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To cite this article: M A îu et al 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **572** 012042

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Optimization of the objective function –surface quality by end-milling dimensional machining of some aluminum alloys

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Abstract. In the aerospace industry, the milling of aluminum alloy parts is a machining process with the primary purpose of removing high volumes of material. Aluminum alloys are materials that have relatively good machinability, which helps the process because many of the components of the aircraft are of high dimensions. These parts have many pockets more or less deep, and the removal by cutting off about 90% of the initial volume of the workpiece is a matter of consideration. The manufacturing process is protracted and involves long semi-finishing and finishing operations, so it is recommended that any researcher who begins and finishes an experimental study should do it base on a specific experimental plan. Mathematical statistics techniques and methods are used, but also optimization methods that lead to a rational choice of process parameters, process input data and objective functions that need to be improved. This scientific paper presents applied research based on an extremely pertinent active experiment that has led to some practical solutions applied in the aerospace industry worldwide. The dedicated objective function on which the study conducted in this case was the mean arithmetic deviation of the surface profile. The independent variables were chosen by the concrete application of a dispersion analysis applied to the milling process, namely the cutting speed, the cutting depth and the feed per tooth. Interpretation of the results was performed by a graphical evaluation of the normality of the data distribution, by presenting the histogram responses as well as by the dispersion diagrams. It was used for a better correlation a 3D graphical analysis that followed the R_a variation of the mean arithmetic deviation of the machined surface profile under the influence of the cutting parameters and the independent variables respectively. The obtained conclusions led to the validation of the experimental model and the application of the research presented within an aerospace industry organization with important global valences.

1. Machining of aluminum alloys

Nowadays, aluminum and its alloys are considered the most practical metals for many reasons. Low price, low weight and modern appearance are among the main reasons for using these materials on a large scale. Aluminum has electrical conductivity, is a good thermal conductor, is not magnetic, and is



reflexive and resistant to chemicals. It is commonly used in the construction, marine and aircraft industry due to its ease of machining, non-toxicity and corrosion resistance.

In the case of the aluminum alloys machining, the use of high speeds in order to increase productivity is a real challenge, since a speed increase implies an acceleration of the cutting tools wear [1]. The most commonly cutting operations used in aluminum processing are turning and milling.

The choice of cutting tools for a milling operation depends on several criteria, such as the shape of the piece to be machined; alloy type; roughing and finishing operation, and so forth; CNC machine features [2].

Milling operations of aluminum alloys can be classified according to their scope in two categories: the situation where the volume of material to be removed is very high (aerospace components); the processing time is short, but the number of different operations is high (car parts).

In order to highlight the machinability of aluminum and its alloys, several bibliographic materials have been analyzed, and the research paper [3-6] are mentioned in this respect.

The present paper aims to carry out an active experiment to issue a series of solutions applied practically in the aerospace industry. The objective function on which the study was conducted in this case was R_a of the surface profile. The independent variables were chosen by applying detailed dispersion analysis to the milling process. Interpretation of the results was also accomplished by graphical evaluations of the normality of the data distribution, by presenting the histogram responses as well as by the dispersion diagrams. It was used for a better correlation and a 3D graphical analysis that followed the variation of the R_a of the surface profile under the influence of the cutting parameters and the independent variables respectively. The obtained conclusions led to the validation of the experimental model and the application of the research presented within an aerospace industry organization with important global valences.

2. The place and purpose of modeling and optimizing the milling process of aluminum alloys

A researcher starts an experimental research having a particular working plan, i.e., he will create an experimental plan or a specific experimental project. The researcher can obtain the proper result based on his knowledge of the field or his intuition, but this is rarely achievable. By doing in this manner, time and money may be lost until a good result is reached, or it may never reach the purpose. That is why Țîțu [7] mentions that it is desirable to use methods related to mathematical statistics and optimization methods for a logical choice of the experimental determinations to be made and to obtain reliable and coherent information.

For the acceleration of the experimental works it is reasonable that their volume is reduced to the strict necessity, says Țîțu [7]. One method for reducing the number of experiments in research is that the experimental work should be conducted according to a particular scheme that includes only the experimental determinations strictly necessary for the desired information [9-17].

3. The experiment proposed to be studied

3.1. Planning the experimental research

Regardless of the objectives considered, before the actual trials are carried out, a mandatory first step is the rigorous planning of all experimental research. Table 1 lists all elements of the experimental plan. In the current research, it was determined the use of a complete factorial experiment for the three factors chosen for the study: feed per tooth, cutting speed and cutting depth, and corresponding levels thereof, mentioned in Table 1.

