




Article

Design of Experiment in the Milling Process of Aluminum Alloys in the Aerospace Industry

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Received: 26 August 2020; Accepted: 29 September 2020; Published: 4 October 2020



Abstract: For many years, surface has quality received a serious attention due to its influence on various mechanical properties. The main contribution made in this scientific paper is the performance of actual experiments, as well as the experimental processing obtained in order to develop a model for predicting the surface roughness based on the optimization of cutting parameters. The novelty of this paper is brought by the method of obtaining the regression equation of the surface roughness, resulted from a standard end-milling process (standard milling tools, standard milling parameters, recommended by the tool manufacturer, 3 axis CNC machine and standard vice), on aluminum alloy 7136 in temper T76511, through two statistical methods of data analysis. This material is used for the production of extruded parts and is poorly understood for the proposed line of research. This study's aim is to determine the surface roughness equation obtained by the milling of aluminum alloy 7136 in two ways: using Taguchi's experimental design once and the other, using the central composite design. The Taguchi method and the central composite design are used to develop an efficient mathematical model to predict the optimal level of certain processing parameters. Using ANOVA analysis, a comparative study of calculated and experimental surface roughness values is carried out. The initial characteristics (surface roughness) and the controlled factors (cutting speed, depth of cut and feed) are analyzed with the Minitab program. Finally, an analysis of the advantages and disadvantages of the two methods used is presented. This study has a great industrial application, since the main task of every manufacturer is to achieve a better quality of the final product with minimal processing time.

Keywords: aluminum alloy; end-milling process; Taguchi design; central composite design; design of experiments

1. State of the Art

Over the last decade, the use of the aluminum alloys in the manufacturing industry has grown due to the fact that these alloys have an extraordinary ability to combine their two properties: low weight and strength in a single material. Given this, it is imperative to assume knowledge of the machinability properties of these materials when it is desired to provide information for use in industry and by researchers. The aim is to offer the possibility to process these materials by making the best decisions in this regard.

In the automotive industry, aluminum is already well known due to its wide range of applicability [1]. In the aerospace industry, in the 1930s, the most frequently approached aluminum classes were mainly 2xxx, 7xxx and 6xxx [2,3].

The preference felt in this regard in the automotive and aerospace industries is justified by the high strength of these materials against to their low weight but also the fact that they often bring a degree of profitability in the sense that they can replace steel and cast iron in parts manufacturing. Due to the low weight of aluminum, the impact on the environment is also reduced. The supporting argument of this claim is the low energy consumption [3].

Other areas in which aluminum alloys find their applicability, concern the construction area; of course, the electrical, electromechanical, electronic and packaging industries. Aluminum alloys are also used with great success in the manufacture of nanostructures where their property of high mechanical strength and thermal stability is required. A good example of this is the 6061-T6 aluminum alloy [1].

Compared to steels, aluminum alloys have a third of their density and modulus of elasticity, but also a much higher thermal and electrical conductivity, as well as high corrosion resistance, high coefficient of friction, etc. [1].

According to Demir [4] and Singh [5], aluminum is widely used in the manufacture of motor vehicle parts during turns, because it is lightweight. It is desirable to produce high quality surface products as soon as possible.

The surface roughness of mechanical components plays a major role in the relationship between industrial production and cost. Surface roughness usually depends on the cutting parameters, such as: cutting speed, feed rate and cutting depth [6,7]. Proper selection of the control factors is particularly important for the manufacture of surface components and high strength in a short time. With the processing in recent years, much has been done to improve the quality and efficiency of the product. Many aspects of research have yet to be explored.

Ravindra Thamma tested different models to get the best machining parameters for aluminum 6061 [8]. Studies have shown that shaft speed, strength and nose radii have very good surface quality impact.

Somashekara [9] uses control factors such as cutting speed, feed rate and cutting depth to optimize surface roughness when machining Al 6351-T6 alloy with uncoated carbide tools. The Taguchi technique is used to optimize the process parameters and the reinforcement test has been identified to determine the main factors affecting the surface roughness. This test shows that cutting speed has a greater impact on surface roughness.

The effect of cutting parameters (spindle speed, feed rate, and cutting depth) on surface roughness and tool wear is investigated by Devkumar when turning 6061 aluminum alloys [10]. Many regression models were developed for responses and the adequacy of the developed models was tested at 95% confidence interval using variance analysis (ANOVA) method.

Ranganath [11] studied the parameters that influence the roughness during the machining of Al 6061 on CNC lathes. The Taguchi and ANOVA methods were used to study the experimental results. According to his study, the result is that the feed and the speed levels are the most important parameters.

Ali Abdullah [12] developed the cutting parameters: feed, spindle speed and depth of cut, using the Response Surface Methodology method to reduce the surface roughness and increase the material removal rate of Al6061 material during the turning process.

With the Taguchi and RSM technique, Alagarsamyet [13] has conducted the experiment by turning the 7075 aluminum alloy. The author presents an effective approach in order to optimize the cutting parameters (cutting speed, feed rate and feed per tooth) in order to minimize surface roughness and maximize material removal rate. For processing, he used TNMG 115 100 tungsten carbide tool. The author analyzed the performance characteristics in the turning process based on the orthogonal array, the signal/noise ratio and the ANOVA analysis. Finally, he was able to determine a mathematical model of the response surface [13].

Ezuwanizam [14] found that the optimal cutting factors for speed, feed and depth were the optimal life of the TiN coated tool on aluminum 6061. The results show that as the cutting parameter values increase, the tool wear decreases during the final milling. However, the axial cutting depth does not affect the response in the same way as the cutting speed and feed ratio do.

The research in this article begins with the first original contribution made by the authors for this work, namely some comparative graphs about the state of aluminum alloys in the world. The first graphs have been drawn and describe the aluminum alloys used as a percentage in the aerospace industry in the 2005–2019 period (Figure 1).

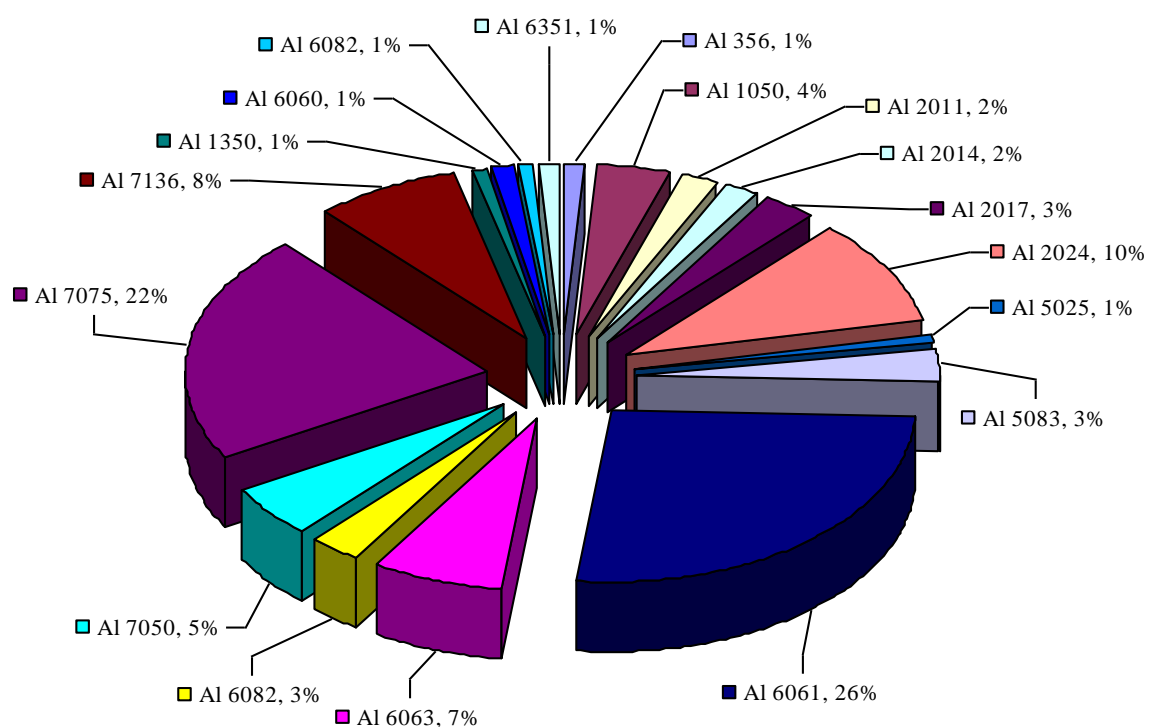


Figure 1. The use of aluminum alloys per year and depending on the number of researches in which they were studied.

