Study of Cumulative Influence of Drilling Parameters on Machinability of Glass Fibre-reinforced Polymeric Composites

CONSTANTIN OCNARESCU[1]*, SERGIU TONOIU[1], MADALIN-GABRIEL CATANA[1], MARIA OCNARESCU[2]
[1]University “Politehnica” of Bucharest, 313 Splaiul Independenţei, 060042, Bucharest, Romania
[2]“Doamna Stanca” High School, 52 Porumbacu Str., 060366, Bucharest, Romania

In-homogeneity, anisotropy, abrasiveness, and low thermal conductivity of glass fibre-reinforced polymeric composites make their machining more difficult as compared to metals. This fact explains numerous machinability studies that were carried out for some of these materials. The experiments presented in this paper were devised to assess the machinability in drilling process of a Romanian made glass fibre-reinforced polymeric composite.

Keywords: polymeric composites, machinability, drilling

Composites are materials made of two or more constituents (phases) not soluble in each other, that are mixed at macroscopic level. Synthetic composites made of reinforcement fibres (one phase) and matrices (another phase) of other material were introduced since 1940s to replace metals in many civilian, military, and aerospace applications [1]. Polymer matrix composites are the most frequently used due to their low cost, high strength and simple manufacturing processes [2]. Plenty of design and fabrication methods are available for different polymeric composite materials [3, 4, 5, 6]. Due to their lower costs, glass fibre-reinforced plastics are the most commonly used polymeric composites [2].

Despite that product components made of glass fibre-reinforced polymers (GFRP) are manufactured to near-net shape, conventional machining operations are often applied on them for meeting prescriptions. However, the in-homogeneity, anisotropy and abrasive nature of the GFRP, make their machining problematic. That is why a lot of experimental work has been done to asses the machinability of different GFRP in varied machining processes [1, 2, 7-14]. Special attention was paid to drilling, the most common machining process of GFRP [1, 2, 9-14].

Current paper studies the cumulative influence of drilling parameters (i.e., speed, feed, and depth of cut) on machinability of a Romanian made GFRP including AROPOL S 599 polyester resin and 40% content of glass fibres EC12-2400-P1800 (65). Machinability is assessed by values of thrust force, cutting torque, and tool wear obtained in drilling operation.

Experimental part

The following equipment was used for performing the experiments:

- *drilling machine* GU25, with the following main characteristics:
  - power P = 2.3 kW;
  - range of spindle revolution 28÷2240 rev/min;
  - range of feed rate 0.08÷0.25 mm/rev;

- *spiral drills* with the following main characteristics:
  - material: high speed steel (HSS);
  - point angle 2k = 130^0;
  - range of diameters 6÷12 mm;
  - code: A102 (produced by DORMER);

- *GFRP probes* with the following structure:
  - polyester resin AROPOL S 599;
  - 40% glass fibres EC12-2400-P1800 (65);

- *experimental stand* with the following components:
  - transducer for measuring thrust force, made by TCM. Department, in University “Politehnica” of Bucharest, Romania [10];
  - transducer for measuring cutting torque, type Hottinger T4A HBM;
  - MGC amplifier, produced by Hottinger;
  - data acquisition board, type DAQ Pad 6020E;
  - PC with LabVIEW software;
  - universal microscope for measuring tool wear parameter VB.

A schematic representation of experimental stand is presented in figure 1.

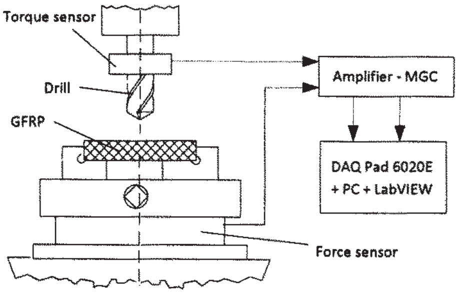

Fig. 1. Sketch of experimental stand

By drilling GFRP probes with different combinations of machining parameters (i.e., drill diameter, feed rate, spindle revolution, cutting speed and cutting time) and measuring corresponding values of machinability parameters (i.e., thrust force, cutting torque, and tool wear VB), three sets of experimental data were created. Values of tool wear VB were measured after constant drilling lengths of 2000 mm or 4000 mm, obtained by continuous drilling of 200 or 400 holes in 10 mm-thick probes. Relevant experimental results that were used for determining mathematical relations between the three machinability parameters and related machining parameters are shown in table 1-3.

