Experimental Research on the Roughness of Surfaces Processed Through Milling Polyamide Composites

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For determining the optimal conditions of the cutting process (material and tool geometry, process parameters), quantitative data are necessary concerning the roughness of surfaces. Using experimental research methods, this work aims at determining equations between surface roughness and parameters of the milling, process for some polyamides samples (PA66, PA66 – GF30 and PA66 MoS_2). PA66, PA66 – GF30 and PA66 MoS_2 polyamides are technical thermoplastics with excellent mechanical and physical properties, increasingly used in industrial machinery.

Keywords: surface roughness, milling, polyamides

Polyamide processing through milling presents some characteristics different from metal milling, in terms of the variation in value of output and input parameters [2,4,10].

The cutting process through milling represents approximately 25% of all polyamide cutting processes.

Machinability can be assessed following several criteria, of which the most important are: tool life, the size of the cutting forces, of power consumed, of the specific cutting force and, last but not least, surface roughness [3.10.11].

In specialized literature, especially in the case of metal processing, certain values of v, f_{th} and t are known to influence the roughness of the surface processed; nevertheless, there is not enough data about the importance of this influence when polyamides are milled.

Surface roughness is a characteristic that can influence both dimensional precision, the mechanical performance of the parts and production costs [9]. For these reasons, research has been conducted on the study of the influence that cutting process parameters have on surface roughness, with a view to optimizing it [7].

The main purpose of this work is to obtain data about the influence that each of the input values of v, f_{th} and t has on the roughness parameter R_a.

The materials we analyzed in terms of the surface roughness obtained through polyamide milling have never been studied în other research works.

In the following, will be presented information about the milling of some fibreglass reinforced plastic composite materials in the experimental works of Davim, Reis and Antonio [6]. The two materials studied were 65% fibreglass reinforced polyesters, the Viapal VUP 9731 unsaturated polyester and the ATLAC 382-05 polyester. The authors found that speeds between 47 and110m/min and feed rates between 0.04 and 0.12mm/rev may yield roughness of the machined surface, the R_a criterion between 1.02 and 2.04μm [6].

In Palanikumar's [8] experimental work, concerning the analysis of surface roughness of processed polymeric materials reinforced with fibreglass, the following may be observed:

-for cutting speeds between 47 and 110 (m/min) and feed rates between 0.04 and 0.12 (mm/rev), the obtained values of roughness, the R_a criterion, ranges between 3 and 8.5μm [8];

- for cutting speeds between 50 and 200 (m/min) and cutting depths between 0.25 and 1.75 (mm/rev), the obtained values of roughness, the R_a criterion, ranges between 1.02 and 2.04 μm [8].

Fetecău and Stan [1] conducted research on the turning of PTFE composites using polycrystalline diamond tools in order to analyze the effect of cutting parameters and the top cutting plate radius on resulting forces and roughness during the processing of the surface.

Modelling the cutting process by milling of composite polyamides

Model used in the experimental research of the cutting process

For the experimental research of the cutting process of ployamides, the empirical model was adopted (fig. 1).

The input values varied were: the material of the part to process; the cutting speed, v, [m/min]; the longitudinal feed, f, [mm/rot]; the cutting depth, t, [mm].

Three types of polyamide used on a large scale were taken into consideration: PA66, PA66 – GF30 and PA66 MoS_2. The first is the basic polyamide and the other two have improvement elements.

The output value analyzed was the roughness of the processed surface (R_a), which will be assessed by

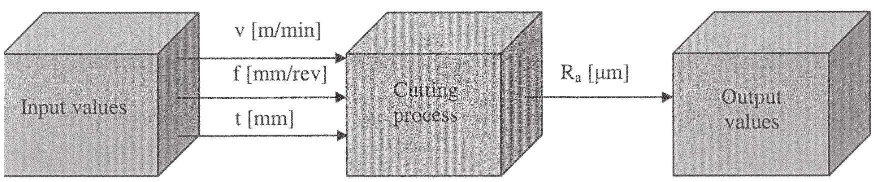

Fig. 1 Empirical model scheme of the cutting process

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parameter R_a, the arithmetic mean deviation of the profile in relation to the average line, expressed in μm (STAS 5730/1-1991).

As model describing the dependence of the output values depending on the input values for each material studied, the linear model was adopted, used on a large scale in the modelling of the cutting process. Considering that the input variables are independent, the equations of the roughness in milling have the form

$$R_a = C_x + a_x \cdot t + b_x \cdot f + c_x \cdot v + d_x \cdot t \cdot f + e_x \cdot t \cdot v + g_x \cdot f \cdot v, \quad (1)$$

where:

C, a, b, c, d, e, g are constants to be determined based on experimental data;

t – cutting depth, in [mm];

f – feed per revolution of the part, in [mm/rev];

v – cutting speed, in [m/min].

The other parameters related to the cutting tool and the cooling conditions were maintained constant.

Experiment plan used in experimental research

The full factorial plan of the 3^3 type was adopted, with the repetition of the experiments in each point. The advantage of this plan is that it allows for the exact determination of the surface roughness and takes into account the interactions between the parameters of the cutting process. Instead, it requires a great number of experiments, which leads to longer periods of time and higher costs for the analysis of the materials used. Therefore, the total number of determinations, N_T, for an experiment was $N_T = 3^3 = 27$ experiments.