As our own finding following the analysis of the graph made, it can be seen that the majority of Al6061 reaches 26%, followed by Al7075 at 22%. The aluminum alloy study is also used in the aviation industry. These alloys have been developed by a number of dedicated companies with the help of principal aircraft manufacturers to improve the production process of various aluminum areas.

This study will focus on Al7136, developed and manufactured by Universal Alloy Corporation. This type of material is used in the aircraft industry. This aluminum alloy, relatively newly developed, has superior properties to other aluminum alloys, among which include its high resistance to traction, also to wear, corrosion, its low value of thermal expansion, high durability, ductility and conductivity. All these properties make Al7136 a versatile material [15].

Another original comparative graph made by the authors is focused on the proportionality of the cutting factors impact exerted on the surface quality.

In Figure 2, this situation is presented. Concerning this case, it can be seen that the most studied parameter is the feed per tooth with 38%, closely followed by the cutting speed with 34% and the cutting depth with 28%.

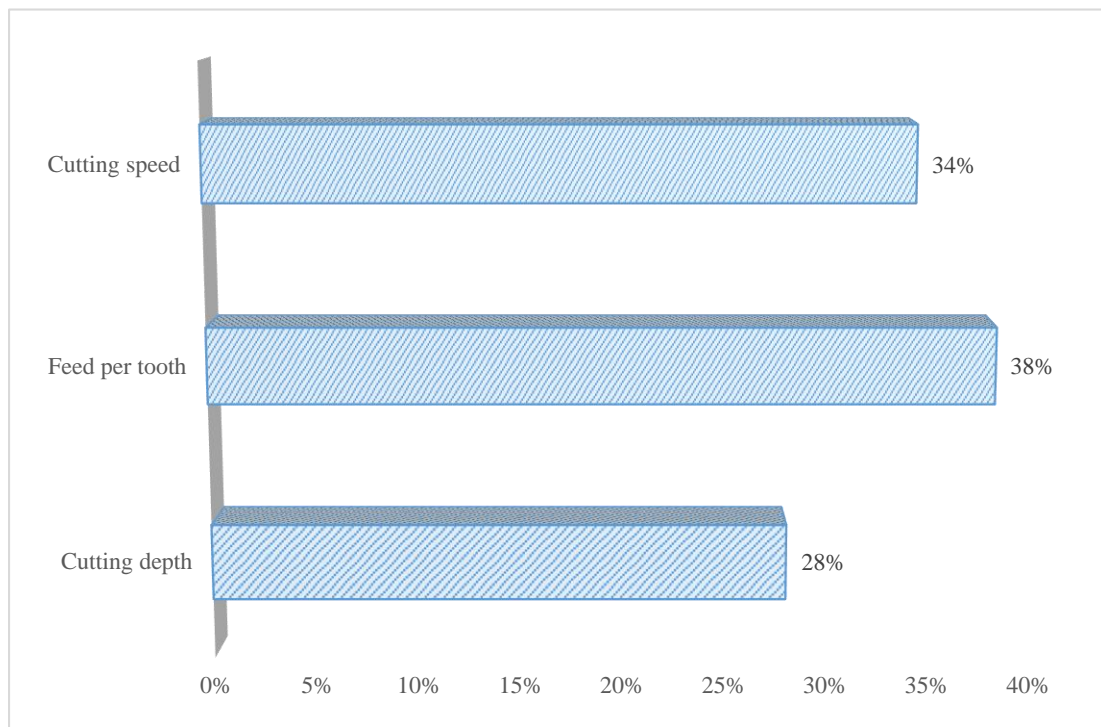


Figure 2. The most studied cutting parameters in the aluminum alloys machining in 2005–2019 period.

Other comparative original graphs are made by the authors on the most studied research directions on aluminum alloy machining (Figure 3), also on the study of the cutting operations frequency of the aluminum alloys (Figure 4), and finally the mathematical methods used to optimize the aluminum alloy cutting processes (Figure 5).

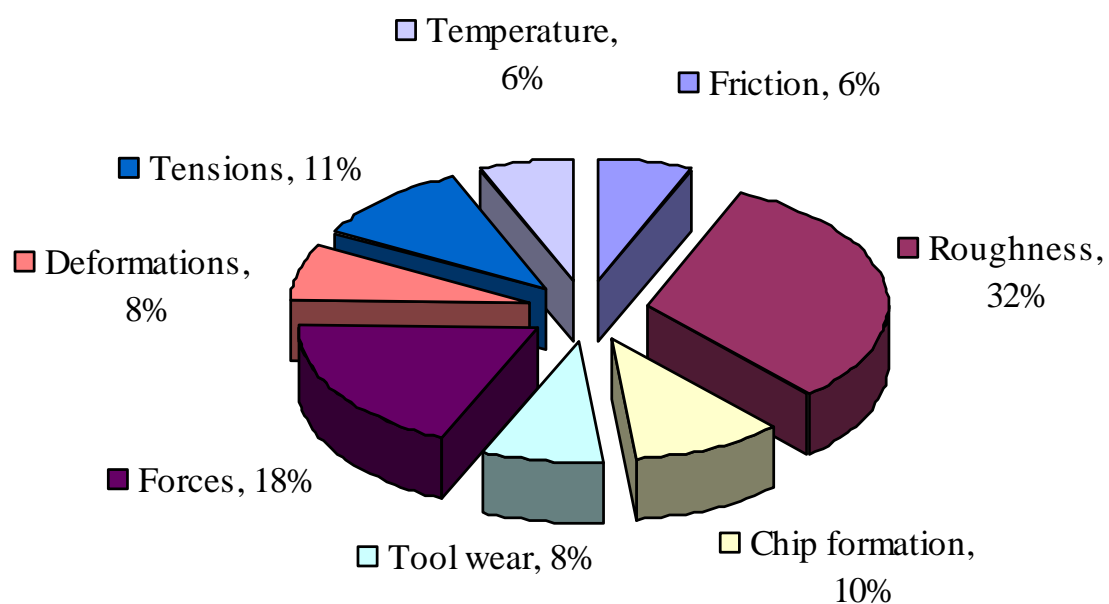


Figure 3. The studied research directions on aluminum alloy machining 2005–2019 period.

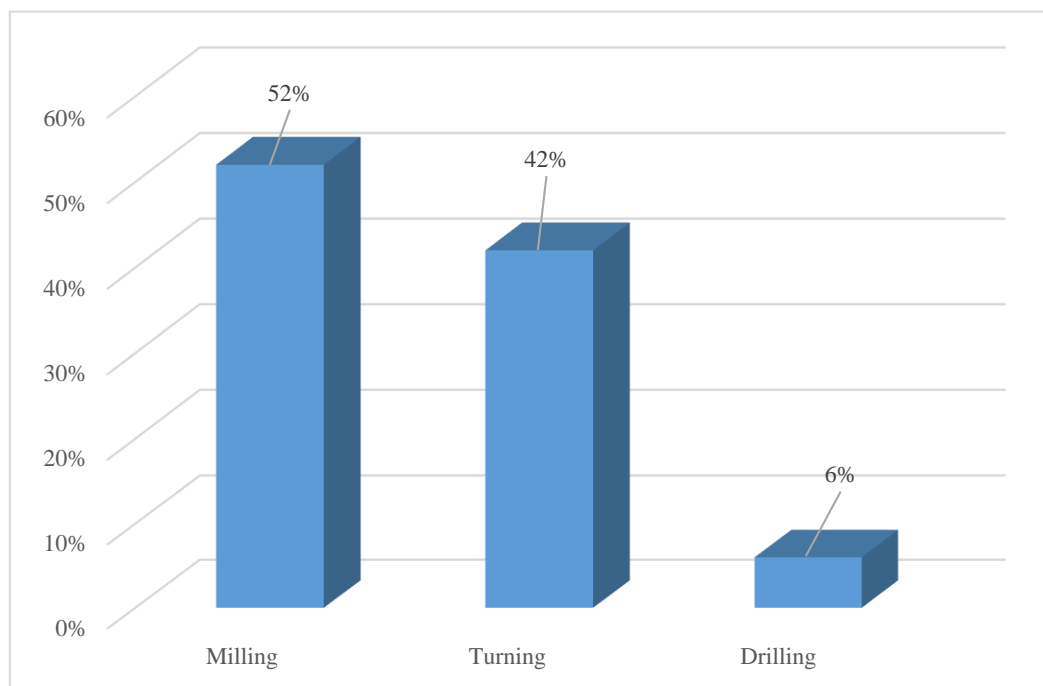


Figure 4. The frequency studying of the cutting operations of the aluminum alloys 2005–2019 period.