General formula provided by technical literature [1, 2, 10, 13] for the calculation of thrust force is:

$$F = C_F \cdot D^{x_F} \cdot f^{y_F} \cdot v_c^{z_F} \text{ [N]} \qquad (1)$$

---

* *email: constantinocnarescu@yahoo.com*

Table 1
EXPERIMENTAL RESULTS FOR SETTING THRUST (AXIAL) FORCE

Exp. no.	Drill diameter D [mm]	Feed rate f [mm/rev]	Spindle revolution n [rev/min]	Cutting speed v_c [m/min]	Thrust force F [N]
1	10	0.25	355	11.15	98.82
2	6	0.25	355	6.69	48.82
3	10	0.125	355	11.15	72.82
4	10	0.25	710	22.30	93.88
5	12	0.125	710	26.76	90.12
6	8	0.25	355	8.92	73.52

Table 2
EXPERIMENTAL RESULTS FOR DETERMINING CUTTING TORQUE

Exp. no.	Drill diameter D [mm]	Feed rate f [mm/rev]	Spindle revolution n [rev/min]	Cutting speed v_c [m/min]	Cutting torque T [Nm]
1	10	0.25	355	11.15	0.840
2	6	0.25	355	6.69	0.415
3	10	0.125	355	11.15	0.619
4	10	0.25	710	22.30	0.798
5	12	0.125	710	26.76	0.750
6	8	0.25	355	8.92	0.625

Table 3
EXPERIMENTAL RESULTS FOR DERIVING TOOL WEAR VB

Exp. no.	Drill diameter D [mm]	Feed rate f [mm/rev]	Spindle revolution n [rev/min]	Cutting speed v_c [m/min]	Drilling length L [mm]	Drilling time t [min]	Drill wear VB [mm]
1	12	0.125	1120	42.223	2000	14.28	0.348
2	8	0.125	1120	28.148	2000	14.28	0.296
3	12	0.125	1120	42.223	4000	28.56	0.819
4	12	0.08	1120	42.223	2000	22.32	0.313
5	12	0.125	355	13.383	2000	45.37	0.468
6	10	0.50	355	11.152	2000	22.54	0.515
7	6	0.08	1120	21.111	2000	22.32	0.232

By linearization of equation (1) with the help of logarithm, the following relationship comes out:

$$\lg C_F + x_F \lg D + y_F \lg f + z_F \lg v_c = \lg F \qquad (2)$$

By giving to parameters D, f, v_c, and F in equation (2) the values provided by the first four experiments in table 1, the following linear inhomogeneous system of four equations with four unknowns was obtained:

$$\begin{cases} \lg C_F + x_F \lg 10 + y_F \lg 0.25 + z_F \lg 11.15 = \lg 98.82 \\ \lg C_F + x_F \lg 6 + y_F \lg 0.25 + z_F \lg 6.69 = \lg 48.82 \\ \lg C_F + x_F \lg 10 + y_F \lg 0.125 + z_F \lg 11.15 = \lg 72.84 \\ \lg C_F + x_F \lg 10 + y_F \lg 0.25 + z_F \lg 22.30 = \lg 93.88 \end{cases} \qquad (3)$$

System (3) has the following solution: $C_F = 7.636$; $x_F = 1.454$; $y_F = 0.440$; $z_F = - 0.074$.

