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Optimization of Surface Roughness and Material Removal Rate in Turning of Al-6061 Using Taguchi Methodology, Fuzzy Logic, and Measurement System Analysis

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Abstract

The optimization of machining parameters plays a crucial role in improving product quality and productivity in manufacturing processes. This study focuses on the turning of aluminum 6061 alloy, aiming to optimize two key performance measures: surface roughness and material removal rate. An integrated approach combining the Taguchi methodology, fuzzy logic, and measurement system analysis (MSA) is proposed to achieve this objective. Taguchi design of experiments using an L9 orthogonal array is employed to determine the effects of process parameters—speed, depth of cut, and feed rate—on the selected responses. Fuzzy logic is utilized to convert the multiresponse problem into a single performance index, facilitating the simultaneous optimization of Ra and material removal rate (MRR). Additionally, MSA is conducted using gauge repeatability and reproducibility (gauge R&R) to ensure the reliability of the measured data. The analysis reveals that the chosen methodology effectively identifies optimal parameter settings, resulting in improved surface quality and machining efficiency.

Keywords: Turning process, Ra, optimization, MRR, Taguchi-Fuzzy hybrid approach, measurement system analysis (MSA)

INTRODUCTION

Turning is a fundamental machining operation widely used in manufacturing to produce cylindrical components with high dimensional accuracy and the desired surface finish. Product quality and productivity are paramount in various fields, such as the automotive, aerospace, and defense industries. Material removal rate (MRR) and Surface Roughness (SR) are two of the most crucial parameters compared with other performance measures. Functional performance is determined by surface roughness, while machining efficiency and cost-effectiveness are measured by MRR.

The Taguchi method, based on design of experiments (DOE), determines the best combination of process parameters with the fewest experimental trials, providing a structured and

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efficient approach. It focuses on reducing variability and improving robustness. Nevertheless, multiobjective problems, such as those involving Ra and MRR, cannot be directly addressed by Taguchi's single-response optimization. To overcome this limitation, fuzzy logic, a soft-computing technique inspired by human reasoning, can be used. It transforms multiple quality characteristics into a single performance index by modeling imprecision and uncertainty. A balanced optimization strategy is thereby integrated into a multiresponse problem. Measurement system analysis (MSA), particularly gauge repeatability and reproducibility (gauge R&R), is used to ensure the precision and accuracy of the measuring instruments used for assessing Ra and MRR [1].

Problem Statement

- To enhance product quality and production efficiency, optimizing Ra and MRR is critical in the turning process.
- Achieving both objectives simultaneously is challenging because of their conflicting nature.
- Additionally, fuzzy logic is applied to balance this trade-off, providing a decision-making approach for achieving optimal performance in operations such as the turning process.

Objectives

- *To identify the effects of key turning parameters*, such as speed, depth of cut, and feed rate, on Ra and MRR during the turning of aluminum alloy 6061.
- *To apply the Taguchi methodology* to design experiments and identify the most influential machining parameters.
- *To utilize fuzzy logic* for multiobjective optimization by converting Ra and MRR into a single comprehensive performance index.
- *To conduct MSA, including gauge repeatability and reproducibility (gauge R&R), to ensure the reliability and accuracy of the experimental data.*

EXPERIMENTAL SETUP

Materials

Aluminum 6061 was used as the target material in this study. The workpieces had dimensions of 25 mm in diameter and 60 mm in length. A total of nine observations were made [2].

Equipment

The equipment used in this investigation is listed below:

1. Computer Numerical Control (CNC) machine (for the turning process)
2. Cutting machine (for cutting the rod to the specified dimensions)
3. Conventional lathe machine (for surfacing the face of the workpiece)
4. Ra tester (for measuring the surface roughness of each workpiece)
5. Digital vernier caliper (for conducting the MSA)

Machining Parameters

In this operation, speed, feed rate, and depth of cut are the three primary process parameters that can be controlled by the operator at the machine. These parameters are speed, feed rate, and depth of cut.