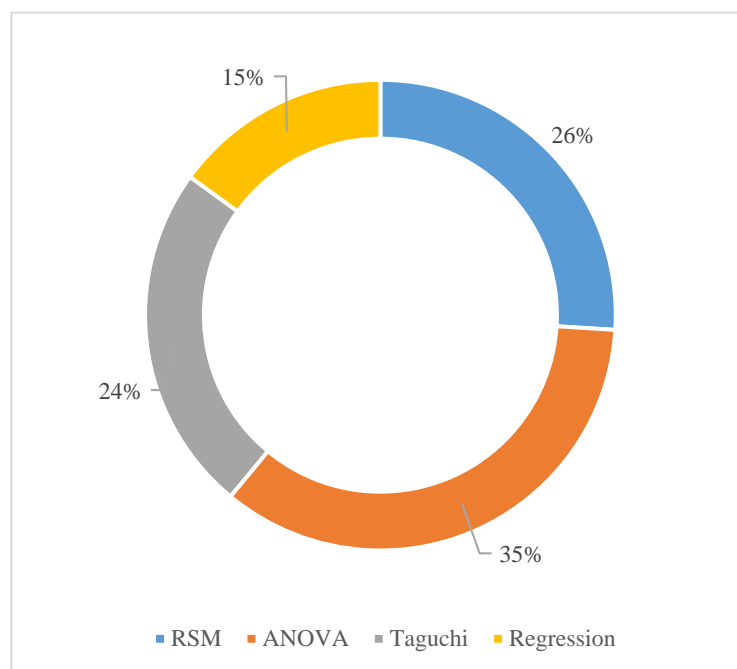


Figure 5. The mathematical methods used to optimize the aluminum alloy cutting processes 2005–2019 period.

As Figure 3 shows, the most studied research direction on aluminum alloy machining is represented by the surface roughness with 32%, followed by the cutting forces with 18%, then by the tensions with 11% and by the chip formation with 10%. The friction, temperature, deformation, and the tool wear were studied less than the above-mentioned parameters.

In the cutting operation case, the most studied machining operation on aluminum alloy is the milling operation with 52%, followed closely by turning with 42%.

Finally, the mathematical methods used to optimize the aluminum alloy cutting processes were analyzed, and the results show that the most studied methods are ANOVA with 35%, RSM with 26% and Taguchi with 24%.

We consider Figures 1–5 important because these graphs are created based on a serious topical documentary.

In this scientific paper, we use the Taguchi, the central composite design and ANOVA methods to obtain the optimal conditions for end-milling process of 7136 aluminum alloy used in the aerospace field. The aim is to obtain the contribution percentage of each parameter in order to confirm the optimal conditions obtained by using the Taguchi and the central composite design methods. Table 1 gives a brief presentation of the research papers in which this 7136 aluminum alloy was also studied.

Table 1. Identified research on Al7136 machining.

| Machining Process | Aluminum Alloy | Process Parameters | Objectives | Optimization/Prediction Technique | Ref. |
|-------------------|----------------|--|--|-----------------------------------|------|
| End-Milling | 7136 | cutting speed, cutting depth | Comparison between the evolution of the machined surfaces quality according to process parameters | Practical experiment | [15] |
| End-Milling | 7136 | cutting speed, feed per tooth, cutting depth | Comparison of the surface quality evolutions in different situations related to the cutting regimes resulting from the combination of the process parameters | Practical experiment | [16] |
| End-Milling | 7136 | cutting speed, feed per tooth, cutting depth | Optimization of the regression equation of the surface roughness | Taguchi | [17] |
| Milling | 7136 | cutting speed, feed per tooth, cutting depth | Determination of the cutting parameters influence, on the surface quality | Taguchi, full factorial design | [18] |
| Milling | 7136 | cutting speed, feed per tooth, cutting depth | Determination of the proper configuration of the optimum values of machining parameter and their interactions to obtain the better cutting process performance and to reduce the surface roughness sensitivity to uncontrollable factors | Taguchi | [19] |
| End-Milling | 7136 | cutting speed, feed per tooth, cutting depth | To reduce manufacturing costs and processing time. To identify the quantitative relationships between cutting parameters and the surface roughness. | Regression analysis, ANOVA | [20] |

This research presents novelty elements in this field due to the experimental programs behind this applied research being permanently improved. Moreover, we consider that the approached subject is very topical, still being associated with the material sampling processes in various industries such as the aerospace industry. We consider that the study we propose represents a topical reference in our field of competence and is argued by topical experimental results that take into account a current stage

of knowledge in the field that was the basis of the proposed research. Considering the purpose of this article, which is to determine the surface quality equation produced by Al7136 end-milling, based on the above comparisons, the full test method will be presented.

2. Experimental Procedure

Experiments were conducted to study the cutting effect of the measurement method: cutting speed, cutting depth and feed, applied to the product response: surface roughness.

2.1. Work Material

Tests are performed based on machining of Al7136-T76511 [21]. This alloy is used in aircraft industries due to its properties, such as:

- High strength to weight ratio;
- High wear resistance;
- Low thermal expansion;
- Corrosion resistance;
- Durability;
- Ductility;
- Conductivity, which makes it a versatile material [22].

The Al7136-T76511 is a type of aluminum alloy code 7136. To achieve the T76511 temper, the metal is heat-treated in solution, and stress relieved, after the natural stabilization of over aging. Helping with stress is done by stretching the metal to some degree, depending on the type of product being produced (rack or tube). Aging has been chosen to increase corrosion resistance. The metal is straightened after expansion. This temper stimulus is closely related to T76510, which does not allow such straightening [23].

The chemical composition of the Al7136 conforms to the percentages by weight shown in Table 2, determined in accordance with AMS2355 Standard [24].

According to AMS4415A Standard [23] of the aerospace material specification, the Al7136-T76511 is an aluminum alloy in the form of extruded bars, rods, wire, profiles (shapes) and tubing. In general, these extrusions are found in structural applications that require a combination of high tensile and compressive strength and good corrosion resistance, but the use of these extrusions is not limited to such applications (Table 3).

Table 2. Al7136 composition according to AMS2355 Standard.

| Element | min | max |
|-----------------------|-----------|------|
| Silicon | - | 0.12 |
| Iron | - | 0.15 |
| Copper | 1.9 | 2.5 |
| Manganese | - | 0.05 |
| Magnesium | 1.8 | 2.5 |
| Chromium | - | 0.05 |
| Zinc | 8.4 | 94 |
| Titanium | - | 0.10 |
| Zirconium | 0.1 | 0.20 |
| Other Elements, each | - | 0.05 |
| Other elements, total | - | 0.15 |
| Aluminum | remainder | |

Table 3. Minimum tensile properties of Al7136.

| Nominal Diameter or Least Thickness (Bars, Rods, Wire, Profiles) or Nominal Wall Thickness (Tubing) Millimeters | Tensile Strength MPa | Yield Strength at 0.2% Offset MPa | Elongation in 50 mm % | Elongation in 5D or 5.65√A |
|---|----------------------|-----------------------------------|-----------------------|----------------------------|
| 1.00–6.300 | 621 | 593 | 7 | - |
| 6.30–12.50 | 627 | 600 | 7 | - |
| 12.50–50.00 | 634 | 607 | - | 6 |
| 50.00–80.00 | 627 | 607 | - | 7 |
| 80.00–100.00 | 621 | 593 | - | 7 |

Extrusions must be heat-treated with solution, stress relieved by stretching after treatment of the solution to produce a permanent set nominal value of 1.5 percent, but not less than 1 percent or more than 3 percent and exceeded by T76511 temper, according to AS1990 [25,26]. Extrusions in the T76511 temper can receive a minor recovery, after stretching, of a required quantity meet the tolerance requirements of 3.6.