It is, therefore, necessary to perform several $6 \times 5 \times 5 = 150$ experiments. The roughness of the machined surfaces measured longitudinally R_a long and transversely R_a transv in the milling direction, are determined. Regarding the planning of experiments, after Montgomery [8], there are three basic principles, namely:

- The principle of random character - based on which statistical methods are requiring observations (or errors) in order to have a randomly character that is to be randomly distributed over the parameters. Randomizing observations makes this hypothesis valid.
- The principle of replication - implies to repeat 3 to 7 times the experiment for every input set, and it is essential to obtain the measurements consistency. In this situation, replication will be performed seven times to get the most accurate results. That is, for each set of parameters several seven measurements will be performed.
- The principle of working in "blocks" - is used to improve the accuracy of comparison between the factors used. Therefore, in the current research, we will work with several seven blocks.

Table 2 clearly shows this working procedure.

Table 1. Elements established for conducting the experiments.

| Cutting operation | End-milling process | | | | | |
|--------------------|--|------|------|------|------|-----|
| Cutting tool type | SECO R217.69-1616.0-09-2AN with two teeth Cutting inserts XOEX090308FR-E05, H15 | | | | | |
| | v [m/min] - Cutting speed | | | | | |
| | 495 | 530 | 570 | 610 | 660 | 710 |
| Cutting regime | a _p [mm] - Cutting depth | | | | | |
| | 2 | 2,5 | 3 | 3,5 | 4 | |
| | f _z [mm/tooth] - Feed per tooth | | | | | |
| | 0,04 | 0,06 | 0,08 | 0,11 | 0,14 | |
| CNC Machine | HAAS VF-YT2 | | | | | |
| Workpiece material | Aluminum alloy code 7136 | | | | | |
| Mesurement device | Mitutoyo SURFTEST SJ-210 Surface tester Optical microscop Micro-Vu VERTEX 310 | | | | | |

Table 2. The procedure under which the experiments will be conducted.

| Control factor | Levels number | | | | | | Measurements | | Replicate |
|--------------------|---|--|--|--|--|--|---------------------|-----------------------|--------------|
| Cutting speed | Six levels 495 530 570 610 660 710 | | | | | | | | |
| Cutting depth | Five levels 2 2,5 3 3,5 4 | | | | | | R _a long | R _a transv | Seven times |
| Feed per tooth | Five levels 0,04 0,06 0,08 0,11 0,14 | | | | | | | | |
| Total experiments | 6x5x5=150 | | | | | | | | |
| Total measurements | | | | | | | 150 | 150 | 150x2x7=2100 |

Each sample will have 50 related machining's of 50 cutting regimes based on the combinations of the studied cutting parameters. The machined surface of a cutting regime will be 50 x 16 mm.

Thus, the 150 combinations of the cutting regimes will be tested by machining of tree blocks with the dimensions mentioned above, and the machining will be resumed in order to achieve the seven replications set.



Figure 1. Preparation of the 21 Al7136 blocks to be machined.

Finally, a total of 21 blocks of Al7136 will be machined (Figure 1).

3.2. Interpretation of experimental data

3.2.1. Histograms. Dispersion diagrams. After the physical realization of the experiments, the data were collected, followed by a visual evaluation of the normal distribution. This can be done by graphically presenting the histogram responses. In Figures 2 and 3, the histograms R_a long, respectively R_a transv, were plotted.

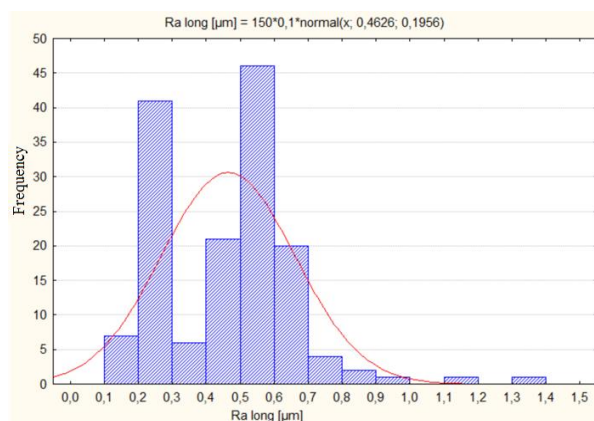


Figure 2. Histogram of R_a long measurements for the 150 cutting regimes.