Methodology used to process experimental data

Roughness depends on several variables of the cutting process: feed rate, cutting depth, and cutting speed. In the research conducted, the influence of the parameters characterizing the cutting process on roughness is analyzed considering the interaction of the parameters mentioned. A separate study of the influences affects the precision in characterizing the force measured. If the roughness is marked with Y and the other variables with X_1, X_2, X_3, etc., the function $Y = f(X_1, X_2, X_3, \ldots)$ is obtained.

When the output size Y depends on the three input variables, it is given by the equation

$$Y = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_{12}X_1X_2 + A_{13}X_1X_3 + A_{23}X_2X_3 + A_{123}X_1X_2X_3 \quad (2)$$

The data obtained will be processed using the ANOVA method, also known as dispersional analysis or analysis of variance.

The variation technique of dispersion (ANOVA) is needed both to calculate the effects of all factors and interactions between factors and to determine the influence of cutting parameters and the interactions between them, in percentages. The analysis was performed with the help of the Minitab 16 software. To calculate the S/N ratio, the Taguchi method allows for the choosing of the performance characteristic between “smaller is better”, “large is better”, or “normal is better” [11]. The signal noise ratio (S/N ratio) is the ratio between the value wanted and the value unwanted as output characteristics.

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \text{ [db]}. \quad (3)$$

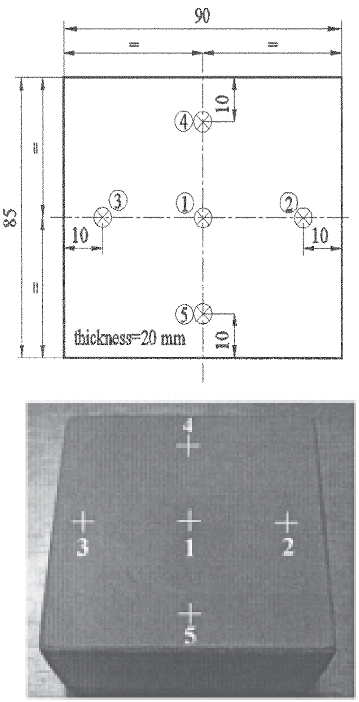

Fig. 2. Specimens to be processed

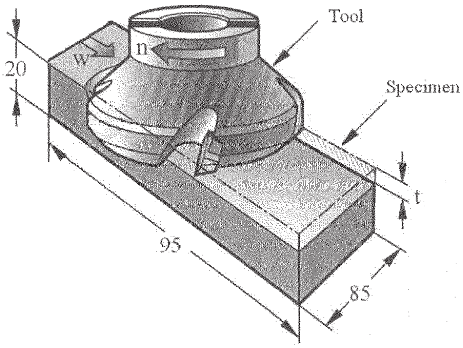

Fig. 3. Cutting scheme

Methods and means used in the experimental research

Specimens used in the experiments

Regarding the dimensions of the specimen, the width l [mm] is established depending on the tool diameter: l=(0.6÷0.8)D (SR ISO 8688-1). For a D=121 mm tool diameter, it results that l=78mm. The 85 mm value will be adopted.

The specimens used for the experiments are shown in figure 2.

Cutting scheme

In view of the experiments, the processing scheme adopted was frontal milling on a VICTOR 55 - FAU processing centre, with a vertical tool axis (fig. 3).

The parameters of the cutting regime corresponding to this scheme are the following:

-v, cutting speed, performed by the number of rotations of the tool, n;

-f_{th}, feed on tooth, performed by the feed speed of the table on which the piece to process is placed and set, *w;*

-*t,* cutting depth, also called axial cutting depth, a_p.

Specimen material

Polyamides (PA), among which polyamides PA 66, PA 66 – GF30 and PA 66 MoS_2, belong to the group of technical plastic mass, along with PET, PC, POM, PPO and UHMW – PE, and are semi-crystalline materials.

In order to modify certain properties of polyamides, glass fibre, carbon fibre, molybdenum disulphide, etc. are used as elements of reinforcement.

Properties	Testing method ISO /(IEC)	Units	PA 66	PA 66-GF30 (30% glass fibre)	PA 66 MoS_2
Density	1183	g/cm^3	1.14	1.29	1.16
Tensile testing: - flow limit/tensile strength	527	MPa	55/-	-/75	50/-
- breaking elongation;	527	%	>100	12	>50
- elasticity modulus	527	MPa	1650	3200	1600
Compression test: - compression effort at 1/2/5% nominal deformation	604	MPa	25/49/92	28/55/90	25/49/88
Tensile creep testing: - stress producing 1% deformation in 1000h ($\sigma_{1/1000}$)	899	MPa	8	18	9
Resistance to shock – Charpy	179/1eU	KJ/m^2	Nu se rupe	>50	Does not break
Brinell hardness by H358/30 or H961/30 ball testing	2039-1	N/mm^2	155	165	160
Rockwell hardness	2039-2	-	M 88	M 76	M 84