Extrusions must comply with the following requirements, determined on the mill product according to AMS2355 [24]. To carry out the tests, the parts have the dimensions 500 × 101 × 24.5 mm: the central composite design and 100 mm × 35 mm and 30 mm: the Taguchi method. Each machined sample was performed according to the cutting procedures set based on the combination of the cutting regime in each methodology case.

2.2. Cutting Tool

The test was made with a basic tool for aluminum machining (16 mm cutting tool, 100% engagement, SECO R217.69-1616.0-09-2AN), which has two cutting inserts ISO code XOEX090308FR-E05, H15 [27]. The tool used in the experiment was a brand-new tool and the tool wear was not considered in the study.

2.3. CNC Machine

The machine used for testing is a 3-axis HAAS VF2 CNC. The specifications of the CNC machine are shown in Table 4.

Table 4. HAAS VF-2YT specifications [28].

| Travels | Metric |
|--|---------------------|
| X Axis | 762 mm |
| Y Axis | 508 mm |
| Z Axis | 508 mm |
| Spindle Nose to Table (~max) | 610 mm |
| Spindle Nose to Table (~min) | 102 mm |
| TABLE | METRIC |
| Length | 914 mm |
| Width | 457 mm |
| T-Slot Width | 16 mm |
| T-Slot Center Distance | 125.0 mm |
| Number of Std T-Slots | 3 |
| Max Weight on Table (evenly distributed) | 1361 kg |
| SPINDLE | METRIC |
| Max Rating | 22.4 kW |
| Max Speed | 8100 rpm |
| Max Torque | 122 Nm @ 2000 rpm |
| Drive System | Inline Direct-Drive |
| Max Torque w/opt Gearbox | 339 Nm @ 450 rpm |

Table 4. Cont.

| Travels | Metric |
|--------------------------|--------------------------|
| Taper | CT or BT 40 |
| Bearing Lubrication | Air/Oil Injection |
| Cooling | Liquid Cooled |
| FEEDRATES | METRIC |
| Rapids on X | 25.4 m/min |
| Rapids on Y | 25.4 m/min |
| Rapids on Z | 25.4 m/min |
| Max Cutting | 16.5 m/min |
| AXIS MOTORS | METRIC |
| Max Thrust X | 11343 N |
| Max Thrust Y | 11343 N |
| Max Thrust Z | 18683 N |
| TOOL CHANGER | METRIC |
| Type | Carousel (SMTC Optional) |
| Capacity | 20 |
| Max Tool Diameter (full) | 89 mm |
| Max Tool Weight | 5.4 kg |
| GENERAL | METRIC |
| Air Required | 113 L/min, 6.9 bar |
| Coolant Capacity | 208 L |

The sample was fixed with one clamp on the CNC table (for the Taguchi methodology) three clamps (for the central composite design) respectively, to obtain the rigidity. In this respect, the samples are parallel with the CNC table and perpendicular to the main shaft.

Throughout the tests, large quantities of Blasocut BC 35 Kombi SW coolant were used in the cutting areas. Among the characteristics of the coolant is the pump pressure, which had a value of 8 bar.

2.4. Response

This paper's goal is to use the Taguchi method and central composite design to analyze the cutting factors impact effects (cutting speed, cutting depth and feed) generated during the milling process on the 7136-aluminum surface. There are several ways to measure the surface quality of a part. Mathematical measurements (R_a) of the surface were obtained and measured in the center of the machine surface using the surface tester Mitutoyo SURFTEST SJ-210 (Figure 6).

The measurement tool resolution was set and tested with a certified gage. The measurement tool available at the time when the experiment was made had a tip diameter of 4 μm . The entire study was based on these data. The measurement tool was set to measure only 5 mm, there were seven measurements conducted in each case. The measurement error was not taken into consideration in order to prove the data reproducible. The sampling length was 2.5 mm with a number of sampling lengths $\times 7$. The type of detector on retractable drive unit type was SJ-210 (4 mN type), the type of filtration used was Gaussian, and standard is ISO 1997, as can be seen in Figure 6. In this figure, it can be seen that the cut-off (λ_c) is equal to 0.8 mm.



Figure 6. The measurements made with Mitutoyo SURFTEST SJ-210.

2.5. Process Variables and Their Parameters

In this article, cutting experiments were designed taking into account three cutting factors: cutting speed (m/min), feed (mm/tooth) and cutting depth (mm). Selected levels for cutting factors are shown in Table 5 and are in accordance with the SECO Equipment Manufacturer's Guide as well as regarding the machine capabilities and technology, cutting tools and CNC machine. In the Taguchi model, the selected levels reflect the minimum and maximum values of the machining factors, according to the test section. In the central composite design, each factor was assigned to the settled values in the experimental field. The original form of the central composite design was chosen—the circumscribed one. The star points are at an alpha distance from the center, based on the properties desired for the design and the number of factors in the design. The star points establish new extremes for the low and high settings for all factors.

Table 5. Cutting regime parameters and their values for Taguchi's method and central composite design.

| Parameter | Taguchi's Method | | Central Composite Design |
|---------------------------------|------------------|---------|------------------------------|
| | Value 1 | Value 2 | Values |
| Cutting Speed v (m/min) | 495 | 660 | 495, 530, 570, 610, 660 |
| Cutting Depth a_p (mm) | 2 | 4 | 2, 2.5, 3, 3.5, 4 |
| Feed per Tooth f_z (mm/tooth) | 0.04 | 0.14 | 0.04, 0.06, 0.08, 0.11, 0.14 |

The surface roughness was determined based on the established parameters as shown in Table 5. For each experiment three surface measurements were performed and then the average of the mean square deviation (R_a med) calculation was used, indicating the mathematical mean of the three measurement lines.

3. Taguchi Design versus Central Composite Design

The design of the experiment is a very strong analysis tool with which it can be modeled and analyzed the influence of the control parameters, which is exerted on the followed response. The standard models are difficult to use, especially on a large number of experiments and when the control factors are varied and numerous [29,30].

This research uses Taguchi methodology and the central composite design to analyze the surface roughness by 7136 aluminum alloy machining as an output variable in end-milling process. The Taguchi method is an effective tool that is widely accepted by industrial engineers to approach the highest possible production at the right price and at the right time. The factors influencing the response are arranged in the form of a lattice square model, this pattern is called an orthogonal array. The design and selection of the orthogonal structure and the reasons for the experiments are the main foundations of the Taguchi process [31].

Malvade and Nipanikar [32] noted that the Taguchi method is more focused on shaping the development of production processes to create high-quality output compared to statistical control systems that attempt to control factors affecting quality.

Moshat [33] demonstrated that the Taguchi method is one of the most effective design test tools to create a high-quality product, developed by Genichi Taguchi. The goals of the orthogonal Taguchi (OA) are a step that gives a small number of very balanced and simultaneous tests.

The controls for this test included: cutting speed, cutting depth and feeding of each tooth. A number of eight experiments, as shows the L8 orthogonal array (Table 6), were obtained by applying the design of experiment (DOE) steps. Following the analyzed output data, the optimal machining condition was deducted.

Table 6. The 8 experiments according to L8 (2^7) orthogonal array.

| Parameters and Interactions | | A - | B | AB | C | AC | BC |
|-----------------------------|---|-----------------------|--------------------|----|---------------------------|----|----|
| Parameter | | Cutting Speed [m/min] | Cutting Depth [mm] | | Feed per Tooth [mm/tooth] | | |
| | | Column | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Experiment | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 2 | 1 | 1 | 1 | 2 | 2 | 2 |
| | 3 | 1 | 2 | 2 | 1 | 1 | 2 |
| | 4 | 1 | 2 | 2 | 2 | 2 | 1 |
| | 5 | 2 | 1 | 2 | 1 | 2 | 1 |
| | 6 | 2 | 1 | 2 | 2 | 1 | 2 |
| | 7 | 2 | 2 | 1 | 1 | 2 | 2 |
| | 8 | 2 | 2 | 1 | 2 | 1 | 1 |

The approach of the problem from the central composite design method perspective consists of the three factors involved, which are taken into account with their corresponding values presented in Table 5, in order to determine their influence level exerted on the response.

