CNC End Milling Process Parameters Optimization on Aluminium Alloy by Using Taguchi and ANOVA Methods

M A Țîțu* and A B Pop1
1 Lucian Blaga University of Sibiu, 10, Victoriei Street, Sibiu, România, The Academy of Romanian Scientists, 54, Splaiul Independenței, Sector 5, Bucharest, Romania
2 SC TECHNOCAD SA, 72, Vasile Alecsandri Street, Baia Mare, România

*E-mail: mihail.titu@ulbsibiu.ro

Abstract. This paper is focused on the experimental research which is carried out on the machining of the aluminum alloy. Its main objective is to find the optimum cutting parameters used in the end-milling process. An experimental plan was established based on the L27 orthogonal matrix. The experiments were performed using the recommended values for the cutting parameters by the cutting tools manufacturer on the aluminum machining. The design of experiment methods that were used, are the Taguchi method, the variance analysis and the regression analysis. The controllable factors were the cutting speed, the cutting depth and the feed per tooth. The surface roughness represents the objective function and this was obtained by the studied cutting process. The surface roughness was measured longitudinally and transversely in the cutting direction.

1. Introduction
Surface roughness is an essential indicator of surface quality. This indicator significantly influences the technological time and costs, in other words the productivity.

We have to define the surface quality starting with the first phase of the product development – the design one, considering some aspects like functionality, costs, appearance, etc. Therefore, numerous scientific papers address the roughness modeling and cutting process optimization to achieve the tracked level of surface quality. For this purpose, the correct selection of the cutting process parameters is essential in order be able to obtain the minimum value of the surface roughness and, at the same time to extend the tool life.

The experimental design is widely used in the cutting process in order to predict it and optimize it to obtain a given surface roughness. Rashid M F F et a. [1] has developed a mathematical model because he wants to predict the surface roughness during the front milling process. Barkallah M et al. [2] have create a statistical model of the surface roughness in the front milling at high cutting speeds with cooling, by changing the rotations number, and also the cutting speed and the cutting depth. By his research, [3] analyzes the cutting depth influence, the rotation speed and the cutting feed exerted on the surface roughness.

Due to the primary impact on the production, but also on the cost and productivity, the investigations of the surface quality represent the main subject in many another research [4, 5].

Modeling the quality of the machined surface of an aluminum alloy using the active type experiment is approached by [6] and [7-8] and the objective function optimization - the surface quality
was approached in [9] based on Montgomery principles [10] (the principle of random character, the principle of replication and the one of working in "blocks").

Taguchi method is a technique frequently utilized to study the process robustness; and was addressed by [11].

In this scientific work, the main objective was to analyze the influence exerted by the cutting parameters on the surface roughness during the end milling process of an aluminum alloy. Then, will be followed by the elaboration of a statistical regression model using the design of experiment methodology in order to predict the surface roughness.

2. Methods and methodology

The aluminum-alloy 7136 end milling experiments were performed using SECO R217.69-1616.0-09-2AN cutting tool, having two teeth, diameter is 16 mm, and the tool engagement consist of 100% (16 mm), and the coding of the corresponding cutting inserts, is XOEX090308FR-E05, H15.

The process parameters with the three levels are listed in Table 1. HAAS VF-YT2 is the CNC machine tool used to carry out the experiments.

| Table 1. Cutting process parameters and their levels. |
|-----------------------------------------------------|
| Factors                                      | Process parameters | Unit  | Level 1 | Level 2 | Level 3 |
| A                                           | Cutting speed (v)  | m/min | 610     | 660     | 710     |
| B                                           | Cutting depth (ap) | mm    | 3       | 3.5     | 4       |
| C                                           | Feed per tooth (fz)| mm/tooth | 0.4    | 0.6     | 0.8     |