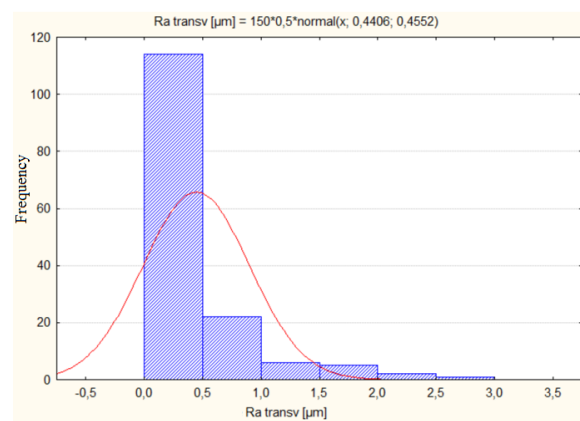


Figure 3. Histogram of R_a trans measures for the 150 cutting regimes.

In both figures, it can be noticed that, under the experiment conditions (material, tool and cutting regime according to the manufacturer's recommendations), relatively low surface roughness values are obtained for the end milling process, approximately 0.5 [μm]. According to the specialized studies carried out in the sphere of cutting processes, in the milling process, roughness values of R_a between 1.6 [μm] and 6.3 [μm] are frequently obtained. Thus, the values obtained from the experiment fit the end milling operation, having the cutting regime parameters used, in the class of fine precision, i.e. below 1.6 [μm]. Regarding the distribution of experimental data from the R_a long histogram, it is noticed that the data have an approximately normal distribution; instead, concerning the histogram related to R_a transv, the experimental data does not have a normal distribution.

Another statistical parameter that allows the graphical representation of a factor by another factor (or several factors) is the Scatter plot. This representation is used together with the state number, for the evaluation of the orthogonics of the experimental plane according to Țîtu [7].

The R_a long dispersion diagrams are made in Figure 4 - Depending on the cutting speed in Figure 5 - Depending on the cutting depth and Figure 6 - Depending on the feed per tooth.

After analyzing the dispersion diagram in Figure 4, it follows that the R_a long values have a tendency to increase in the same time with the cutting speed. This aspect confirms the specialty studies madden in this direction.

However, the particularity of this study is the great distribution of R_a values in the center of the speed range 570 - 610 [m/min]. After a first analysis of the behavior of the CNC machine - cutting tool-workpiece system, we consider the fact that the vibrations are the main cause of these increases. Regarding the dispersion diagram according to the cutting depth, in Figure 5 it can be noticed that with the cutting depth increasing the R_a distribution is increasing too. These values can be the result of the vibrations effect and the chip breaking phenomena due to the high tool load (high depth at the maximum tool width).

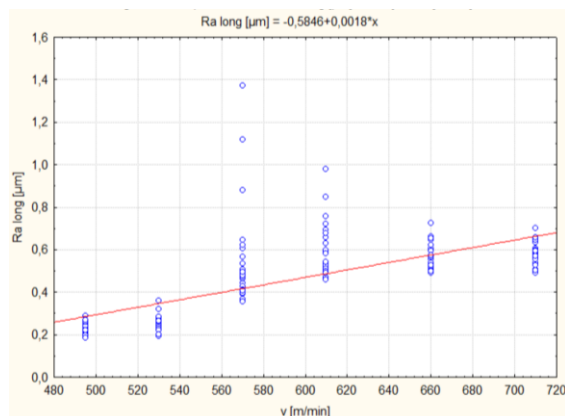


Figure 4. Dispersion diagram of R_a long values according to cutting speed v [m/min].

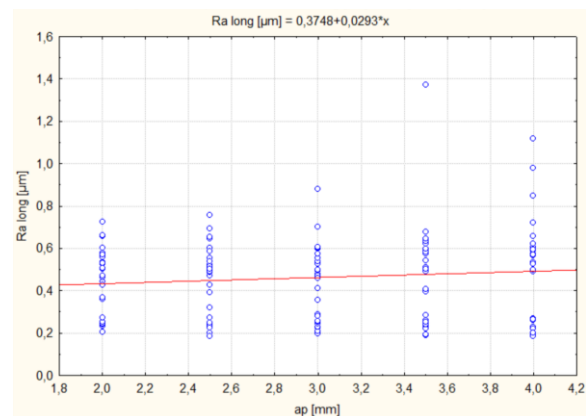


Figure 5. Dispersion diagram of R_a long values according to cutting depth [mm].

Figure 6 shows a slightly roughness downward trend relative to the increase in feed rate. This manifestation is clearly influenced by the high dispersion of roughness values at cutting speeds of 570 [m/min] and 610 [m/min].