The tests were performed respecting the mentioned cutting regimes of the process factors combinations. Minitab 17 design expert software is used to create the tests plan and analyze all responses in a mathematical format.

Overall, eight experiments were carried out for the Taguchi method, each with three R_a measurements and a total of 24 measurements (Table 7).

For central composite design results, 125 experiments and a total of 375 measurements were carried out (Table 8). To determine the surface roughness equation, the contribution of each parameter and their interactions must first be determined.

Table 7. R_a med measurements according to the Taguchi design.

| No. | v (m/min) | a_p (mm) | f_z (mm/tooth) | R_a Med (μ m) |
|-----|--------------|---------------|---------------------|-------------------------|
| 1 | 495 | 2 | 0.04 | 0.235 |
| 2 | 495 | 2 | 0.14 | 0.25 |
| 3 | 660 | 4 | 0.04 | 0.565 |
| 4 | 660 | 4 | 0.14 | 0.561 |
| 5 | 495 | 4 | 0.04 | 0.342 |
| 6 | 495 | 4 | 0.14 | 0.27 |
| 7 | 660 | 2 | 0.04 | 0.549 |
| 8 | 660 | 2 | 0.14 | 0.723 |

Table 8. R_a med measurements according to central composite design [22], pag. 115.

| No. | v (m/min) | a_p (mm) | f_z (mm/tooth) | R_a Med (μ m) |
|-----|--------------|---------------|---------------------|-------------------------|
| 1 | 495 | 2 | 0.04 | 0.235 |
| 2 | 495 | 2 | 0.06 | 0.254 |
| 3 | 495 | 2 | 0.08 | 0.266 |
| 4 | 495 | 2 | 0.11 | 0.325 |
| 5 | 495 | 2 | 0.14 | 0.250 |
| 6 | 495 | 2.5 | 0.04 | 0.234 |
| 7 | 495 | 2.5 | 0.06 | 0.247 |
| 8 | 495 | 2.5 | 0.08 | 0.240 |
| 9 | 495 | 2.5 | 0.11 | 0.303 |
| 10 | 495 | 2.5 | 0.14 | 0.322 |
| 11 | 495 | 3 | 0.04 | 0.226 |
| 120 | 660 | 3.5 | 0.14 | 0.529 |
| 121 | 660 | 4 | 0.04 | 0.565 |
| 122 | 660 | 4 | 0.06 | 0.590 |
| 123 | 660 | 4 | 0.08 | 0.526 |
| 124 | 660 | 4 | 0.11 | 0.550 |
| 125 | 660 | 4 | 0.14 | 0.561 |

3.1. Contribution of Parameters and Their Interactions

A good understanding of the various aspects of different conditions can be seen using the method called ANOVA [5,6]. The purpose of ANOVA is to determine the magnitude associated with each component in the target operation and to reduce the error. ANOVA has also selected the highest quality components from a wide range of options. ANOVA is used to determine which actual metrics affect specified values.

Using the Taguchi method and the central design of the ANOVA analysis, the inclusion and impact of each factor and their interaction with the surface current was determined. Table 9 shows the analysis of variance, using Minitab 17.

The confidence interval in ANOVA was considered to be 95%. In this table (Table 9), the ANOVA analysis revealed that the cutting speed has the highest influence and affects the surface in both cases: Taguchi's method and central composite design.

The reason why the cutting speed has the greatest influence and affects the surface roughness is because if it is not correlated with the rotation speed of the tool, there is a settlement of the processed material that generates tool vibrations and thus leads to higher roughness.

The main contributing factor is the cutting speed and the interaction between the cutting speed and the depth of cut. In this experiment, the effect of the other parameters as well as the interactions between them have a smaller impact on the surface roughness.

Table 9. The variance analysis (Taguchi's method and central composite design).

| Source | DF (Degree of Freedom) | | Contribution | | | |
|--------------------|---------------------------|--------------------------|--------------|-------|--------------------------|-------|
| | Taguchi | Central Composite Design | Taguchi | p | Central Composite Design | p |
| Regression | 7 | 7 | 99.85% | 0.078 | 88.93% | 0.000 |
| Cutting Speed (A) | 1 | 1 | 94.00% | 0.270 | 85.53% | 0.283 |
| Cutting Depth (B) | 1 | 1 | 0.76% | 0.455 | 0.00% | 0.017 |
| Feed per Tooth (C) | 1 | 1 | 0.02% | 0.179 | 1.00% | 0.193 |
| A × B | 1 | 1 | 2.44% | 0.345 | 2.06% | 0.003 |
| A × C | 1 | 1 | 1.43% | 0.159 | 0.00% | 0.154 |
| B × C | 1 | 1 | 0.26% | 0.278 | 0.07% | 0.148 |
| A × B × C | 1 | 1 | 0.95% | 0.238 | 0.27% | 0.094 |
| Error | 1 | 118 | 0.15% | - | 11.07% | - |
| Total | 8 | 125 | 100.00% | - | 100.00% | - |

3.2. The Regression Equation of the Surface Roughness

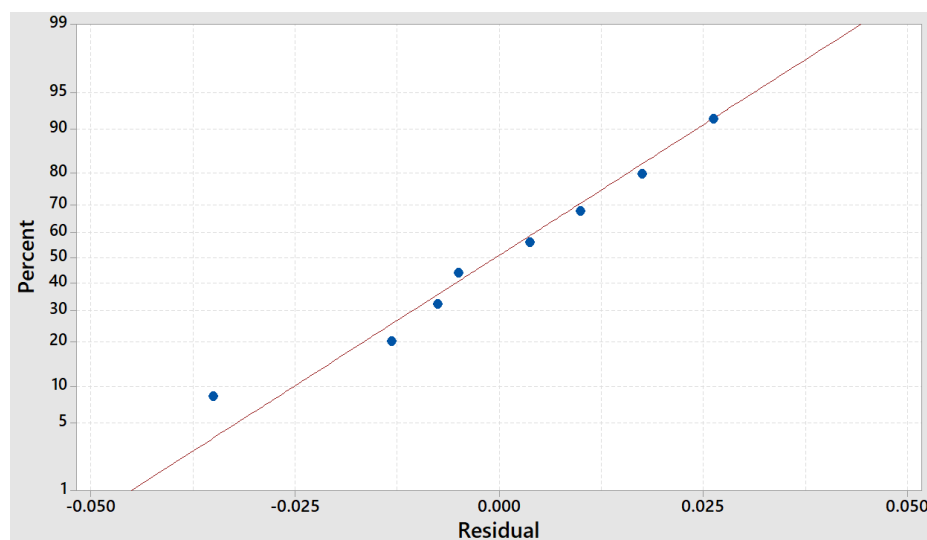
According to the obtained results obtains by Table 8, the R_a regression equation in both situations, the Taguchi method and central composite design, was determined. Using Minitab 17, the surface roughness equation for Taguchi method is (1):

$$R_a = 0.000444A - 0.0955B - 13.51C + 0.000256AB + 0.02708AC + 3.04BC - 0.00634ABC, \quad (1)$$

Using Minitab 17, the surface roughness equation (2) for central composite design (CCD) is:

$$R_a = 0.000393A - 0.340B - 10.17C + 0.00800AB + 0.0199AC + 4.20BC, \quad (2)$$

The normal probability plot in both cases Taguchi and CCD, are presented in Figures 7 and 8. Using the Minitab software, the regression equations related to the R_a surface roughness were determined. The aim is to describe the relationship between the answer (R_a) and the terms in the model (cutting speed, depth of cut, feed per tooth). The regression equation is an algebraic representation of the regression line. In the regression equations, the numerical values represent the estimated coefficients for the terms in the model. These coefficients were calculated based on the statistical methods applied in this scientific research paper.

