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Original Research Article

Multi-response optimization of CNC turning parameters for IS 319 grade I free-cutting brass using hybrid Taguchi-Grey relational analysis

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ABSTRACT
This study presents the multi-response optimization of CNC turning parameters for IS 319 Grade I free-cutting brass using a hybrid Taguchi–Grey Relational Analysis (GRA) approach. The machining parameters, namely spindle speed, feed rate, and depth of cut, were selected and varied at three levels based on a Taguchi L9 orthogonal array. Material removal rate (MRR) and surface roughness (Ra) were chosen as performance measures to represent productivity and surface quality. Signal-to-noise (S/N) ratio analysis was used to evaluate the effect of individual parameters on each response, while Analysis of Variance (ANOVA) was applied to determine their statistical significance and contribution. Grey Relational Analysis was then used to convert the multi-response problem into a single performance index, called the Grey Relational Grade (GRG), for simultaneous optimization. The results indicate that feed rate was the most influential parameter affecting both MRR and surface roughness. The optimal combination of machining parameters was found to be a spindle speed of 2200 rpm, feed rate of 0.05 mm/rev, and depth of cut of 1.5 mm. Under these conditions, the GRG increased from a mean value of 0.604 to 0.784, indicating an overall improvement of 29.8%. The study demonstrates that the Taguchi–Grey Relational Analysis approach is a simple and effective method for multi-response optimization in CNC turning operations.

1. Introduction

CNC turning is widely used for producing cylindrical components with high dimensional accuracy and surface finish. The performance of the process depends on machining parameters such as spindle speed, feed rate, and depth of cut. Improper selection of these parameters can lead to poor surface quality and reduced productivity [1].

In machining operations, surface roughness (Ra) and material removal rate (MRR) are two important performance measures. Surface roughness affects the functional performance and service life of the component, while MRR represents productivity. Previous studies have reported that feed rate significantly influences surface roughness, whereas feed rate and depth of cut mainly affect MRR, leading to a trade-off between surface quality and productivity [2, 3].

Traditionally, machining parameters are selected based on experience or trial-and-error methods, which are time-consuming and may not provide optimal results. To overcome this limitation, statistical optimization techniques are widely used. The Taguchi method is commonly preferred because it reduces the number of experiments and provides a systematic approach using orthogonal arrays and signal-to-noise (S/N) ratios [4].

Several researchers have reported that feed rate is the most significant factor affecting surface roughness, while cutting speed and depth of cut also influence machining performance [5, 6]. In practical machining conditions, multiple performance characteristics must be optimized simultaneously. Grey Relational Analysis (GRA) is used as a multi-response optimization technique, which converts multiple responses into a single Grey Relational Grade (GRG) to identify optimal machining parameters [7]. The combined Taguchi–GRA approach has been successfully applied to achieve improved surface quality and productivity [8-10].

Most existing studies focus on steels and composite materials, while limited work has been reported on IS 319 Grade I free-cutting brass. Although this material has good machinability and corrosion resistance, achieving a balance between surface finish and productivity remains a challenge.

Therefore, this study aims to optimize CNC turning parameters for IS 319 Grade I brass under dry machining conditions using a hybrid Taguchi–Grey Relational Analysis approach to achieve higher material removal rate along with improved surface finish.

2. Methodology

2.1 Experimental setup and parameters

The experiments were carried out on a CNC turning center (Jyoti DX-200-3) using IS 319 Grade I free-cutting brass as the work material. Cylindrical specimens of 25 mm diameter and 50 mm length were prepared for machining. For all experimental runs, turning was performed over a constant length of 35 mm to maintain uniform cutting conditions and ensure consistency in the results. Figure 1 shows (a) CNC turning setup, (b) workpiece before and after machining, and (c) measurement arrangement.

Figure 1: Experimental setup showing (a) CNC turning setup, (b) workpiece before and after machining, and (c) measurement arrangement.

A carbide insert tool (VCGT 160404, uncoated) was used for the turning operation. The experiments were conducted under dry cutting conditions to evaluate machining performance without the influence of cutting fluid, allowing direct assessment of the effect of machining parameters on the responses.

Three machining parameters—spindle speed, feed rate, and depth of cut—were selected as control factors based on their significant influence on machining performance. Spindle speed controlled the cutting velocity, feed rate determined the tool advancement per revolution, and depth of cut defined the material removed in a single pass. Each parameter was varied at three levels to study its effect on material removal rate and surface roughness. The selected parameters and their corresponding levels are presented in Table 1.