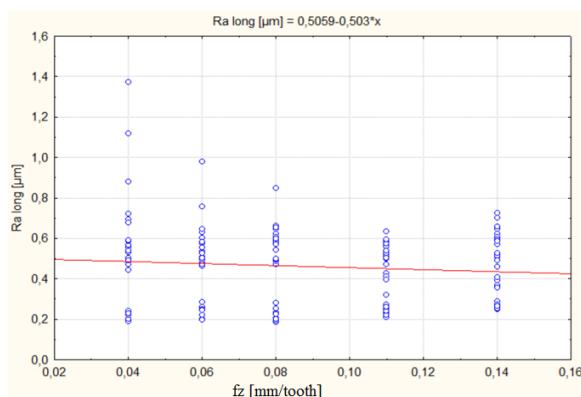


Figure 6. Dispersion diagram of R_a long values according to feed per tooth [mm/tooth].

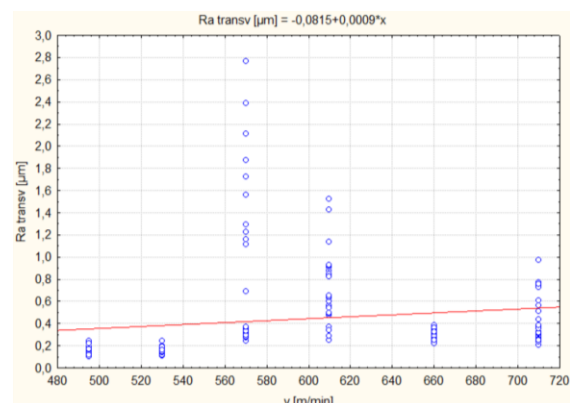


Figure 7. Dispersion diagram of R_a transv values according to cutting speed v [m/min].

However, considering the distribution of most R_a values obtained at the other cutting speeds of 495, 660 and 710 [m/min], respectively the entire cutting depth range of 2, 2.5, 3, 3.5, 4 [mm], one can observe the increasing trend of the roughness relative to the increase of the feed rate (Figure 6).

The diagrams of the R_a transv are shown in Figure 7 - Depending on the cutting speed in Figure 8 - depending on the cutting depth and in Figure 9 - depending on the feed per tooth.

Depending on the cutting speed (Figure 7), it can be observed that the large dispersions of R_a transv occur at 570 [m/min] and 610 [m/min] respectively. The large data dispersion is mainly due to the surface texture, which may result from vibrations that occur during milling. Similar is also the case with the cutting depth (Figure 8), in which the roughness values, as well as their dispersion, increase with the cutting depth value.

In Figure 9, too, the large dispersion of values at each feed rate can be observed. As an immediate conclusion, the speeds of 570 and 610 [m/min] lead to a large dispersion of transversely roughness values.

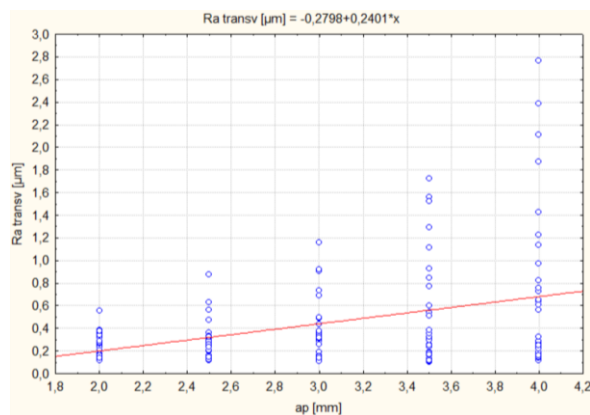


Figure 8. Dispersion diagram of R_a transv values according to cutting depth [mm].

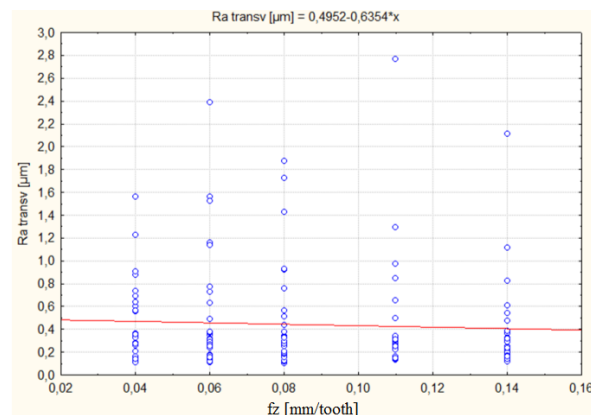


Figure 9. Dispersion diagram of R_a transv values according to feed per tooth [mm/tooth].

