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Optimization of Machining Parameters on 7050 Aluminum Alloy for Surface Roughness

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Abstract: *This study investigates surface roughness in the end-milling process of aluminum alloy 7050-T7451, a material commonly used for extruded parts but with limited research on its machinability in this context. The core contribution is the development of a predictive model for surface roughness based on optimized cutting parameters. We employed two statistical methods: Taguchi's experimental design and the central composite design, to derive regression equations for surface roughness. Experiments were conducted using standard milling tools and a 3-axis CNC machine, adhering to manufacturer-recommended parameters. The research focuses on analyzing the impact of cutting speed, depth of cut, and feed on surface roughness. ANOVA analysis was utilized to compare predicted and experimental surface roughness values, with data processing performed using Minitab software. Finally, a comparative assessment of the advantages and disadvantages of both statistical methods is presented. This research offers significant industrial relevance by providing insights into achieving optimal product quality with minimized processing time.*

Keywords: CNC machine

I. INTRODUCTION

1.1 Background

Aluminum alloys are fundamental in modern industries like aerospace, automotive, and construction, primarily due to their superior strength-to-weight ratio. Their adoption significantly contributes to fuel efficiency and reduced environmental impact by enabling the replacement of heavier materials. While extensive research exists on the machining characteristics of common alloys such as Al6061 and Al7075, a gap remains concerning the newer, high-strength Alloy 7050- T7451.

Effective machining of aluminum necessitates optimizing cutting parameters like cutting speed, feed rate, and depth of cut to achieve desired surface quality and performance. Researchers commonly employ statistical methods such as Taguchi design, ANOVA, and Response Surface Methodology (RSM) to optimize these parameters. Previous studies have consistently highlighted the significant influence of feed rate and spindle speed on surface roughness.

This study specifically addresses the limited understanding of Al7050's machining behavior. We aim to optimize cutting parameters for this alloy in end-milling operations using a combination of Taguchi, Central Composite Design (CCD), and ANOVA methods to achieve optimal surface finish and machining efficiency.

1.2 Problem Statement

Despite the widespread use of high-strength aluminum alloys in critical industries like aerospace (e.g., for wing spars, fuselage frames, and landing gear supports) and automotive (e.g., for suspension components and chassis parts), a persistent challenge lies in optimizing their machining parameters for superior surface quality and overall efficiency. While alloys such as Al6061 and Al7075 have been thoroughly investigated, there is a distinct lack of comprehensive research on the machining of Alloy 7050-T7451, a vital high-strength material used in the aerospace industry.

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This research seeks to address this gap by optimizing cutting parameters for the end-milling of Al7050. Our objective is to identify conditions that minimize surface roughness and enhance machining efficiency, thereby improving manufacturing processes for high-performance aluminum components.

1.3 Objectives

The primary objectives of this study are:

1. To analyze the machining behavior of Al7050 aluminum alloy during end-milling operations.
2. To optimize key cutting parameters (cutting speed, feed rate, and depth of cut) to improve surface quality and machining efficiency.
3. To apply Taguchi, Central Composite Design (CCD), and ANOVA methods for identifying the most influential factors affecting surface roughness.
4. To develop a robust mathematical model capable of predicting optimal machining conditions.
5. To contribute to enhanced manufacturing strategies for Al7050, benefiting aerospace and other high-performance applications.

1.4 Scope of the Study

This study is focused exclusively on optimizing the cutting parameters for the end-milling process of aluminum alloy 7050-T7451. The investigation will specifically analyze the impact of three critical machining factors: cutting speed, feed rate, and depth of cut, on measured surface roughness.

The research utilizes Taguchi design, Central Composite Design (CCD), and ANOVA as the primary optimization and analysis techniques. Experiments will be conducted using standard milling tools and a 3-axis CNC machine. The findings are intended to directly support industries requiring precision machining of aluminum alloys, particularly in aerospace and high-performance automotive sectors.

1.5 Methodology

The methodology for this study involves the following systematic steps:

1. Material Selection: Al7050 aluminum alloy was chosen for its high strength, wear resistance, and relevance to aerospace applications.
2. Experimental Setup: End-milling operations will be conducted using a CNC machine and standard uncoated carbide tools to analyze the machining behavior of Al7050.
3. Cutting Parameters: The study will systematically vary and optimize cutting speed, feed rate, and depth of cut based on the experimental design.
4. Optimization Techniques:

o Taguchi Method: Employed for identifying the most influential cutting parameters.
o Central Composite Design (CCD): Utilized for response surface modeling and subsequent optimization.
o ANOVA Analysis: Applied to determine the statistical significance of cutting parameters on surface roughness.