Table 1: Machining parameters and their levels.

Parameter	Level 1	Level 2	Level 3
Spindle Speed (rpm)	1200	1700	2200
Feed Rate (mm/rev)	0.05	0.10	0.15
Depth of Cut (mm)	0.50	1.00	1.50

2.2 Experimental design and measurement of responses

The experiments were designed using a Taguchi L9 orthogonal array to study the influence of machining parameters with a reduced number of experimental trials [4]. In this design, each row of the L9 array represented a unique combination of spindle speed, feed rate, and depth of cut, ensuring systematic experimentation with a minimum number of trials.

For each experimental condition, three trials were conducted to ensure reliability and repeatability. Each trial consisted of five consecutive turning passes under identical machining conditions, and the measured values were averaged to reduce experimental error and improve accuracy.

Material removal rate (MRR) was determined using the weight loss method. The workpiece was weighed before and after machining, and the difference in weight was calculated. This weight loss was converted into volume using material density, and MRR was obtained by dividing the removed volume by machining time. The experimentally obtained MRR values were also verified using theoretical calculations to ensure consistency.

Surface roughness (Ra) was measured using a stylus-type surface roughness tester (Mitutoyo SJ-210). Measurements were taken along the machined surface, where the stylus traced the surface profile to capture irregularities. Multiple readings were recorded at different locations, and the average value was considered for each experimental run to ensure reliable measurement.

The experimental design along with the observed values of MRR and surface roughness are presented in Table 2.

Table 2: Experimental design and observed responses

Exp. No.	Spindle Speed (rpm)	Feed (mm/rev)	Depth of Cut (mm)	MRR (mm^3/min)	Ra (µm)
1	1200	0.05	0.50	2018.078	0.380
2	1200	0.10	1.00	6881.535	1.516
3	1200	0.15	1.50	12996.176	2.609
4	1700	0.05	1.00	4855.437	0.306
5	1700	0.10	1.50	12278.630	0.806
6	1700	0.15	0.50	8104.198	2.796
7	2200	0.05	1.50	8095.675	0.313
8	2200	0.10	0.50	6916.389	1.300
9	2200	0.15	1.00	17086.550	1.939

2.3 Signal-to-Noise (S/N) ratio analysis

The Taguchi method was used to evaluate the performance of machining parameters through the signal-to-noise (S/N) ratio by considering both the mean and variability of the responses. The S/N ratio helped in identifying parameter settings that minimized the effect of noise factors and improved process stability.

In this study, different S/N ratio criteria were selected based on the nature of the response. For material removal rate (MRR), the larger-the-better criterion was used since higher MRR indicates better productivity. For surface roughness (Ra), the smaller-the-better criterion was applied because a lower Ra value represents better surface quality.

The S/N ratio for the larger-the-better characteristic was calculated using Equation (1), while the smaller-the-better characteristic was calculated using Equation (2).

Equation (1): Larger-the-better (MRR)

$$S/N = -10\log\left(\frac{1}{n}\sum\frac{1}{y^2}\right)$$

Equation (2): Smaller-the-better (Ra)

$$S/N = -10\log\left(\frac{1}{n}\sum y^2\right)$$

where,
y = observed response value
n= number of observations

The calculated S/N ratios were used to analyze the effect of machining parameters and to determine the optimal levels for individual performance characteristics.

2.4 Grey Relational Analysis (GRA)

Grey Relational Analysis (GRA) was applied to perform multi-response optimization by combining material removal rate and surface roughness into a single performance index [7]. This method was used to identify the optimal machining parameters when multiple responses with conflicting objectives were involved.

The GRA procedure consisted of three main steps: normalization of experimental data, calculation of grey relational coefficients, and determination of grey relational grade.

In the first step, the experimental data were normalized to bring all response values within a comparable range between 0 and 1. For MRR, the larger-the-better normalization was applied, while for Ra, the smaller-the-better normalization was used.

In the second step, the grey relational coefficient (GRC) was calculated to represent the relationship between the ideal and actual normalized values. The coefficient indicated how close a particular experiment was to the optimal condition.

