APPLICATION OF THE FACTORIAL EXPERIMENT IN THE QUALITY ANALYSIS OF THE MACHINED SURFACE OF AN ALUMINUM ALLOY RELATED TO THE VARIATION OF THE CUTTING PARAMETERS

Alina Bianca POP[1], Constantin OPREAN[2], Costel CEOCEA[3], Aurel Mihail ȚÎȚU[4]

Rezumat. *În industria prelucrărilor prin așchiere, finisarea suprafeței și rezistența produsului sunt esențiale în determinarea calității. În această lucrare științifică este analizat efectul variației parametrilor de prelucrare prin așchiere asupra rugozității suprafeței. Frezarea cilindro-frontală a unui aliaj de aluminiu utilizat în industria aeronautică, a fost procesul de așchiere ales spre desfășurarea cercetărilor. Metoda de cercetare adoptată este experimentul fizic realizat pe baza aplicării metodei experimentului factorial. Datele obținute au fost supuse unei analize statistice. Concluziile desprinse au la bază interpretarea rezultatelor obținute în urma interpretării histogramelor, diagramelor de dispersie, a suprafețelor de răspuns și a curbelor de nivel constant. Datele obținute pot fi utilizate spre optimizarea procesului de așchiere și îmbunătățirea calității produselor realizate fizic prin intermediul prelucrărilor prin așchiere în industria aeronautică.*

Abstract. *In the cutting industry, surface finishing and product strength are essential in determining the quality. In this scientific research paper it is desired to analyze the way in which the influence of some cutting parameters that take different values, on the obtained quality of the processed surface is felt. An aluminum alloy often used in the aerospace industry was chosen for the research. This material will be subjected to end-milling machining. As a research method, the factorial experiment was approached in order to plan the physical experiments. The obtained data were subjected to the statistical analysis. The conclusions drawn are based on the results obtained by the interpretation of histograms, scatter diagrams, response surfaces and contour plots curves. The obtained data can be used to improve the cutting process and also the quality physically produced products through cutting operations in the aeronautical industry.*

Keywords: factorial experiment, quality, surface roughness, aluminum alloy, cutting parameters

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[1]PhD, SC TECHNOCAD SA, 72, Vasile Alecsandri Street, Baia Mare, Romania, bianca.bontiu@gmail.com.
[2]Professor, Lucian Blaga University of Sibiu, 10, Victoriei Street, Sibiu, România, constantin.oprean@ulbsibiu.ro.
[3]A/Professor, Vasile Alecsandri University of Bacău, 157 Mărăști Street, Bacău, code 600115, email: costelceocea@gmail.com.
[4]Professor, Lucian Blaga University of Sibiu, 10, Victoriei Street, Sibiu, România The Academy of Romanian Scientists, 54, Splaiul Independenței, Sector 5, Bucharest, Romania, mihail.titu@ulbsibiu.ro.

1. Introduction

Often, milling is adopted in manufacturing industries. Nowadays, CNC machines are commonly used due to their versatility and flexibility, but also because they facilitate the production of products in a short time, and the necessary costs are acceptable, and the quality of the surface obtained after processing is good [1]. Two very important problems are reported in the cylinder-front milling process. One of them is the surface finishing, on which the attention of both industry and research and development personnel must be focused. The second aspect is the removal rate of the material. This aspect is similar to the first one. The argument made in this regard is that the aforementioned factors exert a great influence on the processing performance. In order to obtain high quality products in a very short time and with minimal costs, these CNC machines are recommended [2].

Predictive modeling of cutting processes is an essential step for process control and optimization. A predictive model is an exact the connection between independent input variables and dependent output performance measures. There are two types of approaches that are well known for achieving such a relationship [3]:

- The empirical approach that is considered to be the most suitable short-term practical method suitable for industrial applications, and

- Fundamental approach that involves analytical means.

Nowadays, there are various researches that have had this direction as the main subject of approach. For example, [4] performed an analysis of the machinability of aluminum alloy 6082 by comparing a complete factorial experiment with a central composite inscribed experiment. The problem analyzed by this author is summarized by the effect manifested by the cutting speed but at the same time by the cutting feed on the cutting force. Subsequently, the effects and interactions of the factors were tracked using ANOVA analysis. In [5] it was studied using the full factorial experiment, the influence of the cutting process factors on the cutting force by H13 tool steel machining. What emerges from this is that the cutting depth has the most important influence. This factor is followed closely by the cutting speed and then finally by the feed rate. Other authors using DOE, wanted to optimize the cutting parameters in the way that their influence is felt on the milled surface, more precisely on its quality, are [6], [7] and [8], whose researches were carried out using Taguchi's method.