**Figure 7.** Normal probability plot—response in R_a (Taguchi case).

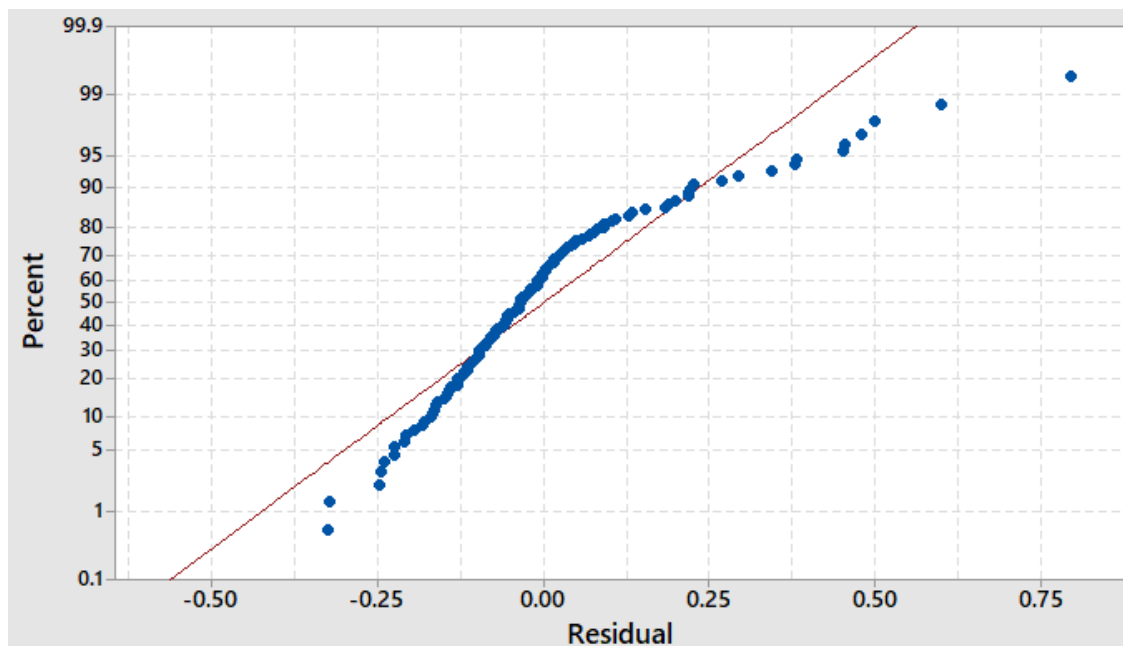


Figure 8. Normal probability plot—response in R_a (central composite design (CCD) case)).

3.3. Comparison Between the Two Regression Equations Determined

To make a comparison between the accuracy of these two determined equations using Taguchi's method and central composite design, Table 10 presents the surface roughness measured values. The surface roughness relative error was calculated between the measure's values and the calculated values of R_a in both situations (Taguchi's method and central composite design).

Table 10. The relative errors between the measured and the calculated surface roughness values [22], p. 178.

| No | A | B | C | R_a (measured) | R_a Taguchi (calculated) | R_a Central Composite Design (calculated) | Relative Error ϵ_x [%] | |
|-----|-----|-----|------|---------------------|-------------------------------|---|---------------------------------|---|
| | | | | | | | ϵ_x Taguchi | ϵ_x Central Composite Design |
| 1 | 495 | 2 | 0.04 | 0.235 | 0.270 | 0.288 | 15% | 23% |
| 2 | 495 | 2 | 0.06 | 0.254 | 0.264 | 0.279 | 4% | 10% |
| 3 | 495 | 2 | 0.08 | 0.266 | 0.258 | 0.269 | 3% | 1% |
| 4 | 495 | 2 | 0.11 | 0.325 | 0.249 | 0.256 | 23% | 21% |
| 5 | 495 | 2 | 0.14 | 0.250 | 0.240 | 0.242 | 4% | 3% |
| 6 | 495 | 2.5 | 0.04 | 0.234 | 0.284 | 0.315 | 21% | 34% |
| 7 | 495 | 2.5 | 0.06 | 0.247 | 0.277 | 0.305 | 12% | 23% |
| 8 | 495 | 2.5 | 0.08 | 0.240 | 0.270 | 0.295 | 12% | 23% |
| 9 | 495 | 2.5 | 0.11 | 0.303 | 0.259 | 0.280 | 14% | 8% |
| 10 | 495 | 2.5 | 0.14 | 0.322 | 0.249 | 0.265 | 23% | 18% |
| 11 | 495 | 3 | 0.04 | 0.226 | 0.297 | 0.341 | 32% | 51% |
| 121 | 660 | 4 | 0.04 | 0.565 | 0.578 | 0.891 | 2% | 58% |
| 122 | 660 | 4 | 0.06 | 0.590 | 0.574 | 0.830 | 3% | 41% |
| 123 | 660 | 4 | 0.08 | 0.526 | 0.570 | 0.770 | 8% | 46% |
| 124 | 660 | 4 | 0.11 | 0.550 | 0.563 | 0.679 | 2% | 24% |
| 125 | 660 | 4 | 0.14 | 0.561 | 0.557 | 0.589 | 1% | 5% |

4. Results and Discussions

After the regression equation determining for the R_a , the results were predicted at any area of the experimental domain, based on the determined regression models. Thus, the R_a values of the surface profile were determined using the obtained regression equations. The R_a calculated values results afferent to the R_a measured values are shown in Table 10.

Starting with these calculations, the comparative graphical representations were made between the experimentally determined measurements and the calculated values using the regression equation determined by the Taguchi method and the central composite design (Figure 9).

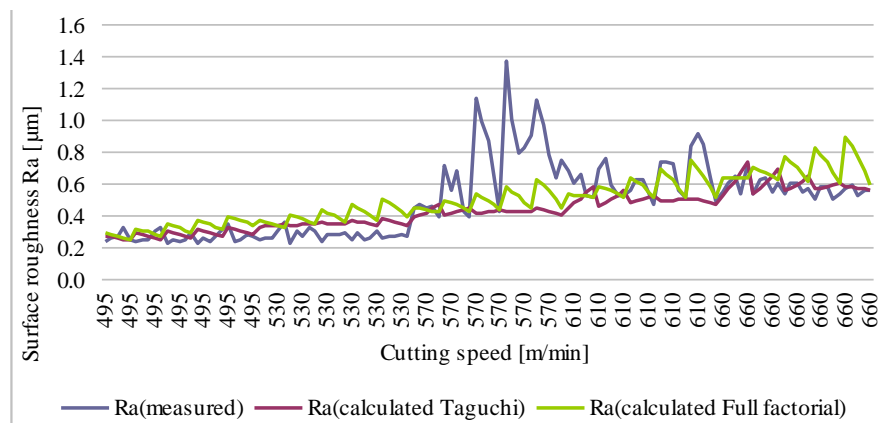


Figure 9. Comparison between the R_a measured versus R_a calculated using Taguchi's method and central composite design.

Figure 10 compares the relative errors obtained in these two situations. In the graphs in Figures 9 and 10, the evolution of the R_a values was presented, depending on the cutting speed, which is the most important factor in the surface roughness.

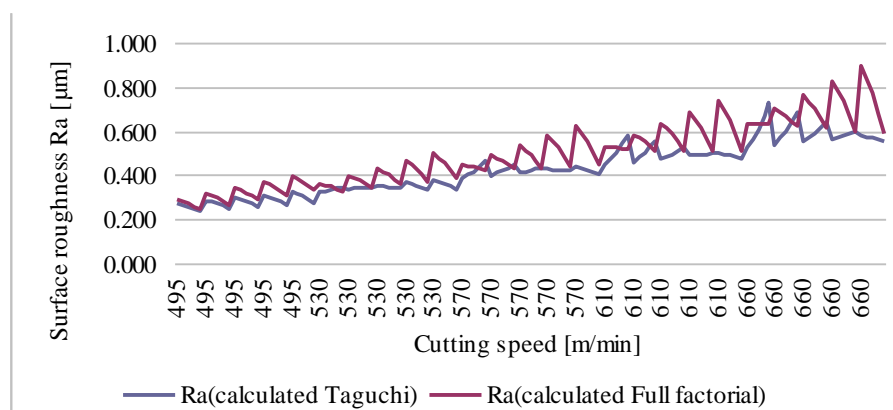


Figure 10. Comparison between the relative errors obtained (Taguchi's method versus central composite design).

Based on the graph analysis, it was found that the calculated arithmetic means deviations of the surface profile based on the regression equations approximate the experimental values with a total average error of 22% for the Taguchi's method and 27% for the central composite design.

Divided by cutting speed intervals, this error accumulates the averages of the following errors presented in Table 11.

