OPTIMIZATION OF MACHINING PARAMETERS FOR TURNING OPERATION WITH MULTIPLE QUALITY CHARACTERISTICS USING GREY RELATIONAL ANALYSIS

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Original scientific paper

Optimization of machining processes is essential for achieving of higher productivity and high quality products in order to remain competitive. This study investigates multi-objective optimization of turning process for an optimal parametric combination to provide the minimum surface roughness (*Ra*) with the maximum material-removal rate (*MRR*) using the Grey–Based Taguchi method. Turning parameters considered are cutting speed, feed rate and depth of cut. Nine experimental runs based on Taguchi's L_9 (3^4) orthogonal array were performed followed by the Grey relational analysis to solve the multi-response optimization problem. Based on the Grey relational grade value, optimum levels of parameters have been identified. The significance of parameters on overall quality characteristics of the cutting process has been evaluated by the analysis of variance (ANOVA). The optimal parameter values obtained during the study have been validated by confirmation experiment.

Keywords: *ANOVA; Grey relational analysis; multi-objective optimization; Taguchi method; turning*

Optimizacija parametara obrade tokarenja s više kriterija kvalitete uporabom Grey relacijske analize

Izvorni znanstveni članak

Optimizacija procesa obrade je neophodna za postizanje veće produktivnosti i visoke kvalitete proizvoda kako bi ostali tržišno konkurentni. Ovaj rad istražuje više-kriterijsku optimizaciju procesa tokarenja s optimalnom kombinacijom parametara obrade koji osiguravaju minimalnu hrapavost površine (*Ra*) s maksimalnim učinkom uklanjanja materijala (*MRR*) uporabom Grey–based Taguchi metode. Razmatrani parametri obrade tokarenjem su brzina rezanja, posmak i dubina rezanja. Primjenom Taguchijevog L_9 (3^4) ortogonalnog plana provedeno je devet eksperimenata te je korištena Grey relacijska analiza kako bi se riješio višekriterijski problem optimizacije. Temeljem vrijednosti Grey relacijskog stupnja utvrđene su optimalne razine parametara. Signifikantnost parametara na sveukupne kriterije kvalitete procesa tokarenja ocijenjena je analizom varijance (ANOVA). Optimalne vrijednosti parametara dobivene tijekom istraživanja potvrđene su verifikacijskim eksperimentom.

Ključne riječi: *ANOVA; Grey relacijska analiza; Taguchijeva metoda; tokarenje; višekriterijska optimizacija*

1 Introduction

Determination of optimal machining parameters is continuous engineering task whose goals are to reduce the production costs and to achieve the desired product quality. In turning process, surface quality is one of the most important performance measures. Surface roughness (*Ra*) is a widely used index of product quality and in most cases a technical requirement for mechanical products. Achieving the desired surface quality is of great importance for the functional behavior of a part. At the same time higher material removal rate (*MRR*) is considered as the factor that directly affects the production cost and the machining hour rate.

In a turning operation, it is an important task to select cutting parameters to achieve high cutting performance for a particular machine and environment. Hence, multiple quality optimization method based on a combination of Grey relational analysis (GRA) and the Taguchi method was used in this paper to determine the optimal values of cutting parameters in order to obtain better surface roughness and increased material removal rate in the finish turning operation. To search for the optimal process condition through a limited number of experimental runs Taguchi's L_9 orthogonal array consisting of three factors and three levels was applied to optimize the multiple quality characteristics of the finish turning process.

The three controlling factors, including the cutting speed (*V*), the depth of cut (*d*) and feed rate (*f*), were selected. Grey relational grade is used to convert multi objective problem into a single objective. To identify the optimal combination of process parameters that concurrently minimize the surface roughness (*Ra*) and maximize the material removal rate (*MRR*) Grey relational analysis was employed. Grey relational analysis (GRA) utilizes a specific concept of information. It defines situations with no information as black, and those with perfect information as white [1]. Additionally, an analysis of variance (ANOVA) was also utilized to examine the most significant influential factors for the *Ra* and *MRR* in the turning process. Confirmation test was conducted using the optimum cutting parameters determined by the Taguchi optimization method. Based on this analysis, valuable remarks about presented optimization approach are pointed out in the conclusion of this study. Many researchers have studied the effects of optimal selection of machining parameters in turning.

Tzeng and Chen [2] used grey relational analysis to optimize the process parameters in turning of tool steels. They performed Taguchi experiments with eight independent variables, the optimum turning parameters were determined based on grey relational grade which maximizes the accuracy and minimizes the surface roughness and dimensional precision.