3.2.2. Surface plots. Contour plots. After performing the histograms - to track the normality of the experimental data distribution and dispersion diagrams - to track the scatter or grouping of the measured values related to R_a long or R_a transv, these objective functions may be subjected to a 3D (spatial) analysis in order to track variation under the influence of controllable factors (cutting parameters).

Making such a 3D graph involves plotting response surfaces, depending on two factors of influence.

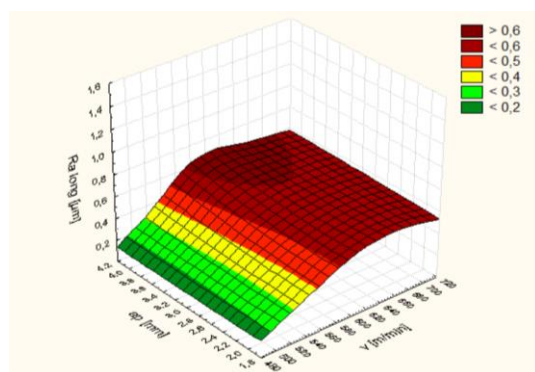


Figure 10. Spatial variation of R_a long according to v [m/min] and a_p [mm] (Spline).

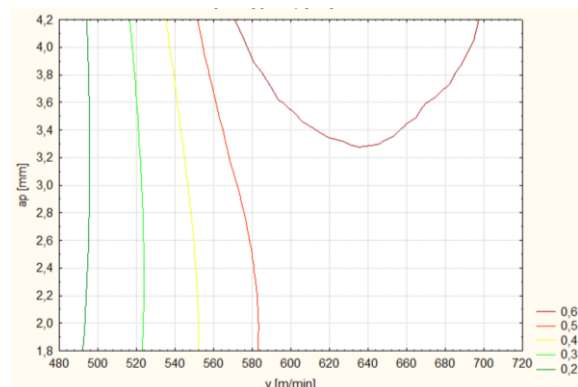


Figure 11. An indication of the contour plot variation of R_a long according to v [m/min] and a_p [mm] (Spline).

Thus, in a first analysis, regarding to the spatial variation of the R_a long, one can observe an increase of the roughness in the first part of the speed range of 495-570 [m/min], throughout the

cutting depth range. As the analysis result, it can be noticed that the cutting depth have not such a significant roughness influence when we have small cutting speeds, but it changes for speeds above 570 [m/min] (Figure 10). In the case of contour plot variation curves (Figure 11), according to the cutting speed and the cutting depth, it was found that:

- For cutting speeds of up to 570 [m/min], cutting depths do not have any influence on the roughness;
- For speeds higher than 570 [m/min], depths up to 3 [mm] do not affect roughness, but depths over 3 [mm] at higher cutting speeds have an impact giving roughness greater than 0.6 [μm].

These graphical representations highlight how the interaction between the two parameters influences the surface roughness. Figure 12 shows the spatial variation of the R_a long, depending on the cutting parameters speed and feed. It results that 570 and 610 [m/min] in combination with a small feeds have an impact on the R_a measured values, which increased throughout the experimental field. The cause of these increases in the values can be the vibrations that occurred during the cutting process. From the graph of the contour plots curves (Figures 13), it results that R_a measurements are influenced in the same time by the cutting speed and also by the feed rate, i.e., these values increase with the increase of the values of these parameters.

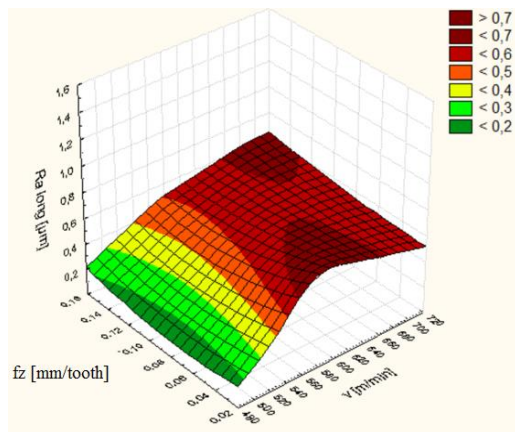


Figure 12. Spatial variation of R_a long according to v [m/min] and f_z [mm/tooth] (Spline).

