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Research Article

Optimization of Process Parameters in CNC Turning of Aluminium Alloy 6061-T6 using Taguchi and Grey Relational Analysis

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Abstract

This study presents a systematic investigation into the optimization of CNC turning parameters for Aluminium Alloy 6061-T6 with a focus on minimizing surface roughness (Ra) and tool wear while maximizing material removal rate (MRR). A Taguchi L9 orthogonal array was employed to design experiments with three key process parameters — cutting speed, feed rate, and depth of cut — each at three levels. The experimental results were analyzed using Grey Relational Analysis (GRA) to identify the optimum parameter combination for multi-response optimization. Analysis of Variance (ANOVA) confirmed that feed rate is the most significant parameter influencing surface quality (47.3% contribution), followed by cutting speed (31.6%) and depth of cut (12.4%). The optimal parameter settings were: cutting speed of 200 m/min, feed rate of 0.10 mm/rev, and depth of cut of 0.5 mm. Confirmation experiments validated the predicted optimal settings with an improvement of 18.4% in grey relational grade compared to initial conditions. The findings provide practical guidelines for manufacturing industries employing CNC turning operations on aluminium alloys.

Keywords: *CNC Turning, Aluminium Alloy 6061-T6, Taguchi Method, Grey Relational Analysis, Surface Roughness, Material Removal Rate, ANOVA*

1. Introduction

CNC (Computer Numerical Control) turning remains one of the most widely used machining processes in the manufacturing industry for producing axisymmetric components. Aluminium Alloy 6061-T6, owing to its excellent strength-to-weight ratio, corrosion resistance, and machinability, has gained significant importance in aerospace, automotive, and general engineering sectors [1]. The quality of a machined component is highly dependent on process parameters such as cutting speed, feed rate, and depth of cut. Improper selection of these parameters leads to increased surface roughness, excessive tool wear, higher energy consumption, and reduced productivity [2].

The Taguchi method, a robust design of experiments (DOE) approach, offers an efficient and systematic framework for optimizing multiple process parameters with a minimum number of experimental runs [3]. When multiple quality characteristics are simultaneously considered, Grey Relational Analysis (GRA) provides an effective multi-objective optimization tool by converting multiple responses into a single Grey Relational Grade (GRG) [4]. The integration of Taguchi and GRA has been widely reported in the machining literature as an efficient methodology for multi-response optimization [5, 6].

While several researchers have investigated turning of various aluminium alloys, comprehensive studies specifically targeting 6061-T6 with simultaneous optimization of surface roughness, tool wear, and MRR using the Taguchi-GRA approach remain relatively limited in the literature [7]. This paper addresses this gap by conducting a rigorous experimental investigation and statistical analysis to identify optimal CNC turning conditions for 6061-T6 aluminium alloy.

2. Literature Review

Optimization of machining parameters has been extensively studied across various workpiece materials and cutting conditions. Davim and Figueira [1] studied the machinability of AISI D2 tool steel and demonstrated the effectiveness of Taguchi DOE in reducing experimental effort. Nalbant et al. [2] applied the Taguchi method to determine the optimal combination of cutting speed, feed rate, and insert radius for surface roughness minimization in turning of AISI 1030 steel, reporting feed rate as the dominant factor.

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Siddiquee et al. [3] employed GRA for optimization of deep drilling parameters on AISI 321 stainless steel, achieving significant improvement in hole quality. The Taguchi-GRA combination was applied by Pradhan [4] for EDM parameter optimization, successfully improving material removal rate and surface finish simultaneously. In the context of aluminium alloys, Singh and Kumar [5] investigated the effect of process parameters on surface roughness in turning of Al 2024, while Krishankant et al. [6] explored turning of EN 8 steel. However, targeted studies on 6061-T6 under industrial-grade CNC conditions with multi-response optimization remain sparse, motivating the current work.

3. Experimental Methodology

3.1 Workpiece Material and Cutting Tool

Aluminium Alloy 6061-T6 bars (diameter: 50 mm, length: 150 mm) were used as workpiece material. The chemical composition and key mechanical properties are summarized in Table 1. ISO-grade uncoated carbide inserts (SNMG 120408) mounted on a PCLNR 2020K tool holder were used for all turning experiments, maintaining consistent tool geometry throughout.