Equation (3): Grey Relational Coefficient

$$\xi_i = \frac{\Delta_{\min}+\zeta\Delta_{\max}}{\Delta_i+\zeta\Delta_{\max}}$$

where,
Δ_i= deviation sequence.
$\Delta_{\min}$, $\Delta_{\max}$= minimum and maximum deviation values,
ζ= distinguishing coefficient (taken as 0.5)

In the final step, the grey relational grade (GRG) was obtained by averaging the grey relational coefficients of all responses. The GRG represented the overall performance of each experimental run. A higher GRG value indicated better combined performance of material removal rate and surface roughness.

The GRG values were further used to determine the optimal combination of machining parameters and to rank the experimental runs based on overall performance.

3. Results and Discussion

3.1 Signal-to-Noise ratio analysis

The signal-to-noise (S/N) ratios for material removal rate (MRR) and surface roughness (Ra) are presented in Table 3. These values were used to evaluate the influence of machining parameters and to identify optimal experimental conditions.

Table 3: Signal-to-noise ratios for MRR and surface roughness.

Exp. No.	S/N Ratio (MRR) (dB)	S/N Ratio (Ra) (dB)
1	66.0988	8.4120
2	76.7537	-3.6121
3	82.2763	-8.3302
4	73.7246	10.2950
5	81.7830	1.8709
6	78.1742	-8.9321
7	78.1651	10.0922
8	76.7976	-2.2781
9	84.6531	-5.7506

For material removal rate, the larger-the-better criterion was applied. The highest S/N ratio of 84.6531 dB was obtained for Experiment 9, indicating maximum material removal rate due to higher feed rate and depth of cut, which increased the material removal per unit time.

For surface roughness, the smaller-the-better criterion was used. The highest S/N ratio of 10.2950 dB was observed for Experiment 4, indicating the best surface finish. This was mainly due to the lower feed rate, which reduced tool mark spacing and produced a smoother surface. Experiment 7 showed a comparable S/N ratio (10.0922 dB), suggesting that higher spindle speed also improved surface finish.

However, the optimal conditions for MRR and surface roughness were different, indicating a trade-off between productivity and surface quality. This behavior is typical in machining operations and highlights the need for multi-response optimization [7]. Therefore, Grey Relational Analysis was used to determine the optimal machining parameters for balanced performance.

3.2 Grey Relational Analysis

Grey Relational Analysis (GRA) was applied to combine material removal rate (MRR) and surface roughness (Ra) into a single performance index known as the Grey Relational Grade (GRG), enabling simultaneous optimization of both responses with conflicting requirements [7].

The normalized values, Grey Relational Coefficients (GRC), and Grey Relational Grade (GRG) for all experimental runs are presented in Table 4.

Table 4: Grey Relational Analysis results.

Exp. No.	Norm MRR	Norm Ra	GRC (MRR)	GRC (Ra)	GRG	Rank
1	0.000	0.902	0.333	0.836	0.585	5
2	0.574	0.277	0.540	0.409	0.474	8
3	0.872	0.031	0.796	0.340	0.568	6
4	0.411	1.000	0.459	1.000	0.730	2
5	0.845	0.562	0.764	0.533	0.648	4
6	0.651	0.000	0.589	0.333	0.461	9
7	0.650	0.989	0.588	0.979	0.784	1
8	0.577	0.346	0.541	0.433	0.487	7
9	1.000	0.165	1.000	0.375	0.687	3

The GRG values were used to evaluate overall machining performance, where a higher GRG indicated better combined performance of productivity and surface quality.

Experiment 7 achieved the highest GRG value of 0.784 and was ranked first, indicating the optimal machining condition with a balanced combination of material removal rate and surface finish.

Experiments 4 and 9 were ranked second and third, with GRG values of 0.730 and 0.687, respectively. Experiment 4 provided superior surface finish due to lower feed rate, while Experiment 9 resulted in higher material removal rate due to increased feed and depth of cut. However, neither condition alone produced the best overall performance compared to Experiment 7.

These results show that Grey Relational Analysis effectively converted multiple responses into a single performance index, resolving the conflict observed in S/N ratio analysis and identifying a balanced machining condition.

3.3 Response table and optimal parameter selection

The response table for Grey Relational Grade (GRG) is presented in Table 5, which shows the average GRG values at each level of machining parameters used to determine the optimal parameter combination.