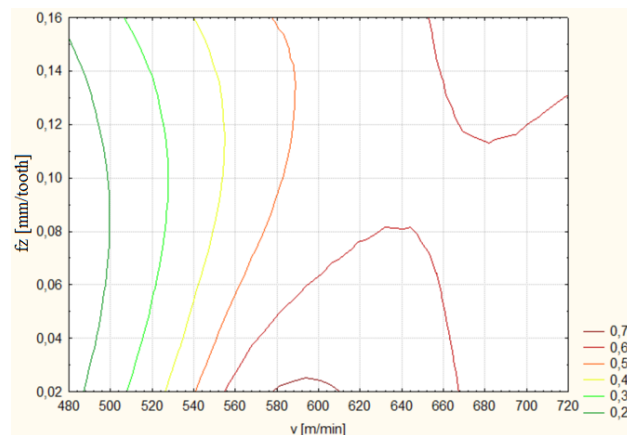


Figure 13. An indication of the contour plot variation of R_a long according to v [m/min] and f_z [mm/tooth] (Spline).

It can also be seen from these charts that values greater than 0.6 [μm] is around 570 and 610 [m/min], as follows:

- At low feed rate, although the tool loading is high, primary observations justify that vibrations are the cause of these increases in roughness values;
- At high feed rate, this phenomenon may also occur due to tool loading;
- However, in the middle of the feed rate range, there is a slight stabilization of the system, i.e. the vibrations that appear do not influence the quality of the surface so much.

Regarding the spatial variation of the roughness measured longitudinally in the direction of the feed motion, under the influence of the cutting depth and the feed per tooth is shown in Figures 14 and 15.

Following this analysis, it was found that the R_a values are influenced by the combination of depth and feed, resulting in small roughness. At higher feed rates and low depths due to the cutting speeds influence of 570 and 610 [m/min], occurs a trend to increase the R_a values.

As a general conclusion, following the analysis of the spatial graphs, the following findings are presented:

- The cutting speed is the most significant parameter with the influence on the R_a long;

- At certain cutting speeds, in combination with particular values of the cutting depth, respectively the feed per tooth, we assume that the vibration phenomenon occurs in the measured values of the average arithmetic deviation of the surface profile and its texture;
- The cutting speed with the feed per tooth combination, have the highest influence on the surface roughness;
- The cutting depth together with the feed per tooth, have little influence on the surface quality.

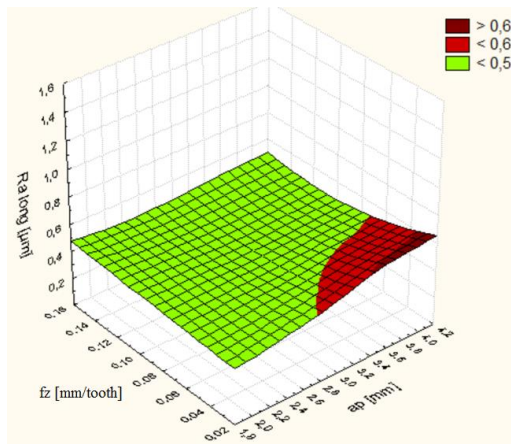


Figure 14. Spatial variation of R_a long according to a_p [mm] and f_z [mm/tooth] (Spline).

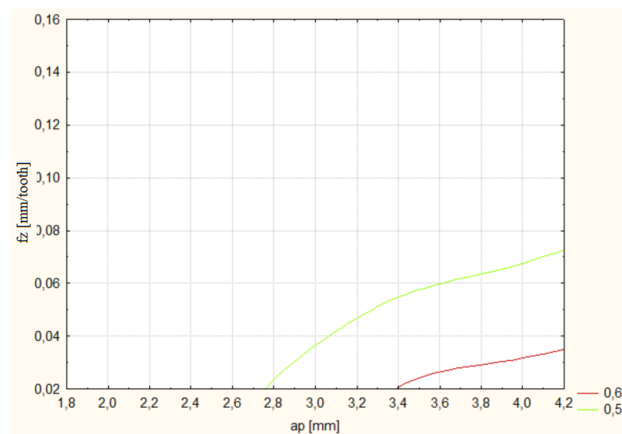


Figure 15. An indication of the contour plot variation of R_a long according to a_p [mm] and f_z [mm/tooth] (Spline).

Regarding the spatial variation of the arithmetic average deviation of the surface profile measured transversely on the feed motion direction, it can be seen an increase of the much larger roughness in the speed interval of 495-570 [m/min] over the entire cutting depth, but especially at the higher values of this parameter. As a result of the analysis, it can be noticed that the cutting depth significantly influences the surface quality when we have v more than 570 [m/min] (Figure 16).