Table 1
MECHANICAL PROPERTIES OF POLYAMIDES PA 66, PA 66 – GF30, PA66 MoS_2 [12]

Properties	Units	PA 66	PA 66-GF30 (30% glass fibre)	PA 66 MoS_2
Melting temperature	°C	255	255	220
Thermal conductivity at 23°C	W/(K·m)	0.28	0.30	0.30
Coefficient of linear thermal expansion: - mean value between 23° and 60°C;	m/(K·m)	80x10^6	50x10^6	80x10^6
- mean value between 23° and 100°C	m/(K·m)	95x10^6	60x10^6	90x10^6
Temperature of deflection under load (1,8 MPa)	°C	85	150	80
Maximum allowable working temperature in air: - for short periods of time;	°C	180	240	170
- continuously: for 5000h / 20000h	°C	95/80	120/110	105/90
Minimum working temperature	°C	-30	-20	-30

Table 2
THERMAL PROPERTIES OF POLYAMIDES PA66, PA66 – GF30, PA66 MoS_2 [12]

The mechanical properties of polyamides PA 66, PA 66 – GF30 and PA 66 MoS_2 are presented in table 1, and the thermal ones in table 2.

The testing samples used to determine the flow limit/ tensile strength and breaking elongation are of the 1B type according to ISO 527. It is noted that the glass fibre in polyamide PA66 – GF30, as compared to polyamide PA66, leads to the increase of the tensile strength, of the elasticity modulus, 3200 MPA, in the case of polyamide PA66 – GF30, as compared to 1650 MPa, in the case of polyamide PA66, and the decrease of the breaking elongation, 12% for PA66 – GF30, and greater than 100% for PA66.

Cylinder type specimens, ∅12x30 mm, are used for the compression test, and the testing speed is 1 mm/min. Comparing the values of the compression resistance, it is noted that, in the case of a nominal deformation of 5%, glass fibre in PA66 – GF30, as well as molybdenum disulphide in PA66 MoS_2 lead to a decrease of this resistance as compared to polyamide PA66. Compression resistance values of 90 MPa for PA66 – GF30 and 88 MPa for PA66 MoS_2 are obtained, as compared to 92 MPa for PA66.

Hardness is measured on specimens 10 mm thick. It is noted that the elements of reinforcement, glass fibre and molybdenum disulphide, lead to an increase of the Brinell hardness: 155 N/mm^2 for PA66, 165 N/mm^2 for PA66 – GF30 and 160 N/mm^2 for PA66 MoS_2.

Cutting tool used in the experiments

The cutting tool used for plane milling is a milling cutter consisting of body 2 and a single replaceable plate 1 (fig. 4).

A mandrel with conical tail type ISO50 was used to connect the milling cutter to the machine-tool. The shape and the dimensions of the mandrel were imposed by the body of the tool and the bore of the main shaft of the milling machine.

Cutting plates used in the experiments

Considering the recommendations of some companies and the acquisition possibilities, a SEMN 12 04 AZ plate,

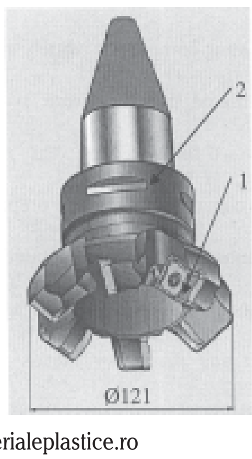

Fig. 4. Cutting tool: 1-plate; 2-mandrel

Table 3
MODULMILL 145 R/L260.22 PLATE DIMENSIONS

Dimension, [mm]	$l=i_c$	s	B_s	l_a
Prescribed value	12	4.76	2	9.6

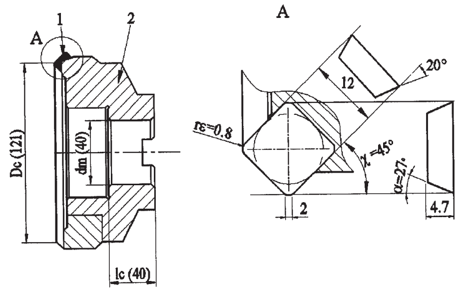

Fig. 5. Bolster shape and plate dimensions

produced by SANDVIK Coromant, was used for the experiments.

The shape of the bolster and the dimensions of the plate are presented in figure 5 and in table 3.

The significance of plate symbols, according to ISO 1832-1991, is: S - square form; E - constructive alignment angle (20°); M - tolerances (in mm); N - fixation with sloping wedges; 12 - rounded value of the square side and of the inscribed circle ($l=i_c=12$ mm); 04 - rounded value of plate thickness (s=4.76mm); A - main angle of attack (χ = 45°); Z - secondary angle of attack (χ_1).

The material of the plate is H10 (HW) rough bare metal, containing mainly tungsten carbide (CW). The SANDVIK Coromant company recommends this material to process non-ferrous and plastic materials, and wood.

Functional geometry of the plate

The functional geometry of the plate at cutting corresponds to the position it has in the body of the milling cutter (fig. 6).

The values prescribed for the angles of the cutting part of the cutter, using notations according to STAS 6599/1-88, are presented in table 4.