| Table 2. L27 orthogonal array to conduct the experiments and the obtained measurements of surface roughness. |
|---------------------------------------------------------------|
| No. Exp. | A - Cutting speed (v) [m/min] | B - Cutting depth (ap) [mm] | C - Feed per tooth (fz) [mm/tooth] | R_z [µm] | R_ςT [µm] |
|----------|-------------------------------|------------------------------|-----------------------------------|----------|----------|
| 1        | 610                           | 3                            | 0.4                               | 3.167    | 2.301    |
| 2        | 610                           | 3                            | 0.6                               | 5.978    | 5.390    |
| 3        | 610                           | 3                            | 0.8                               | 3.850    | 4.498    |
| 4        | 610                           | 3.5                           | 0.4                               | 4.778    | 4.177    |
| 5        | 610                           | 3.5                           | 0.6                               | 5.768    | 3.027    |
| 6        | 610                           | 3.5                           | 0.8                               | 6.667    | 4.150    |
| 7        | 610                           | 4                            | 0.4                               | 4.394    | 10.234   |
| 8        | 610                           | 4                            | 0.6                               | 8.017    | 6.780    |
| 9        | 610                           | 4                            | 0.8                               | 6.867    | 5.455    |
| 10       | 660                           | 3                            | 0.4                               | 3.167    | 2.042    |
| 11       | 660                           | 3                            | 0.6                               | 4.141    | 1.213    |
| 12       | 660                           | 3                            | 0.8                               | 4.114    | 1.492    |
| 13       | 660                           | 3.5                           | 0.4                               | 3.620    | 1.592    |
| 14       | 660                           | 3.5                           | 0.6                               | 4.261    | 1.302    |
| 15       | 660                           | 3.5                           | 0.8                               | 3.901    | 1.724    |
| 16       | 660                           | 4                            | 0.4                               | 4.299    | 1.650    |
| 17       | 660                           | 4                            | 0.6                               | 3.528    | 1.549    |
| 18       | 660                           | 4                            | 0.8                               | 3.177    | 2.433    |
| 19       | 710                           | 3                            | 0.4                               | 4.349    | 3.620    |
| 20       | 710                           | 3                            | 0.6                               | 4.104    | 2.923    |
| 21       | 710                           | 3                            | 0.8                               | 4.913    | 3.078    |
| 22       | 710                           | 3.5                           | 0.4                               | 4.780    | 2.345    |
The end milling operations were carried out in accordance with the experiment array L27 presented in Table 2. With the portable Mitutoyo SURFTEST SJ-210 were obtained the experimental data. In Table 2 are also presented the roughness values measurements obtained longitudinally (Rz) and transversely (RzT) in the milling direction.

3. Results and discussion

For the above experimental conditions, the results were explained using the figures, diagrams and graphs presented below, using Minitab Statistical Software.

Using Taguchi design the Orthogonal Array Design L27 (3^3) was obtained. The 27 experimental tests were obtained based on the 3 factors with 3 levels each. The influence of the surface roughness on each individual factor (A, B, C) and on the interaction between them (AB, AC, CA and ABC) was followed.

The percentage of influence of the factors and their interactions on the Rz and RzT measured on the milling direction was determined. These percentages are shown in Table 3.

| No. | Exp. | A - Cutting speed (v) [m/min] | B - Cutting depth (ap) [mm] | C - Feed per tooth (fz) [mm/tooth] | Rz [µm] | RzT [µm] |
|-----|------|-----------------------------|---------------------------|----------------------------------|--------|--------|
| 23  | 710  | 3.5                         | 0.6                       | 3.850                             | 4.261  |
| 24  | 710  | 3.5                         | 0.8                       | 3.189                             | 3.826  |
| 25  | 710  | 4                           | 0.4                       | 3.756                             | 4.006  |
| 26  | 710  | 4                           | 0.6                       | 4.647                             | 2.722  |
| 27  | 710  | 4                           | 0.8                       | 3.743                             | 5.253  |

As it results from Table 3 the cutting process variable with the highest influence exerted on the surface roughness is the cutting speed (A) in both situations for the Rz longitudinally (Rz) - the percentage being 21.35%; as well as for the Rz transversely (RzT) - the percentage being 10.36%. Regarding the interaction of the parameters, the greatest influence has the cutting speed associated with the cutting depth (A*B) being a percentage of 12.2% for the Rz longitudinally and 4.99% for the Rz transversely. A noteworthy aspect is that on the Rz transversely a significant influence has the interaction of the 3rd degree of the process parameters (A*B*C), which has a percentage of 9.16%. This influence is not felt on Rz longitudinally.

