The Relationship Between the Cutting Process Parameters and the Surface Roughness during the Aluminum Machining

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Abstract. The purpose of this paper is to identify based on the composite central factorial experiment, the mathematical model between the arithmetic mean deviation of the surface profile and the cutting process parameters (cutting speed, cutting depth and feed per tooth), which describes the studied system in any point of the chosen experimental domain. The coefficients of these equations represent the influence of the variables on the response. The analysis of the variance ANOVA is focused on estimating the different types of variability of the response and the estimations made with the Fisher test. This test analyses the coefficients significance of the regression equation, by comparing the ratio of two variants. The Fisher test indicates the probability to be a statistical difference between them or not. In any case, the experimental results are associated with experimental errors. It is essential to find the prediction accuracy of the coefficient’s values, and not only their absolute value. In the end, will be determined the arithmetic mean deviation of the surface profile $R_a$, based on the mathematical model, and will be compared with the experimental results.

1. Introduction

Aluminum alloys are widely utilized as the principal workpiece material in automotive and aeronautical sectors. The surface quality, more exactly the surface roughness - represent an essential feature of product quality, as it has a significant influence on the superior capacities of the mechanical parts but also on the cost of production. Aluminum alloys have a higher workability index.

Among the most used processes is the milling one, in the aluminum alloys machining. Nowadays there are various researches that have been carried out to evaluate the influence and also the interaction of the cutting process parameters, respectively the cutting speed, the feed rate and the cutting depth exerted on the surface roughness in milling processes, using statistical techniques like Taguchi’s method [1-3]. Dobrotă D et al [4] addressed the issue of chemical composition in the castings process of aluminum alloys. Țîțu A M et al [5] debate the problem of an experience plan using Taguchi’s method to track the different cutting parameters influence to be able to optimize the performance of a process or system. Vamshi I and Gopinath V [6] addressed the issue of cutting forces and surface quality in the machining of aluminum alloys, using it as a technique for optimizing the Response Surface Methodology process. On the other hand, [7] studied in the cutting process, the fact that almost all the mechanical energy that is used to remove the material, is converted into heat and in this way generates a high temperature in the cutting area. As the cutting speed increases, so does the
heat, which generates higher temperatures. For these authors, the newest machining challenge is to use the cutting speed with an increased value which can lead to the productivity increasing and to achieve a better surface finish. They found that this generated heat will lead to the faster tool wear and surface roughness. Other authors have studied the effect of the cutting process factors on the surface quality using the design of experiments method [8-10] like the factorial experiment, Taguchi’s method, ANOVA. These methods were used to investigate the main effect of the cutting parameters, on the surface roughness in the end milling process of the Al 7136 and it results that the cutting speed, cutting depth and feed per tooth are influencing the surface quality.

In this research paper, it will be pursued to obtain a quantitative relation of the cutting process variables and the $R_a$ (the arithmetic mean deviation of the surface profile) based on the method of the central composite experiment.

2. Research methodology

2.1. The workpiece material

The material chosen to conduct the research is the 7136 - aluminum alloy. The workpiece dimensions are 500 x 110 x 24.50 [mm]. The chemical composition of this Al7136 alloy is shown in Table 1 [9].

| Element    | Min | Max |
|------------|-----|-----|
| Silicon    | -   | 0.12|
| Iron       | -   | 0.15|
| Copper     | 1.90| 2.50|
| Manganese  | -   | 0.05|
| Magnesium  | 1.80| 2.50|
| Chromium   | -   | 0.05|
| Zinc       | 8.40| 9.40|
| Titanium   | -   | 0.10|
| Zirconium  | 0.10| 0.20|
| Other Elements, each | - | 0.05|
| Other Elements, total | - | 0.15|
| Aluminum   | remainder |

2.2. Cutting tool

SECO R217.69-1616.0-09-2AN is the cutting tool chosen to carry out the research. The related two cutting inserts are XOEX090308FR-E05, H15. The tool is a standard one in aluminum machining.

2.3. Coolant

The coolant is a mineral oil - Blasocut BC 35 Kombi SW.

