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Selected Energy Aspects of GFRP Drilling

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Summary: Original research results of GFRP drilling, using HSS steel drill bit, process energy indicators were presented in the article. The research stand was a 5-axis DMU50 machining center, equipped with a Kistler force gauge with a signal amplifier and a DAQ data acquisition system. The obtained measurement data were processed using the force gauge manufacturer's software, a spreadsheet and the Statistica statistical data analysis package. As a result of the analysis, on the basis of technological parameters and measured and determined values of cutting force and torque, changes in the values of selected process status indicators were determined; total and specific energy (per unit of material volume removed) generated when making individual holes as a function of the number of holes made. Moreover, the empirical value of the specific cutting resistance k_c was determined. As a result of the experimental work carried out and the analysis of available literature in the scope of the article, conclusions were formulated regarding the energy indicators of the process – total and specific energy generated during processing, as well as possible causes of thermal damage to the processed material were indicated.

Key words: drilling, GFRP, composite material, material removal rate, specific cutting energy

1. Introduction

The development of materials engineering has resulted in a significant increase in the use of polymer composite materials for making machine elements. Drilling is a common procedure when producing elements made of composites. The properties of the polymer composite material, especially low thermal conductivity and difficult machinability of the reinforcement material, cause difficulties when making holes. As a result, drilling holes in such materials is generally carried out using low cutting speeds and feed rates [15], however, there are also reports related to high-performance drilling machining of GFRP [13]. Proper selection of technological parameters allows minimizing the occurrence of delamination and thermal damage to the material (burning). The available literature contains many publications on tool geometry [4] and the selection of drilling machining parameters when drilling holes in polymer composite materials in terms of their impact on machining forces [1, 3, 7, 12] and delamination [8, 9, 11, 12], commonly referred to as delamination coefficient. Work is also carried out on modeling [2, 6, 10, 14] of the composite materials processing process. However, there are only few scientific reports on the energy aspects of drilling machining of polymer composite materials [5]. The article presents the results of original research on high-performance dry drilling in GFRP in terms of analysis of the energy generated in the process and thermal damage to the processed material.

2. Methodology and technique of the experiment

The experiment was performed on a 5-axis DMU50 DMG-Mori milling center, on which a Kistler 9257B piezoelectric force meter was installed, connected to a 5017 signal amplifier. The test stand was equipped with a DAQ 5697A data acquisition system. Data acquisition and processing were performed using Dynoware 2825D-02 software. The force meter had an attached calibration card, on the basis of which the sensitivities of individual channels were determined, resulting in measurement results of forces in N and torque in Nm. The software has a database structure enabling post-processing. The orientation of the X, Y, Z axes of the force gauge was the same as the orientation of the X, Y, Z axes of the machine tool. The basic technical data of the 3-component force gauge are summarized in Table 1.

Polymer composite material GFRP drilling conditions were:
- material thickness 8mm,
- 8mm HSS EI 13 Würth drill bit, standard geometry,
- cutting speed v_c = 150 m/min, feedrate v_f = 300 mm/min,
- dry drilling (neither fluid coolant nor compressed air were used),
- straight drilling cycle (without removing and breaking chips),
- number of holes made – 60.

Table 1. 3-component Kisler 9257B dynamometer main technical data

Range Fx , Fy , Fz Fz for Fx and Fy≤0.5 Fz	Fx , Fy , Fz Fz	kN kN	-5 ... 5 -5 ... 10
Threshold	-	n	<0.01
Sensitivity (calibrated)	Fx Fy Fz	PC /N PC /N PC /N	- 7.92 - 7.90 - 3.69
Hysteresis , all ranges	-	%FSO	≤0.5
cross-talk	-	%	≤±2
natural frequencies	fn (x,y,z)	kHz	≈3.5
natural frequencies (mounted on flanges	fn (x,y) fn (z)	kHz kHz	≈2.3 ≈3.5

3. Measurements

The maximum values of cutting forces and torque were determined for individual experimental points (holes) – Figure 1.