5. Data Collection & Analysis: Surface roughness measurements will be recorded after each milling experiment. The percentage contribution of each cutting parameter will be analyzed, and regression models will be developed for predicting machining performance.
6. Validation & Conclusion: Optimized cutting conditions will be validated through additional experiments. The study's findings will then be used to propose improved machining strategies for Al7050 in relevant industrial applications.

II. LITERATURE REVIEW

Over the past decade, aluminum alloys have gained significant prominence in the manufacturing sector due to their unique blend of lightweight properties and high strength. This combination makes them highly desirable for various industrial applications, necessitating a thorough understanding of their machining characteristics to optimize manufacturing processes.

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Aluminium's versatility has led to its extensive use across diverse industries. In the automotive sector, it is a preferred material for numerous components [1]. The aerospace industry has utilized aluminum alloys since the 1930s, with the 2xxx, 6xxx, and 7xxx series being particularly widespread [2, 3]. Their high strength-to-weight ratio has been instrumental in advancing aerospace engineering, enabling the replacement of heavier materials like steel and cast iron. This substitution not only enhances component performance but also contributes to improved fuel efficiency, reduced energy consumption, and a lower environmental footprint [3]. Beyond these sectors, aluminum alloys are integral to construction, electrical, electronics, and packaging industries. Notable for their excellent mechanical strength and thermal stability, alloys like Al6061-T6 are even employed in nanostructure manufacturing [1]. Compared to steel, aluminum alloys possess one-third the density and elastic modulus, superior thermal and electrical conductivity, high corrosion resistance, and a high coefficient of friction [1].

Efficient machining is crucial, particularly for components requiring high-quality surface finishes, as noted by Liu [4] and Sailaja [5] regarding motor vehicle applications. The surface roughness of mechanical components significantly impacts both industrial production quality and overall manufacturing costs [6, 7]. Key cutting parameters, including cutting speed, feed rate, and depth of cut, are primary determinants of surface finish. Therefore, selecting optimal control factors is vital for producing high-strength components efficiently. While significant advancements have been made in enhancing product quality and machining efficiency, several areas still require further research.

Numerous studies have explored the optimization of machining parameters for various aluminum alloys:

• Zakharov [8] investigated different machining models for aluminum 6061, finding that spindle speed, cutting force, and tool nose radius substantially influence surface quality.

• Aswal [9] utilized the Taguchi technique to optimize machining parameters for Al 6351-T6 alloy using uncoated carbide tools. Their study indicated that cutting speed was the most significant factor affecting surface roughness.

• Rashmi Lmalghan [10] analyzed the effect of spindle speed, feed rate, and cutting depth on surface roughness and tool wear during the turning of 6061 aluminum alloy. Regression models were developed and validated using ANOVA.

• Gautam [11] applied Taguchi and ANOVA methods to study factors affecting surface roughness during CNC lathe machining of Al 6061, concluding that feed rate and spindle speed were the most critical parameters.

• Hidayat [12] optimized parameters for turning Al6061 using Response Surface Methodology (RSM) to enhance surface quality and material removal rate.

• Muralitharan [13] conducted experiments on 7075 aluminum alloy using Taguchi and RSM to minimize surface roughness and maximize material removal rate, developing a mathematical response surface model.

• Das [14] focused on maximizing the lifespan of TiN-coated tools during aluminum 6061 machining, noting that cutting speed and feed rate had a greater impact on tool wear than axial depth of cut.

This research builds upon existing knowledge by focusing on Alloy 7050-T7451, an advanced aluminum alloy primarily used in the aircraft industry due to its superior mechanical properties [15]. Al7050 exhibits high tensile strength, excellent wear and corrosion resistance, low thermal expansion, high durability, good ductility, and enhanced electrical and thermal conductivity, making it highly versatile for aerospace applications [15].

The authors' original comparative analyses, derived from extensive research and current industry trends, provide valuable insights into machining research focus areas.

• Aluminum Alloy Usage: Research trends indicate that Al6061 (26%) and Al7075 (22%) are the most widely studied aluminum alloys, reflecting their extensive use in aviation.

