Regarding to the Variance Analysis of Regression Equation of the Surface Roughness obtained by End Milling process of 7136 Aluminium Alloy

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Abstract In the metal cutting process, surface quality is intrinsically related to the cutting parameters and to the cutting tool geometry. At the same time, metal cutting processes are closely related to the machining costs. The purpose of this paper is to reduce manufacturing costs and processing time. A study was made, based on the mathematical modelling of the average of the absolute value deviation (Ra) resulting from the end milling process on 7136 aluminium alloy, depending on cutting process parameters. The novel element brought by this paper is the 7136 aluminium alloy type, chosen to conduct the experiments, which is a material developed and patented by Universal Alloy Corporation. This aluminium alloy is used in the aircraft industry to make parts from extruded profiles, and it has not been studied for the proposed research direction. Based on this research, a mathematical model of surface roughness Ra was established according to the cutting parameters studied in a set experimental field. A regression analysis was performed, which identified the quantitative relationships between cutting parameters and the surface roughness. Using the variance analysis ANOVA, the degree of confidence for the achieved results by the regression equation was determined, and the suitability of this equation at every point of the experimental field.

1. Introduction
Previous research was focused on the investigation of the effect of the feed rate on the surface roughness and on the reduction of processing time [1]. This time, the attention will be focused on the mathematical modeling of a regression equation of the surface roughness obtained on the end milled profile.

In the scientific literature, there are studies based on mathematical modeling which can be mentioned: [2] which used the Response Surface Methodology (RSM) as optimization technique, [3] and [4] which used the Taguchi’s method, [5] used the regression analysis and [6] which used ANOVA and the regression analysis.

Regression analysis is a statistical method of identifying the quantitative relationships between independent variables (factors) and dependent variables (responses). This method allows the use of experimental data in order to calculate the equation coefficients, an equation that describes the studied system at any point of the experimentally range studied [7].

The technique known as the analysis of variance (ANOVA) uses tests which are based on the variance ratio, to determine if there are significant differences between averages of several data groups and if each data group has a normal distribution. The technique was initially developed and used by R.A. Fisher and his colleagues in England in the early 1920s about ANOVA.
About ANOVA, Fisher says that "it is a cheap and convenient technique for understanding asymmetry" [7]. The variance analysis is a basic tool used to assess the fit of a regression analysis, respectively, the model generated from regression analysis.

ANOVA focuses on estimating various types of variability of responses and estimates made by F-test [7].

To use the ANOVA test for evaluation of the quality match, it is necessary to repeat the experiment at least once in the centre of the experimental range. In these circumstances, using ANOVA, it is possible to divide in two the total variance of a response, one due to the regression model and one due to residual. If the situation in which there exists experimental data obtained from repeated experiments under the same conditions, the residual variance can be divided into the variance related to the model error and related to the variance of replication error [7].

Thus, the first step of the method, is to assume that the experimental plan model was well chosen. Subsequently, the experimental plan model is tested and evaluated to determine if the model and the estimated parameters are significantly different from the experimental data obtained.

After the calculation of the model coefficients, they are evaluated to determine if they were well calculated and if the response value deviation obtained related to the anticipated response value is due to a random variation or due to the uncontrolled influencing factors.

2. Research methods

2.1. Process variables and their parameters

Experiments were conducted based on three machining parameters: cutting speed, feed per tooth and cutting depth.

All of these three parameters takes variables values according to the tool manufacturer recommendation for aluminium machining.

The experiment planning was done respecting the three principles of Montgomery [8]:

- The randomization principle - under which the statistical methods require that the observations (or errors) have random distributions to the parameters. The observation randomization makes this assumption valid.
- The replication principle - involves the repeating of experiment by 3-7 times for each set of input parameter values. This procedure is necessary to determine the consistency of measurements. In this case, to obtain precise results, a 7x experimental replication was applied.
- The principle of working in "blocks" –It is used to improve the comparison accuracy of the used factors. In this research 7 blocks were used. In the Table 1 is presented this specific working procedure. Under this procedure, I was able to achieve the full factorial experimental plan with 7 blocks.

| Table 1. Experimental procedure. |
|----------------------------------|
| **Cutting speed [m/min]**        | Levels number |
| 495                              | 6 levels |
| 530                              |          |
| 570                              |          |
| 610                              |          |
| 660                              |          |
| 710                              |          |
| **Cutting depth [mm]**           | 5 levels |
| 2                                |          |
| 2,5                              |          |
| 3                                |          |
| 3,5                              |          |
| 4                                |          |
| **Cutting feed [mm/tooth]**      | 5 levels |
| 0,04                             |          |
| 0,06                             |          |
| 0,08                             |          |
| 0,11                             |          |
| 0,14                             |          |
| **Total experiments**            | 6x5x5=150 |
| **Replications**                 | 7 |
| **Total Mesurements**            | 150x7=1050 |

2.2. Work Material
The investigations are conducted based on the Al7136 material used in the aircraft industry, which properties are superior to other materials, including high strength to weight ratio, high wear resistance, low thermal expansion, corrosion resistance, durability, ductility, and conductivity, which make it a versatile material.