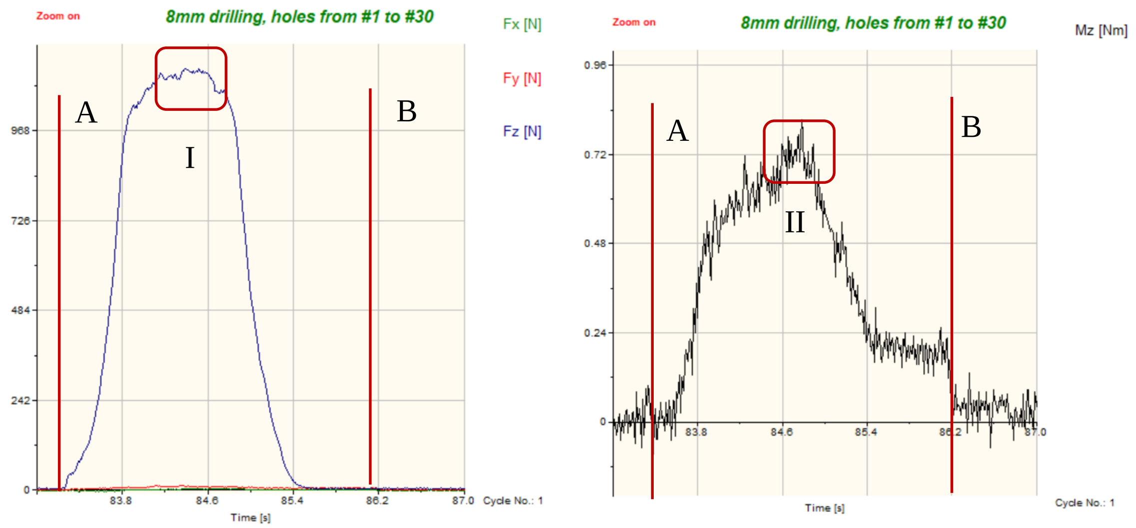

Fig. 1. Fx, Fy, Fz and Mz values changes during GFRP drilling, hole #18, A – drill entry, B – toll backward, I – area for determining the maximum values of Fx , Fy , Fz , II – area for determining the maximum values of Mz

Digitally unfiltered values were analyzed; a hardware low-pass filter of the amplifier 10 Hz and sample rate 100 Hz was used. The obtained volumetric machining efficiency for the assumed parameters was 15000 mm^3/min and the time of making a single hole was about 2 s. Maximum acquired cutting force measurement results; F_{xmax}, F_{ymax}, F_{zmax} in N and torque M_{zmax} in Nm were presented in the Table 2.

Table 2. F_{xmax}, F_{ymax}, F_{zmax} in N and torque M_{zmax} in Nm values for each hole

no	F_{xmax}	F_{ymax}	F_{zmax}	M_{zmax}	no	F_{xmax}	F_{ymax}	F_{zmax}	M_{zmax}
1	4.88	6.26	256.3	0.59	31	3.36	12.51	1336	0.84
2	2.44	5.65	528	0.39	32	0.92	15.41	1459	0.67
3	2.44	11.14	704	0.49	33	0.92	10.07	1471	0.63
4	2.59	9.30	768.1	0.54	34	2.29	7.48	1506	0.78
5	1.98	6.10	859.1	0.58	35	2.29	11.29	1529	0.76
6	1.83	9.61	891.4	0.63	36	1.68	7.63	1563	0.79
7	3.66	6.71	965.6	0.70	37	2.29	7.02	1560	0.85
8	1.83	5.34	985.7	0.75	38	2.75	4.88	1468	0.82
9	1.53	4.43	980.5	0.73	39	2.44	4.73	1386	0.90
10	3.05	5.04	908.2	0.76	40	3.05	4.43	1283	0.79
11	2.75	3.82	963.7	0.75	41	1.53	3.05	1253	0.85
12	3.05	4.73	1029	0.63	42	4.73	3.66	1421	0.66
13	3.20	4.27	1087	0.66	43	3.66	4.27	1537	0.84
14	2.44	4.12	1156	0.69	44	4.27	4.27	1601	0.81
15	2.44	6.26	1210	0.69	45	5.34	5.65	1640	0.78
16	3.97	6.10	1214	0.64	46	4.88	6.56	1617	0.74
17	2.59	8.70	1175	0.70	47	3.36	9.61	1535	0.74
18	4.27	12.66	1134	0.81	48	4.73	9.92	1618	0.71
19	2.90	16.63	1163	0.73	49	4.43	12.97	1542	0.76
20	5.04	19.23	1074	0.96	50	3.82	18.77	1379	0.82
21	15.72	20.90	1075	1.98	51	5.49	19.99	1370	0.85
22	13.73	17.85	1208	1.33	52	7.17	17.85	1562	0.80
23	8.70	17.40	1323	1.14	53	7.63	15.26	1674	0.82
24	8.85	20.75	1237	1.23	54	11.14	12.36	1654	0.97
25	11.75	12.21	1297	0.98	55	11.29	10.07	1658	0.98
26	11.29	11.90	1302	0.95	56	12.21	5.95	1588	0.86
27	10.07	10.83	1404	0.94	57	13.58	5.04	1570	0.75
28	11.75	9.31	1265	0.92	58	9.92	4.12	1442	0.59
29	11.60	3.66	1158	0.89	59	5.34	2.44	1248	0.57
30	10.38	4.73	1049	1.11	60	1.37	2.75	1076	0.79