Response Parameters

1. MRR
2. SR

Parameter Design

The initial stage of Taguchi's method involves selecting an L9 orthogonal array, conducting experiments, analyzing the data, identifying the optimal conditions, and confirming the test results to achieve significant improvements in product quality and consistency while reducing overall manufacturing costs [3].

LITERATURE REVIEW

Several researchers have contributed to the optimization of machining processes using various techniques. The following are a few notable studies.

Sovan Bhowmick, Rupam Mondal, and Subhasish Sarkar conducted experiments using powder-mixed electrical discharge machining (PMEDM) to analyze its effects on Ra and MRR. The process aimed to enhance surface finish and machining speed compared with conventional Electrical Discharge Machining (EDM). Key variables included powder concentration, pulse duration, pulse current, gap voltage, and pulse-on time. Both experimental results and fuzzy logic modeling were used, yielding prediction accuracies of 89.21% for MRR and 91.23% for Ra. The optimum settings involved a powder concentration of 8 g/L, pulse current of 9.5 A, gap voltage of 60 V, and pulse-on time of 150 µs.

Akkus applied the Taguchi method to optimize surface finish in the turning of AISI 1040 steel alloy. An L16 orthogonal array (OA) was used to design experiments with various process parameters. Analysis of the signal-to-noise (S/N) ratio indicated that feed rate had the greatest impact on Ra. This result shows that the Taguchi model achieved approximately 94% accuracy in predicting Ra.

A. Mufarrih, H. Istiqlaliyah, and M.M. Ilha conducted a study focusing on CNC turning optimization using a Taguchi–GRA hybrid model. The parameters analyzed included roundness, MRR, and Ra, which were subsequently converted into grey relational grades (GRGs) for multiobjective optimization. An L9 OA was used to better understand the process. The optimal parameters were a depth of cut of 1 mm, a feed rate of 0.085 mm/rev, and a cutting speed of 75.36 m/min. The GRG increased from 0.7017 to 0.9403, resulting in a 34% improvement in performance.

METHODOLOGY

In this study, a comprehensive method was adopted, incorporating the Taguchi DOE, fuzzy logic, and MSA to optimize important parameters such as Ra and MRR while performing the turning process on aluminum 6061 alloy.

The workpieces to be turned were prepared with dimensions of 25 mm × 60 mm, and these nine parts were used for the turning operation. An L9 OA was used for the Taguchi approach, allowing the three selected factors to be systematically controlled. A carbide cutting tool was used for the turning process [4].

To validate the consistency and reliability of the measured responses (Ra and MRR), a gauge repeatability and reproducibility (gauge R&R) study was performed as part of the MSA.

Post-experimentation, the collected data were statistically evaluated using S/N ratio analysis and analysis of variance (ANOVA) to identify the most significant process parameters affecting the responses. Subsequently, a fuzzy logic model was constructed to transform the two individual response variables (Ra and MRR) into a unified fuzzy performance index (FPI) for multiobjective

Figure 1. Experimental test setup.

Figure 2. Center Lathe Machine (Model CQ9332A).

Figure 3. MTAB CNC vertical machining center (VMC).

Table 1. Orthogonal array used for input parameters in Taguchi method.

S.N.	Spindle speed	Feed speed	Cutting depth	MRR	SR
1	700	60	0.2	140	0.520
2	700	80	0.3	280	0.440
3	700	90	0.4	420	0.431
4	800	60	0.3	240	0.446
5	800	80	0.4	426.7	0.426
6	800	90	0.2	240	0.448
7	900	60	0.4	360	0.439
8	900	80	0.2	240	0.446
9	900	90	0.3	405	0.435

Table 2. Taguchi analysis: MRR versus speed rate, depth of cut, and feed rate.