Thus, the formula for thrust force on drilling the studied GFRP material results as follows:

$$F = 7.636 \cdot D^{1.454} \cdot f^{0.440} \cdot v_c^{-0.074} \text{ [N]} \qquad (4)$$

The accuracy of equation (4) was tested with data of the last two experiments in table 1, and calculation errors lower than 2 % were found.

General relationship found in technical literature [1, 2, 10, 11] for the calculation of cutting torque is:

$$T = C_M \cdot D^{x_M} \cdot f^{y_M} \cdot v_c^{z_M} \text{ [Nm]} \qquad (5)$$

The linearization of equation (5) by use of logarithm function gives the following alternative relationship:

$$\lg C_M + x_M \lg D + y_M \lg f + z_M \lg v_c = \lg T \qquad (6)$$

By giving to parameters D, f, v_c, and T in equation (6) the values provided by the first four experiments in table 2, the following linear inhomogeneous system of four equations with four unknowns was obtained:

$$\begin{cases} \lg C_M + x_M \lg 10 + y_M \lg 0.25 + z_M \lg 11.15 = \lg 0.840 \\ \lg C_M + x_M \lg 6 + y_M \lg 0.25 + z_M \lg 6.69 = \lg 0.415 \\ \lg C_M + x_M \lg 10 + y_M \lg 0.125 + z_M \lg 11.15 = \lg 0.619 \\ \lg C_M + x_M \lg 10 + y_M \lg 0.25 + z_M \lg 22.30 = \lg 0.798 \end{cases} \qquad (7)$$

System (7) has the following solution: $C_M = 0.065$; $x_M = 1.454$; $y_M = 0.440$; $z_M = - 0.074$.

It results the following formula for cutting torque on drilling the studied GFRP material:

$$T = 0.065 \cdot D^{1.454} \cdot f^{0.440} \cdot v_c^{-0.074} \text{ [Nm]} \qquad (8)$$

The accuracy of equation (8) was checked with data provided by the last two experiments in table 2, and calculation errors lower than 2 % were found.

General relationship given by technical literature [2, 9, 10, 14] for the calculation of drill wear VB is:

$$VB = C_{VB} \cdot D^{x_{VB}} \cdot f^{y_{VB}} \cdot v_c^{z_{VB}} \cdot t^{w_{VB}} \text{ [mm]} \qquad (9)$$

By linearization of equation (9) with logarithm function, the following equation was obtained:

$$\lg C_{VB} + x_{VB} \lg D + y_{VB} \lg f + z_{VB} \lg v_c + w_{VB} \lg t = \lg VB \qquad (10)$$

By giving to parameters D, f, v_c, t, and VB in equation (10) the values provided by the first five experiments in table 3, the following linear inhomogeneous system of five equations with five unknowns is created:

$$\begin{cases} \lg C_{VB} + x_{VB} \lg 12 + y_{VB} \lg 0.125 + z_{VB} \lg 42.223 + w_{VB} \lg 14.28 = \lg 0.348 \\ \lg C_{VB} + x_{VB} \lg 8 + y_{VB} \lg 0.125 + z_{VB} \lg 28.149 + w_{VB} \lg 14.28 = \lg 0.296 \\ \lg C_{VB} + x_{VB} \lg 12 + y_{VB} \lg 0.125 + z_{VB} \lg 42.223 + w_{VB} \lg 28.56 = \lg 0.819 \\ \lg C_{VB} + x_{VB} \lg 12 + y_{VB} \lg 0.08 + z_{VB} \lg 42.223 + w_{VB} \lg 22.32 = \lg 0.313 \\ \lg C_{VB} + x_{VB} \lg 12 + y_{VB} \lg 0.125 + z_{VB} \lg 13.383 + w_{VB} \lg 45.07 = \lg 0.468 \end{cases} \qquad (11)$$

System (11) has the following solution: $C_{VB} = 0.03$; $x_{VB} = - 0.578$; $y_{VB} = 1.473$; $z_{VB} = 0.978$; $w_{VB} = 1.235$.