2. Experimental research

2.1. Establishing the cutting process

Al 7136 was used to conduct the researches through the end-milling operation.

2.2. Choosing the tool and the machining

The type of the cutting tool chosen is a standard one in the aluminum machining, and the CNC on which the machining took place is of the HAAS VF2 type.

2.3. Establishing the workpiece material

The 7136 aluminum alloy is developed by a company which activity is in the aeronautical industry and has good corrosion and stress corrosion cracking resistance, superior mechanical properties to other alloys and good workability. Al 7136 contains a higher level of zinc compared to other alloys in class 7xxx (8.4-9.4%), and first uses 0.05% chromium to follow grain growth and recrystallization, similar to the well-known 7075 alloy. This aluminum alloy contains 0.10-0.20% zirconium as a microstructural modifier, similar to the 7x5x alloy family. Al7136 gives superior mechanical properties to 7075 aluminum alloy with great quality and guaranteed EB exfoliation corrosion according to ASTM G 34 standard [9].

2.4. Research method

The steps of the method used to conduct the experimental research and the processing of the obtained data, is shown in figure 1.

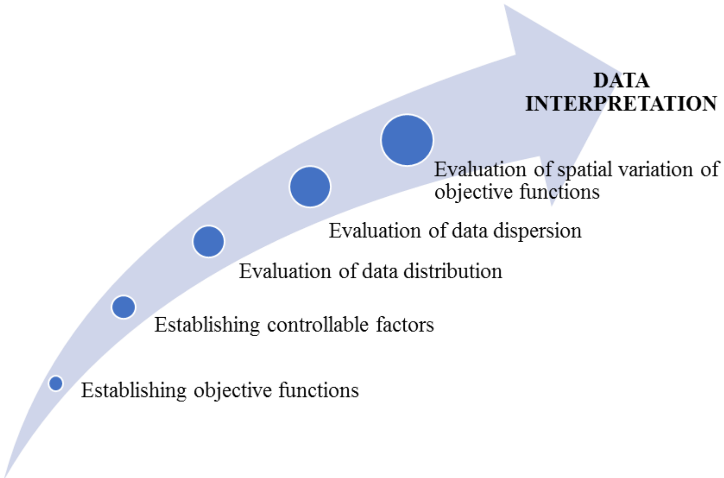

Fig. 1. Conducting the experimental research

2.5. The research purpose

A first step in conducting the study is to establish the research purpose. Therefore, using the method of the factorial experiment in the STATISTICA application, the variation and influence of the end-milling factors on the machined surface of Al 7136, used in the aeronautical industry, will be evaluated.

2.6. Objective functions

The objective functions will be the surface roughness measured longitudinally R_z L [μm] and transversely R_z T [μm] in the direction of the forward movement of the tool.

2.7. Establishing controllable factors

The end-milling factors and each values used in the experiment are presented in table 1.

Table 1. The end-milling factors

No.	*Controllable factor*	*Simbol*	*Levels*
1	Cutting speed	v [m/min]	495 / 530 / 570 / 610 / 660 / 710
2	Cutting depth	a_p [mm]	2 / 2.5 / 3 / 3.5 / 4
3	Feed per tooth	f_z [mm/tooth]	0.04 / 0.06 / 0.08 / 0.11 / 0.14

2.8. Measurements

Following the researches carried out with the help of the cutting regimes obtained according to the complete factorial experiment, with a surface tester were obtained the R_z measurements, and the results were centralized in table 2.