2.4. Experiment design

The end milling of Al7136 was carried out on the CNC HAAS VF-YT2. The design of experiment (DOE) implies a central composite factorial design, which is presented in Table 2. STATISTICA Software was chosen for this research.

| Name          | Units   | Type   | Low (-1) | Center (0) | High(1) |
|---------------|---------|--------|----------|------------|---------|
| A Cutting speed | [m/min] | Numeric | 495      | 570        | 660     |
| B Cutting depth | [mm]   | Numeric | 2        | 3          | 4       |
| C Feed per tooth | [mm/tooth] | Numeric | 0.04     | 0.06       | 0.08    |

For this study, the design of a central composite experiment (cube plus star) was chosen with 3 factors having 16 experimental tests and 1 single block.

In the STATISTICA Software there are the following options for selecting options:
• For the Compute / use alpha for rotatability option - Alpha axial distance will be calculated by STATISTICA Software. Thus, the axial distance in this case does not depend on the number of center points in the DOE.
• When the Compute / use alpha for orthogonality option is selected, then STATISTICS calculates the alpha axial distance that depends on the number of center points in the DOE.
• In the current research the interest is the Face center star points option (for example, ± 1), to set the values of the points as being equal to the minimum and maximum of the respective factor.
• Add center points (for orthogonality & rotatability) is indicated to add center points to the design to obtain (approximately) orthogonality and rotatability. Specifically, STATISTICA Software adds the central design points.

The points location determines whether the design is orthogonal (that is, if the effects of the factor are orthogonal) or rotary. The concept of DOE rotatability refers to the characteristics by which DOE can extract the same amount of information (i.e., make predictions with the same precision) in all the analyzed directions.

In this case Alpha for rotatability calculated by STATISTICA Software is 1.6818 and Alpha for orthogonality is 1.2872.

In the construction of the central composed design of three factors, the experimental domain is a cube and the 8 experimental points (nc = 8) represented by the corners of the cube, are added 6 experimental points on the three perpendicular axes (ns = 6) and two replication experiments in the center of the experimental domain (ns = 0), experiments 15 (C) and 16 (C).

The design array developed to accomplish the 16 studies runs the central composite factorial design, as presented in Table 3.

Table 3. Design matrix.

| Standard Run | Control factors | Response |
|--------------|----------------|----------|
|              | A - Cutting speed [m/min] | B - Cutting depth [mm] | C - Feed per tooth [mm/diente] | Rₐ - Surface roughness [µm] |
| 1            | -1 495          | -1 2     | -1 0.04 | 0.235 |
| 2            | -1 495          | -1 2     | 1 0.14  | 0.250 |
| 3            | -1 495          | 1 4      | -1 0.04 | 0.342 |
| 4            | -1 495          | 1 4      | 1 0.14  | 0.270 |
| 5            | 1 660           | -1 2     | -1 0.04 | 0.549 |
| 6            | 1 660           | -1 2     | 1 0.14  | 0.723 |
| 7            | 1 660           | 1 4      | -1 0.04 | 0.565 |
| 8            | 1 660           | 1 4      | 1 0.14  | 0.561 |
| 9            | -1 495          | 0 3      | 0 0.08  | 0.232 |
| 10           | 1 660           | 0 3      | 0 0.08  | 0.604 |
| 11           | 0 570           | -1 2     | 0 0.08  | 0.450 |
| 12           | 0 570           | 1 4      | 0 0.08  | 0.777 |
| 13           | 0 570           | 0 3      | -1 0.04 | 1.133 |
| 14           | 0 570           | 0 3      | 1 0.14  | 0.424 |
| 15 (C)       | 0 570           | 0 3      | 0 0.08  | 0.872 |
| 16 (C)       | 0 570           | 0 3      | 0 0.08  | 0.872 |

3. Analysis of variance ANOVA
The variance analysis ANOVA uses the variance ratio tests to determine whether or not exist some very large differences between the averages of several data groups and each data group has a normal distribution or not. The analysis of variance is an elementary instrument, used to evaluate the degree of matching of a regression analysis and of the generated model following the regression analysis.
variance analysis considers the estimation of various types of response variability and the F-test estimates [11].