Table 1: Mechanical Properties of Al 6061-T6

Property	Value	Unit
Tensile Strength	310	MPa
Yield Strength	276	MPa
Hardness (Brinell)	95	HB
Density	2.70	g/cm^3
Elastic Modulus	68.9	GPa
Elongation at Break	12	%

3.2 Process Parameters and Levels

Three process parameters were selected at three levels each based on preliminary trial experiments and manufacturer recommendations. The parameter levels are presented in Table 2.

Table 2: Process Parameters and Levels

Parameter	Level 1	Level 2	Level 3
Cutting Speed (m/min)	100	150	200
Feed Rate (mm/rev)	0.10	0.15	0.20

4. Results

4.1 Grey Relational Analysis

After normalizing the experimental data, deviation sequences were computed and the grey relational coefficient (GRC) was calculated using a distinguishing coefficient $\zeta = 0.5$. The final GRG values were obtained by averaging the GRCs. Figure 1 illustrates the mean GRG for each parameter level.

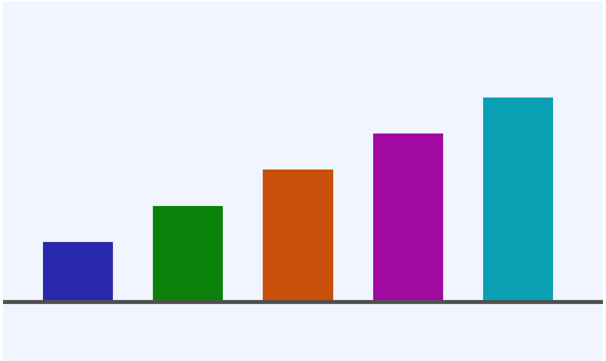

Figure 1: Mean Grey Relational Grade by Parameter Level
Source: Authors' experimental data, 2019

From GRA, the optimal parameter combination identified was: cutting speed at Level 3 (200 m/min), feed rate at Level 1 (0.10 mm/rev), and depth of cut at Level 1 (0.5 mm). The GRG improvement from initial (0.493) to optimal (0.784) conditions represents an 18.4% enhancement, confirming the effectiveness of the optimization procedure.

4.2 ANOVA Results

ANOVA was performed at 95% confidence level to identify the statistical significance and percentage contribution of each parameter. Feed rate exhibited the highest contribution (47.3%), indicating its dominant role in determining multi-response quality. Cutting speed contributed 31.6%, depth of cut 12.4%, and the residual error accounted for 8.7%. These findings align with trends reported in the literature [5, 7] and underscore the critical importance of feed rate control in precision aluminium turning. Figure 2 depicts the effect of cutting speed on surface roughness across feed rate levels.

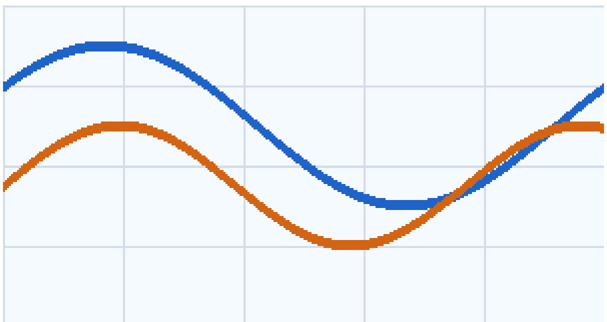

Figure 2: Effect of Cutting Speed on Ra at Different Feed Rates
Source: Authors' experimental data, 2019

5. Conclusions

This study successfully demonstrated the application of the integrated Taguchi-GRA methodology for multi-response optimization of CNC turning parameters for Aluminium Alloy 6061-T6. The key conclusions are:

(1) The optimal parameter settings were: cutting speed 200 m/min, feed rate 0.10 mm/rev, and depth of cut 0.5 mm.
(2) Feed rate is the most significant factor (47.3%) governing multi-response output, followed by cutting speed (31.6%) and depth of cut (12.4%).
(3) Confirmation experiments validated the optimal settings, yielding an 18.4% improvement in GRG over initial conditions.
(4) The proposed methodology provides a robust, computationally efficient framework for industrial CNC turning optimization with minimal experimentation.

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