Table 2. Surface roughness measurements

No.	*v [m/min]*	*a_p [mm]*	*f_z [mm/tooth]*	*R_z L [μm]*	*R_z T [μm]*
1	495	2	0.04	1.958	0.862
2	495	2	0.06	2.211	1.269
3	495	2	0.08	2.416	1.817
4	495	2	0.11	2.814	1.279
5	495	2	0.14	2.762	1.318
6	495	2.5	0.04	1.613	0.849
7	495	2.5	0.06	2.162	0.954
8	495	2.5	0.08	2.193	0.697
9	495	2.5	0.11	2.438	1.191
10	495	2.5	0.14	2.616	1.166

No.	*v [m/min]*	*a_p [mm]*	*f_z [mm/tooth]*	*R_z L [μm]*	*R_z T [μm]*
11	495	3	0.04	1.811	1.575
12	495	3	0.06	2.132	0.958
13	495	3	0.08	1.918	2.199
14	495	3	0.11	2.415	2.506
15	495	3	0.14	2.448	1.792
16	495	3.5	0.04	2.332	1.257
17	495	3.5	0.06	2.432	1.405
18	495	3.5	0.08	2.11	1.079
19	495	3.5	0.11	1.743	1.349
20	495	3.5	0.14	2.26	1.26
21	495	4	0.04	3.502	2.988
22	495	4	0.06	2.173	1.698
23	495	4	0.08	2.034	1.148
24	495	4	0.11	2.508	1.861
25	495	4	0.14	2.858	1.59
26	530	2	0.04	1.742	1.234
27	530	2	0.06	1.745	1.073
28	530	2	0.08	1.903	0.819
29	530	2	0.11	1.606	1.214
30	530	2	0.14	2.842	2.055
31	530	2.5	0.04	1.556	1.409
32	530	2.5	0.06	2.495	1.538
33	530	2.5	0.08	2.379	1.612
34	530	2.5	0.11	2.413	1.285
35	530	2.5	0.14	2.277	2.002
36	530	3	0.04	2.209	1.742
37	530	3	0.06	2.322	2.073
38	530	3	0.08	2.542	1.195
39	530	3	0.11	2.397	1.689
40	530	3	0.14	2.1	1.842
41	530	3.5	0.04	2.23	1.835
42	530	3.5	0.06	1.905	3.836
43	530	3.5	0.08	2.024	1.645
44	530	3.5	0.11	2.21	0.984
45	530	3.5	0.14	1.893	1.234
46	530	4	0.04	1.748	1.624

No.	*v [m/min]*	a_p *[mm]*	f_z *[mm/tooth]*	R_z *L [µm]*	R_z *T [µm]*
47	530	4	0.06	2.11	1.689
48	530	4	0.08	3.359	3.804
49	530	4	0.11	1.846	1.41
50	530	4	0.14	2.122	4.031
51	570	2	0.04	3.124	1.999
52	570	2	0.06	2.472	2.196
53	570	2	0.08	2.613	1.838
54	570	2	0.11	2.493	2.265
55	570	2	0.14	2.325	1.141
56	570	2.5	0.04	8.624	7.279
57	570	2.5	0.06	4.594	13.528
58	570	2.5	0.08	10.214	11.123
59	570	2.5	0.11	2.48	1.818
60	570	2.5	0.14	2.932	1.449
61	570	3	0.04	3.721	9.893
62	570	3	0.06	4.79	12.322
63	570	3	0.08	2.42	12.968
64	570	3	0.11	3.763	3.34
65	570	3	0.14	5.702	6.71
66	570	3.5	0.04	5.103	4.395
67	570	3.5	0.06	11.927	9.758
68	570	3.5	0.08	5.181	11.41
69	570	3.5	0.11	2.876	11.482
70	570	3.5	0.14	2.88	6.412
71	570	4	0.04	4.421	3.298
72	570	4	0.06	10.774	8.404
73	570	4	0.08	8.374	3.994
74	570	4	0.11	4.71	12.792
75	570	4	0.14	3.338	13.55
76	610	2	0.04	4.277	5.148
77	610	2	0.06	4.83	5.274
78	610	2	0.08	5.318	5.592
79	610	2	0.11	2.982	2.971
80	610	2	0.14	3.455	2.24
81	610	2.5	0.04	5.317	3.577
82	610	2.5	0.06	2.85	7.112

