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Applying experimental research management to a technological process using Taguchi's Method

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Abstract

The surface quality is dependent on certain cutting process parameters that can vary, causing variations on the surface roughness. The main subject of this paper focuses on the experimental research management applied to a technological process whose final purpose was to determine an equation of the surface roughness depending on the process parameters, obtained by the Al7136 end milling process. The research method used in this paper is the Taguchi's method. According to the research management steps, in order to perform the experimental determination of the surface roughness, an experimental stand used to determine the objective function was presented. The surface roughness equation was determined using the Minitab 17 software. The regression equation allows to calculate the surface roughness at any point in the established experimental field.

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Keywords: Experimental research management, Surface Roughness, Quality, Taguchi's Method, Cutting Process Parameters

1. Introduction

Genichi Taguchi has developed a method that bears his name, in order to improve the quality of the manufactured products, with applications in engineering, biotechnology, marketing and advertising. The Taguchi method is a method that applies to experimental research, and is often used in processes, products and services modeling and

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optimizing in certain situations. The emergence of various concepts of the quality management methods panoply is presented below (Oprean & Țîțu, 2007):

1. Product - Final inspection:
   - Final products sampling;
   - Problem solving activities.
2. Manufacturing processes - Quality assurance in production:
   - Statistical process control (SPC);
   - Warning devices (Poka yoke).
3. Functional entities and the relationships between them – Quality Ensuring implied in all functions:
   - Design;
   - Manufacturing and suppliers;
   - Sales;
   - Service.
4. Organization - All collaborators training:
   - Changing attitudes and behaviors.
5. Economic balance - Quality starting with the processing phase:
   - Parameter optimizing to achieve the robustness.
6. Customer - The loss of quality function:
   - Quality quantification in financial terms.
7. Targets – Quality Function Deployment (QFD):
   - The "close-to-close declining" of customer wishes in terms of specifications and actions.

The experimental design techniques with quality loss considerations, are combined by using the Taguchi's method in order to achieve the robustness.

Taguchi addresses quality into a very cost sensitive area based on the decisions that are made with respect to the each activities and also to improve the quality in the product and process development stages.

G. Taguchi's contribution stands at 5 and 6 level. Definitely profitable is the implementation of this method in design studies and products industrialization, where the quality it is implemented and it the future productivity increases are prepared (Oprean & Țîțu, 2007).

Taguchi proposes an improving strategy of the product quality on the production line, given that none of control can replace the product quality. Some of the relevant research papers aimed to debate this method is the Murthy's one (Murthy, Babu & Kumar, 2014), in which the authors wants to optimize the cutting regime parameters used on aluminum alloy Al6061 turning, using Taguchi's method. He wants to determine the influence levels of these parameters, exerted on the surface roughness.

The influence of the process parameters on the impact forces produced by water jets using the Taguchi design and full factorial design, was treated by Medan (Medan & Bănică, 2016).

The friction and the tool wear have been the research subjects of Mishra's work (Mishra, Sheokand & Srivastava, 2012). The author used the Taguchi's experimental plan establishing the controllable factors as: cutting forces, sliding speed and sliding distance. A linear regression equations led to friction and wear but not before data's testing obtained by ANOVA – the variance analysis. To conduct an experimental research, to follow the next steps it is recommended (Montgomery, 2013):

- The problem statement recognition;
- The response variable selection;
- The factors (process parameters), levels and ranges choosing;
- The experimental design choosing;
- The experiment performing;
- The statistical data analysis;
- Conclusions and recommendations.

In this research paper an interesting topic is presented which consist of an experimental research management applied to improve a technological process using Taguchi's Method. The present paper is a part of the studies conducted within the doctoral thesis entitled ,,Surface quality analysis of machined aluminum alloys using end mill tool'' (Bonțiu, 2015). Also, the first results of the present study were obtained in (Bonțiu Pop, 2015), but in this case the results were substantiated in more detail.

The experimental research has been conducted with the support of the UACE Europe Company, which is focused on the aerospace machining parts.