Machine-tool used in the experimental research

The machine-tool used for the experiments is a VICTOR 55 – FAU milling centre, property of the Laboratory of

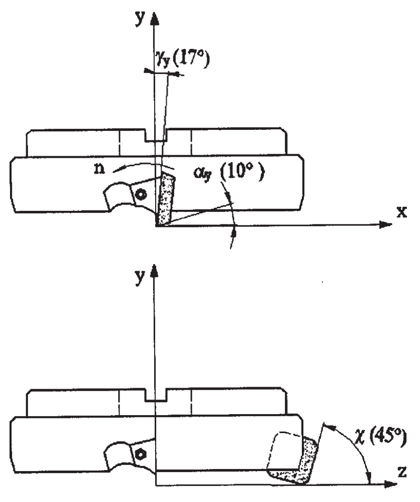

Fig. 6. Functional geometry of the plate

Tabel 4
PRESCRIBED VALUES AND VALUES OBTAINED BY MEASURING THE ANGLES OF THE CUTTER

Angle	Prescribed value, [°]
Back clearance angle (γ_p) or axial (γ_y)	17°
Back relief angle (α_p) or (α_y)	10°
Angle of attack (χ)	45°
Side relief angle (α_f) or (α_x)	5°

Advanced Processing Technologies, at “Stefan cel Mare” University of Suceava. Its characteristics are presented in table 5.

Equipment used to measure the roughness of processed surfaces

The goal of the experiments was to measure the roughness of the processed surface. The SURTRONIC 3+ tester, produced by the English company Rank Taylor Hobson Limited, property of the laboratories of the Faculty of Mechanical Engineering, “Dunarea de Jos” University of Galati was used for measurements.

The roughness of the surfaces processed on specimens was measured by displacing the standard transducer according to the direction corresponding to the feed movement. The device has a data processor which acquires, processes and displays data.

The device was connected to a computer where the data of the measurements was recorded and the graphs of evolution of roughness on the length measured were made.

The evaluation of surface roughness in system M, according to STAS 5730/1-1991, was made using one or more roughness parameters:

-arithmetic mean deviation of the profile, R_a;
-height of irregularities in 10 points, R_z;
-maximum height of the profile, R_y;
-medium pass of profile irregularities, S_m;
-medium pass of local prominences of the profile, S;
-relative bearing length of the profile, t_p.

Of all these roughness parameters, parameter R_a was measured in the experiments.

The specifications regarding surface roughness must indicate the numerical value (maximum, minimum, nominal or value interval) of the roughness parameter and the value of the basic length on which it is measured.

According to SR ISO 468-1997, the values of the basic length 1 must be chosen from the following string of values: 0.08; 0.25; 0.8; 8; 25, in mm, depending on roughness size (for example, for R_a below 2.5μm – as is the case of polyamide processing in the conditions presented above – considering l=0.8 mm).

The measurement was performed with a diamond indicator, with a top radius of 5 μm. This was positioned to the piece so that there was an oscillation reserve to cover the micro-irregularities of the surface of the piece. The overall view of the SURTRONIC 3+ tester, produced by the company Rank Taylor Hobson Limited, is presented in figure 7.

Table 5
CARACTERISTICS OF THE VICTOR 55 – FAU MILLING CENTRE

	Characteristic	Value
1	Speed of the main shaft, in [rev/min]	45-4.500 (performed continuously)
2	Velocity stages of feed, in [mm/min]	0- 5.08 (performed continuously)
3	Power of the electromotor to drive the main shaft, in [kw]	11
4	Power of the feed electromotor, in [kw]	2.2

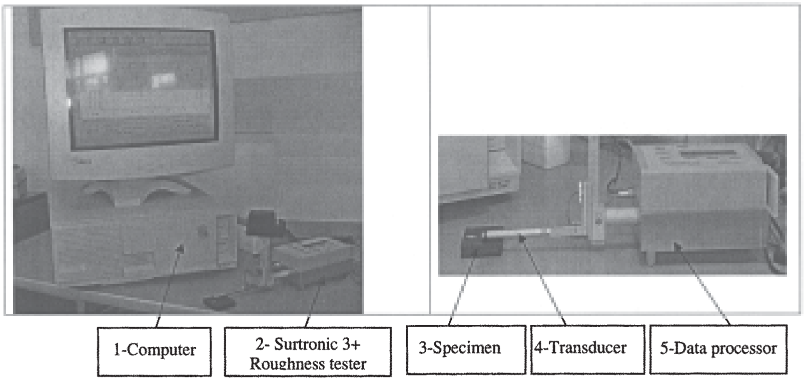

Fig. 7. SURTRONIC 3+ tester used to measure roughness

Tabel 6
VALUES OF THE CUTTING PROCESS PARAMETERS

Values of the cutting process parametres			
Independent variables / Level	v, [m/min]	f_{th}, [mm/th]	t, [mm]
Superior (+1)	294.37	0.157	1.56
Medium (0)	235.5	0.125	1.25
Inferior (-1)	186.43	0.1	1

The system for roughness measuring consists of: a computer (1), the SURTRONIC 3+ tester (2), the specimen (3); the SURTRONIC 3+ tester is made of a transducer (4) and a data processor (5).

