \tag{3}$$

$$Ra = 3.20456 - 8.71364E - 005 \times n - 23.85039 \times s + 9.5E - 004 \times n \times s + 4.94416E - 008 \times n^2 + 98.97662 \times s^2 \text{ [°µm] for T2} \tag{4}$$

The 3D and 2D representations of the roughness variation in relation with the process parameters are shown in the next four pictures.
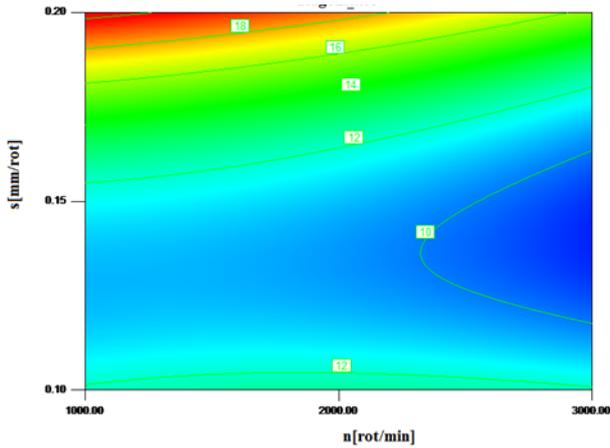
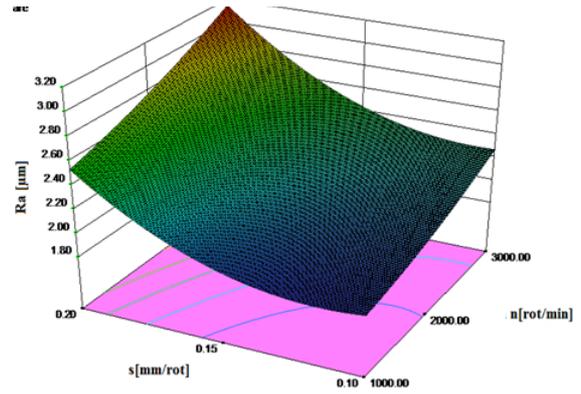Fig. 5. 2D surface obtained when drilling with T1

Figure.8. 3D obtained when drilling with T2

3.4. Model Validation

Further the roughness obtained with the developed equations was compared with the roughness obtained by experimental measurements. The results, which are shown in the next two charts, indicate an accurate determination of the roughness as the difference between the calculated values and the measured values did not overcome 10%.
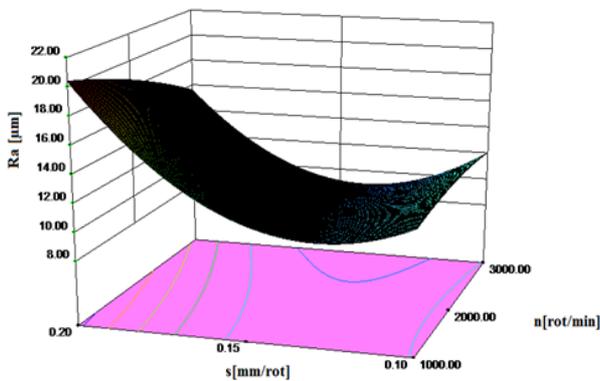

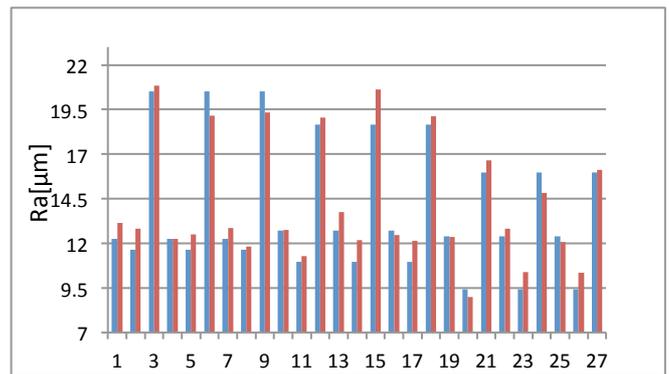Fig. 6. 3D surface obtained when drilling with T1