Sahoo et al. [3] have used Grey relational analysis to perform multi-objective optimization of surface roughness and *MRR* in turning of AA 1040 steel and determined that cutting speed is the most influencing parameter affecting combined Grey relational grade followed by depth of cut and feed rate.

Tzeng et al. [4] have used Grey relational analysis to perform optimization of turning operations with multiple performance characteristics such as roughness average, roughness maximum, and roundness. The depth of cut was identified to be the most influencing parameter

affecting the Grey relational grade followed by cutting speed and feed rate.

Similarly, the researchers have applied the Grey relational analysis (GRA) to different processes with multiple performance characteristics and greatly improved through this approach. Tosun [5] investigated optimization of drilling parameters to minimize surface roughness and burr height, Chang and Lu [6] investigated optimization of cutting parameters for side milling operations, Datta et al. [7] investigated optimization of bead geometry in submerged arc welding process, Chakradhar and Gopal [8] investigated optimization of electrochemical machining of EN31 steel, etc. In the recent times researchers have also tried to optimize the machining parameters using various methods like Genetic Algorithm, Particle swarm optimization, ANN, Simulated annealing method, Multi-Objective Evolutionary Algorithm, etc. [9÷12].

2 Experimental procedure
2.1 Machining conditions

Experimental research was performed on lathe machine "Georg Fisher NDM-16". Test samples were carbon steel bars DIN Ck45 with 100 mm in diameter and 380 mm in length. Chemical composition and mechanical properties of DIN Ck45 steel are given in Tab. 1 and Tab. 2. Experiments were carried out by the external machining turning tool with the holder mark DDJNL 3225P15 and the coated inserts type DNMG 150608-PM4025 under dry cutting conditions. The tool geometry was: rake angle 17°, clearance angle 5°, main cutting edge 93° with nose radius 0,8 mm. Before each cut, the insert was changed to eliminate the effect of toolwear. Surface roughness measurements were performed with SurftestMitutoyo SJ-201P. The surface roughness measured in the paper is the arithmetic mean deviation of surface roughness of profile Ra [13÷15].The material removal rate of the work piece is the volume of the material removed per minute. It can be calculated using the following equation:

$$MRR = Vfd, \qquad (1)$$

where three main cutting parameters are cutting speed V (m/min), feed rate f (mm/r) and depth of cut d (mm).

Table 1 Chemical composition of carbon steel Ck45 (wt%)

Element	C	Si	Mn	P	S	Ni	Mo
Content	0,467	0,309	0,657	0,014	0,021	0,039	0,0087

Table 2 Mechanical properties of carbon steel Ck45

Material	Tensile strength (MPa)	Yield strength (MPa)	% of Elongation	Hardness (HB)
Ck45	650	420	24,2	179

2.2 Design of experiments

The Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a limited number of experiments [16]. The experiments have been carried out by using the standardized Taguchi-based experimental design, a L$_9$ (3^4) orthogonal arrays, with three levels (coded by: 1; 2 and 3) of three main cutting parameters, namely, cutting speed V, feed rate f and depth of cut d (shown in Tab. 3).

Table 3 Cutting parameters and their limits

Symbol	Parameters	Levels		
	Coding – orthogonal array	1	2	3
A	$X_1 = V$ (m/min)	400	450	500
B	$X_2 = f$ (mm/rev.)	0,1	0,15	0,2
C	$X_3 = d$ (mm)	0,4	0,8	1,2

The necessary number of test runs is nine. The last column (for the fourth factor) in the L$_9$ (3^4) orthogonal array is left empty for this specific study. The experimental results and the Taguchi L$_9$ (3^4) orthogonal array are shown in Tab. 4.

Table 4 Orthogonal array L9(3^4) of the experimental runs and results

Exp. No.	A V	B f	C d	$\overline{Ra}$ (μm)	MRR (cm^3/min)
1.	1	1	1	0,77	16
2.	1	2	2	1,33	48
3.	1	3	3	2,14	96
4.	2	1	2	1,11	36
5.	2	2	3	1,13	81
6.	2	3	1	2,01	36
7.	3	1	3	1,19	60
8.	3	2	1	1,05	30
9.	3	3	2	1,93	80

3 Results and discussions
3.1 Grey relational analysis

Grey relational analysis was proposed by Deng in 1989 [17] and it is widely used for measuring the degree of relationship between sequences by Grey relational grade [18].