The purpose of this article is to determine the surface roughness equation depending on the end milling process parameters. The research method used is a powerful tool to design optimization for quality - the Taguchi's method. An orthogonal array, the signal-to-noise (S/N) ratio, and the analysis of variance (ANOVA) are employed to investigate the cutting characteristics of 7136 aluminum alloy using a standard set of tools for aluminum machining. The process parameters influence exerted on the surface roughness was determined. Using Taguchi's method for design of experiment (DOE), other significant effects such as the interaction among milling parameters are also investigated. The surface roughness equation based on the parameters influence was also determined. The experimental results are provided to confirm the effectiveness of this approach.

Nomenclature

R_a arithmetic average of the roughness profile

2. The experimental stand and the measurements methodology

Milling is a versatile and useful machining operation. End milling is the most important milling operation and it is widely used in most of the manufacturing industries due to its capability of producing complex geometric surfaces with reasonable accuracy and surface finish. However, with the inventions of CNC milling machine, the flexibility has been adopted along with versatility in end milling process. It is found that many research works have been done so far on continuous improvement of the performance of end milling process.

Fig. 1. The experimental stand.

In end milling, surface finish is an important aspect, which require attention both from industry personnel as well as in Research & Development, because this factor greatly influence machining performances. In modern industry, one of the trends is to manufacture low cost, high quality products in short time. Automated and flexible manufacturing systems are employed for that purpose. CNC machines are considered most suitable in flexible manufacturing system. Above all, CNC milling machine is very useful for both its flexibility and versatility. These machines are capable of achieving reasonable accuracy and surface finish. Processing time is also very low as compared to some of the conventional machining process (Moshat, Datta, Bandyopadhyay & Kumar, 2010). In this paper in order to measure the surface roughness an experimental stand has been designed (Bonțiu, 2015). This experimental stand includes the workpiece material, the cutting tools and the cutting regime used to machine the samples, also the CNC machine and the measurement devices. Well, as the Fig. 1 shows, the workpiece material used to conduct the experiments is the Al7136 alloy T76511 (SAE-AMS4451A-2008). The aluminum alloy dimensions chosen for the experiment are 500 mm × 101 mm and 24.5 mm (Fig. 1).

The effective experiments will go towards to detailed study of the behavior of 7136 aluminum alloy in accordance with the proposed objectives taking into account the variation of the cutting regime parameters.

The experiment will be performed using a standard set of tools for aluminum 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.

The machine used for the milling tests is a 3 axis - HAAS VF2 CNC.

To make an optical determination and evaluation of the finished surface, the optical microscope Micro-Vu VERTEX 310 was used.

Also, to analyze the surface roughness for different machining conditions it was used the portable surface roughness tester - TESA RUGOSURF 20. The covered distance by the measuring device sensor is 5 mm.

With this experimental stand they have been fulfilled the main necessary requirements to achieve the sets objectives and also to obtain the experimental data on which can be analyzed the cutting parameters influence (cutting speed, cutting depth and feed per tooth) exerted on the roughness of the end milled surface.

After the experimental stand presentation the research methods used in this paper may be approached. For the beginning, the Taguchi's Method will be used for the determination of the parameters percentages and their interactions influence exerted on the surface roughness.

3. Taguchi Method

3.1. The process parameters establishment and their setting levels

Taguchi's philosophy, is an efficient tool for designing the high quality manufacturing system.

This experimental work seeks to evaluate the optimal result for selection of cutting speed [m/min], cutting depth [mm] and feed per tooth [mm/tooth] in order to achieve a good surface roughness (R_a value) during the CNC end milling process.

Table 1. Process parameters and level values for Taguchi method.

Abbreviation	Parameter	Name	Values		
A	Parameter 1	Cutting speed [m/min]	495	530	660
B	Parameter 2	Cutting depth [mm]	2	3	4
C	Parameter 3	Feed per tooth [mm/tooth]	0.04	0.08	0.14

The selected process control parameters used during the experiments are indicated in Table 1. These parameters have been allowed to vary in three different levels.

3.2. Establishing the experimental plan using Taguchi method

Choosing an array of experiences is causing total degrees of freedom required. The freedom degrees of the associated factors are calculated with the formula:

$$GL_f = N_f \cdot (N_n - 1) = 3 \cdot (3-1) = 6 \quad (1)$$

Where: Nf represented the factors numbers,
Nn represents the number levels of each factor.