The determined regression equations that describe the surface roughness according to the factors chosen for the established experimental field are the following:

Table 3. Determining the percentage influence of the factors and interactions on the surface roughness.

| Source    | Rz Contribution | RzT Contribution |
|-----------|-----------------|------------------|
| Regression| 49.13%          | 37.21%           |
| A         | 21.35%          | 10.36%           |
| B         | 3.12%           | 9.70%            |
| C         | 2.44%           | 0.00%            |
| A*B       | 12.20%          | 4.99%            |
| A*C       | 8.03%           | 1.83%            |
| B*C       | 0.16%           | 1.18%            |
| A*B*C     | 1.82%           | 9.16%            |
| Error     | 50.87%          | 62.79%           |
| Total     | 100%            | 100%             |
\[ R_z = 14 - 0.020 \cdot A + 6.0 \cdot B - 100 \cdot C + 0.0105 \cdot A \cdot B + 0.156 \cdot A \cdot C + 38.3 \cdot B \cdot C \]  
\[ R_{zT} = -347 + 0.513 \cdot A + 107.6 \cdot B + 491 \cdot C - 0.1579 \cdot A \cdot B - 0.727 \cdot A \cdot C - 147.8 \cdot B \cdot C \]  

Figures 1 and 2 show the graphs of the main effects of the roughness related to the cutting process parameters: A (cutting speed), B (cutting depth) and C (feed rate).

**Figure 1.** The main effect plot for \( R_z \).

**Figure 2.** The main effect plot for \( R_{zT} \).
As can be seen from these graphs, the maximum value of the $R_z$ of 8,017 [$\mu$m] is obtained at the $A = 610$ [m/min], $B = 4$ [mm] and $C = 0.6$ [mm/tooth]. Regarding the $R_{zT}$, the maximum value of 10,234 [$\mu$m] is obtained at $A = 610$ [m/min], $B = 4$ [mm] and $C = 0.4$ [mm/tooth]. The only difference between the two measurements is the feed per tooth parameter.

Figures 3 and 4 show the influences of the interactions of the cutting parameters exerted on the surface roughness.

The interactions graphs of the process parameters show that both surface roughness $R_{zT}$ and $R_z$ measured in the milling direction are largely influenced by the interaction of $A$ and $B$ process parameters. Specifically, from Figures 3 and 4 it results that that the greatest roughness values is recorded when $A = 610$ [m/min] associated with $B = 4$ [mm]. If it is desired to have the best surface quality, in other words, the surface roughness measured longitudinally $R_z$ as small as possible, it is recommended - according to the obtained data - to adopt a cutting regime in which all the analyzed process parameters take the minimum values. Regarding $R_{zT}$, the recommended cutting regime is that $A = 660$ [m/min], $B = 3$ [mm] and $C = 0.6$ [mm/tooth].

Figure 3. Interaction plot for $R_z$.

Figure 4. Interaction plot for $R_{zT}$.
In the Figures 5 and 6 are presented the residual diagrams related to the regression equations obtained for the two objective functions analyzed.

**Figure 5.** The residual plots for $R_z$.

**Figure 6.** The residual plots for $R_{zT}$. 
The first graph of these figures presents the probability of the normal distribution. From here it can be seen that the residuals are to a certain extent approximating a straight line and the histogram of the residual distribution shows the residual values which exceed the Gauss's distribution curve.

Regarding the fitted values diagrams and the one of their observation orders, results that the residuals distribution is not uniform respecting the zero line and, sometimes, they show large jumps value from one to another, caused by the recorded values at cutting speeds of 610 [m/min].

4. Conclusions

The surface quality resulted by the end milling process is particularly important because it significantly influences the productivity.

To obtain an optimal roughness the base is the correct selection of the cutting parameters from the design phase of the product development.

Starting from the main objective of analyzing the influence of the cutting process variables which is manifested on the surface roughness machined by the end milling process of the 7136-aluminum alloy, was developed a statistical regression model to predict the surface quality using the DOE methodology.

The influence percentage of the factors and their interactions on the surface roughness measured longitudinally (R_z) and transversely (R_{zT}) on the milling direction was determined.

The conclusions which were drawn punctually, are:
- the cutting process parameter which have the greatest influence exerted on the surface roughness is the cutting speed (A);
- regarding the interaction of the parameters, the greatest influence is the cutting speed associated with the cutting depth (A*B);
- on the surface roughness measured transversely (R_{zT}) a significant influence has the interaction of 3rd degree of the process parameters (A*B*C);
- the regression equations describing the surface roughness were determined according to the factors chosen for the established experimental field;
- the maximum R_z value measured of 8.017 [µm], is obtained when A (cutting speed) is 610 [m/min], B (cutting depth) is 4 [mm] and C (feed per tooth) is 0.6 [mm/tooth];
- the maximum value of the R_{zT} of 10.234 [µm] is obtained when the A (cutting speed) is 610 [m/min], B (cutting depth) is 4 [mm] B (cutting depth) is 0.4 [mm/tooth];

To obtain the lowest roughness value, it is recommended to adopt a cutting regime in which all the analyzed process parameters take the minimum values.

5. References

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