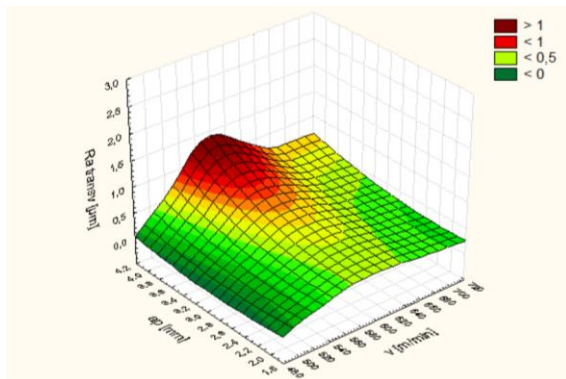


Figure 16. The 3D variation of R_a transv according to v [m/min] and a_p [mm] (Spline).

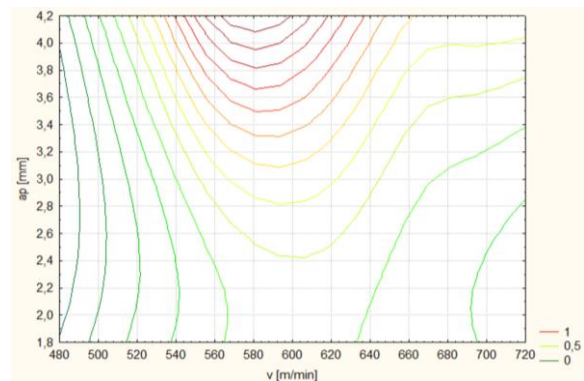


Figure 17. An indication of the contour plot variation of R_a transv according to v [m/min] and a_p [mm] (Spline).

In the case of the 3D variation of R_a transv, according to the cutting speed and the cutting depth, it was found (Figure 17):

- For up to 570 [m/min], the cutting depths do not have any influence on the roughness. Similarly, it was also found in speeds above 660 [m/min];

• For cutting speeds of 570 and 610 [m/min], cutting depths of up to 3 [mm] do not affect roughness, but over 3 [mm] cutting depth the cutting speeds in the field have a considerable influence, giving roughness greater than 1 [μm].

Figure 18 shows the 3D variation of the R_a transv in terms of cutting speed and feed rate.

Analyzing these figures it was found that 570 and 610 [m/min] joinong with a small feed rate presents an impact on the measured roughness values, increasing in the entire experimental field, but predominantly at the same speeds as in the previous situation 570 and 610 [m/min]. From the contour plot graph (Figure 19), it follows that the values of the arithmetic mean deviation of the surface profile are influenced by both the cutting speed and the feed rate, i.e. these values increase with the increase of the values of these parameters.

It also follows that values greater than 0.6 [μm] are around the cutting speed values of 570 and 610 [m/min] and therefore:

- At low feed rate, although the tool loading is high, we assume that the vibration effect, which influences the surface quality, occurs due to the resonance of the CNC machine – cutting tool-workpiece;
- At high feeds, this phenomenon may also occur due to tool loading;
- There is a slight stabilization of the system in the middle of the feed rate range.

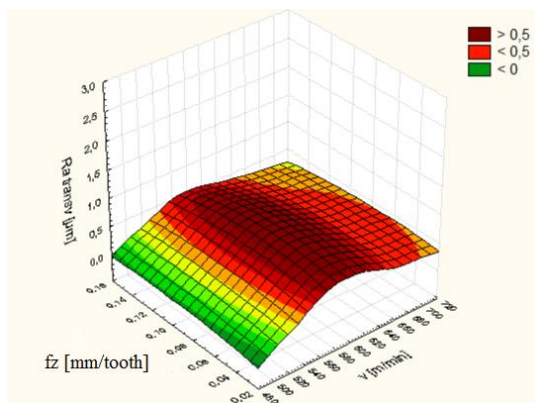


Figure 18. Spatial variation of R_a transv according to v [m/min] and f_z [mm/tooth] (Spline).

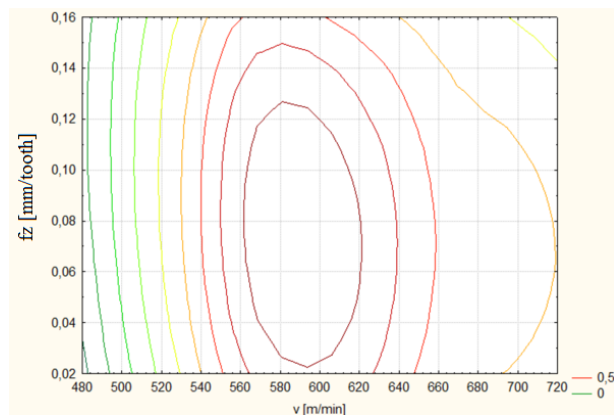


Figure 19. An indication of the contour plot variation of R_a transv according to v [m/min] and f_z [mm/tooth] (Spline).