4. Analysis and discussion

In order to determine the value of the net cutting power, the equation (1) was used:

$$P = \frac{M*\pi*n}{30}\ [\text{W}] \tag{1}$$

where:

P – net cutting power [W],
M – torque during drilling [Nm],
n – number of drill revolutions per unit of time [rpm].

The total energy E_{tot} generated in the process of drilling each hole took form (2):

$$E_{tot} = P * t = \frac{M*\pi*n}{30} * t \text{ [J]} \tag{2}$$

where:

t – machining time [s].

The specific cutting energy was determined based on relationship (3):

$$E_k = \frac{M*\omega*1000}{MRR} \text{ [J/cm}^3\text{]} \tag{3}$$

where:

ω – angular velocity in rad/s,

MRR – material removal rate in mm^3/s, determined on the basis of the feed rate and tool diameter.

Values of specific cutting force coefficient were determined from the relationship (4):

$$P = \frac{f_n*v_c*D_c*k_c}{240} \text{ [W]} \tag{4}$$

where:

f_n – feed per revolution [mm/rev],

D_c – drill diameter [mm],

k_c – specific cutting force coefficient [N/mm^2].

The obtained analysis results are presented graphically in Figure 2. The left vertical axis concerns the value of total energy E_{tot} , expressed in J and specific cutting energy E_k, expressed in J/cm^3 . The right vertical axis concerns the value of net cutting power P, expressed in W, and specific values cutting force coefficient k_c, expressed in N/mm^2. The horizontal axis shows the numbers of individual holes. The obtained results were characterized by a significant range in the obtained values of the measured and determined quantities, despite the unchanged settings (technological parameters). The reasons for obtaining such results could be: variable properties of the processed material due to the different distribution of glass fibers in the composite, heterogeneity resulting from the different distribution of the matrix, the possibility of occurrence of inclusions (e.g. gas cavities), tool wear and variable energy dissipation conditions. The average values of individual values obtained in the experiment were:

- E_{tot} – 1063 J,
- E_k – 2016 J/cm^3,
- P – 506 W,
- k_c – 2025 N/mm^2.

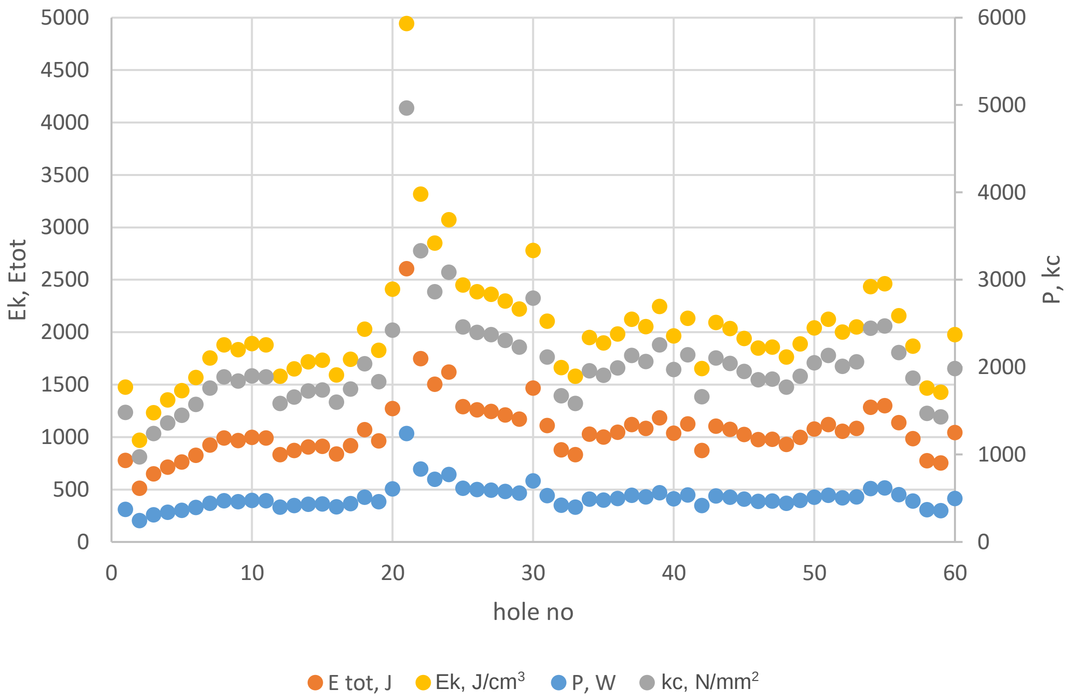

Fig. 2. E_{tot}, E_k, P and k_c values changes during GFRP drilling for each hole (1-60)