The freedom degrees associated to the interactions are calculated with the formula:

$$GL_i = N_i \cdot (N_n - 1) = 3 \cdot (3-1) = 6 \quad (2)$$

Where: Ni represents the interactions numbers.

The total number of freedom degrees calculated:

$$GL_t = GL_f + GL_i = 6 + 6 = 12 \quad (3)$$

Number of freedom degrees of the experiences matrix must be at least minimum 12 (experiments).

According to Taguchi method nearest array of experiences that meet the condition is the matrix L9 Orthogonal Array design (3^3) (Fig. 2).

$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 2 & 2 \\ 1 & 3 & 3 \\ 2 & 1 & 2 \\ 2 & 2 & 3 \\ 2 & 3 & 1 \\ 3 & 1 & 3 \\ 3 & 2 & 1 \\ 3 & 3 & 2 \end{pmatrix}$$

Fig. 2. Orthogonal array L9 (3^3), according to Taguchi method.

For each 9 experiments three measurements sets of the surface roughness were performed.

Table 2. The surface roughness measured according to the parameters set.

No. of exp.	Parameter			Values			
	Cutting speed [m/min]	Cutting depth [mm]	Feed per tooth [mm/tooth]	R_a1	R_a2	R_a3	R_aM
1	495	2	0.04	0.272	0.296	0.209	0.259
2	495	3	0.08	0.180	0.210	0.189	0.193
3	495	4	0.14	0.210	0.221	0.223	0.218
4	530	2	0.08	0.240	0.271	0.203	0.238
5	530	3	0.14	0.246	0.268	0.258	0.257
6	530	4	0.04	0.236	0.219	0.224	0.226
7	660	2	0.14	0.795	0.712	0.740	0.749
8	660	3	0.04	0.579	0.544	0.588	0.570
9	660	4	0.08	0.448	0.454	0.491	0.464

3.3. The percentages determination of the parameters and their interactions influence exerted on the surface roughness

For each experiment was determined the average roughness (R_aM). The experimental data of R_a value corresponding to L9 Orthogonal Array design of experiment has been tabulated below (Table 2).

According with the Taguchi's experimental plan, table 2 shows the parameter values of L9 orthogonal array with the three measured roughness values (R_a) and their average for each cutting regime. The determination of the level of influence for each parameter exerted on the surface roughness is based on these measurement values. Starting with L9 experimental, the main effects of each factor's and their interactions (cutting speed, cutting depth and feed per tooth) were calculated using a dedicated software to experimental research and data processing. Since the Taguchi method is superior to the classical method of experimental plans, the next step is to determine the signal/noise ratio - a performance indicator (Ţîţu, Oprean & Boroiu, 2011), (Bonţiu, 2015), where the performance is the output of a system with one or more inputs. The Signal/Noise ratio used for the result measurements; simultaneously take into account the relative average measurements of each test and the dispersion. So, the higher measurement is the algebraic value of S/N ratio, the loss incurred is lower, thus cutting process performance is better. Therefore, the signal/noise ratio must mainly be used to properly select the control factor levels. Starting with the centralized results listed in table 2, the evolution graphs regarding the measured values' effects have been created, which demonstrate the signal/noise ratio based on the obtained surface roughness measurements – Fig. 3 and Fig. 4.

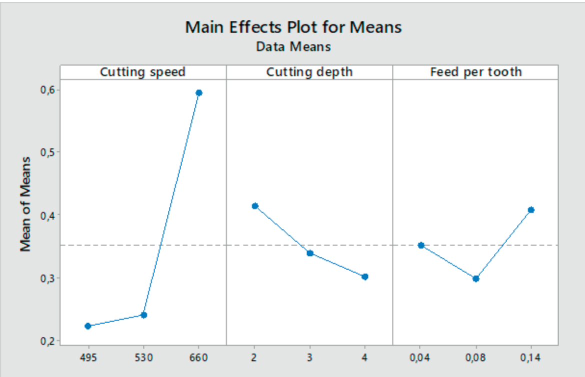

Fig 3. Main effects plot for means.