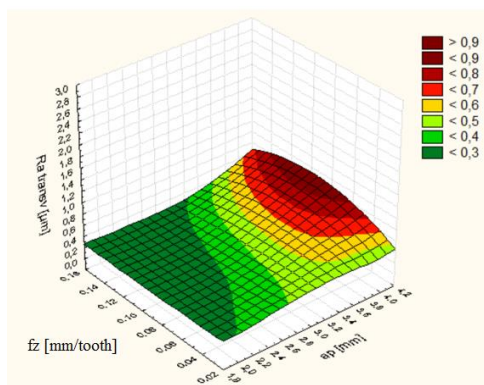


Figure 20. Spatial variation of R_a transv according to a_p [mm] and f_z [mm/tooth] (Spline).

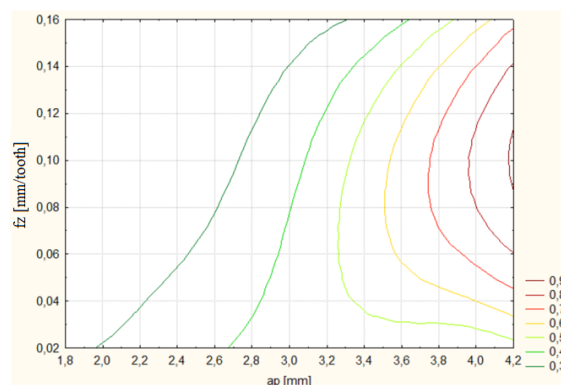


Figure 21. An indication of the contour plot variation of R_a transv according a_p [mm] and f_z [mm/tooth] (Spline).

About the 3D variation of the roughness measured transversally in the direction of the feed motion, under the influence of the cutting depth of and the advance on the tooth, the findings resulted from the analysis of Figures 20. Therefore, the cutting depth relative to the feed rate influences the arithmetic means deviation of the profile, resulting in small roughness.

Based on the contour plot analysis of Figures 21, it has been found that the value of the R_a increases once the cutting depth increasing irrespective of the feed per tooth values.

4. Conclusions

The final aim of making a successive series of tests under predefined variable conditions was to find the best results concerning others. Taking into account all the controlled factors and all the possible interactions between them, giving a quick, precise and unequivocal interpretation of the test results.

Graphical evaluation of normality distribution was performed by presenting histogram responses, and it was found that:

- Under the set conditions of the experiment (tool, material and cutting regime according to the manufacturer's recommendations), relatively low surface roughness for the end-milling process is obtained, approximately 0.5 [μm], in both situations R_a long and R_a transv;
- The values obtained from the experiment include the milling process, with the used cutting parameters, in the fine precision class;
- By the R_a long histogram results that the data have an approximately normal distribution, but not the case of R_a transv.

Another graphical representation of the R_a of the surface profile, according to each cutting parameter, was made using dispersion diagrams. The dispersion of the results was evaluated and the types of relationships of the cutting process parameters and the R_a of the surface profile were identified. We used a 3D analysis to interpret the obtained results from the R_a measurements. This analysis was followed by the variation of the R_a of the surface profile under the influence of the cutting process parameters. The influence of cutting speed and cutting depth on R_a long is thus manifested by a rather large increase in roughness, in the range up to 570 [m/min], over the entire cutting depth range. The influence of cutting speed and feed per tooth exerted on R_a long is felt by the fact that the cutting speeds of 570 and 610 [m/min], combined with a small feed, are impacting the measured R_a values, which increase all experimental field. The cause of these increases values may be due to the vibrations that occurred during the cutting process. The influence of the cutting depth and the feed per tooth, on R_a long, is manifested by the obtaining of small roughness after the machining. However, when we have higher feed per tooth and smaller cutting depths due to the cutting speeds influence of 570 and 610 [m/min], there is a trend to increase the R_a values. Consequently, the parameter with the most significant influence on the R_a long is the cutting speed. Of the interactions, the cutting speed along with the feed per tooth has the most considerable influence on surface quality. For R_a , the influence of cutting speed and cutting depth is manifested by increasing the roughness in the speed range of 495-570 [m/min] over the entire cutting depth range, but especially at the higher values of this parameter. The cutting depth significantly influences the surface quality at cutting speeds higher than 570 [m/min]. The influence of cutting speed and feed per tooth exerted on R_a transv is manifested by the fact that the 570 and 610 [m/min] in combination with a small feed per tooth exerting their impact on the R_a measured values, increasing in the whole experimental interval. Vibrations occurring during the cutting process may be the cause of these increases in values. The cutting depth about the feed rate influences the R_a of the machined surface, resulting in small roughness.

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