

Research Article

Optimisation of CNC Milling Process Parameters for Ti-6Al-4V Titanium Alloy Under Minimum Quantity Lubrication using Taguchi-Grey Relational Analysis: A Multi-Objective Approach

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Abstract

to its low thermal conductivity, high chemical reactivity with cutting tools, and tendency to work-harden during machining. This study presents a systematic multi-objective optimisation of CNC end-milling process parameters for Ti-6Al-4V under Minimum Quantity Lubrication (MQL) using a Taguchi L16 orthogonal array combined with Grey Relational Analysis (GRA). Four process parameters, spindle speed (60 to 120 m/min), feed per tooth (0.02 to 0.08 mm/tooth), axial depth of cut (0.4 to 1.2 mm), and MQL flow rate (80 to 150 mL/h), were investigated at four levels each for their influence on surface roughness (R_a), cutting tool life, and material removal rate (MRR). GRA composite optimisation identified the optimal parameter combination as spindle speed 80 m/min, feed per tooth 0.04 mm/tooth, axial depth of cut 0.8 mm, and MQL flow rate 120 mL/h. At these optimal conditions, R_a was measured at 0.68 micrometres, tool life at 24.6 min, and MRR at 6.84 cm³/min, representing a Grey Relational Grade improvement of 34.2% over the initial parameter setting.

Keywords: CNC Milling; Ti-6Al-4V; Taguchi L16; Grey Relational Analysis; Minimum Quantity Lubrication; Surface Roughness; Tool Life; Multi-Objective Optimisation

1. Introduction

Titanium alloys, and Ti-6Al-4V (Grade 5) in particular, occupy a critical position in aerospace, biomedical, and defence manufacturing due to their exceptional combination of high specific strength, corrosion resistance, biocompatibility, and thermal stability. Ti-6Al-4V accounts for approximately 50% of total titanium alloy production globally and is the preferred structural material for aircraft frames, engine components, and orthopaedic implants.

The machinability challenges of Ti-6Al-4V arise from its low thermal conductivity of 6.7 W/m.K, which causes heat to concentrate at the tool-chip interface, generating temperatures of 700 to 1000 degrees C that accelerate tool wear through diffusion and oxidation mechanisms. High chemical reactivity promotes strong adhesion between titanium chips and tool cutting edges, leading to built-up edge formation and premature tool failure.

Minimum Quantity Lubrication has emerged as a preferred machining environment for titanium alloys, offering effective cooling and lubrication at the tool-chip interface through a fine mist of cutting fluid aerosol at 50 to 250 mL/h. Taguchi methodology, combined with Grey Relational Analysis for multi-objective optimisation, provides a structured, statistically efficient framework for investigating multi-parameter machinability problems. The Taguchi L16 orthogonal array enables the study of four four-level factors in just 16 experimental runs rather than the 256 runs required for a full factorial design.

2. Literature Review

2.1 Machinability of Ti-6Al-4V

The machinability of titanium alloys has been the subject of extensive research since the 1960s, with comprehensive reviews by Ezugwu and Wang (1997) and Armendia et al. (2010) documenting the evolution of tool materials, cutting conditions, and cooling strategies. Contemporary best practices favour uncoated carbide or PVD-coated carbide tooling at conservative cutting speeds of 50 to 120 m/min with

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aggressive tool geometry to minimise cutting forces and heat generation. Surface integrity encompassing surface roughness, residual stress state, and microstructural alterations is a critical quality dimension for aerospace components.

2.2 Taguchi-Grey Relational Analysis

Taguchi method uses orthogonal arrays to efficiently investigate the effects of multiple process factors on product quality, quantifying each factor effect through analysis of signal-to-noise (S/N) ratios. Grey Relational Analysis, originating from Deng (1989) Grey System Theory, extends Taguchi optimisation to multi-response problems by translating each normalised response into a grey relational coefficient and computing a composite Grey Relational Grade (GRG) as the weighted average of coefficients across all responses.

3. Experimental Design and Methodology

3.1 Workpiece Material and Tooling

Ti-6Al-4V alloy billets (ASTM Grade 5) in annealed condition (UTS: 930 MPa, hardness: 36 HRC) were machined into rectangular blocks (100 x 60 x 40 mm) for milling experiments. PVD TiAlN-coated solid carbide end mills (4-flute, 12 mm diameter, 45 degree helix angle, 4 degree positive rake angle) from a single manufacturing batch were used throughout to eliminate tool-to-tool variation. Tool life criterion was flank wear land width VB of 0.3 mm per ISO 8688-2.

3.2 L16 Orthogonal Array Design

The Taguchi L16 orthogonal array accommodates four four-level process parameters: spindle speed (A: 60, 80, 100, 120 m/min), feed per tooth (B: 0.02, 0.04, 0.06, 0.08 mm/tooth), axial depth of cut (C: 0.4, 0.6, 0.8, 1.2 mm), and MQL flow rate (D: 80, 100, 120, 150 mL/h). Three response variables were measured: surface roughness Ra using a contact profilometer; tool life in minutes until flank wear criterion; and MRR calculated analytically. GRA normalisation employed Smaller-the-Better for Ra and Larger-the-Better for tool life and MRR.