• Cutting Parameter Impact: Feed per tooth (38%) and cutting speed (34%) are the most frequently analyzed parameters affecting surface quality, with cutting depth (28%) also playing a significant role.

• Primary Research Directions: Most research efforts (30%) are concentrated on surface roughness optimization, followed by cutting forces (20%), tensions (12%), and chip formation (9%).

• Cutting Operation Frequency: Milling (52%) and turning (42%) are the most studied machining operations, highlighting their crucial role in achieving high-quality surface finishes and efficient material removal.

• Mathematical Method Analysis: Taguchi Method (28%), ANOVA (22%), and Response Surface Methodology (RSM) (10%) are the most widely applied optimization and analysis techniques in aluminum alloy cutting processes.

This study contributes to the field by continually improving experimental programs related to applied research in material machining processes. Our work, particularly relevant to the aerospace industry, serves as a key reference, supported by up-to-date experimental results aligned with the latest advancements. The primary objective is to determine the surface quality equation for Al7050 during end-milling, based on a comprehensive testing methodology outlined in subsequent sections.

III. EXPERIMENTAL SETUP AND OBSERVATIONS

Experiments were systematically conducted to evaluate the influence of varying cutting parameters (cutting speed, cutting depth, and feed rate) on the surface roughness of the machined product. The specific details of the experimental setup, materials, tools, and measurement
procedures are outlined below.

3.1 CNC Machine Details

All machining tests were performed on a HAAS VF2 CNC vertical machining center, a 3-axis machine known for its precision in milling operations. For enhanced stability during the tests, a single clamp was utilized for the Taguchi methodology, while three clamps were employed for the central composite design. Samples were securely positioned parallel to the CNC table and perpendicular to the main spindle to ensure optimal rigidity. A high-pressure, water-miscible coolant (Blasocut BC 35 Kombi SW) was consistently supplied at 8 bar pressure to ensure effective lubrication and cooling.

3.2 Cutting Parameters

The experimental design incorporated three primary cutting parameters: cutting speed (v, m/min), feed per tooth (fz, mm/tooth), and cutting depth (ap, mm). The selection of parameter levels, was guided by the SECO Equipment Manufacturer's Guide, machine capabilities, and cutting tool specifications.

For the Taguchi method, two distinct levels (minimum and maximum machining values) were chosen based on test requirements. In contrast, the Central Composite Design (CCD) utilized a circumscribed design, distributing star points at a calculated alpha distance from the center. This approach established new upper and lower limits for each parameter, enhancing the reliability and range of the experimental setup.

Surface roughness was assessed for each cutting parameter combination. To ensure accuracy and reliability, three surface roughness measurements were recorded for each experiment. The final surface roughness value was calculated as the average of these three measurements using the mean square deviation (Ra med) method.

3.3 Aluminum Alloy 7050 Properties

The machining experiments were conducted on Al7050-T7451 aluminum alloy [21]. This alloy is extensively used in the aerospace industry due to its outstanding properties, including:

• High strength-to-weight ratio
• Excellent wear and corrosion resistance
• Low thermal expansion
• High durability and good ductility
• Effective electrical and thermal conductivity [22]

The T7451 temper is achieved through a specialized heat-treatment process. This process involves solution heat treatment followed by rapid cooling, stress relief via stretching (with a permanent set deformation of approximately 1.5%), natural aging (over-aging), and a final straightening step [23]. This tempering process differs from T76510, which omits the final straightening.

The chemical composition of Al7050 adheres to the AMS2355 Standard [23], Al7050 is available in various extruded forms (bars, rods, wire, profiles, tubing) and is primarily applied in structural components requiring high tensile and compressive strength alongside good corrosion resistance.

For testing purposes, the samples had specific dimensions: 500 mm × 125 mm × 30 mm for the Central Composite Design method, and 110 mm × 40 mm × 30 mm for the Taguchi method. Each sample was machined following predefined cutting procedures corresponding to the experimental parameter combinations.

3.4 Cutting Tool

A standard aluminum machining tool, the SECO R217.69-1616.0-09-2AN (16 mm diameter), was utilized for all experiments, featuring 100% engagement. This tool was equipped with two cutting inserts (ISO code XOEX090308FR-E05, H15) [27]. A new tool was used for the testing, and tool wear was not a parameter considered in this study.