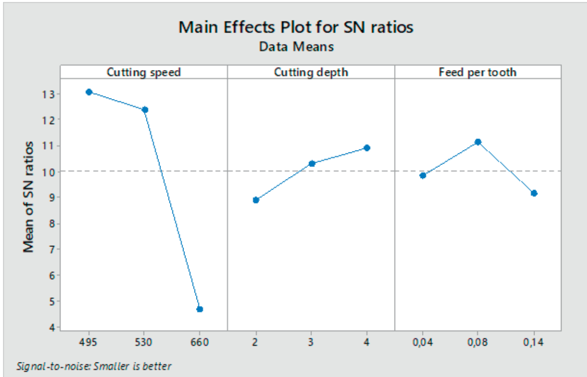

Fig. 4. Main effects plot for Signal/Noise ratio.

The aim of these graphs is to ease the comparison of these two result types regarding the measured values - i.e. average surface roughness and the S/N, in µm.

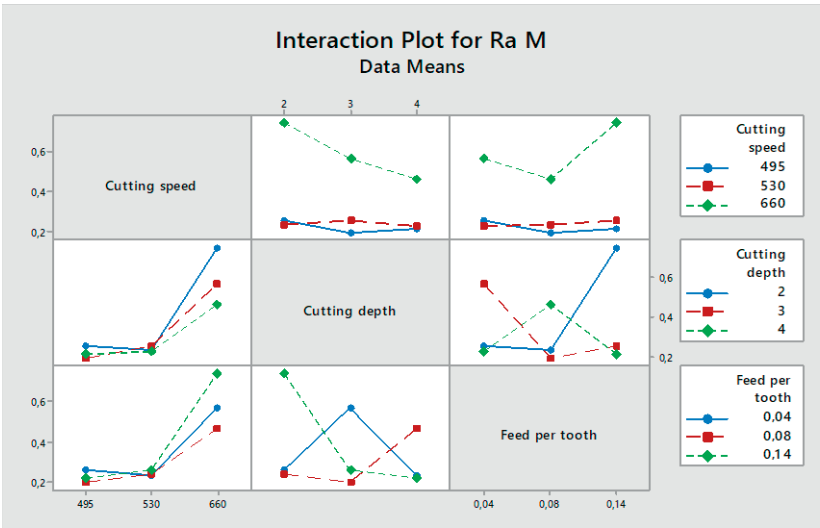

Fig. 5. Interaction plot for R_a M.

The representation of the influence parameters interactions exerted on the surface roughness, starts with a tabular layout of the average values corresponding of two parameters, followed by a simple mathematical calculation owned by Minitab 17 (Fig. 5). The effect of the interaction between two factors are calculated by the program. These values are used for plotting interactions between parameters to see their effect exerted on the surface roughness (Fig. 5).

To calculate the percentage contributions of the studied parameters and their interactions were used the table 2 data's. Based on the Taguchi's method result, the Variance Analysis ANOVA was conducted to determine the influence of each parameter and their interactions on the surface roughness.

Table 3. Analysis of Variance.

Source	DF (degree of freedom)	SS (sum of square)	Contribution
Regression	6	0.304	99.17%
Cutting speed (A)	1	0.256	83.44%
Cutting depth (B)	1	0.018	6.17%
Feed per tooth (C)	1	0.006	2.17%
A x B	1	0.013	4.51%
A x C	1	0.001	0.53%
B x C	1	0.007	2.35%
Error	2	0.002	0.83%
Total	8	0.307	100%

Table 3 shows the results of ANOVA for surface roughness. This table highlights the parameters and their interactions contribution on the surface roughness:

- The cutting speed, with an influence percentage of 83.44%;
- The cutting depth, with an influence percentage of 6.17%;
- The feed per tooth, with an influence percentage of 2.17%.

It can be found that the cutting speed is the significant cutting parameter that affecting the surface roughness. The change of the cutting depth and the feed per tooth in the range given by Table 1 has an insignificant effect on surface roughness. Therefore, based on the S/N and ANOVA analyses, the optimal cutting parameters for surface roughness are the cutting speed at level 1, the cutting depth at level 3, and feed per tooth at level 2. Based on these results the next step to be performed consists in the determination of the surface roughness equation that will be presented below.