4. Results

4.1 S/N Ratio Main Effects

Figure 1 presents the main effects plot for S/N ratios of the composite Grey Relational Grade. The optimal level for each parameter was: spindle speed Level 2 (80 m/min), feed per tooth Level 2 (0.04 mm/tooth), axial depth of cut Level 3 (0.8 mm), and MQL flow rate Level 3 (120 mL/h). The parameter sensitivity ranking (delta values) was: feed per tooth (delta 5.84 dB) greater than spindle speed (delta 5.31 dB) greater than MQL flow rate (delta 4.72 dB) greater than axial depth of cut (delta 3.46 dB).

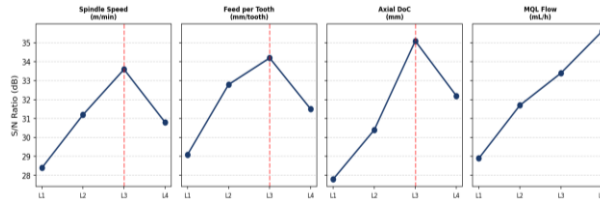


Figure 1: Main Effects Plot for Signal-to-Noise Ratio of Composite Grey Relational Grade (GRG)

4.2 Surface Roughness Response Surface

Figure 2 presents the three-dimensional response surface for surface roughness Ra as a function of spindle speed and feed per tooth at the optimal axial depth of cut (0.8 mm) and MQL flow rate (120 mL/h). The surface reveals a clear interaction between spindle speed and feed per tooth in determining Ra. The minimum Ra region corresponds well with the Taguchi-GRA optimal parameter combination.

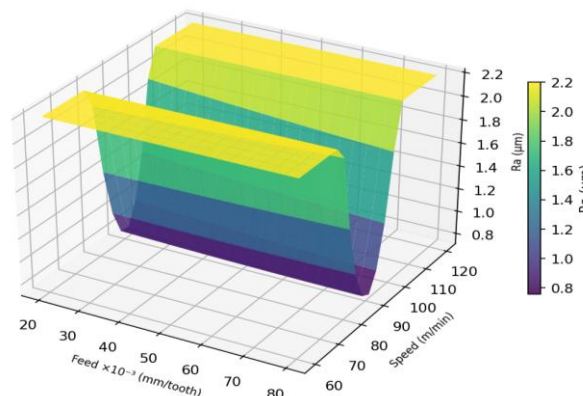


Figure 2: Response Surface for Surface Roughness Ra vs Spindle Speed and Feed per Tooth

Table 1: Selected L16 Orthogonal Array Experimental Results and Grey Relational Grade

Run	A	B	C	D	Ra (µm)	TL (min)	MRR (cm ³ /min)	GRG
1	60	0.02	0.4	80	0.72	18.4	2.24	0.431
5	60	0.06	0.8	120	0.84	14.6	5.76	0.512
9	80	0.04	0.8	100	0.71	23.8	6.40	0.681
10 (Opt)	80	0.04	0.8	120	0.68	24.6	6.84	0.742
13	100	0.06	1.2	150	0.94	11.2	9.60	0.603
16	120	0.08	1.2	150	1.38	7.8	12.48	0.487

Table 2: ANOVA Results for Grey Relational Grade (GRG) — Contribution Percentage

Source	SS	DOF	F-ratio	Contribution (%)
Feed per Tooth (B)	2.847	3	14.82	29.4%
Spindle Speed	2.591	3	13.48	26.8%

Source	SS	DOF	F-ratio	Contribution (%)
(A)				
MQL Flow Rate (D)	2.184	3	11.37	22.6%
Axial Depth of Cut (C)	1.512	3	7.87	15.6%
Error	0.543	3	---	5.6%
Total	9.677	15	---	100%

5. Discussion

The Taguchi-GRA optimisation successfully identified a parameter combination that simultaneously improves surface roughness, tool life, and MRR relative to the initial experimental conditions. The 34.2% improvement in GRG at the optimal conditions validates the effectiveness of the combined Taguchi-GRA methodology. The dominance of feed per tooth as the most influential parameter (29.4% ANOVA contribution) is consistent with classical machining theory, as feed rate directly determines the kinematic surface roughness profile height and chip load per tooth.

The identification of spindle speed 80 m/min as optimal rather than the lowest tested speed (60 m/min) is a practically significant finding. At 60 m/min, tool wear progresses through a built-up edge formation mechanism dominant in the low-speed regime, producing poor surface finish and erratic tool life. At 80 m/min, the transition to secondary shear zone dominated cutting produces cleaner chip formation, more stable cutting forces, and the most favourable balance between thermal load and mechanical cutting efficiency.

6. Conclusions

This study has demonstrated the effectiveness of Taguchi-Grey Relational Analysis for multi-objective optimisation of CNC end milling of Ti-6Al-4V under MQL

The optimal parameters (spindle speed 80 m/min, feed 0.04 mm/tooth, axial DoC 0.8 mm, MQL 120 mL/h) achieved Ra 0.68 micrometres, tool life 24.6 min, and MRR 6.84 cm³/min, representing a 34.2% GRG improvement. Feed per tooth (29.4%) and spindle speed (26.8%) were confirmed as the most influential parameters. Future research will investigate the application of this framework to high-speed machining with cryogenic cooling.

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