3.5 Observations and Data Collection

The primary objective of data collection was to assess how cutting speed, cutting depth, and feed rate affect the surface quality of 7050 aluminum during the milling process. Both the Taguchi method and Central Composite Design were applied to analyze the impact of these parameters on the machined surface.

Surface roughness (Ra) was measured using a Mitutoyo SURFTEST SJ-210 surface tester [1]. Measurements were consistently taken at the center of each machined surface. Before testing, the instrument was calibrated using a certified gauge to ensure accuracy. The tester's tip diameter was 4 µm. Each measurement spanned 5 mm, with a total of seven readings per test. The sampling length (λc) was set to 2.5 mm, and seven sampling lengths were recorded. To ensure reproducibility, measurement errors were not factored into the study. The instrument featured a retractable drive unit (SJ-210 (4 mn type)) and applied Gaussian filtration as per ISO 1997 standard. The cut-off length (λc) was set to 0.8 mm

IV. DATA ANALYSIS AND RESULTS

This chapter presents the data analysis and key findings from the experimental investigation into the end-milling of Al7050-T7451. The impact of cutting parameters on surface roughness was evaluated using two distinct optimization techniques: Taguchi Design and Central Composite Design (CCD).

4.1 Optimization Techniques: Taguchi Design vs. Central Composite Design

Design of Experiments (DOE) serves as a robust analytical framework for modeling and evaluating the influence of control parameters on a desired response. It is particularly valuable in scenarios where traditional analytical models become complex due to numerous experiments and multiple varying control factors [29, 30].

In this study, both the Taguchi methodology and Central Composite Design (CCD) were employed to assess the surface roughness (Ra) of Al7050 during end-milling. The Taguchi method is widely recognized in industrial engineering for its efficiency in optimizing production quality cost-effectively and within tight timelines. It systematically arranges influencing factors into an orthogonal array (OA), which facilitates efficient experimentation [31]. Researchers like Kumar [32] and Sahare [33] emphasize Taguchi's focus on process optimization for enhanced product quality through a reduced yet balanced set of experiments.

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For the Taguchi portion of this study, cutting speed (A), cutting depth (B), and feed per tooth (C) were selected as control factors. Eight experiments were conducted following an L8 orthogonal array. This array significantly minimizes the number of experiments required (8 instead of 128 for seven factors), while still enabling the study of main effects and parameter interactions for process optimization.

Table - Ra med Measurements Based on the Taguchi Design

No.	V (m/min)	A_p (mm)	F_z (mm/tooth)	R_a Med (μm)
1	495	2	0.04	0.240
2	495	2	0.14	0.255
3	660	4	0.04	0.570
4	660	4	0.14	0.555
5	495	4	0.04	0.350
6	495	4	0.14	0.280
7	660	2	0.04	0.540
8	660	2	0.14	0.710

The Central Composite Design (CCD) methodology also considered these three key machining factors, with specific values assigned to each. The circumscribed form of CCD was utilized, with star points positioned at a calculated alpha distance from the center. This approach established new upper and lower limits for all machining parameters, thereby enhancing the reliability of the experimental setup.

All experiments were executed according to the defined cutting conditions, ensuring a systematic testing of all process factor combinations. Minitab (version 22.2.0) software was utilized for designing the experimental plan and mathematically analyzing the responses.

In total, eight experiments were performed using the Taguchi method, with three surface roughness (Ra) measurements recorded for each, yielding a total of 24 measurements. For the CCD, 125 experiments were conducted, generating a comprehensive dataset of 378 surface roughness (Ra) measurements [22]. Establishing the surface roughness equation necessitates a thorough analysis of the contribution of each machining parameter and their interactions.

Table - Ra med Measurements Based on Central Composite Design

No.	V (m/min)	A_p (mm)	F_z (mm/tooth)	R_a Med (μm)
1	495	2.0	0.04	0.240
2	495	2.0	0.06	0.258
3	495	2.0	0.08	0.270
4	495	2.0	0.11	0.330
5	495	2.0	0.14	0.255
6	495	2.5	0.04	0.230
7	495	2.5	0.06	0.250
8	495	2.5	0.08	0.244
9	495	2.5	0.11	0.308
10	495	2.5	0.14	0.328
11	495	3.0	0.04	0.220
120	660	3.5	0.14	0.534
121	660	4.0	0.04	0.570
122	660	4.0	0.06	0.595
123	660	4.0	0.08	0.530

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124	660	4.0	0.11	0.553
125	660	4.0	0.14	0.567

4.2 Contribution of Parameters and Their Interactions

The Analysis of Variance (ANOVA) method was applied to comprehensively understand the influence of different machining conditions [5, 6]. ANOVA's primary objective is to quantify the impact of each factor while minimizing experimental error and identifying the most significant parameters within a larger set of variables.