Levels	Speed	Feed rate	Depth of cut
1	48.11	47.22	46.59
2	49.82	49.72	49.57
3	50.29	51.29	52.06
Delta	2.18	4.07	5.47
Rank	3	2	1

Table 3. Response table for means.

Level	Spindle speed	Feed rate	Depth of cut
1	280.0	246.7	223.3
2	318.9	315.6	308.3
3	335.0	371.0	402.2
Delta	55.0	125.0	178.0
Rank	3	2	1

Table 4. Analysis of variance (ANOVA).

Parameters	DF	Adj SS	Adj MS	F-Value	P-Value
Speed rate	2	4797.4	2398.7	5.55	0.153
Feed rate	2	23519.4	11759.7	27.21	0.035
Depth of cut	2	48047.4	24023.7	55.58	0.018
Error	2	864.4	432.2		
Total	8	77228.7			

optimization (Figures 1–3). Finally, a confirmation experiment was conducted using the optimized parameters derived from the integrated approach to verify the improvements in Ra and MRR (Tables 1–4).

Regression Equation

$$\begin{aligned} \text{MRR} = {} & 311.30 - 31.30\ \text{Speed Rate}_{700} + 7.60\ \text{Speed Rate}_{800} + 23.70\ \text{Speed Rate}_{900} \\ & - 64.63\ \text{Feed Rate}_{60} + 4.27\ \text{Feed Rate}_{80} + 60.37\ \text{Feed Rate}_{90} \\ & - 87.97\ \text{Depth of cut}_{0.2} - 2.97\ \text{Depth of cut}_{0.3} \\ & + 90.93\ \text{Depth of cut}_{0.4} \end{aligned}$$

FUZZY LOGIC

In multiobjective optimization problems, particularly in machining processes, improving one response (e.g., material removal rate) often negatively affects another (e.g., surface roughness) [5–10]. To effectively handle this multiobjective task, fuzzy logic is used to combine multiple responses into a single FPI, enabling more practical and balanced decision-making (Figures 4 and 5).

Steps in Fuzzy Logic Implementation

Normalization of Responses

Each response value (e.g., Ra and MRR) was normalized on a scale from 0 to 1 based on its type. Surface roughness (Ra) and MRR were normalized using formulas such as:

- *For smaller-the-better:* X = (Max − X)/(Max − Min)
- *For larger-the-better:* X = (X − Min)/(Max − Min)

Fuzzification

The normalized values were converted into fuzzy membership values (0–1) using linguistic terms such as low, medium, and high. Typically, triangular or trapezoidal membership functions are used to define these fuzzy sets.

Rule Evaluation

A fuzzy rule base is established using IF–THEN rules that represent the desired outcomes. For example:

- IF (Ra is Low) AND (MRR is High), THEN (Performance is excellent).
- IF (Ra is Medium) AND (MRR is Medium), THEN (Performance is moderate).

MEASUREMENT SYSTEM ANALYSIS

Accurate and consistent measurements are of great importance in all experimental studies, especially when data are used for optimization and decision-making. This study demonstrates that, at this level, the instruments and procedures can be reliably used to measure Ra and MRR (Figures 6 and 7).

Output of the MSA

The (MSA) was performed to assess the accuracy, repeatability, and reproducibility of the measurement system. The results confirmed the reliability and consistency of the measurement process, ensuring that the collected experimental data were suitable for further analysis.