Experimental research on surface roughness in polyamide milling

Experiment plan used in experimental research on the roughness

The experimental plan was adopted according to 2.2. The natural values of the process parametres correspond to the three levels (+1, 0, -1) and are presented in table 6.

Surface roughness measurments for milling polyamides PA66, PA66 – GF30 and PA66 MoS_2

The data obtained will be processed using the ANOVA method, developed to calculate the effects of all factors and their interactions, as well as to determine the influence of cutting parametres and their interactions, in percentages, taking into account freedom degrees and residues [6, 11]. The analysis was performed using the Minitab 16 programme.

ANOVA analysis for PA 66

Table 7 presents the numerical, mean and experimental values of roughness and of the S/N ratio for each level of the three factors analysed. The mean was determined by the five recorded roughness values for each experiment.

In order to study the main effects of the process and constructive parametres of the cutting tool on the surface roughness R_a, the graphs in figure 8 were represented.

Figure 8 leads to note that an increase of the cutting depth and the feed determines an increase of roughness R_a, whereas an increase of the cutting speed determines a decrease of roughness R_a.

To find the statistical significance of process variables and their interactions on surface roughness when milling material PA 66, the ANOVA analysis was performed (table 8).

As can be noted in table 8, the feed, the cutting depth and the cutting speed have a significant effect on roughness R_a because the value of *P* is lower than 5%. The last column represents the contribution in percentages of each factor of the total variance indicating its influence on each term of the model.

Table 7
L_{27} FULL FACTORIAL PLAN OF SURFACE ROUGHNESS AND S/N RATION FOR PA 66

Experiment no.	Level			R_a	S/N ratio
	t	*f*	*v*	[μm]	dB
1	-1	1	1	1.47	-1.28916
2	-1	1	0	1.93	0.17548
3	-1	1	-1	1.65	3.60912
4	-1	-1	1	0.66	-7.27224
5	-1	-1	0	0.98	-5.71115
6	-1	-1	-1	1.16	-3.34635
7	-1	0	1	1.08	-4.29688
8	-1	0	0	1.34	-2.54210
9	-1	0	-1	1.64	-0.66848
10	0	1	1	1.59	0.08730
11	0	1	0	1.94	0.44553
12	0	1	-1	2.41	1.11035
13	0	-1	1	0.88	-5.24902
14	0	-1	0	0.99	-4.13652
15	0	-1	-1	1.19	-4.02794
16	0	0	1	1.21	-2.41148
17	0	0	0	1.38	-2.14420
18	0	0	-1	1.72	-1.65571
19	1	1	1	1.80	4.01319
20	1	1	0	1.97	1.61844
21	1	1	-1	2.46	-0.34067
22	1	-1	1	1.02	-1.28916
23	1	-1	0	1.03	-4.45433
24	1	-1	-1	1.18	-5.10545
25	1	0	1	1.38	0.81917
26	1	0	0	1.39	-2.67078
27	1	0	-1	1.91	-2.98438

The model of roughness R_a based on the linear regression of the ANOVA analysis is

$$Ra = 0.009 - 0.505 \cdot t + 14.719 \cdot f + 0.0005 \cdot v \ [\mu m]. \quad (4)$$

For this model, the coefficient of correlation, R^2, is 93.8%. The statistical index Durbin-Watson is 1.67.

To have an image of the differences between the roughness value obtained experimentally and the roughness value obtained by modelling, the relative error was calculated

$$\varepsilon = \frac{Val_{exp} - Val_{model}}{Val_{exp}} \cdot 100, \quad (5)$$

where:

ε is the error;

Val_{exp} – the value obtained in the experiment;

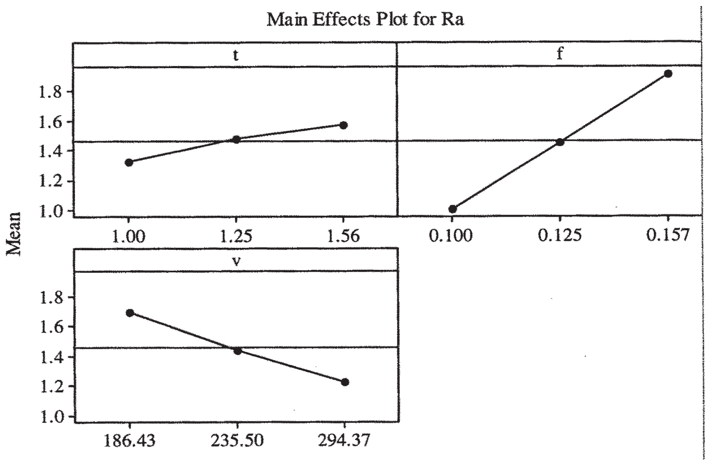

Fig. 8. Graph of the effects of the three parametres on surface roughness, R_a, for PA 66