The first step assumes to use the F test where the variance of the modeled results it is compared to the variance of the unmodified results. Then it is considered significant if \( p \) is less than 0.05. The next phase consists of the model comparison with the replication error than the results are significant if the \( p \) value has a greater value than 0.05.

Specifically, the objective of ANOVA technique is to evaluate the influence and the interaction of machining parameters that significantly affect the surface quality. Therefore, the proper combinations of the process variables are predicted. Table 4 presents the results obtained from this analysis carried out using STATISTICA Software.

**Table 4.** The variance analysis of the surface roughness of Al7136.

| Source of variation | Sum of square (SS) | Degree of freedom (d.o.f) | Mean Square = SS/d.o.f | F Value | P Value |
|---------------------|-------------------|--------------------------|------------------------|---------|---------|
| A                   | 0.246332          | 1                        | 0.246332               | 15.2348 | 0.003602 | significant |
| B                   | 0.043963          | 1                        | 0.043963               | 2.71899 | 0.133561 |
| C                   | 0.010977          | 1                        | 0.010977               | 0.67891 | 0.431256 |
| AB                  | 0.023891          | 1                        | 0.023891               | 1.47759 | 0.255075 |
| AC                  | 0.041271          | 1                        | 0.041271               | 2.55246 | 0.144587 |
| BC                  | 0.007539          | 1                        | 0.007539               | 0.46628 | 0.511896 |
| Error               | 0.145521          | 9                        | 0.016169               |         |         |
| Total SS            | 0.514799          | 15                       |                        |         |         |

R-squared = 0.71732; Pred R-squared = 0.8542, Adj. R-squared = 0.52887

By this analysis results that the cutting speed is the variable with the greatest effect on the surface quality. Statistically, the model value F of 15.23480 assumes that the model is significant. Moreover, the P value less than 0.05 indicates that factor A - cutting speed is important.

Next, the standardized estimation of the effects of the factors and the interactions between them will be made using the Pareto diagram (Figure 1).

As can be seen, a vertical line is displayed indicating the minimum size of statistically significant effects, taking into account the current model and choosing the error term using the statistical significance criterion. This graph shows very clearly the influence of factor A - the cutting speed on the roughness of the machined surface of the aluminum alloy.

Another important aspect is that the objective function can be undergone to a three-dimensional analysis, to follow their variation under the influence of controllable variables (cutting process parameters). By plotting the response surfaces, an equation of the regression model is obtained, which can be successfully used to estimate the values of the objective function, throughout the experimental field. The response surface corresponding to the regression equation of the model with the estimated coefficients, belongs to a multifactorial space located between the extreme levels of the influence factors, so to the interpolation of the values of this objective function (that is, with a dimension with one larger than the number of influence factors included in the model) and as such, in general (for more than two influencing factors), it can only be described analytically. However, often, in order to form an image that is more intuitive than that provided by the regression equation, one uses the graphical representation of this response surface, depending on two influencing factors [11-13]. However, it is important to note that the interpretation of experimental results, solely 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 representation party). 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 [11].

**Figure 1.** The Pareto Chart of the Standardized Effect.

Analyzing the graph in Figure 1, it is observed that the interactions that has the greatest effect on the roughness is the AC - the cutting speed and the feed per tooth. Therefore, the effect of this interaction on the surface roughness will be presented in Figure 2.

**Figure 2.** Fitted surface – $R_a$ related to AC variation.
By Figures 2 and 3 it follows that with the increase of the two cutting parameters, the cutting speed and the feed rate, the value of the surface roughness increases.

The regression equation for the graph has the following form:

\[
z = -1.1725290986626 + 0.0023274260714661 \cdot x - 8.8302925001351 \cdot y - 0.0066185580512082 \cdot 3 \cdot x + 0.017328190259503 \cdot x \cdot y - 0.61153657258854 \cdot 3 \cdot y + 1.51093249
\] (1)

4. Statistical analysis of the coefficients of the regression equations for the surface roughness

\( R^2 \) is a statistical parameter that evaluates the fit degree of the regression model. \( R^2 \) is the coefficient of multiple regression (or the coefficient of determination) and represents the response variation that can be explained by the model. \( R^2 \) takes values between 0 and 1:

- 0 means that the experiments data do not match the chosen regression model at all;
- The closer the values for \( R^2 \) are to 1, the better the experimental data are matching with the chosen model, and the ability to predict the experimental plan is better [12].

| Factor  | Regression Coeff. | Std. Err. | t (9)  | p     | 95% Cnf.Limt. | 95% Cnf.Limt. |
|---------|-------------------|-----------|--------|-------|---------------|---------------|
| Mean/Interc. | -1.17253 | 1.157552 | -1.01294 | 0.337546 | -3.7911 | 1.446036 |
| A       | 0.00233 | 0.001953 | 1.19147 | 0.263939 | -0.0021 | 0.006746 |
| B       | 0.50364 | 0.325591 | 1.54686 | 0.156300 | -0.2329 | 1.240181 |
| C       | -8.83029 | 6.846863 | -1.28968 | 0.229314 | -24.3190 | 6.658388 |
| AB      | -0.00066 | 0.000544 | -1.21556 | 0.255075 | -0.0019 | 0.000570 |
| AC      | -0.01733 | 0.010846 | 1.59764 | 0.144587 | -0.0072 | 0.041864 |
| BC      | -0.61154 | 0.895570 | -0.68285 | 0.511896 | -2.6375 | 1.414383 |

R-squared = 0.71732; Pred R-squared = 0.52887, MS Residual = 0.16169
• 1 is a perfect model. The fit degree of the regression equation obtained is 71.7% (Rsqr=0.71732) (Table 5).

![Figure 4. Observed versus predicted values of Ra.](image)

The final conclusion that can be drawn based on the obtained data (Figure 5), is that the regression equation for $R_a$ predicts the chosen experimental plan, in every point in the experimental domain, with a probability degree of 72%.

5. Conclusions
The surface quality and, implicitly its roughness, is an essential indicator of the product quality as it affects the product performance and also the production cost.

The reason for which the aluminum was chosen for this research is that its alloys have a higher index of workability than other materials. The milling process was chosen considering that it is the most widely used process for the aluminum machining.

Starting from the principal purpose of this research, it was identified based on the method of the central composite experiment, the quantitative relation between the parameters of the cutting process parameters: cutting speed, cutting depth and feed per tooth and the arithmetic mean deviation of the surface profile, to describe the system studied at any point of the chosen experimental field.

We chose to use the ANOVA analysis to estimate the different types of response variability to determine whether or not are significant differences between the averages of the analyzed data groups and whether they have a normal distribution. This analysis followed the influence and interaction of the cutting process parameters that significantly affect the surface quality and predicted the optimal combinations of the end milling process.

At the same time, the fit degree of a regression analysis and the generated model was evaluated. The coefficients significance which belong to the regression equation was tested using the Fisher test, and the probability of a statistical difference was shown. From this analysis it resulted that the cutting speed has the greatest effect on the roughness. Statistically, the model value is $F = 15.23480$ which
assumes that the model is significant. Moreover, the P value which is less than 0.05 indicates that the factor A - cutting speed is important.

Using the Pareto diagram, a standardized estimation of the effects of the factors and of the interactions between them was performed. It results that the highest influence on the surface roughness of the 7136-aluminum alloy, is exerted by the factor A - the cutting speed, followed by the interaction between the cutting depth, the cutting speed and the feed rate.

Analyzing the variation of the objective function under the effect of the cutting factors, the evolution of the surface roughness was subjected to a three-dimensional analysis. Thus, by plotting the response surfaces, an equation of the regression model was obtained, which can be used to approximate the values of the objective function, throughout the experimental domain. The graphical representation was associated with the obtained regression equation and interpreted in this context. The interaction which has the highest effect on the surface roughness was found to be the AC - the cutting speed and the feed per tooth. It was also observed that with the increase of the two cutting parameters, the value of the surface roughness increases.

It was also taken into account that the experimental results must be associated with experimental errors. Therefore, the coefficients values accuracy was predicted and not only their absolute value was determined but also a regression model was identified that predicts the chosen experimental plan, at any point of the experimental domain with an accuracy of 72%.

6. References

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