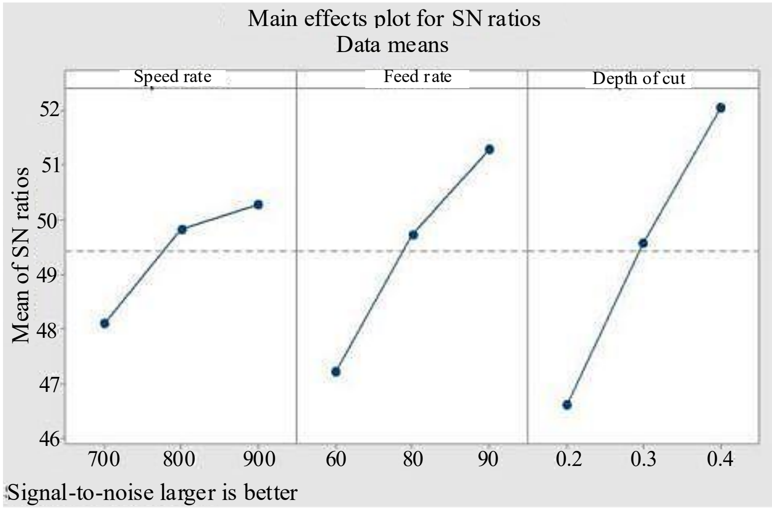

Figure 4. Graphs of signal-to-noise ratio (SN) ratios.

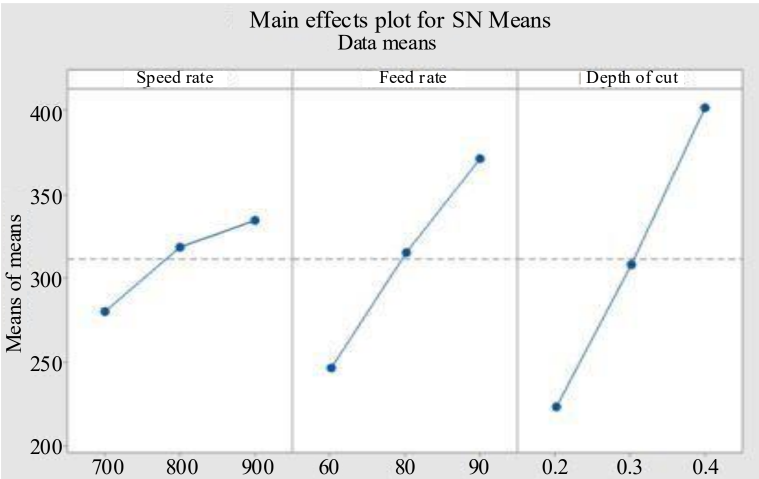

Figure 5. Graph of means.

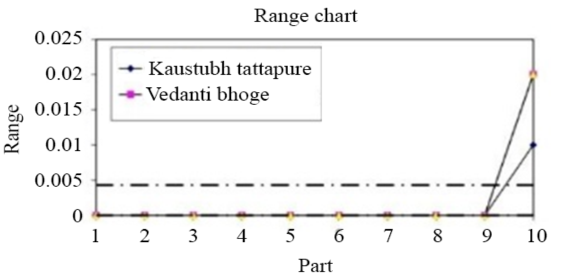

Figure 6. Graph for output of MSA.

% Total variation (TV)		
Measurement capability index (%GRR)		
%GRR	=	100 [GRR/TV]
	=	100(0.001/0.006)
	=	16.35
Gage system acceptable		
Number of distinct categories		
NDC	=	1.41(PV/GRR)
	=	8
Gage system acceptable		

Figure 7. Output of MSA with respect to total variation.

CONCLUSION

This study presents a systematic approach for optimizing the turning process of aluminum 6061 alloy by combining the Taguchi method, fuzzy logic, and MSA. There are two different characteristics, Ra and MRR, which are highly conflicting in machining operations; with traditional methods, we can optimize only one of them at a time. The Taguchi method uses three parameters, N, f, and D, through a DOE based on an L9 OA, reducing the required number of experiments while improving consistency and efficiency.

Fuzzy logic was implemented to overcome single-objective optimization and introduce a multiobjective system. Here, the two responses were converted into an FPI, which provides a balanced trade-off between surface finish and machining efficiency.

MSA ensured gauge R&R, confirming that the measurements were reliable. Finally, the optimal parameters obtained from this study improved surface quality and material removal performance. This system is robust and can be extended to various other materials, machining operations, and environments.

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