No.	*v [m/min]*	a_p *[mm]*	f_z *[mm/tooth]*	R_z *L [µm]*	R_z *T [µm]*
83	610	2.5	0.08	2.965	3.758
84	610	2.5	0.11	3.412	2.254
85	610	2.5	0.14	3.116	3.35
86	610	3	0.04	3.167	2.301
87	610	3	0.06	5.978	5.39
88	610	3	0.08	3.85	4.498
89	610	3	0.11	2.939	6.164
90	610	3	0.14	2.829	3.894
91	610	3.5	0.04	4.778	4.177
92	610	3.5	0.06	5.768	3.027
93	610	3.5	0.08	6.667	4.15
94	610	3.5	0.11	3.706	6.295
95	610	3.5	0.14	2.702	5.849
96	610	4	0.04	4.394	10.234
97	610	4	0.06	8.017	6.78
98	610	4	0.08	6.867	5.455
99	610	4	0.11	6.541	3.838
100	610	4	0.14	3.911	5.644
101	660	2	0.04	3.593	2.239
102	660	2	0.06	3.982	1.542
103	660	2	0.08	3.824	2.917
104	660	2	0.11	3.868	2.826
105	660	2	0.14	4.328	2.35
106	660	2.5	0.04	3.504	1.711
107	660	2.5	0.06	3.791	1.268
108	660	2.5	0.08	3.926	1.705
109	660	2.5	0.11	3.389	0.872
110	660	2.5	0.14	3.786	1.743
111	660	3	0.04	3.167	2.042
112	660	3	0.06	4.141	1.213
113	660	3	0.08	4.114	1.492
114	660	3	0.11	3.712	3.016
115	660	3	0.14	3.995	4.01
116	660	3.5	0.04	3.62	1.592
117	660	3.5	0.06	4.261	1.302
118	660	3.5	0.08	3.901	1.724

No.	*v [m/min]*	a_p *[mm]*	f_z *[mm/tooth]*	R_z *L [μm]*	R_z *T [μm]*
119	660	3.5	0.11	3.474	1.927
120	660	3.5	0.14	3.51	3.031
121	660	4	0.04	4.299	1.65
122	660	4	0.06	3.528	1.549
123	660	4	0.08	3.177	2.433
124	660	4	0.11	3.053	1.664
125	660	4	0.14	3.455	1.884
126	710	2	0.04	3.297	1.377
127	710	2	0.06	3.514	2.529
128	710	2	0.08	3.078	2.763
129	710	2	0.11	3.484	2.046
130	710	2	0.14	3.245	1.763
131	710	2.5	0.04	3.449	1.331
132	710	2.5	0.06	3.55	1.821
133	710	2.5	0.08	3.61	1.099
134	710	2.5	0.11	3.739	2.542
135	710	2.5	0.14	3.098	2.192
136	710	3	0.04	4.349	3.62
137	710	3	0.06	4.104	2.923
138	710	3	0.08	4.913	3.078
139	710	3	0.11	3.76	3.389
140	710	3	0.14	4.382	3.809
141	710	3.5	0.04	4.78	2.345
142	710	3.5	0.06	3.85	4.261
143	710	3.5	0.08	3.189	3.826
144	710	3.5	0.11	3.972	4.089
145	710	3.5	0.14	5.201	1.315
146	710	4	0.04	3.756	4.006
147	710	4	0.06	4.647	2.722
148	710	4	0.08	3.743	5.253
149	710	4	0.11	3.7	4.884
150	710	4	0.14	4.712	4.178

3. Experimental data processing and data interpretation

The values of the obtained and centralized surfaces roughness presented in table 2, were subjected to a statistical analysis. The evaluation of the obtained data implies the completion of stages that involve a series of statistical parameters, which will be detailed below.

3.1. Evaluation of data distribution

The normality distribution evaluation of the obtained data may by graphically presented using the histogram. If the values of a response have an approximately normal distribution, it can be analyzed directly. If the values of a response do not have normal distribution, it is recommended that the logarithm of the values of the answers or the experimental data will be statistical analyzed to eliminate the aberrant values, to verify the data randomness and finally to verify the normality of the tested data. In the end, the distribution of data becomes about normal.