Parametres	DOF	Seq SS	Adj SS	Adj MS	F-Test	P	Contribution [%]
t	2	0.28229	0.28229	0.14114	6.86	0.018	5.26
f	2	3.67287	3.67287	1.83643	89.32	0	68.38
v	2	0.99887	0.99887	0.49943	24.29	0	18.60
t*f	4	0.06591	0.06591	0.01648	0.8	0.557	1.23
t*v	4	0.10891	0.10891	0.02723	1.32	0.34	2.03
f*v	4	0.07813	0.07813	0.01953	0.95	0.483	1.45
Error	8	0.16449	0.16449	0.02056			3.06
Total	26	5.37147					100.00
			R^2 = 96.9%				

Tabel 8

ANOVA ANALYSIS FOR R_a, MATERIAL PA 66

Table 9

L_{27} FULL FACTORIAL PLAN OF SURFACE ROUGHNESS AND S/N RATION FOR PA 66 – GF 30

Experiment no.	Level *t*	*f*	*v*	R_a [µm]	S/N ratio dB
1	-1	1	1	0.845	-1.28916
2	-1	1	0	1.160	0.17548
3	-1	1	-1	1.345	3.60912
4	-1	-1	1	0.620	-7.27224
5	-1	-1	0	0.890	-5.71115
6	-1	-1	-1	0.980	-3.34635
7	-1	0	1	0.750	-4.29688
8	-1	0	0	1.050	-2.54210
9	-1	0	-1	1.275	-0.66848
10	0	1	1	1.080	0.08730
11	0	1	0	1.170	0.44553
12	0	1	-1	1.370	1.11035
13	0	-1	1	0.850	-5.24902
14	0	-1	0	0.910	-4.13652
15	0	-1	-1	1.030	-4.02794
16	0	0	1	0.960	-2.41148
17	0	0	0	1.160	-2.14420
18	0	0	-1	1.300	-1.65571
19	1	1	1	1.110	4.01319
20	1	1	0	1.310	1.61844
21	1	1	-1	1.330	-0.34067
22	1	-1	1	0.910	-1.28916
23	1	-1	0	0.980	-4.45433
24	1	-1	-1	1.050	-5.10545
25	1	0	1	1.090	0.81917
26	1	0	0	1.240	-2.67078
27	1	0	-1	1.320	-2.98438

Val_{model} – the value prescribed by the linear regression model.

In the case of material PA 66, the maximum error calculated was 8.66% for R_a.

ANOVA analysis for PA 66 –GF 30

In table 9 there are presented the numerical, average and experimental values of roughness and the ratio signal/noise for each level of the three factors analysed. The mean was determined by recording five values of roughness for each experiment.

To study the main effects of process and constructive parametres on surface roughness, R_a, the graphs in figure 9 were represented.

Figure 9 leads to note that an increase of the cutting depth and the feed determines an increase of roughness

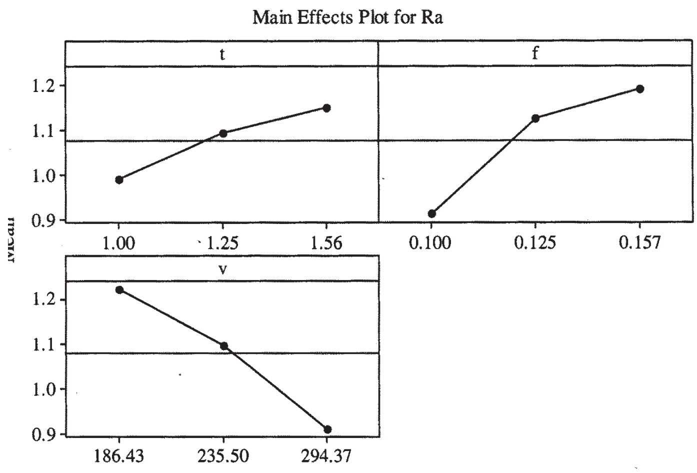

Fig. 9. Graph of the effects of the three parameters on the surface roughness, R_a, for PA 66 – GF 30

R_a, whereas an increase of the cutting speed determines a decrease of roughness R_a.

To find the statistical significance of process variables and their interactions on surface roughness when milling material PA 66 - GF 30, the ANOVA analysis was performed (table 10).

As can be noted in table 10, the feed, the cutting depth and the cutting speed have a significant effect on roughness R_a because the value of *P* is lower than 5%. The last column represents the contribution in percentages of each factor of the total variance indicating its influence on each term of the model.

The model of roughness R_a based on the linear regression of the ANOVA analysis is

$$R_a = 1.497 - 0.666 \cdot t + 9.559 \cdot f - 0.006 \cdot v + 0.004 \cdot t \cdot v - 0.016 \cdot f \cdot v \ [\mu m] \quad (6)$$

For this model, the coefficient of correlation, R^2, is 91.42%. The statistical index Durbin-Watson is 1.21.

To have an image of the differences between the roughness value obtained experimentally and the roughness value obtained by modelling, the relative error was calculated using relation (5).