Table 5: Response table for GRG

Level	Spindle Speed	Feed	Depth of Cut
1	0.542	0.699	0.511
2	0.613	0.537	0.630
3	0.653	0.572	0.667
Delta	0.110	0.163	0.156
Rank	3	1	2

The highest GRG values were observed at spindle speed Level 3 (0.653), feed rate Level 1 (0.699), and depth of cut Level 3 (0.667). Based on this, the optimal machining condition was identified as a spindle speed of 2200 rpm, feed rate of 0.05 mm/rev, and depth of cut of 1.5 mm, providing a balanced improvement in both material removal rate and surface roughness.

The delta values represent the difference between the maximum and minimum GRG values and indicate the relative influence of each parameter. Feed rate showed the highest delta value (0.163) and was ranked first, indicating the most significant effect on GRG. Depth of cut was ranked second (0.156), while spindle speed showed the least influence (0.110).

This result indicates that feed rate plays a dominant role in controlling both productivity and surface quality in CNC turning of brass [11]. Higher feed rate increases material removal rate but adversely affects surface finish, making its proper selection critical for achieving balanced performance.

3.4 Main effects plot for GRG

The main effects plot for Grey Relational Grade (GRG) is shown in Figure 2, illustrating the influence of spindle speed, feed rate, and depth of cut on overall machining performance.

The plot shows the variation of GRG with different levels of machining parameters. A steeper slope indicates a stronger influence on performance. Feed rate exhibited the highest variation in GRG, confirming its dominant effect on combined performance. The highest GRG was obtained at feed Level 1 (0.05 mm/rev), indicating that lower feed rate improved surface quality and overall performance.

Depth of cut showed a consistent increasing trend, suggesting that higher depth of cut improved material removal rate without significantly affecting surface finish within the selected range. In contrast, spindle speed showed a gradual increase in GRG, indicating a comparatively lower influence.

Overall, the observed trends agree with the response table and ANOVA results, where feed rate was the most significant parameter, followed by depth of cut and spindle speed.

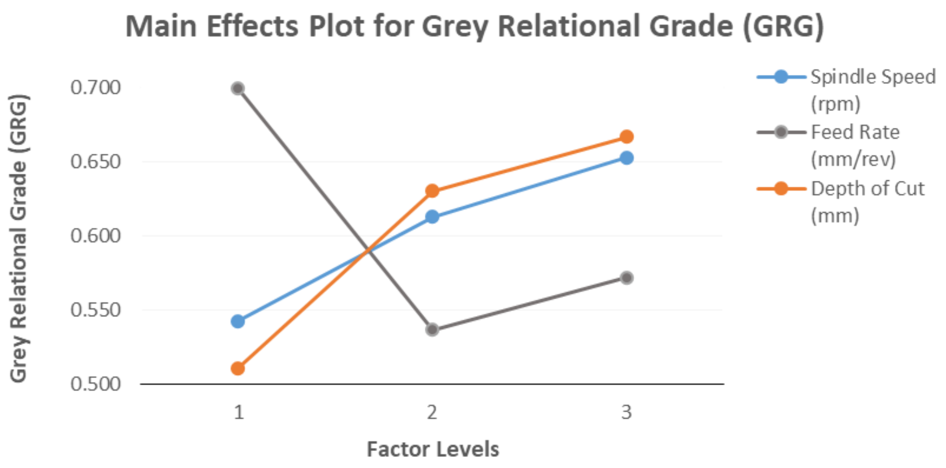

Figure 2: Main effects plot showing the influence of spindle speed, feed rate, and depth of cut on Grey Relational Grade (GRG).

3.5 Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) was performed to quantify the contribution of machining parameters—spindle speed, feed rate, and depth of cut—on material removal rate (MRR), surface roughness (Ra), and Grey Relational Grade (GRG), and to identify the most influential parameters.

3.5.1 ANOVA for Material Removal Rate

The ANOVA results for material removal rate are presented in Table 6.

Table 6: ANOVA results for MRR.

Source	DF	SS	Contribution (%)	F-value	P-value
Spindle Speed (rpm)	2	18037130	10.73	1.41	0.416
Feed (mm/rev)	2	89899752	53.47	7.00	0.125
Depth of Cut (mm)	2	47365101	28.17	3.69	0.213
Error	2	12836325	7.63	–	–
Total	8	168138308	100.00	–	–

Feed rate was the most influential parameter, contributing 53.47% to MRR, as it directly controlled the volume of material removed per revolution. Depth of cut also showed a significant contribution of 28.17%, while spindle speed had a comparatively lower influence (10.73%) within the selected range.