Table 11. Average errors of the R_a measurements according to the cutting speed values.

| Cutting Speed [m/min] | Medium Error Taguchi [%] | Medium Error Central Composite Design [%] |
|-----------------------|--------------------------|---|
| 495 | 16% | 26% |
| 530 | 28% | 48% |
| 570 | 36% | 28% |
| 610 | 21% | 10% |
| 660 | 8% | 23% |

The error problem is generated by the values of 570 m/min and 610 m/min. At these cutting speeds, the average roughness of the area, measured by experiments, registers the critical distribution. The roughness value increasing was generated by the vibrations as a result of the machining. It was found that the poorest quality results at 570 m/min and 610 m/min cutting speed. The values of the surface roughness recorded at these speeds are quite high compared to those at lower speeds and upper speeds, respectively.

Vibration events lead to a rough surface. This vibration is the effect of a resonance phenomenon given by tool (piece) materials used. The vibration has not been measured during the experiment, but the statement is based on the fact that all other experiment conditions were respected on all combinations: the same CNC machine, the same setup, the same type of material (certified material by lab tests, mechanical and chemical test). The causes, consequences and production process have to be studied further.

Several papers dealing with this subject have been identified in the literature. For example, [34] in his paper presents the effects of the spindle attributed forced vibrations on the processing characteristics of the vertical milling process. The effects of three spindle levels attributed to forced vibrations together with feed rate and axial cutting depth are evaluated on surface roughness, dimensional accuracy and tool wear under constant conditions of radial cutting depth and cutting speed. He found that the vibration amplitude of machine tools and the axial cutting depth are statistically significant at a 95% confidence level for surface roughness, the vibration amplitude being the most important factor followed by the axial cutting depth. It is found that higher values of vibration amplitude and feed speed result in excessive tool wear, with the vibration amplitude combined with the feed rate and axial depth, resulting in a catastrophic damage to the tool.

Another research belongs to [35], who found that the profile milling processes are very sensitive to vibrations caused by the cutter leakage, especially when it comes to operations in which the diameter of the cut varies on a scale of a few millimeters. The aim of his research was to experimentally analyze the effect of cutter runout on cutter vibration and how it affects chip removal and therefore the topomorphy of the workpiece. He evaluated the effect of vibration phenomena, caused by cutter runout, on the workpiece topomorphy in end-milling.

Overall, Figure 11 shows the significant spatial variation related to cutting speed and feed per tooth. The graph analysis highlights that the speeds of 570 and 610 m/min in addition to a small feed showed an effect on R_a values, which increased in all experiments. We suppose that the vibration may be the reason for this increase. Figure 12 shows the diagrams of the constant level cycles, from which the gradual values increase with increasing cutting speed and feed per tooth value.

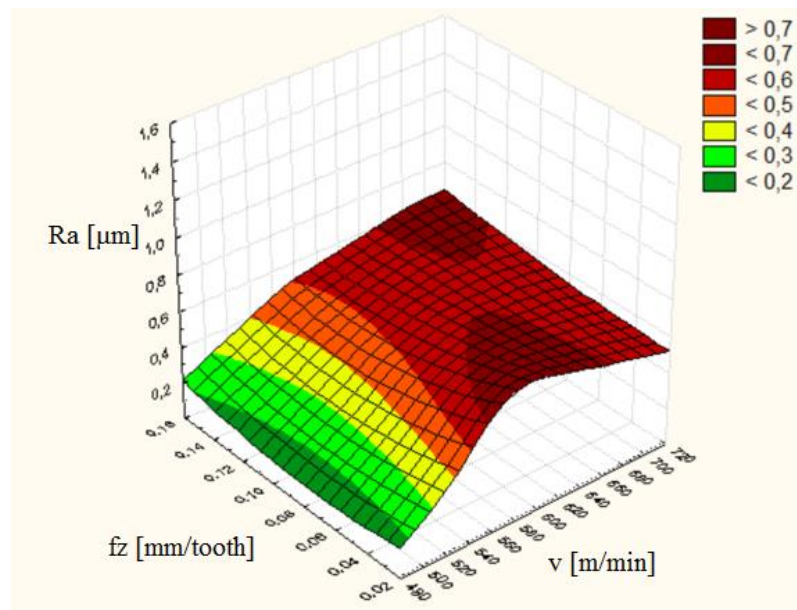


Figure 11. The spatial variation of R_a according to v and f_z .

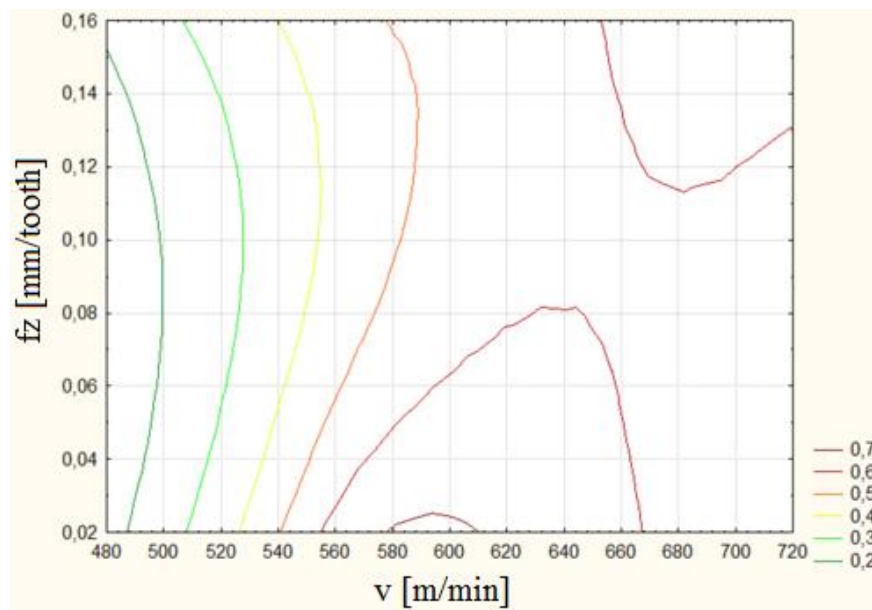


Figure 12. Indication of the spatial variation curves of R_a according to v and f_z .

5. Conclusions

This study's aim was to determine the R_a equations by dimensional process measurement methods in two ways: first using the Taguchi design of experiments and second using the central composite design.

Analysis of variance (ANOVA) is performed to identify key variables and clarify their impact on response characteristics.

The conclusion of both cases is the same: the cutting speed is the factor which has the highest effect on the end-milled surface. It can be seen by the percentage effect of each factor on the surface that there is a very weak correlation between the control factors affecting the surface quality.

The other two parameters, have a meaningless contribution (less than 1%) and can be forgotten.

By comparing relative errors between two measurement equations on the R_a scale it can be seen ϵ_x for the Taguchi method, the median value of relative errors is 22% and for the central composite design ϵ_x the relative error is 27%.

In general, the values derived from the central composite design are closer to the measured roughness.

The main R_a advantage of the Taguchi method is the reduction in the number of tests, lower costs and shorter time. The disadvantages include the fact that this method is not as good as the central composite design.

On the other hand, the advantage of the central composite design is the accurate comparison according to the Taguchi method. The disadvantages include the large number of tests, the cost of the tests, and the extra time spent on the tests.

It is difficult to say which method is the best. The selection belongs to the researcher and depends on the research experience, time and resources, as well as how accurate the results should be.

As a further research direction, there is the possibility of extending the studies and the research, taking into account other parameters and other indicators in a more complex form.

The vibration leads to the rough surface and is given by the resonance phenomenon of tool (piece) materials used. This can be a direction for further research because the causes, consequences and production process have to be studied further.