To conduct the experiment, the specimens have the following dimensions: 500 x 101 x 24.5 mm. On each specimen 50 machining operations were performed for the 50 cutting regimes set based on the combinations of the studied cutting parameters. The machined surface was 50 mm long and 16 mm wide. Thus, the 150 cutting regimes obtained under the combinations, were tested by processing of 21 blocks with dimensions mentioned above, the number of blocks covered the whole number of experiments, including the replications (figure 1).

![Figure 1. The Al7136 -21 blocks prepared for machining procedures.](image1)

![Figure 2. The tool SECO R217.69-1616.0-09-2AN use to conduct the experiments.](image2)

2.3. Cutting tool

The experiment was performed using a standard set of tools for aluminium machining - 16 mm End milling cutter milling with 100% tool engagement - SECO R217.69-1616.0-09-2AN, holding two indexable cutting inserts XOEX090308FR-E05, H15 (figure 2). For each of the seven blocks tested from Al7136, out of 21, a set of cutting inserts were used (of 2 pieces each – total 6 cutting inserts).

2.4. CNC Machine

The machine used for the milling tests is a HAAS VF2 CNC. Abundant amounts of Blasocut BC 35 Kombi SW mineral coolant were provided at the cutting zone throughout the experiment. The pressure of the coolant pump of the machine was 8 bar. Three hoses of Ø6 diameter have been used to route the jet. Each specimen was fixed on the CNC table with three clamps, in order to obtain rigidity. So, the specimens are parallel to the table and perpendicular to the main shaft (figure 3). In figure 4 it can be seen, for example, two milled blocks of Al7136.

2.5. Response

After the milling of the 21 blocks of aluminium alloy Al7136, the measurements of the surface roughness were carried out over 5 mm distance using the portable surface roughness tester Mitutoyo SURFTEST SJ-210, with a resolution of 0.002 μm. The delimitation of the performed roughness measurements are indicated in figure 5.
2.6. Results

After the measurements performing, the Ra roughness evolution can be analysed according to the studied cutting parameters, as shown below.

Figure 6 shows that with the increasing of cutting speeds between 495 m/min and 660 m/min, the mean roughness values, has an upward trend. Thus, when the cutting speed is 495 m/min, the Ra value is 0.27 μm and for 660 m/min the Ra is 0.57 μm. Regarding the cutting speed of 710 m/min average roughness is 2.3 times higher, having a value of 0.62 μm. When the cutting speed is 570 m/min, the Ra distribution is high enough so that the ratio between the maximum and minimum recorded Ra value is 8 times compared with other cutting speed values for which the ratio is between 2.2 (660 m/min) and 4.99 times (at 495 m/min).

In figure 7, the direct influence exerted on the surface roughness is shown by the combination of cutting feed and feed per tooth at the cutting speed 570 m/min. In this figure, the roughness values obtained at different depths of cut are plotted. The large distribution of the roughness values at cutting speeds of 570 m/min and 610 m/min affects also the maximum roughness values in relation to cutting depth. Given that, the average Ra values are almost linear, it appears that the cutting depth variation does not produce a high fluctuation of roughness values.

The figure 8 shows the experimental data regarding the surface roughness obtained at different feed per tooth values. This indicates that an increase of the feed per tooth values does not the influence
significantly the surface quality. This is due to the correlation of feed rate with cutting speed, correlation given by the cutting tools manufacturer.

Figure 6. The cutting speed influence on Ra values.

Figure 7. The cutting depth influence on Ra values.

Figure 8. The feed per tooth influence exerted on surface roughness.

3. Regression analysis
Using as a starting point the experimental results, the regression analysis was performed in order to obtain a regression equation of the surface roughness according with the studied cutting parameters.

Thus, the regression analysis was carried out using the Methods for Least Squares, a method which can estimate the polynomial equation coefficients which describes the model by minimizing the squared distances between the experimental value and the calculated value. Thus, it was determined
the percentage contribution of the cutting parameters influence on the surface roughness, as shown in Table 2.

To facilitate the calculations necessary to achieve the research objective, MINITAB 17 was applied, which is a statistical application and it was determined the sum of squares and the distribution percentage for each factor or factors interaction separately.

Table 2. The cutting parameters influence exerted the surface roughness [%]

| Source           | FD | SS       | %   |
|------------------|----|----------|-----|
| Regression model | 7  | 199,482  | 86,12% |
| Cutting speed A  | 1  | 194,322  | 83,89% |
| Cutting depth B  | 1  | 0,040    | 0,02%  |
| Feed per tooth C| 1  | 1,157    | 0,50%  |
| A x B            | 1  | 3,093    | 1,34%  |
| A x C            | 1  | 0,316    | 0,16%  |
| B x C            | 1  | 0,366    | 0,14%  |
| A x B x C        | 1  | 0,188    | 0,08%  |
| Error            | 827| 32,156   | 13,88% |
| Fitting error    | 143| 18,735   | 8,09%  |
| Pure error       | 684| 13,421   | 5,79%  |
| Total            | 834| 231,638  | 100%   |

Thus, by using the calculation procedure predefined on MINITAB 17, the regression coefficients were determined and, therefore, the Ra regression equation is:

\[
Ra = 0.000287 \cdot A - 5.808 \cdot C + 0.000196 \cdot A \cdot B + 0.01345 \cdot A \cdot C - 0.001582 \cdot A \cdot B \cdot C
\] (1)

4. The Variance analysis (ANOVA) of the regression equation

To use the ANOVA test in order to evaluate the match quality, it is necessary to repeat the experiment at least once in the centre of the experimental range. In this research, the experiments were repeated seven times.