It results the following formula for tool wear VB on drilling the studied GFRP material:

$$VB = 0.03 \cdot D^{-0.578} \cdot f^{1.473} \cdot v_c^{0.978} \cdot t^{1.235} \text{ [mm]} \qquad (12)$$

The accuracy of equation (12) was tested with data of the last two experiments in table 3, and calculation errors lower than 2 % were found.

Results and discussions

Graphical representations of dependencies (4), (8), and (12) for drilling conditions taken into account during the experimental part are presented in figure 2 to 11.

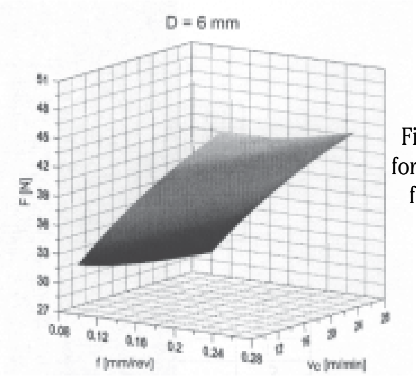

Fig. 2. Variation of thrust force with feed and speed for the 6 mm diameter spiral drill

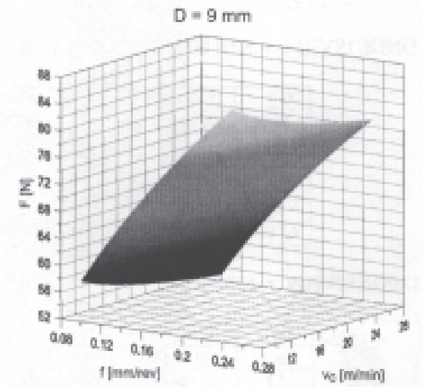

Fig. 3. Variation of thrust force with feed and speed for the 9 mm diameter spiral drill

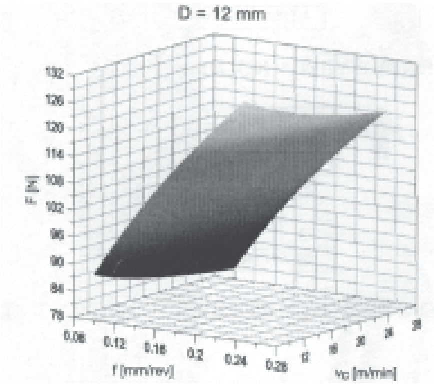

Fig. 4. Variation of thrust force with feed and speed for the 12 mm diameter spiral drill

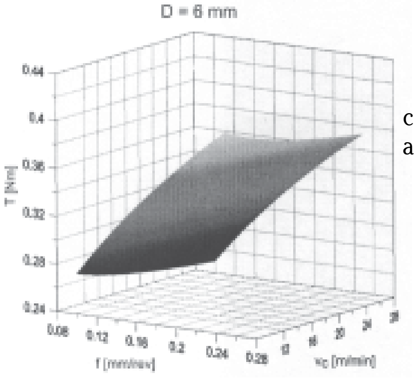

Fig. 5. Variation of cutting torque with feed and speed for the 6 mm diameter spiral drill

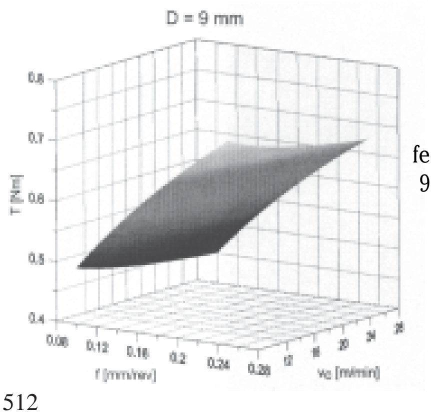

Fig. 6. Variation of cutting torque with feed and speed for the 9 mm diameter spiral drill

