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PROCESS TEMPERATURE DETERMINATION AT THE DRILLING CARBON FIBER REINFORCED COMPOSITES

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Abstract: *Due to the damaging effects that the lubricants have on composite materials the machining of these materials is performed without coolant. On the other hand dry machining involves the risk of a thermal damage induced by high process temperatures that could influence the geometrical deviations and the quality of the processed part. Temperature measurements were accomplished using an IR camera for industrial applications, the Infratec, Variocam HR 500. Due to the disproportional evolution of the process temperatures in relation with the process parameters mathematical models were developed and presented in this paper. The mathematical models were elaborated using response surface method (RSM). Analysis of variance (ANOVA) was used to check the validity of the developed mathematical equations.*

Key words: *CFRP (Carbon fibre reinforced composites), IR Thermography, ANOVA, RMS.*

1. INTRODUCTION

Fibre-reinforced composite materials have become an economic alternative to other materials in highly corrosive industrial applications. In the family of CFRP's, carbon fibre reinforced plastics (CFRP), have 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 [1]. When CFRP composites are machined, it is clearly seen that the fibres are cut across and along their lay direction, leaving deformed projecting and partially disclosed fibres on the machined surface [5].

Previous research show that the thermo physical properties of the fibre 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 fibre reinforced polymer materials is performed without cooling lubricant. The coolant can imbue the plastic material and it can induce chemical reactions with certain functional groups of the macromolecules. Since the spreading of the coolant, cannot be completely avoided, the effect can lead to shape and accuracy errors, not only of the processed surface, but also of the entire work piece. The latter 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 between the polymer and the carbon fibre. On the other hand dry machining offers the risk of a thermal damage induced by high process temperatures [7].

Thermography is a modern technique, of high performance, which allows the temperature visualization and generates thermal maps in real time (thermal images) of the biological or technical systems being under investigation [3]. For the accomplishment of the thermal scanning activities special devices are used, named thermal cameras, which look and have the same dimensions as a normal video camera.

In this research work, the temperatures that are generated when drilling fibre-reinforced composites are measured using infrared thermography and the dependencies of process parameters, tool geometry and temperature are discussed. In the present work, mathematical models have been developed, using response surface methodology, to predict the process temperatures and surface quality when drilling CFRP. Analysis of variance (ANOVA) was used to check the validity of the models.

2. STRUCTURE OF AN ERP SYSTEM

2.1. Infrared Camera

For the temperature measurements the thermal camera Wariocam HR from Infratec was used, presented in figure 1, it was specially produced for research and industrial applications,

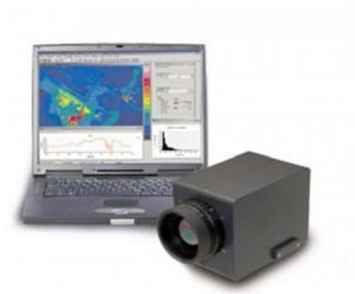

Fig.1. Variocam Hr 500 Infratec

This infrared camera can measure temperatures up to 2000°C with an accuracy of ±2%, and can determine temperature differences of 0.01°C. This camera is not provided with a built in screen, the thermal maps can be visualized directly on a computer connected to the camera. Thermal images can be memorized automatically in the computer using the dedicated software named Irbis 3 Plus. This program allows the user to memorize thermal maps at a wanted period of time. The thermal images can be interpreted using this software that allows the determination of the minimum and the maximum temperature of the investigated object. When desired, it also allows the isolation of a certain area of the thermal map, in order to determine the maximal or minimal temperature of that area.

Technical data IR Camera *Table 1.*

Measurements	**Infratec Variocam HR**
Sensitivity: Measuring Domain:	<0.05°C up to 30°C -40…. 1200°C, optional to 2000°C
Accuracy:	±1,5°C (0-100°C), ±2% (<0 şi >100°C)
Spectrum: Emissivity: Zoom:	7.5 to 14 µm 0,1-1,0 8X Digital
Image memorize	
Digital: Memory:	Standard images JPG External (PC), or internal (SD card)
Operating temperature:	(-15 up to +50°C)
Dimensions	103mmx106mmx110mm
Weight:	< 1.3 Kg

2.2. Roughness measurement device

Fig. 2. Mitutoyo SJ-201

Mitutoyo Sj-201 presented in the above picture is a roughness measurement device, used for analysing and interpretation of the different surface roughness parameters (Ra, Ry, Rz, Rq). The obtained results are 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. It has two components: the display unit and the feeler unit. The feeler unit is designed in a way, so that it can be assembled or 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. The technical data of the roughness device is presented in table 2.