By applying ANOVA to the results obtained from both the Taguchi method and the Central Composite Design, the individual and interactive contributions of each machining parameter to surface roughness were determined. The ANOVA results, generated using Minitab (version 22.2.0), are summarized.

Interpretation of Variance Analysis:

• DF (Degree of Freedom): Indicates the number of independent values available to estimate a parameter.

• Contribution (%): Quantifies the percentage of total variation in surface roughness explained by each factor or interaction.

• P-value: Assesses statistical significance. A P-value <0.05 indicates statistical significance (strong evidence against the null hypothesis), while a P-value >0.05 suggests the factor may not be statistically significant but could still hold practical importance.

Key Observations from ANOVA:

• Cutting speed (A) consistently demonstrates the most significant influence on surface roughness in both Taguchi and CCD analyses.

• The interaction between cutting speed and cutting depth ($A \times B$) exhibits a moderate influence and is statistically significant in the CCD results (P-value = 0.004).

• Feed per tooth (C) and cutting depth (B) show minor individual influence in the Taguchi analysis. However, CCD, with its greater degrees of freedom (118 error DF compared to Taguchi's 1 error DF), provides a more refined resolution of parameter variations.

• The significant impact of cutting speed is primarily attributed to material buildup on the tool when speed is not synchronized with rotational speed, leading to increased vibrations and a rougher surface finish. Thus, cutting speed and its interaction with cutting depth emerge as the dominant factors influencing surface roughness.

4.3 The Regression Equation of the Surface Roughness

Based on the experimental data , regression equations for surface roughness (Ra) were developed for both the Taguchi method and Central Composite Design (CCD) using Minitab (version 22.2.0). These equations quantitatively describe the relationship between surface roughness and the machining parameters: cutting speed (A), depth of cut (B), and feed per tooth (C).

The surface roughness equation for the Taguchi method is:

$$Ra=0.000444A-0.0955B-13.51C+0.000256AB+0.02708AC+3.04BC... \text{ (Equation 1)}$$

For the Central Composite Design (CCD), the corresponding equation is:

$$Ra=0.000393A-0.340B-10.17C+0.00800AB+0.0199AC+4.20BC... \text{ (Equation 2)}$$

The numerical values in these equations represent the statistically estimated coefficients for each factor and their interactions, quantifying their impact on surface roughness. Normal probability plots for the responses in Ra for both Taguchi and CCD cases are presented in Chart 1 and Chart 2 (see original document), respectively.

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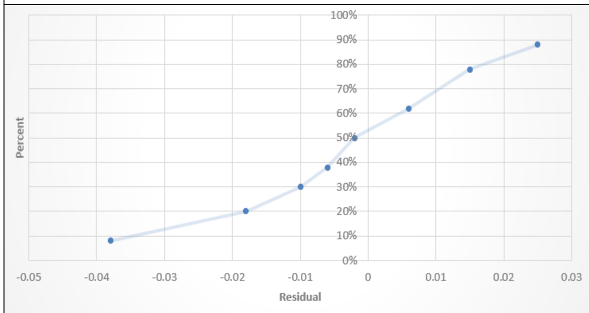
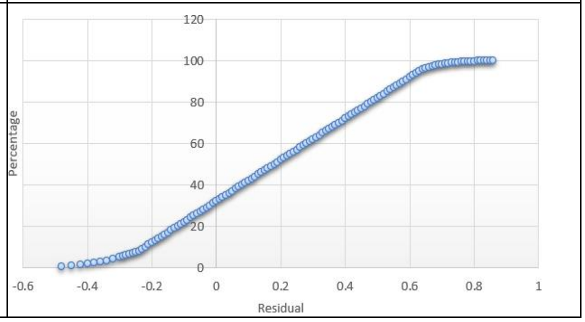
Chart 1- Normal probability plot— response in Ra (Taguchi case).	Chart 2- Normal probability plot— response in Ra (central composite design (CCD) case).
	

4.4 Comparison Between the Two Determined Regression Equations

To evaluate the accuracy of the regression equations derived from Taguchi's method and Central Composite Design, a comparison was made between the measured and calculated surface roughness values. Following table presents the measured (Ra) values alongside the calculated values from both models, including their respective relative errors (ϵx in %).