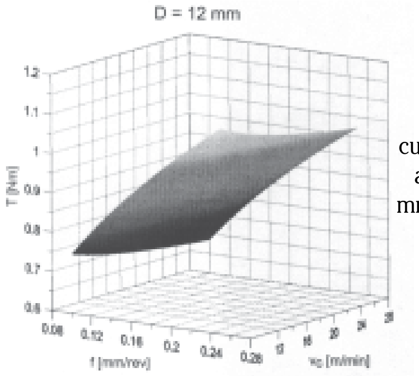

Fig. 7. Variation of cutting torque with feed and speed for the 12 mm diameter spiral drill

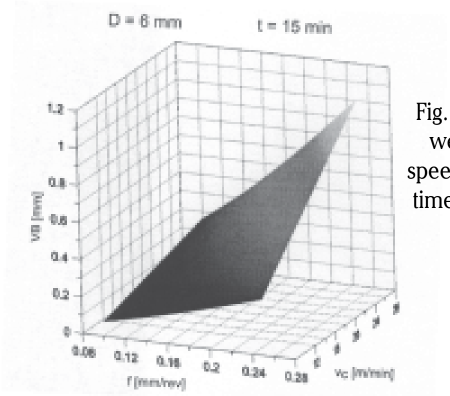

Fig. 8. Variation of tool wear with feed and speed for 15 min cutting time of 6 mm diameter spiral drill

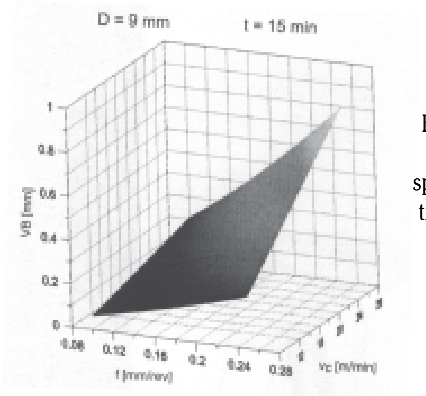

Fig. 9. Variation of tool wear with feed and speed for 15 min cutting time of 9 mm diameter spiral drill

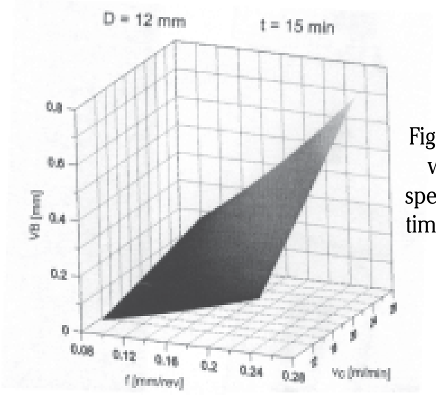

Fig. 10. Variation of tool wear with feed and speed for 15 min cutting time of 12 mm diameter spiral drill

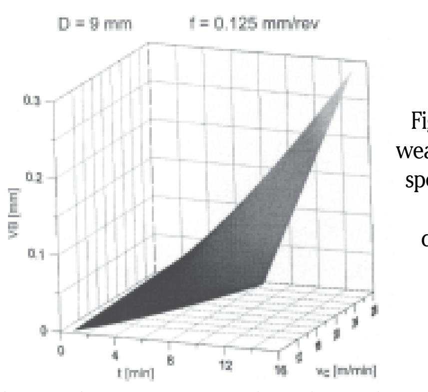

Fig. 11. Variation of tool wear with cutting time and speed for 0.125 mm/rev feed rate of 9 mm diameter spiral drill

The following ranges were used within the graphical plots for the variation of drilling process parameters: D [mm] = {6, 9, 12}; f [mm/rev] = 0.1÷0.25; v_c [m/min] = 8÷28; t [min] = 1÷15.

In figure 2 to 4 can be noticed the exponential increase of thrust force with increase of drilling feed rate and decrease of cutting speed. Also, for the same pair of feed and speed values, thrust force increases with drill diameter.

Figure 5 to 7 show the exponential increase of cutting torque with increase of drilling feed rate and decrease of cutting speed. Also, an increase of cutting torque with drill diameter can be observed.