Technical data Roughness device *Table 2*

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, 2,5 mm
Analysed parameters:	Ra, Ry, Rz, Rq, S, Sm, Pc, R3z, mr, Rt, Rp
Peak:	Diamond 90°, R5 µm; Carbid (R40 mm)
Display:	(LCD)
Operating temperature:	5°C…40°C
Dimensions:	

Display Unit:	156 x 62 x 57 mm
Feeler Unit	140 x 23 x 26 mm
Weight:	0,5 kg

2.3. Hermle UWF1202 H

Fig. 3. Hermle UWF 1202 H

The CNC Machine Hermle UWE 1202 H built in 95 is a 4-axis machine with a rotary table and a Heidenhain TNC 426 CNC control. It has an automatic HTC tool charger with a capacity of 34 tools. Technical data of the CNC machine is presented in table 3.

Technical data CNC Machine *Table 3*

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
Voltage	50 Hz 3x400 Volt
Milling spindle	Motor 14 kW
Total power required	21 kVA
Machine's weight	About 6500 kg
Overall dimensions machine:	
Length	3700 mm
Width	2400 mm
Height	2400 mm

3. EXPERIMENTAL MEASUREMENTS

The research is based on thermal measurements, using an infrared camera (figure 1), when drilling carbon fibre reinforced composites. For the experiments three different drills were used. Previous research has shown that the maximum process temperature, when drilling composite materials, is registered when the tool exits the work piece. In this case the authors have chosen an experimental setup as shown in the next two figures (figure 4 and 5).

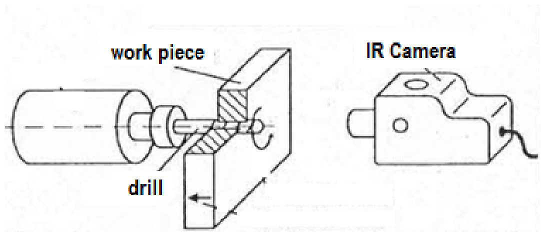

Fig. 4. Experimental setup [7]

As shown in figures 4 and 5 the camera was positioned, so, that it allows the measurement of the temperatures when the tool exits the work piece. For every hole, that was drilled, over 20 thermal maps were memorized, starting from when the drill enters the work piece until the drilling process ends. The material was processed with three different tools; two conventional helicoidally drills having a diameter of 6.8 mm and an unconventional drill with one edge having a diameter of 9 mm. The difference between the two helicoidally drills are: the peak angle, and the material, which they are produced of. The first drill, named WZ-01, has a peak angle of 118° produced from high-speed steel; the second one, named WZ-02, has a 155° peak angle produced from carbide; the one edge drill was named WZ-03, also made of carbide.

The material used for the experiments is formed in plates 150x150mm with a thickness of 5 mm, produced by IFB Stuttgart, containing: 55-60% Toho Tenax 12K carbon fibre, a hardener Hexion RIMH 236 and an epoxy Hexion RIMR 235, formed from 14 layers at 0°/90°. In the next figure the authors have shown the experimental setup on the CNC machine from Hermle UWF 1202 H.

Fig. 5. Experimental setup

During the drilling process two process parameters were varied: the spindle speed from 1000 up to 3000 rpm and the feed from 0.1 mm/rot up to 0.2 mm/rot.

4. EXPERIMENTAL RESULTS

The thermal maps were memorized using the dedicated software, IRBIS 3 Plus. At first, the thermal maps that registered the highest temperature, when the drill exits the work piece, were identified (figure 6, 7 and 8).