Analysis of the relative errors reveals varying accuracy across the experimental range for both methods. While both models aim to predict surface roughness, the results indicate that the accuracy differs depending on the specific cutting conditions. Notably, the relative errors for the CCD model tend to be higher in some instances, particularly at higher experiment numbers, suggesting that while CCD offers a more comprehensive experimental space, its predictive accuracy for certain combinations may vary. Conversely, the Taguchi model, despite its limited experimental runs, demonstrates comparable or even lower relative errors in several cases, particularly for lower experiment numbers. This highlights the trade-offs between experimental effort and predictive precision offered by each methodology.

No	A	B	C	Ra (measured)	Ra Taguchi (calculated)	Ra Central Composite Design (calculated)	Relative Error εx [%]	
							Ex Taguchi	Ex Central Composite Design
1	495	2	0.04	0.236	0.269	0.284	14%	20%
2	495	2	0.06	0.252	0.263	0.276	4%	10%
3	495	2	0.08	0.267	0.259	0.271	3%	2%
4	495	2	0.11	0.328	0.250	0.258	24%	21%
5	495	2	0.14	0.251	0.239	0.244	5%	3%
6	495	2.5	0.04	0.232	0.282	0.313	21%	34%
7	495	2.5	0.06	0.246	0.276	0.302	11%	23%
8	495	2.5	0.08	0.241	0.271	0.296	12%	23%
9	495	2.5	0.11	0.305	0.261	0.282	14%	8%
10	495	2.5	0.14	0.320	0.250	0.266	22%	17%
11	495	3	0.04	0.227	0.298	0.342	31%	51%
121	660	4	0.04	0.563	0.577	0.888	2%	58%
122	660	4	0.06	0.588	0.573	0.832	3%	41%
123	660	4	0.08	0.527	0.571	0.768	8%	45%
124	660	4	0.11	0.551	0.562	0.681	2%	24%
125	660	4	0.14	0.560	0.556	0.592	1%	6%

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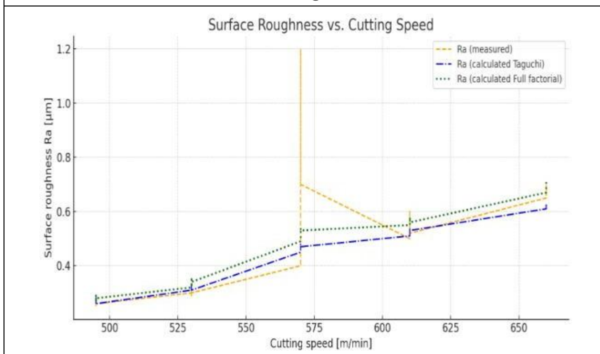
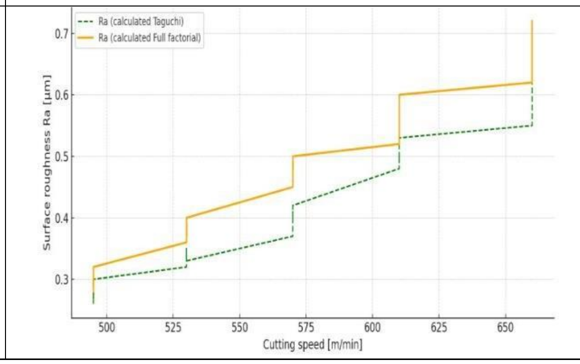
V. CONCLUSION AND FUTURE SCOPE

This study successfully developed predictive regression equations for surface roughness (Ra) in the end-milling of Al7050-T7451, utilizing both Taguchi design and Central Composite Design (CCD) methodologies. The efficacy of these models was assessed by comparing predicted Ra values against experimental measurements.

5.1 Key Findings

The calculated Ra values, derived from the developed regression models, were directly compared against the experimentally measured Ra values.

Further analysis involved a visual comparison between measured and calculated Ra values for both the Taguchi method and CCD, as depicted in Chart 3. This graphical representation effectively illustrates the predictive performance and accuracy of each approach. Chart 4 additionally compares the relative errors obtained from both methods, offering insights into their respective precision. Both charts highlight the strong influence of cutting speed on Ra, confirming its status as the most significant factor affecting surface roughness.