Figure 8 to 10 show that for the same cutting time drill wear increases with both feed rate and cutting speed, and decreases with diameter of drill. Moreover, fig. 11 proves the increase of drill wear with cutting time.

Conclusions

This paper presents a set of experiments carried out for demonstrating cumulative influence of drilling parameters on machinability of a GFRP containing AROPOL S 599 polyester resin and 40% content of glass fibres EC12-2400-P1800 (65).

Experimental data were used to determine specific dependency relationships between thrust force, cutting torque, and tool wear (machinability parameters) and drilling speed, feed, and diameter (process parameters). In addition, tool wear is influenced also by drilling time.

For graphical representation of dependencies were used two process parameters simultaneously, in order to evaluate their cumulative influence on machinability parameter.

Obtained results are useful in industrial practice and for future studies concerning other GFRP materials or machining processes.

References

1.SHEIKH-AHMAD, J., Machining of Polymer Composites, Springer Science+Business Media, New York, 2009

2.KRISHNARAJ, V., ZITOUNE, R., DAVIM, J.P., Drilling of Polymer-Matrix Composites, SpringerBriefs in Applied Sciences and Technology, Springer Science+Business Media, Heidelberg, 2013

3.OWEN, M.J., MIDDLETON, V., JONES, I.A., Integrated Design and Manufacture Using Fibre-Reinforced Polymeric Composites, Woodhead Publishing Limited, Cambridge, 2000

4.ADVANI, S., HSIAO, K.-T., Manufacturing Techniques for Polymer Matrix Composites (PMCs), Woodhead Publishing Limited, Cambridge, 2012

5.HADAR, A., BORDEASU, I., MITELEA, I., VLASCEANU, D., Validarea experimentală a unui model teoretic folosit în calculul de rezistenţă al structurilor realizate din materiale compozite, Mat. Plast., **43**, no. 1, 2006, p. 70

6.ILIESCU, M., SPANU, P., NUTU, E., MIHON, L., Experimental and Theoretical Studies on Mechanical Characteristics of an Important Composite Material, Mat. Plast., **46**, no. 1, 2009, p. 62

7.AZMI, A.I., LIN, R.J.T., BHATTACHARYYA, D., Tool Wear Prediction Models During End Milling of Glass Fibre-Reinforced Polymer Composites, Int. Journal of Advanced Manufacturing Technology, **67**, 2013, p. 701–718

8.ILIESCU, M., SPANU, P., COSTOIU, M., Glass Fibres Reinforced Polymeric Composites - Statistic Models of Surface Roughness, Mat. Plast., **44**, no. 4, 2007, p. 365

9.JIMENO, J.T., Analysis of Tool Wear After Machining of Fibre Reinforced Polymers, PhD Thesis, Vienna University of Technology, Wien, 2012

10. OCNĂRESCU, M., Cercetări privind prelucrabilitatea prin găurire şi lărgire a materialelor compozite polimerice, Teză de doctorat, U.P.B., Bucureşti, 2007

11. OCNĂRESCU, C., VLASE, A., OCNĂRESCU, M., SINDILA, G., Determination of New Equations for Torque when Drilling in Polymeric Materials, Mat. Plast., **43**, no. 5, 2008, p. 301

12. PRABHU, P., JAWAHAR, P., BALASUBRAMANIAN, M., Machinability Study of Hybrid Nanoclay-Glass Fibre Reinforced Polyester Composites, International Journal of Polymer Science, 2013, Hindawi Publishing, p. 1-11

13. VLASE, A., OCNĂRESCU, C., OCNĂRESCU, M., Processing Composites Materials with Polymeric Matrix, Mat. Plast., **44**, no. 2, 2007, p. 118

14. VLASE, A., OCNĂRESCU, C., OCNĂRESCU, M., BAYER, M., New Equations for Determining Tool Wear when Machining Polymeric Materials, Mat. Plast., **44**, no. 4, 2007, p. 374

Manuscript received: 12.02.2015