Table 10
ANOVA ANALYSIS FOR R_a, MATERIAL PA 66 - GF 30

Parametres	DOF	Seq SS	Adj SS	Adj MS	F-Test	P	Contribution [%]
t	2	0.11585	0.11585	0.057925	66.41	0	11.33
f	2	0.380972	0.380972	0.190486	218.39	0	37.27
v	2	0.436006	0.436006	0.218003	249.94	0	42.65
t*f	4	0.002744	0.002744	0.000686	0.79	0.565	0.27
t*v	4	0.063444	0.063444	0.015861	18.18	0	6.21
f*v	4	0.016272	0.016272	0.004068	4.66	0.031	1.59
Error	8	0.006978	0.006978	0.000872			0.68
Total	26	1.022267					100.00
			R2 = 99.32%				

Table 11
L_{27} FULL FACTORIAL PLAN OF SURFACE ROUGHNESS AND S/N RATION FOR PA 66 - MoS_2

Experiment no.	Level *t*	Level *f*	Level *v*	R_a [μm]	S/N ratio dB
1	-1	1	1	1.22	-1.28916
2	-1	1	0	1.19	0.17548
3	-1	1	-1	1.27	3.60912
4	-1	-1	1	0.49	-7.27224
5	-1	-1	0	0.67	-5.71115
6	-1	-1	-1	0.79	-3.34635
7	-1	0	1	0.83	-4.29688
8	-1	0	0	0.88	-2.54210
9	-1	0	-1	0.98	-0.66848
10	0	1	1	1.47	0.08730
11	0	1	0	1.81	0.44553
12	0	1	-1	1.94	1.11035
13	0	-1	1	0.59	-5.24902
14	0	-1	0	0.99	-4.13652
15	0	-1	-1	1.26	-4.02794
16	0	0	1	0.95	-2.41148
17	0	0	0	1.21	-2.14420
18	0	0	-1	1.61	-1.65571
19	1	1	1	1.78	4.01319
20	1	1	0	2.20	1.61844
21	1	1	-1	2.45	-0.34067
22	1	-1	1	0.62	-1.28916
23	1	-1	0	1.30	-4.45433
24	1	-1	-1	2.14	-5.10545
25	1	0	1	1.02	0.81917
26	1	0	0	1.71	-2.67078
27	1	0	-1	2.26	-2.98438

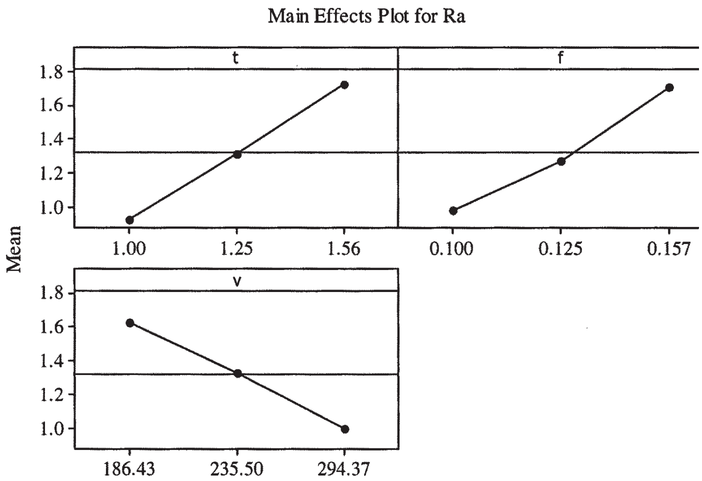

Fig. 10. Graph of the effects of the three parameters on the surface roughness, R_a, for PA 66 – MoS_2

Tabel 12
ANOVA ANALYSIS FOR R_a, MATERIAL PA 66- MoS_2

Parametres	DOF	Seq SS	Adj SS	Adj MS	F-Test	P	Contribution [%]
t	2	2.8445	2.8445	1.42225	122.35	0	35.35
f	2	2.36698	2.36698	1.18349	101.81	0	29.41
v	2	1.82835	1.82835	0.91417	78.64	0	22.72
t*f	4	0.04803	0.04803	0.01201	1.03	0.447	0.60
t*v	4	0.71906	0.71906	0.17976	15.46	0.001	8.94
f*v	4	0.14751	0.14751	0.03688	3.17	0.077	1.83
Error	8	0.093	0.093	0.01162			1.16
Total	26	8.04742					100.00
			R2 = 99.8%				

In the case of material PA 66 – GF 30, the maximum error calculated was 8.93% for the value of R_a.

ANOVA analysis of PA 66 –MoS_2

Table 11 presents the numerical, average and experimental values of roughness and the signal/noise ratio for each level of the three factors analysed. The mean was determined by recording five values of roughness for each experiment.

To study the main effects of process and constructive parametres on surface roughness R_a, the graphs in figure 10 were represented.

Figure 10 leads to note that an increase of the cutting depth and the feed determines an increase of roughness R_a, whereas an increase of the cutting speed, as in the other two cases, determines a decrease of roughness R_a.

To find the statistical significance of process variables and their interactions on surface roughness when milling material PA 66 - MoS_2, the ANOVA analysis was performed (table 12).

As can be noted in table 12, the feed, the cutting depth and the cutting speed have a significant effect on roughness R_a because the value of *P* is lower than 5%. The last column represents the contribution in percentages of each factor of the total variance indicating its influence on each term of the model.