In these circumstances, using ANOVA, it is possible to divide the total variance of a response in two, one due to the regression model and one due to the residual. If the situation in which existing experimental data can be used, (from repeated experiments under the same conditions) the residual variance can be divided into the variance of model error and the variance replication error [7].

In the first stage of the method, the model assumes that the experimental plan was well chosen. Subsequently, it is tested and evaluated whether the model and estimated parameters are significantly different from the experimental data obtained.

After calculating the coefficients model, it is assessed whether they were well calculated as well as whether the deviation value of the responses to the responses predicted value is due to random variation or due to the influence of uncontrolled factors.

The first phase of the method assumes that the experimental plan was well chosen. Subsequently, this aspect is tested and then the model and the estimated parameters are evaluated, in order to observe if they are significantly different from the experimental data obtained.

After the calculation of the model coefficients, the deviation of the obtained response against the value of the predicted responses will be evaluated to determine if the deviation is due to the random variation or due to the influence of uncontrolled factors. Therefore, the calculation method is based on the total sum of squares SSTOTAL define as the sum of squares of differences from the average value.
The next phase implies that the absolute values of these estimated variance have to be compared using Fisher test F [7].

F test compares the ratio of two variances and shows the probability that a statistical difference between two variances will exist. In the first step, using the F-test, the variance of the modelled results is compared with the variance of non-modelled results and, it is considered satisfactory if p - the level of confidence is less than 0,05.

In the second step, the model is compared with the replication error and the results are considered satisfactory if p - the confidence level is greater than 0,05 [7].

Each sum of squares can be divided by the number of freedom degrees (fd) to get the average squares (MS) [7]. Going through these steps by using the MINITAB 17, the ANOVA test can be performed for the regression equation Ra. Thus, the Table 3 presents the analysis results. Since the calculated F value is greater than the tabular F value (Fcalc> Ftab) and is always greater than 1, it may be considered that the relation between the modification of the factors levels and the response it is adjusting the relation statistically significant.

Therefore, the mathematical model is acceptable and it is permitted to describe the evolution of the studied phenomenon in the experimentally studied range, with a strong correlation between the studied factors and responses and therefore a strong correlation between the regression equation and the obtained experimental date.

This is confirmed by the value representing 86% of the suitability of the regression model, determined after this analysis. Specifically, the regression equation Ra predicts the chosen experimental plan at any point of the experimental field, with a degree of probability of 86%.

| Source           | FD  | SS     | MS    | Fcalc | Ftab |
|------------------|-----|--------|-------|-------|------|
| Regression       | 5   | 199,38 | 39,876| 1025,09 | 2,225 |
| A                | 1   | 194,322| 0,197 | 5,054 | 3,853 |
| C                | 1   | 1,194  | 3,685 | 94,717 | 3,853 |
| A x B            | 1   | 0,569  | 0,873 | 22,429 | 3,853 |
| A x C            | 1   | 2,795  | 2,528 | 64,997 | 3,853 |
| A x B x C        | 1   | 0,501  | 0,501 | 12,871 | 3,853 |
| Residual         | 829 | 32,258 | 0,039 |       |      |
| Fitting error    | 145 | 18,837 | 0,130 | 6,628 | 1,222 |
| Pure error       | 684 | 13,421 | 0,020 |       |      |
| Total            | 834 | 231,638| 39,915|       |      |

5. Conclusion

After the performing of the regression analysis, the quantitative relationships were identified between the studied cutting process parameters (cutting speed, cutting depth and feed per tooth) and the mean deviation of the surface profile.

The percentages of the influence of each cutting parameter were determined (or combination of cutting parameters) exerted on Ra of the machined surface profile, so:

- Cutting speed holds a majority of influence on surface roughness - by 83,89%, depth of cut affects the surface roughness with a rate of 0,02% and the influence on the feed per on Ra is 0,05%;
- Cutting speed with cutting depth influences the surface roughness with 1,34%, cutting speed with feed per tooth, affects the surface roughness with a rate of 0,16%, cutting depth and feed per tooth, influence the surface roughness with a rate of 0,14% and the combination of cutting speed, cutting depth and feed per tooth, affects the surface roughness with a rate of 0,08%.
To evaluate the experimental data relating to the regression equation, the analysis of variance (ANOVA) was used, and finally it was found that the significance of the confidence in the obtained results is 85.92%.

6. Future work
- Methods identification that will lead to obtain some mathematical models of others factors – like tool wear, which influence the surface quality.
- The study of the tool wear evolution in the aluminium machining, based on the varying of the cutting parameters regime.
- Expanding the range of current research on other materials and compared to the studied 7136 aluminium alloy.

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