The energy generated in the drilling process was transferred, primarily, to the chips. Due to the low thermal conductivity of GFRP, there were difficulties in energy dissipation, which resulted in high temperatures of chips remaining on the sample surface and led to significant surface burns, as shown in Figure 3.

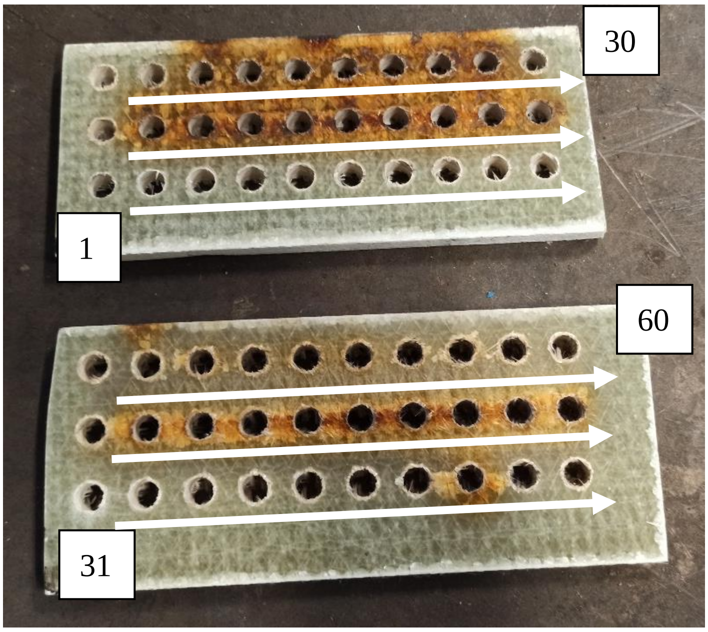

Fig. 3. View of the upper part of the samples, with the numbers of holes and the sequence of treatments marked

The heating of the tool while making individual holes may also have been an important factor – it took 140 seconds to make all the holes in each sample. No interoperative cooling was used. The experiment clearly shows the technological limitations associated with high-efficiency machining of GFRP. Obtained average specific value cutting force coefficient k_c is similar to the value of this coefficient for materials such as austenitic steels or cast iron. Table 3 includes basic statistics made after the experiment.

Table 3. Basic statistics

	Mean	Median	Minimum	Maximum	Variance	Standard deviation	Standard error
F_{xmax}	5.34	3.74	0.92	15.72	15.26	3.91	0.50
F_{ymax}	9.09	7.25	2.44	20.90	27.32	5.23	0.67
F_{zmax}	1265.28	1290.00	256.30	1674.00	88790.21	297.98	38.47
M_{zmax}	0.81	0.78	0.39	1.98	0.05	0.23	0.03
E_{tot}	1063.28	1025.37	510.38	2605.95	89826.31	299.71	38.69
$E_{k.}$	2016.65	1944.74	967.99	4942.51	323121.74	568.44	73.39
P	506.33	488.27	243.04	1240.93	20368.78	142.72	18.42
k_c	2025.30	1953.08	972.14	4963.71	325900.46	570.88	73.69

5. Conclusions

Based on the literature review and the results of own work, the following conclusions were formulated:

- high-performance machining performed by drilling in the GFRP material with a cutting speed of 150 m/min and a feed speed of 300 mm/min resulted in thermal damage on the upper (entrance) side of the machined material,
- the specific cutting force coefficient determined on the basis of analytical calculations, taking into account the cutting torque values obtained as a result of the experiment, reached a significant average value of 2025 N/mm2,
- the obtained values of total and specific energy clearly indicate significant technological risks when performing high-performance drilling in GFRP, related to the low thermal conductivity of the material,
- variable values of cutting forces and torque were observed despite unchanged settings, which indicates different energy dissipation conditions and variable cutting conditions related to tool wear,
- the statistical analysis performed indicates the need to perform a significant number of repetitions when planning experimental work on polymer composite materials cutting due to the heterogeneity of the material and complex energy dissipation conditions.

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