3.5.2 ANOVA for surface roughness

The ANOVA results for surface roughness are presented in Table 7.

Table 7: ANOVA results for surface roughness

Source	DF	SS	Contribution (%)	F-value	P-value
Spindle Speed (rpm)	2	0.1546	2.07	0.39	0.722
Feed (mm/rev)	2	6.7769	90.95	16.91	0.056
Depth of Cut (mm)	2	0.1191	1.60	0.30	0.771
Error	2	0.4007	5.38	–	–
Total	8	7.4513	100.00	–	–

Feed rate was the predominant factor influencing surface roughness, with a contribution of 90.95%, due to its direct effect on the spacing between successive tool marks. Spindle speed and depth of cut showed negligible contributions.

3.5.3 ANOVA for Grey Relational Grade

The ANOVA results for Grey Relational Grade are presented in Table 8.

Table 8: ANOVA results for GRG.

Source	DF	SS	Contribution (%)	F-value	P-value
Spindle Speed (rpm)	2	0.0187	17.07	2.68	0.272
Feed (mm/rev)	2	0.0442	40.31	6.32	0.137
Depth of Cut (mm)	2	0.0398	36.25	5.69	0.150
Error	2	0.0070	6.37	–	–
Total	8	0.1098	100.00	–	–

Feed rate remained the most influential parameter, contributing 40.31%, followed by depth of cut (36.25%) and spindle speed (17.07%). This indicates that both feed rate and depth of cut significantly affect the combined performance of MRR and surface roughness.

These results confirm that feed rate has the dominant influence on overall machining performance, consistent with the response table and main effects plot. This trend is consistent with machining theory, where feed rate directly influences chip load and surface generation mechanism, thereby significantly affecting both productivity and surface quality.

3.6 Confirmation results

The optimal machining parameters identified through Grey Relational Analysis were a spindle speed of 2200 rpm, a feed rate of 0.05 mm/rev, and a depth of cut of 1.5 mm, corresponding to Experiment 7 in the Taguchi L9 orthogonal array.

The Grey Relational Grade (GRG) results in Table 4 show that Experiment 7 achieved the highest GRG value among all experimental trials, indicating the best overall performance.

Since this optimal parameter combination was already included in the experimental design, the results of Experiment 7 were directly used for validation.

The mean GRG of all experimental runs was 0.604, while the optimal condition yielded a GRG of 0.784, corresponding to an improvement of 29.8%. This indicates a significant enhancement in overall machining performance.

The improvement reflects a balanced optimization, where higher material removal rate was achieved while maintaining lower surface roughness under the optimal parameter combination.

4. Conclusion

This study presented the multi-response optimization of CNC turning parameters for IS 319 Grade I free-cutting brass using a hybrid Taguchi–Grey Relational Analysis approach. The effects of spindle speed, feed rate, and depth of cut on material removal rate and surface roughness were systematically investigated.

The signal-to-noise ratio analysis showed that the optimal conditions for material removal rate and surface roughness were different, indicating conflicting performance characteristics. Grey Relational Analysis effectively combined these responses into a single Grey Relational Grade, enabling simultaneous optimization.

The optimal machining condition was identified as a spindle speed of 2200 rpm, feed rate of 0.05 mm/rev, and depth of cut of 1.5 mm (Experiment 7), which produced the highest Grey Relational Grade of 0.784.

Analysis of Variance confirmed that feed rate was the most influential parameter affecting both material removal rate and surface roughness, followed by depth of cut, while spindle speed showed comparatively lower influence.

An improvement of 29.8% in Grey Relational Grade was achieved compared to the initial condition, indicating a significant enhancement in overall machining performance. The proposed methodology can be effectively applied in industrial machining to improve productivity and surface quality.

Overall, the Taguchi–Grey Relational Analysis approach was found to be an effective and reliable method for optimizing machining parameters and achieving a balanced improvement in productivity and surface quality during CNC turning of IS 319 Grade I brass. The obtained results are in good agreement with existing machining principles, confirming the reliability of the adopted optimization approach.

5. Future scope

Future work may include the investigation of different lubrication techniques such as minimum quantity lubrication (MQL) and cryogenic cooling to improve machining performance. Additional studies on tool wear, cutting forces, and energy consumption can provide a more comprehensive understanding of the process. Advanced optimization methods may further enhance multi-response optimization efficiency.

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Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

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