Author Contributions: Each author of this paper contributed equally to the research. Conceptualization and Supervision (A.M.T.); Data curation (A.B.) Formal analysis (A.B.P.); Validation (D.N.F.); Validation (C.C.); Visualization (S.T.); Writing—review & editing (A.V.S.), All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Santos, M.C.; Machado, A.R.; Barrozo, M.A.S.; Jackson, M.J.; Ezugwu, E.O. Multi-objective optimization of cutting conditions when turning aluminum alloys (1350-O and 7075-T6 grades) using genetic algorithm. *Int. J. Adv. Manuf. Technol.* **2015**, *76*, 1123. [\[CrossRef\]](#)
2. Tan, E.; Ögel, B. Influence of heat treatment on the mechanical properties of AA6066 alloy. *Turk. J. Eng. Environ. Sci.* **2007**, *31*, 53–60.
3. Troeger, L.P.; Starke, E.A.Jr. Microstructural and mechanical characterization of a superplastic 6xxx aluminum alloy. *Mater. Sci. Eng.* **2000**, *A 277*, 102–113. [\[CrossRef\]](#)
4. Demir, H.; Gündüz, S. The effects of aging on machinability of 6061 aluminium alloy. *J. Mater. Des.* **2009**, *30*, 1480–1483. [\[CrossRef\]](#)
5. Singh, D.P.; Mall, R.N. Optimization of surface roughness of aluminium by ANOVA based Taguchi method using Minitab15 software. *Int. J. Technol. Res. Eng.* **2015**, *2*, 2782–2787.
6. Aamir, M.; Tu, S.; Giasin, K.; Tolouei-Rad, M. Multi-hole simultaneous drilling of aluminium alloy: A preliminary study and evaluation against one-shot drilling process. *J. Mater. Res. Technol.* **2020**, *9*, 3994–4006. [\[CrossRef\]](#)
7. Aamir, M.; Tolouei-Rad, M.; Giasin, K.; Vafadar, A. Machinability of Al2024, Al6061, and Al5083 alloys using multi-hole simultaneous drilling approach. *J. Mater. Res. Technol.* **2020**, *9*, 10991–11002. [\[CrossRef\]](#)
8. Ravindra, T. Comparison between multiple regression models to study effect of turning parameters on the surface roughness. In Proceedings of the 2008 IAJC-IJME International Conference, Nashville, TN, USA, 17–19 November 2008; Volume 133.
9. Somashekara, H.M.; Swamy, N.L. Optimizing surface roughness in turning operation using taguchi technique and ANOVA. *Int. J. Eng. Sci. Technol.* **2012**, *4*, 1967–1973.
10. Devkumar, V.; Sreedhar, E.; Prabakaran, M.P. Optimization of machining parameters on AL 6061 Alloy using response surface methodology. *Int. J. Appl. Res.* **2015**, *1*, 1–4.
11. Ranganath, M.S.; Vipin, R.; Mishra, S. Optimization of process parameters in turning operation of aluminium (6061) with cemented carbide inserts using taguchi method and ANOVA. *Int. J. Adv. Res.* **2013**, *1*, 13–21.

12. Abdallah, A.; Bhuvenesh, R.; Embark, A. Optimization of cutting parameters for surface roughness in CNC turning machining with aluminum alloy 6061 material. *IOSR J. Eng.* **2014**, *4*, 1–10. [CrossRef]
13. Alagarsamy, S.V.; Rajakumar, N. Analysis of influence of turning process parameters on MRR & surface roughness of AA7075 using taguchi's method and RSM. *Int. J. Appl. Res. Stud.* **2014**, *3*, 1–8.
14. Ezuwanizam, M. Optimization of Tool Life in Milling. Ph.D. Thesis, Universiti Malaysia Pahang, Pahang, Malaysia, 2010.
15. Țițu, M.; Pop, A.B. A comparative analysis of the machined surfaces quality of an aluminum alloy according to the cutting speed and cutting depth variations. In *New Technologies, Development and Application II, NT 2019, Lecture Notes in Networks and Systems*; Karabegović, I., Ed.; Springer: Cham, Switzerland, 2020; Volume 76. [CrossRef]
16. Pop, A.B.; Țițu, M. A comparative analysis of the machined surfaces quality of an aluminum alloy according to the cutting speed and feed per tooth variations. In *New Technologies, Development and Application II, NT 2019, Lecture Notes in Networks and Systems*; Karabegović, I., Ed.; Springer: Cham, Switzerland, 2020; Volume 76. [CrossRef]
17. Pop, A.B.; Țițu, M.A. Optimization of the surface roughness equation obtained by Al7136 End-Milling. *MATEC Web Conf.* **2017**, *137*, 3011. [CrossRef]
18. Pop, A.B.; Țițu, M.A. Experimental research regarding the study of surface quality of aluminum alloys processed through milling. *MATEC Web Conf.* **2017**, *121*, 05005. [CrossRef]
19. Țițu, M.; Pop, A.B. Contribution on taguchi's method application on the surface roughness analysis in end milling process on 7136 aluminum alloy. *Mater. Sci. Eng.* **2016**, *1*, 012014. [CrossRef]
20. Pop, A.B.; Țițu, M. Regarding to the variance analysis of regression equation of the surface roughness obtained by end milling process of 7136 aluminum alloy. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *161*, 012014. [CrossRef]
21. Bonțiu Pop, A.B.; Lobonțiu, M. The influence of feed per tooth variation on surface roughness of 7136 aluminum alloy in end milling. *Appl. Mech. Mater.* **2015**, *808*, 34–39. [CrossRef]
22. Bonțiu Pop, A.B. Surface Quality Analysis of Machined Aluminum Alloys Using End Mill Tool. Ph.D. Thesis, Technical University of Cluj-Napoca, Baia Mare, Romania, 2015.
23. SAE Aerospace - AMS4451A, Aerospace Material Specification, Aluminum Alloy Extrusions 8.9Zn - 2.2Cu - 2.2Mg - 0.15Zr (7136-T76511, -T76510) Solution Heat Treated, Stress-Relieved, Straightened, and Overaged; SAE International: Warrendale, PA, USA, 2008.
24. AMS2355M—Quality Assurance, Sampling and Testing Aluminum Alloys and Magnesium Alloy Wrought Products (Except Forging Stock), and Rolled, Forged, or Flash Welded Rings; SAE International: Warrendale, PA, USA, 2019.
25. SAE Aerospace AS1990—Aluminum Alloy Tempers; SAE International: Warrendale, PA, USA, 1990.
26. DIN EN515 E, 2017—Aluminium and Aluminium Alloys—Wrought Products—Temper Designations; German Institute for Standardisation (Deutsches Institut für Normung), Comité Européen de Normalisation: Brussels, Belgium, 2017.
27. *Catalog and Technical Guide Seco, Milling 2014*, SECO. Available online: <https://pdf.directindustry.com/pdf/seco-tools/mn-2014-milling/5699-261905.html> (accessed on 8 December 2017).
28. Technical Book HAAS VF-2YT, Haas Technical Publications, Manual_Archive_Cover_Page Rev A June 6. 2013. Available online: <https://www.haascnc.com/content/dam/haascnc/en/service/manual/service/english---vf-series-service-manual---2002.pdf> (accessed on 8 December 2017).
29. Blasocut BC 35 Kombi SW. Available online: <https://www.lastuamisinesteet.fi/wp-content/uploads/2017/02/Blasocut-BC-35-esite.pdf> (accessed on 8 December 2017).
30. Hanif, I.; Aamir, M.; Ahmed, N.; Maqsood, S.; Muhammad, R.; Akhtar, R.; Hussain, I. Optimization of facing process by indigenously developed force dynamometer. *Int. J. Adv. Manuf. Technol.* **2019**, *100*, 1893–1905. [CrossRef]
31. Kumar, S. Optimization and process parameters of CNC end milling for aluminum alloy 6082. *Int. J. Innov. Eng. Res. Technol.* **2015**, *2*, 2394–3696.
32. Malvade, N.V.; Nipanikar, S.R. Optimization of cutting parameters of end milling on VMC using taguchi method. *J. Eng. Res. Stud.* **2014**, *5*, 14–17.
33. Moshat, S.; Datta, S.; Bandyopadhyay, A.; Pal, P. Optimization of CNC end milling process parameters using PCA-based Taguchi method. *Int. J. Eng. Sci. Technol.* **2010**, *2*, 95–102. [CrossRef]

34. Zahoor, S.; Mufti, N.A.; Saleem, M.Q.; Mughal, M.P.; Qureshi, M.A.M. Effect of machine tool's spindle forced vibrations on surface roughness, dimensional accuracy, and tool wear in vertical milling of AISI P20. *Int. J. Adv. Manuf. Technol.* **2017**, *89*, 3671–3679. [[CrossRef](#)]
35. David, C.; Sagris, D.; Stergianni, E.; Tsiafis, C.; Tsiafis, I. Experimental analysis of the effect of vibration phenomena on workpiece topomorphy due to cutter runout in end-milling process. *Machines* **2018**, *6*, 27. [[CrossRef](#)]



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