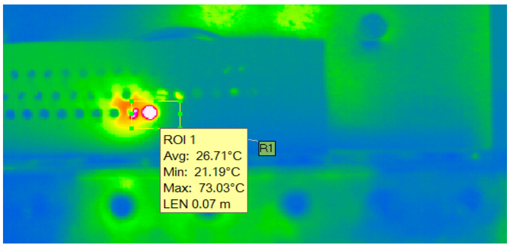

Fig.6. Thermal map registered when drilling with WZ-02

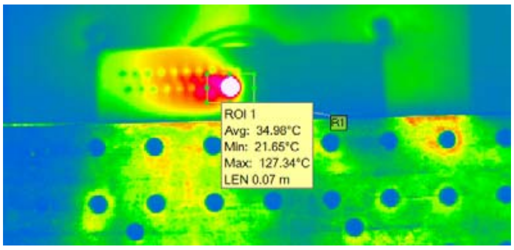

Fig.7. Thermal map registered when drilling with WZ-01

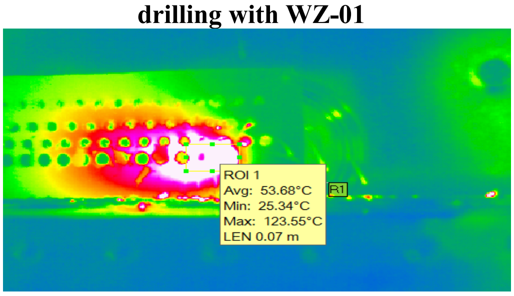

Fig.8. Thermal map registered when drilling with WZ-03

As shown in the previous pictures, the interpretation software, allows the user to isolate an area and to determine the minimal and the maximal temperature registered in that area. It can be observed that the temperatures measured, in the same process conditions, were extremely high when using WZ-01 and WZ-03 (over 120°C), in comparison with the temperatures reached when using WZ-02. The temperatures measured, when drilling with WZ-02, were with over 50°C lower than the temperatures measured when processing with the other two tools. For determining the mathematical model the software De- sign Expert 8.0 was used, which uses the surface response method (RSM).

At first the predominant factors (machining parameters) that have an influence on process temperature were identified and then the experiments were conducted. The factors that influence the process temperature are spin- dle speed ((n) varied from 1000 rpm up to 3000 rpm) and the feed ((f) from 0.1 up to 0.2 mm/rot). After these factors are introduced the software generates a program for the experiments, a design matrix as shown in table 3. Further the experiments were conducted according to the designed matrix (table 3), and the response factors were introduced (in our case the maximal temperature measured).

Design matrix *Table 3*

Factor 1 A: spindle speed [Rot/min]	Factor 2 B: feed [Mm/rot]	Response Temperature [°C]
2000	0.15	72.5
2000	0.1	74.5
2000	0.15	72
2000	0.15	71.5
2000	0.15	70.5
1000	0.2	67.4
3000	0.1	70.5
3000	0.15	68.5
3000	0.2	67.5
2000	0.15	72
1000	0.15	73.5
1000	0.1	81
2000	0.2	68.5

Further the mathematical model was analyzed, using the RSM method, as shown in the next table, and the software suggested the underlined model.

Model suggestion *Table 4*

Model	Std. Dev.	R^2	Adj. R^2	Pred. R^2	PRESS
Linear	1.81	0.79	0.74	0.43	88.44
2FI	0.73	0.96	0.95	0.92	11.22
Quadratic	0.8	0.97	0.95	0.84	24.45

Afterwards the adequacy of the developed model was checked using the ANOVA method (table 5). The coefficient R^2= 0.96, shows that the model is significant. This determination coefficient R^2, calculates the correlation between experimental results and the calculated results. As long as the value of R^2 is very close to 1, the chosen mathematical model is very precise. The "Pred R-Squared" of 0.9288 is in reasonable agreement with the "Adj R-Squared" of 0.959, values shown in table 4, meaning that the model is significant.

Anova analysis *Table 5*

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	152.74	3	50.91	95.37	< 0.0001
A-Speed	39.52	1	39.52	74.04	< 0.0001
B-Feed	85.12	1	85.12	159.46	< 0.0001
AB	28.09	1	28.09	52.62	< 0.0001
Residual	4.8	9	0.53		
Lack of Fit	2.5	5	0.5	0.87	0.56
Pure Error	2.3	4	0.57		
Cor Total	157.54	12			

The Model F-value of 95.37 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate that model terms are significant. In this case A, B, AB are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.
The "Lack of Fit F-value" of 0.87 implies the Lack of Fit is not significant relative to the pure error. Non-significant lack of fit is good because we want the model to fit.

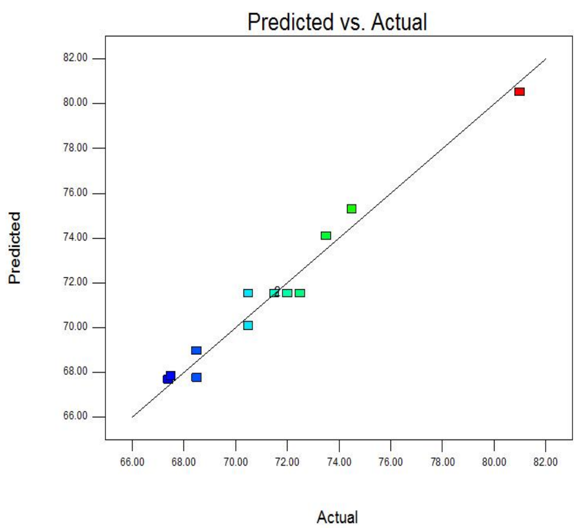

Fig. 9. Corelation grafic

Further, the experimental data and the predicted data by using the aforesaid model are plotted as shown in figure 6, indicating a good correlation, as the determination factor, R^2, shows. After the ANOVA analysis the mathematical equation in terms of actual factors was determined as following:

T=103.8641-0.010517*n-181.33 * f+0.053 *n*f [°C] (2)

The 3D and 2D representation of the temperature variation in relation with the process parameters is shown in the next two figures.