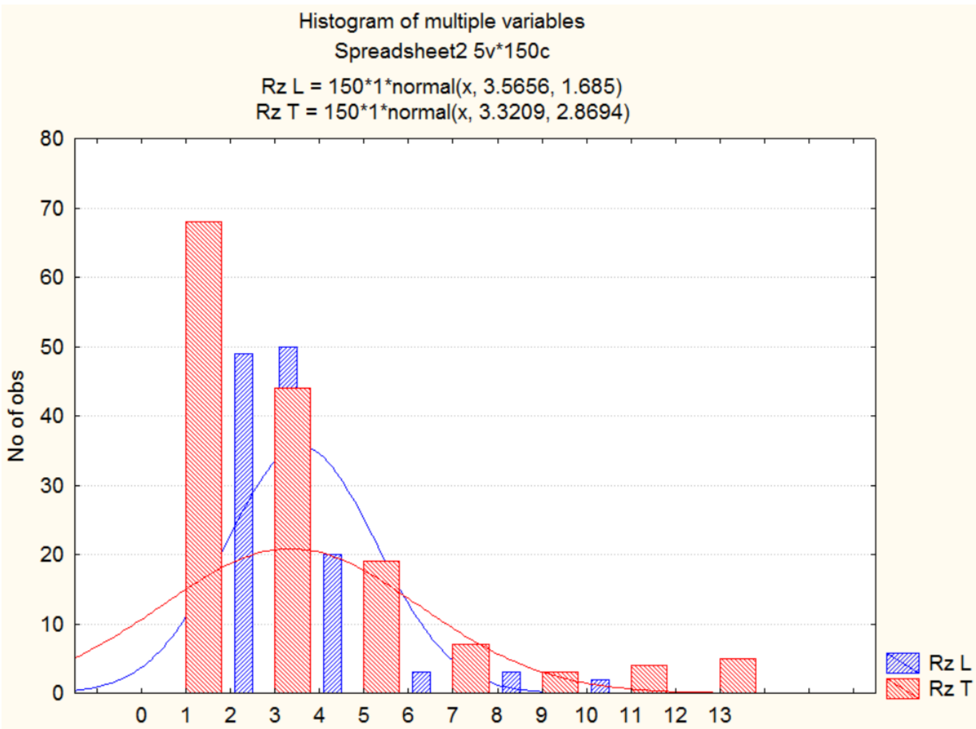

Fig. 2. R_z L versus R_z T histogrammes

Under this experimental conditions (cutting tool, workpiece and end-milling regime taking into account the manufacturer recommendations), very small R_z

values are obtained by the studied process. The histograms presented in Figure 2, shows some normal distribution of the analyzed data.

3.2. Evaluation of data dispersion

Scatter plot evaluates graphically a factor according to one or more answers. This representation is used to evaluate the scattering / grouping of the results in order to identify the relation types by factors with answers (linear or non-linear-curves). Identifying the type of relationships is of importance to verify that the type of model has been well chosen. This analysis can only be applied if a small number of factors / responses are studied and is unusable if the number of factors studied is greater than four and / or the number of responses is greater than four. In this situation, the number of factors is 3, and the answers sought refer to the R_z L and R_z T.