<table>
<tr><td>Chart 3- Comparison between the R_a measured versus R_a calculated using Taguchi′s method and central composite design.</td><td>Chart 4- Comparison between the relative errors obtained (Taguchi′s method versus central composite design).</td></tr>
<tr><td>
</td><td>
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Detailed analysis of the average deviations revealed that the Taguchi method demonstrated an approximate average deviation of 22% between calculated and experimental Ra values, while the Central Composite Design showed an average deviation of 27%. This suggests that, on average, the Taguchi method yielded slightly better accuracy in estimating surface roughness in this study.

Notably, the highest discrepancies between predicted and measured Ra values occurred at cutting speeds of 570 m/min and 610 m/min. At these specific speeds, the experimentally observed surface roughness exhibited a critical distribution, indicating increased vibrations during machining. This suggests that these intermediate speeds are less favorable for achieving optimal surface quality due to vibration-induced roughness.

5.2 Limitations

A significant unmeasured factor influencing the observed surface roughness was vibration during machining. While not directly quantified, the assumption of vibration's impact is based on the consistency of all other experimental conditions, including the CNC machine setup, the certified workpiece material, and identical cutting parameters across all tests. This consistency strongly implies that variations in surface finish, particularly at certain cutting speeds, were predominantly influenced by vibrational phenomena.

Previous research, such as [34], has explored the effects of spindle-induced forced vibrations in vertical milling. Their study confirmed that machine tool vibration amplitude and axial cutting depth are statistically significant factors for surface roughness (at a 95% confidence level), with vibration amplitude being the most dominant. This aligns with our observation that poor surface quality was recorded at speeds where vibrations were likely prevalent. Furthermore, higher vibration amplitudes combined with increased feed rates and axial cutting depths can lead to excessive tool wear and even catastrophic tool failure. These findings underscore the critical importance of vibration control in CNC machining for improving surface quality, extending tool life, and enhancing dimensional accuracy.

5.3 Recommendations

Considering the observed impact of vibrations, particularly at specific cutting speeds, future studies should explicitly incorporate vibration measurement and analysis. Research by [35] highlights that cutter runout significantly contributes to vibrations in profile milling, impacting chip removal and workpiece surface morphology.

Chart 5 and Chart 6 visually illustrate how cutting speed and feed per tooth influence Ra values. The noticeable increase in Ra at cutting speeds of 570 m/min and 610 m/min, especially with small feed rates, supports the hypothesis that vibrations are a root cause for the degraded surface finish. Future research should therefore:

Chart 11- The spatial variation of Ra according to v and fz. Chart 12- Indication of the spatial variation curves of Ra according to v and fz.

• Integrate vibration monitoring: Directly measure tool and workpiece vibrations during machining experiments.
• Investigate dynamic characteristics: Analyze the resonance frequencies of the tool- workpiece-machine system to identify and mitigate critical speeds.
• Explore advanced damping techniques: Research and implement strategies to reduce machining vibrations.
• Optimize tool geometry: Study the effect of tool design on vibration generation and surface quality.

Addressing these aspects will provide a more comprehensive understanding of the machining process and enable the development of more robust optimization strategies.

5.4 Conclusions

This study successfully developed and compared surface roughness (Ra) regression equations using Taguchi's design of experiments and the Central Composite Design (CCD) for the end-milling of Al7050. Analysis of Variance (ANOVA) consistently identified cutting speed as the most influential factor impacting the quality of the end-milled surface. Other control parameters showed a negligible correlation with surface roughness, with some contributing less than 0.85%.

A comparative analysis of the median relative errors indicated that the Taguchi method had a median relative error of 14%, while the Central Composite Design had a median relative error of 16%. This suggests that, in this specific study, the Taguchi method provided marginally better accuracy in surface roughness prediction despite requiring fewer experiments.

Both methodologies offer distinct advantages and disadvantages. The Taguchi method is cost- effective and time-efficient due to fewer experimental runs but may offer less precision. Conversely, CCD provides more accurate and comprehensive results but necessitates a larger number of experiments, leading to higher costs and time investment. The choice between methods ultimately depends on the researcher's experience, available resources, and the required level of result accuracy.

For future studies, expanding the scope to include the direct measurement and analysis of vibrations is crucial. Investigating the causes, consequences, and effective control methods for machining vibrations will significantly advance the understanding of surface roughness generation and contribute to further improvements in machining strategies for high-performance aluminum alloys.

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