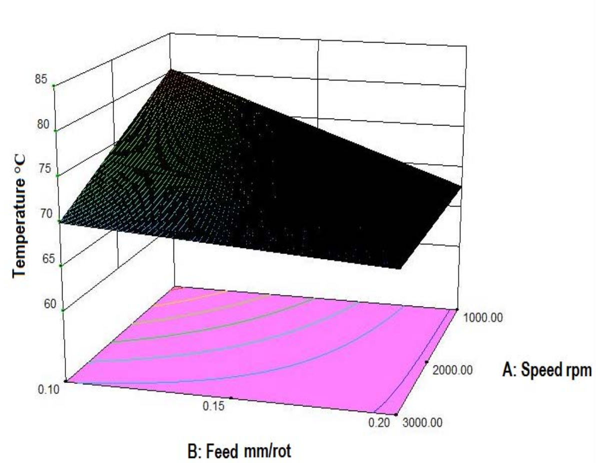

Fig. 10. 3D surface

The process temperature rises inversely related with the feed and spindle speed. So, the highest temperature will be registered when processing fiber-reinforced composites at a speed of 1000 rpm and a feed rate of 0.1 mm/rot. The lowest temperature was registered when processing at a speed of 3000 rpm and a feed rate of 0.2 mm/rot.

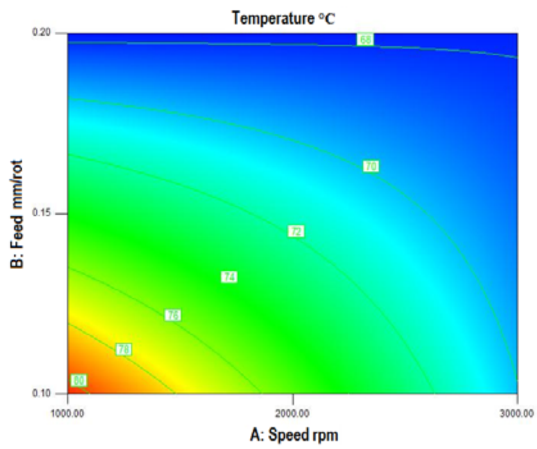

Fig. 11. 2D surface

Process temperature increases, up to 81°C, with the decrease of the cutting speed and the decrease of the feed. Process temperature decreases, down to 67°C, with the increase of the cutting speed and the increase of the feed.

5. CONCLUSIONS

The machining of new materials such as carbon fibre reinforced materials represents a challenge for the industry, research and science. Researches presented in this paper show that the tool geometry influences the process temperatures when drilling fibre reinforced composites. Because of the thermo-physical properties of the fibre reinforced composites the temperatures during the machining process are very high. The tests presented in this paper show that in order to have lower temperatures, when drilling CFRP composites, it's recommended to use speeds, from 1000 up to 3000 rpm.

High process temperatures influence the quality of the processed part. When machining with the carbide drill that has a peak angle of 155° the temperatures registered with the IR camera didn't overcome 85°C. We can also conclude that the process temperatures have a big influence on the surface quality, as the measured roughness Ra was minimal when the temperatures didn't overcome 85°C. On the other hand when the holes were processed with the other two drills, machining temperatures reached over 150°C affecting the surface quality as the measured roughness Ra overcome in some cases 18 µm.

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Determinarea temperaturilor de aşchiere la prelucrarea materialelor compozite armate cu fibre de carbon

Aceasta lucrare prezintă cercetări privind influenta temperaturilor de aschiere inregistrate la prelucrarea materialelor compozite armate cu fibre de carbon aupra calitatii suprafetei obtinute. Lucrarea sintetizează un model matematic de calcul al temperaturii de aşchiere, la prelucrarea materialelor compozite armate cu fibre de carbon. În final modelele sunt validate cu ajutorul experimentelor efectuate de autor în laboratoarele institutului IFW Stuttgart.

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