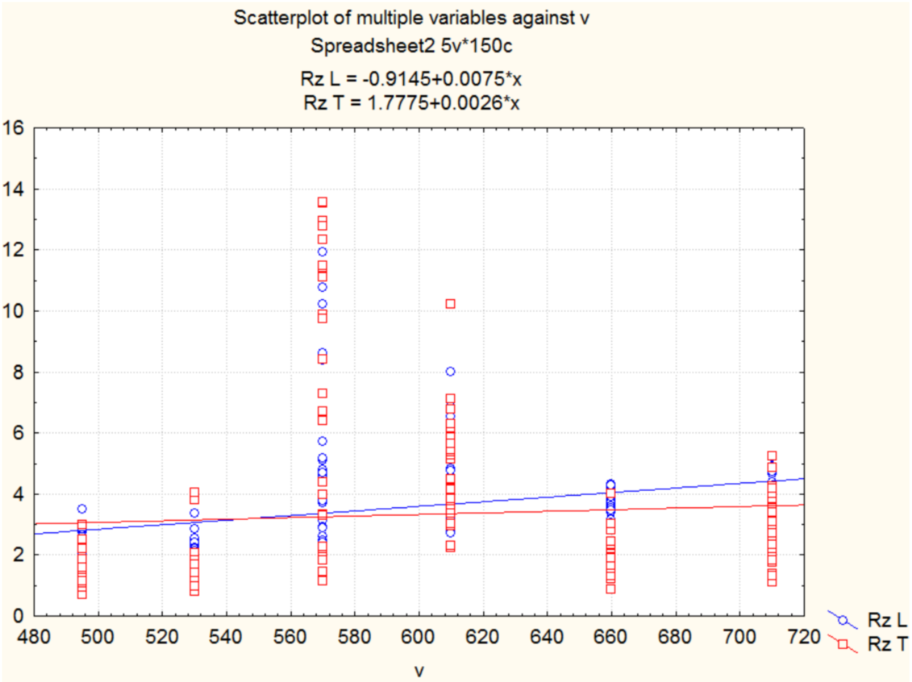

Fig. 3. The cutting speed dispersion graph, R_z L versus R_z T

From the dispersion diagram (figure 2), it turns out that the values of the roughness's resulting from the measurements, have an increasing tendency, as the cutting speed increases. This tendency exists in both cases, but it is more pronounced in the case of R_z L. The big distribution of the roughness's in the middle of the cutting speed interval (570 - 610 m / min) represent the particularity of this study. By the first evaluation of the machine-tool-part system behavior, vibrations are assumed to be the cause of these increases.

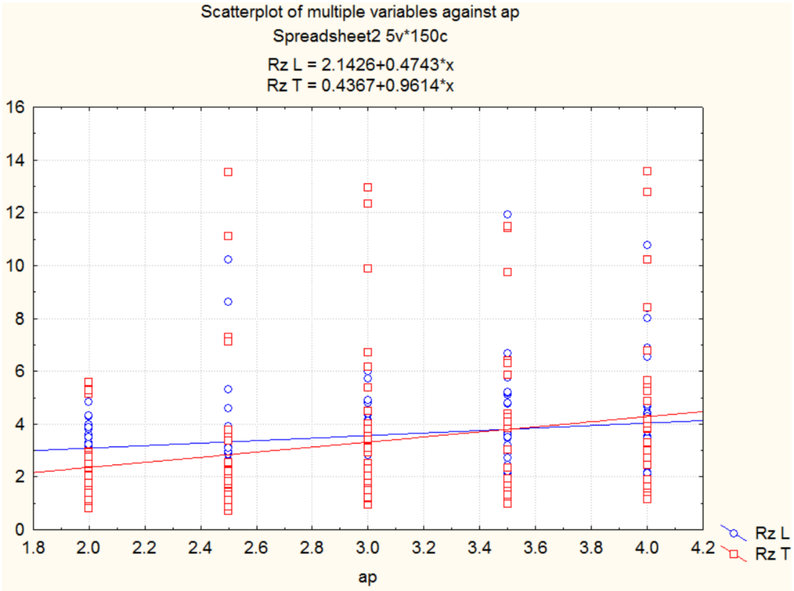

Fig. 4 The cutting depth dispersion graph, R_z L versus R_z T

Figure 4 shows when the cutting depth is increasing, is increasing also the roughness values distribution. The reason may be the same assumption about the effect exerted by vibrations and also by the chip breakage phenomenon, caused by the high cutting tool load.

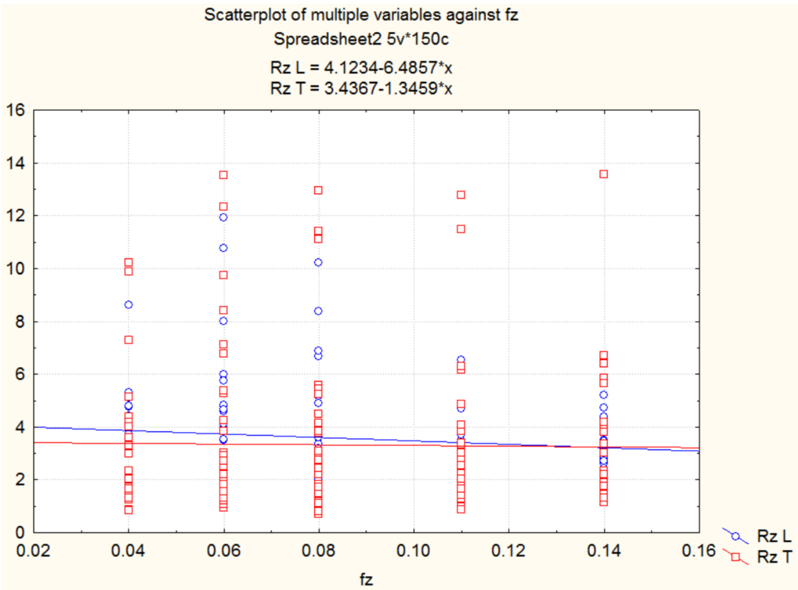

Fig. 5 Dispersion diagram according to the feed per tooth, R_z L versus R_z T

About the dispersion graph presented in figure 5 according to feed per tooth, a slightly decreasing tendency of the roughness values can be observed in relation to the feed per tooth increasing, a decrease observed again in the case of R_z L. This tendency is affected by the roughness's that have a great distribution at 570 or 610 m / min.