4. The determination of the surface roughness equation

To determine the surface roughness equation it was used the Minitab 17 software. A linear regression equation was obtained by using the least squares method. According to the parameters contribution and their interactions of the studied process (table 3) the surface roughness equation has been determined:

$$R_aM = -1.796 + 0.004655 \cdot A + 0.443 \cdot B - 12.49 \cdot C - 0.001059 \cdot A \cdot B + 0.01445 \cdot A \cdot C + 1.414 \cdot B \cdot C \quad (4)$$

From the surface roughness equation (4), the diagrams of the residuals plots for R_aM have been obtained (Fig. 6).

The Residual plots of the machining parameters composed by the normal probability plot of residuals for quality loss, the plot of residuals vs. the fitted value, the histogram and residuals vs. the data order, are shown in Fig. 6. It can be seen from Fig. 6 that all the points on the normal probability plot approximates a straight line (mean line). This implies that the data are fairly normal and a little deviation from the normality is observed. From the histogram chart the residual values shall be consistent with the Gauss distribution, and the fitted value diagram of the residuals have a random distribution of the 0 line. As a conclusion, the regression equation describes the surface roughness according with the R_a measures presented in table 2. Also, the confirmation of the previous experiment was a crucial step and was highly recommended to verify the experimental conclusions.

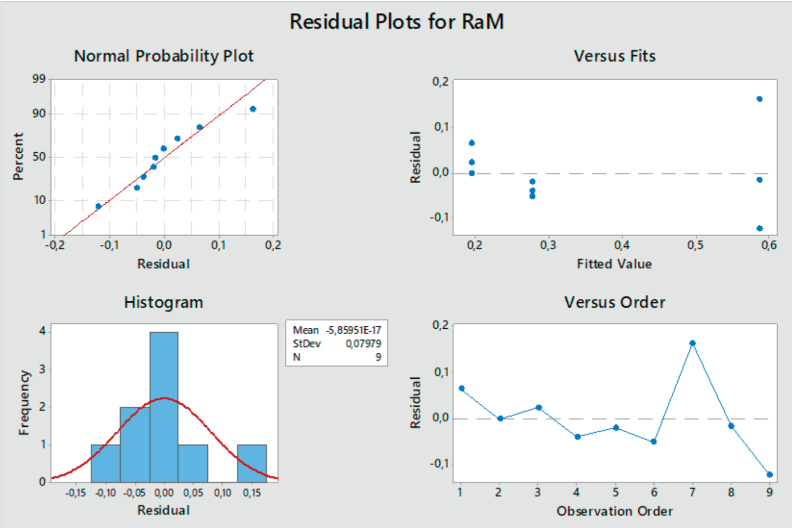

Fig. 6. Residual plots for the surface roughness equation.

5. Conclusions

This scientific paper was done following the management steps of an experimental research.

The following conclusions can be drawn based on the experimental results of this study.

The advantage of using the Taguchi method instead a classical experimentation design is that the Taguchi method is focused on the mean of the quality characteristic while the classical experimentation considers the minimization of the variance of the characteristic of interest.

The experiments were conducted to determine the effects of the established cutting tool parameters on the surface roughness during the end milling operation of aluminum alloy machining.

The surface quality is dependent on the cutting process parameters that can vary, causing variations of the surface roughness.

This research demonstrates how to use Taguchi parameter design to optimizing the machining performance with minimum time and cost. The parameter design of the Taguchi method provides a simple, systematic and efficient methodology to optimize the cutting parameters.

Taguchi's orthogonal array design method is suitable to analyze the surface roughness problem as described in this paper. So, following the Taguchi's method steps in order to calculate the percentage of the parameters and their interactions influence exerted on the surface roughness, it was found that the cutting speed has the greatest influence on the machined surface profile, with a percentage of 83.44%.

The surface roughness values are directly proportional and increase with the cutting speed increasing.

The effect of the cutting depth and the feed per tooth on the surface roughness is less. The cutting depth, is influencing the surface roughness with a percentage of 6.17% and the feed per tooth, has just a smaller influence of 2.17%.

The ANOVA analysis results confirm that the cutting speed is the dominant factor determining the surface roughness. Based on the surface roughness determined by using the Taguchi's method, a regression equation has been determined, which allows calculating the surface roughness at any point in the established experimentally field.

Further study could consider more factors in the research to see how the factors would affect the surface roughness.

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