The model of roughness R_a based on the linear regression of the ANOVA analysis is

$$R_a = -2.403 + 4.447 \cdot t - 12.234 \cdot f + 0.0056 \cdot v - 0.0161 \cdot t \cdot v \; [\mu m]. \quad (7)$$

For this model, the coefficient of correlation, R^2, is 98.3%. The statistical index Durbin-Watson is 1.9.

To have an image of the differences between the roughness value obtained experimentally and the roughness value obtained by modelling, the relative error was calculated using relation (5).

In the case of material PA 66 – MoS_2, the maximum error calculated was 8.7% for R_a.

For the experimental conditions established, regarding the material and the geometry of the cutting plate, the material to be processed and the parametres of the cutting regime, the size of the roughness R_a [μm], obtained by calculus with relations 4, 6, and 7 is centralized in table 13. For each material, the minimum, mean and maximum values obtained by calculus were considered.

Figure 11 presents the evolution of roughness R_a [μm], depending on the number of the experiment for the three materials under analysis.

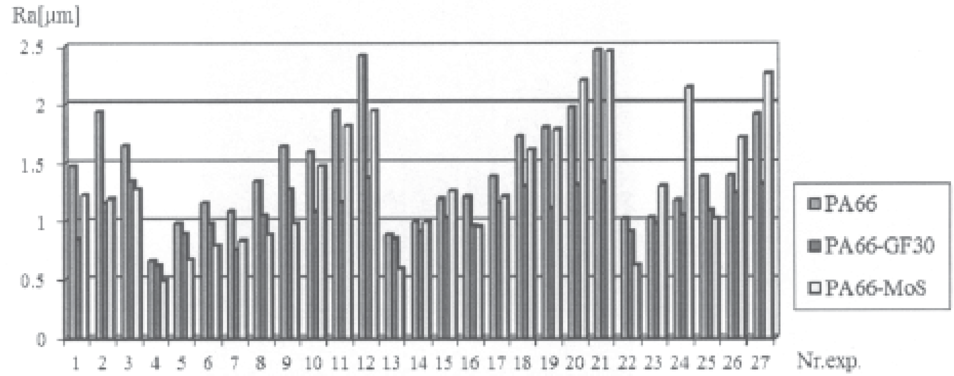

Fig. 11. Variation of roughness according to the number of the experiment and the material

Table 13

CALCULATED ROUGHNESS R_a [μm] VARIATION

Material	PA 66	PA66 - GF 30	PA 66 - MoS_2
Minimum value	0.66	0.62	0.49
Maximum value	2.46	1.37	2.45
Mean value	1.56	0.995	1.47

Model validation for roughness R_a obtained experimentally for PA 66 - GF 30

To validate the roughness model R_a obtained in the process of plane milling of **a PA 66 - GF 30** piece, the values of the cutting regime of a specimen (i.e. t=1.4 m/min, f_{th}= 0.13 mm/th and v=200 m/min) were introduced in relation (6), resulting in

$$R_{a\ calcul} = 1.4972 - 0.666\cdot t + 9.559\cdot f - 0.006\cdot v - 0.641\cdot t\cdot f + 0.004\cdot t\cdot v - 0.016\cdot f\cdot v = 1.21\ [\mu m]. \quad (8)$$

The roughness measured was $R_{a\ measured}$ =1.25 [μm].

To have an image of the differences between the roughness value obtained experimentally and the roughness value obtained by modelling, the relative error for this situation was calculated using relation (5). In the case of material **PA 66 – GF 30,** the error calculated was 7.7% for the parametres of the cutting regime presented above.

Conclusions

Experimental research was performed, regarding the influence of the cutting regime on the value of roughness, R_a, in milling. The work aimed to obtain relations defining the variation of roughness depending on the parametres of the cutting regime when processing some pieces made of polyamides **PA66, PA66 – GF30 and PA66 MoS_2**.

Taking into consideration the material and the geometry of the cutting plate, the experiments performed led to the following conclusions:

Regarding the size of the roughness, R_a, it could be noted that it varies between 0.66 μm and 2.46 μm for **PA 66**, between 0.62 μm and 1.37 μm for **PA 66 – GF 30**, and between 0.49 μm and 2.45 μm for **PA 66 – MoS_2.** When processing each material, the parametres of the cutting regime (cutting speed, feed, and cutting depth) were varied.

The descending order of the size of surface roughness was: **PA 66, PA 66 MoS_2, PA 66 – GF 30**, as can also be noted in figure 11. The lowest values of roughness can be found when processing polyamide **PA 66 – GF 30**, due to the presence of glass fibre, which gives the material good cutting properties.

The roughness, R_a, obtained when milling **PA 66** is approximately 36.2% higher than that of polyamide PA 66 - GF 30.

When cutting polyamide PA 66 MoS_2, due to the MoS_2 reinforcement offering favourable conditions for chip formation, the value of roughness, R_a, decreases, in comparison with the processing of polyamide PA 66, by approximately 5.7%.

The results of the research carried out are very useful in industrial processing as they allow for the determination of the optimum parametres of the cutting regime, with a view to obtaining a prescribed roughness, R_a.

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