However, considering the way in which most of the R_z are distributed, obtained at the other cutting speeds 495, 660 and 710 m/min, respectively the whole cutting depth interval 2, 2.5, 3, 3.5, 4 mm, the increasing tendency can be observed of the roughness values related to the feed increasing.

3.3. Evaluation of spatial variation of objective functions

After performing the histograms in order to determine the normality of the distribution of the experimental data obtained, as well as the dispersion diagrams that have been drawn up in order to evaluate the scattering or grouping of the measured values of R_z L and R_z T, a series can still be performed. of 3D analyzes on the behavior of these objective functions under the influence of process factors.

The realization of 3D graphs can be carried out by plotting the response surfaces, situations in which for each graph a regression equation is obtained, which can be successfully used to approximate the objective function values, throughout the experimental field. In order to form an image more intuitive than the one provided by the regression equation, one uses the graphical representation of the response surface, as a function of two influencing factors. And therefore, the other influencing factors of the model are fixed on particular levels, most often corresponding to the central level (with a coded value equal to zero). Sometimes, by dividing these response surfaces with planes parallel to the plane of the influence factors used in the graphical representation, a family of curves called "constant level" or "equal response" is obtained.

The interpretation of the experimental results, exclusively on the basis of these graphical representations, can lead to serious errors, since they refer only to a particular ("frozen") situation of the parameterized influence factors (which do not take part in the representation). As such, it provides only a partial picture of the response in the investigated multifactorial space (if the objective function depends on more than two influencing factors). For this reason, always these graphical representations must be associated with the regression equation obtained and interpreted in the context offered by the respective equation.

Therefore, the spatial variations of the objective functions, by the effect of the cutting process factors, were carried out using two types of graphical representations, named according to the STATISTICS application:

- Surface Plots – corresponding to the response surfaces and,
- Contour Plots – corresponding to the constant level curves.

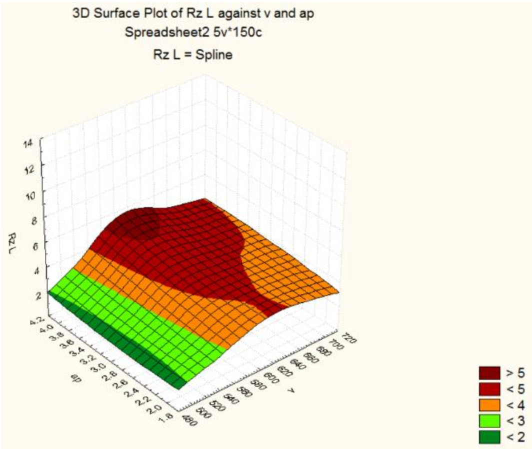

Fig. 6. R_z L versus v and a_p

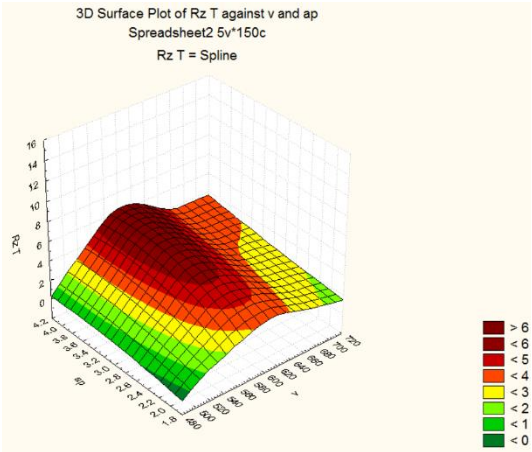

Fig. 7. R_z T against v and a_p

Figures 6 and 7 show the spatial variations of R_z according to the variation of the cutting speed and the depth of cut when the feed per tooth remains constant. From these two figures, result that the R_z increase quite high when the cutting speed is between 495-570 m / min, throughout the range of cutting depths. The cutting depth does not significantly influencing the roughness at low cutting speeds, but its influence changes when the cutting speeds is higher than 570 m / min.