Figure 9. Calculated Ra (blue) versus measured Ra(reed) when drilling with tool T1
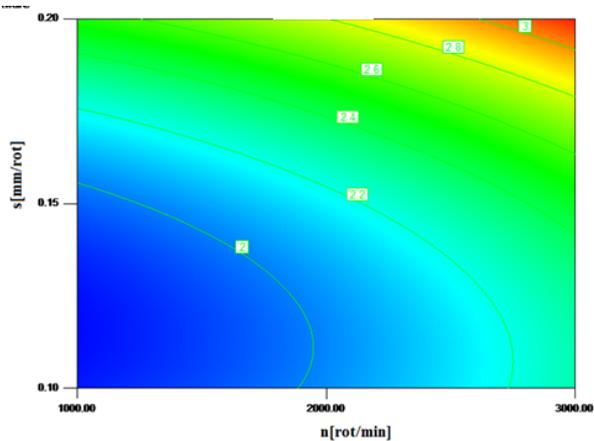

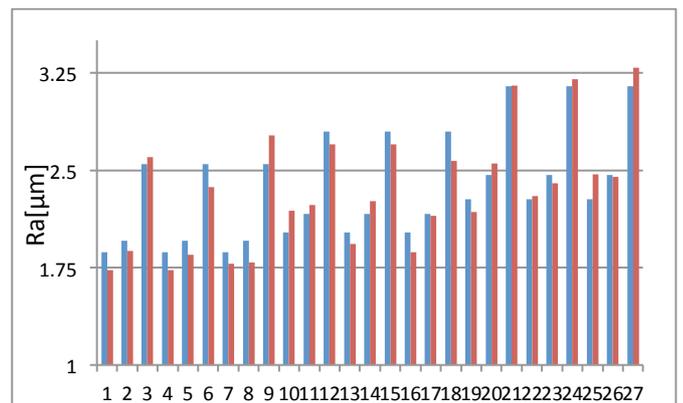Figure.7. 2D surface obtained when drilling with T2

Figure 10. Calculated Ra (blue) versus measured Ra(reed) when drilling with tool T2

The charts presented in figures 9 and 10 indicate that the developed mathematical equations estimate with high precision the obtained surface roughness Ra when drilling the CFRP composites using the tools T1 and T2.

4. CONCLUSIONS

Mathematical models for surface roughness determination have been developed to correlate the important machining parameters in drilling of CFRP composites with the obtained roughness parameter Ra. The developed equations can be used to predict the surface roughness for drilling of GFRP composites within the ranges of studied variable. However, the validity of the procedure is mostly limited to the range of factors considered for this experimental study (material, tools, process parameters).

Based on the conducted experiments the following conclusions could be drawn:

1. The surface roughness parameter Ra decreases with the increase of the spindle speed when processing with tool T1.The surface roughness parameter Ra increases, up to 18μm, with the increase of the feed, when processing with tool T1.

2. The lowest value of the roughness parameter Ra of 10μm, was obtained when drilling with tool T1, at a speed of 2000rev /min and a feed of 0.15mm/rev.

3. The surface roughness parameter Ra increases, up to 3μm, with the increase of the feed, when processing with tool T2.

4. The effect of the spindle speed on surface roughness is minimal when drilling with tool T2

5. The lowest value of the roughness parameter Ra of 1.8μm, was obtained when drilling with tool T2, at a speed of 1000rev/min and a feed of 0.1mm/rev.

6. High process temperatures influence the quality of the processed part. When machining with the carbide drill that has a point angle of 118° the temperatures registered with the IR camera were higher than 145°C. On the other hand, when machining with the carbide drill that has a point angle of 155° the temperatures registered with the IR camera didn't overcome 85°C.

The two important input variables considered for the present research study are the spindle speed (n) and the feed rate (s). When machining with a carbide drill heaving a peak angle of 155° the value of the surface roughness Ra did not overcome 3.5μm.

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