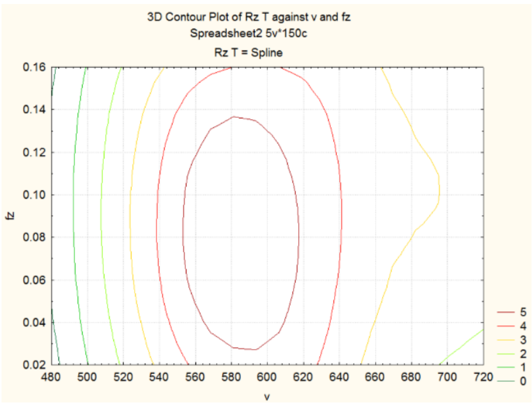

Fig. 8. R_z L against v and f_z

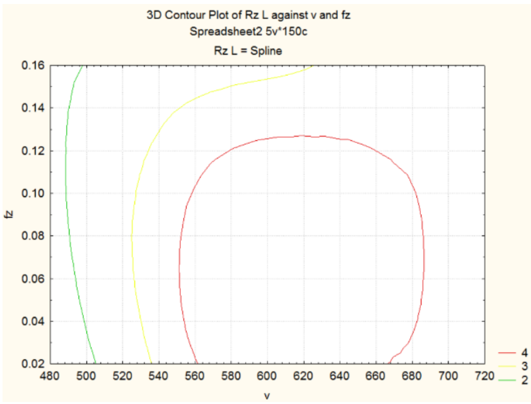

Fig. 9. R_z T against v and f_z

In Figures 8 and 9, the spatial variation of the roughness R_z can be observed depending on the cutting speed and feed rate. After a short analysis one can conclude that the speeds of 570 and 610 m / min combined with a small feed per tooth have a great impact on the measured roughness values, which increase throughout the experimental field. The reason of these values increasing may be to the vibrations occurred during the cutting process.

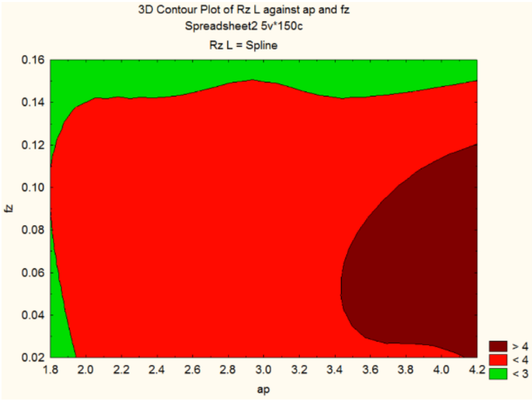

Fig. 10. R_z L against a_p and f_z

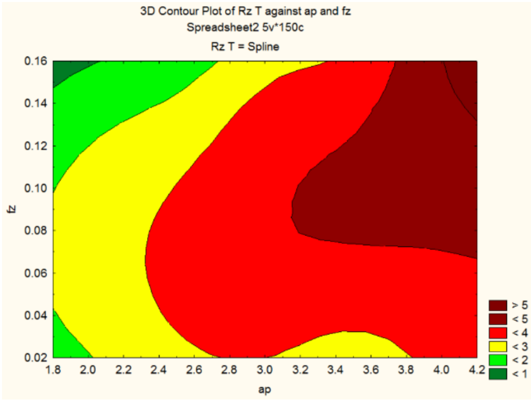

Fig. 11. R_z T against a_p and f_z

In Figs. 10 and 11, the spatial variation of the roughness R_z can be observed depending on the cutting depth and the tooth advance. The depth of the cut in relation to the feed negatively influences the roughness of the milled surface, in the sense that small roughness is obtained. However, at lower values of the feed per tooth and high values of the cutting depth, due to the influence of the cutting speeds of 570 and 610 m / min, there is a tendency to increase the roughness values.

4. Conclusions

In the end-milling process, the surface finishing and the material removal rate are two important issues, which require attention from both industry and research and development staff.

As general conclusions, following the analysis of the performed spatial graphs, the following findings are presented:

- The parameter with the greatest influence on the roughness R_z T and R_z L is the cutting speed;
- The cutting speed together with the feed per tooth, have the greatest influence on the surface quality;
- The cutting depth together with the feed per tooth, have a little influence on the surface quality.

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