By employing Grey relational analysis associated with the Taguchi method, optimization of the complicated multi-response characteristics can be converted into optimization of a single response characteristic with Grey relational grade as an objective function.

In the present work the objectives are to minimize the surface roughness and maximize the MRR of finish turning process. Thus, surface roughness and material removal rate as the multi-responses are combined by Grey relational grade using Grey relational analysis.

3.2 Grey relational generation

In Grey relational analysis the first step is to perform the Grey relational generation in which the results of the experiments are normalized in the range between 0 and 1 due to different measurement units. Data pre-processing converts the original sequences to a set of comparable sequences. Normalizing the experimental data for each quality characteristic is done according to the type of performance response. Thus, the normalized data processing for Ra corresponding to *smaller-the-better* criterion can be expressed as:

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}, \tag{2}$$

The normalized data processing for *MRR* corresponding to *larger-the-better* criterion can be expressed as:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}, \tag{3}$$

where, $i = 1, 2, 3, ..., m$, m is the number of experimental runs in Taguchi orthogonal array, in the present work L_9 orthogonal array is selected then $m = 9$. $k = 1, 2, ...,n$, n is the number of quality characteristics or process responses, in the present work surface roughness and material removal rate are selected, then $n = 2$.

Min $y_i(k)$ is the smallest value of $y_i(k)$ for the kth response. Max $y_i(k)$ is the largest value of $y_i(k)$ for the kth response. $x_i(k)$ is the value after Grey relational generation. The normalized values of surface roughness and material removal rate calculated by Eq. (2) and (3) are shown in Tab. 5.

Table 5 Normalized values and deviation sequences of responses

Exp. No.	Normalized values of responses		Deviation sequences $\Delta_{0i}(k)$	
	Ra	*MRR*	*Ra*	*MRR*
	Smaller-the-better	Larger-the-better		
1.	1,0000	0,0000	1,0000	1,0000
2.	0,5912	0,4000	0,0000	0,6000
3.	0,0000	1,0000	0,4088	0,0000
4.	0,7518	0,2500	1,0000	0,7500
5.	0,7372	0,8125	0,2482	0,1875
6.	0,0948	0,2500	0,2628	0,7500
7.	0,6934	0,5500	0,9051	0,4500
8.	0,7956	0,1750	0,3066	0,8250
9.	0,1532	0,8000	0,2044	0,2000

3.3 Grey relational coefficient and Grey relational grade

The second step is to calculate the Grey relational coefficient based on the normalized experimental data to represent the correlation between the desired and actual experimental data. The overall Grey relational grade is then computed by averaging the Grey relational coefficient corresponding to each performance characteristic. As a result, optimal combination of process parameters is evaluated considering the highest Grey relational grade by using the Taguchi method. Based on the normalized experimental data the Grey relation coefficient can be calculated using the following equations:

$$\xi_i(k) = \frac{\Delta_{\min} + \varsigma\Delta_{\max}}{\Delta_{0i}(k) + \varsigma\Delta_{\max}}, \tag{4}$$

$$\Delta_{0i}(k) = \|x_0(k) - x_i(k)\|, \tag{5}$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \|x_0(k) - x_i(k)\|, \tag{6}$$

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \|x_0(k) - x_i(k)\|, \tag{7}$$

where $\Delta_{oi} = \|x_0(k) - x_i(k)\|$ is difference of the absolute value between $x_0(k)$ and $x_i(k)$, $x_0(k)$ is the reference sequence of the kth quality characteristics.

$\Delta_{\min}$ and $\Delta_{\max}$ are respectively the minimum and maximum values of the absolute differences (Δ_{oi}) of all comparing sequences.

ζ is a distinguishing coefficient, $0 \leq \zeta \leq 1$, the purpose of which is to weaken the effect of $\Delta_{\max}$ when it gets too big and thus enlarges the difference significance of the relational coefficient. In the present case, $\zeta = 0,5$ is used due to the moderate distinguishing effects and good stability of outcomes.

The Grey relation coefficient of each performance characteristic is shown in Tab. 6. After averaging the Grey relational coefficients, the Grey relational grade γ_i can be calculated as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k), \tag{8}$$

where, $i = 1, 2, 3 ... 9$, (L_9 orthogonal array is selected), $\xi_i(k)$ is the Grey relational coefficient of kth response in i^{th} experiment and n is the number of responses. The optimum level of the process parameters is the level with the highest Grey relational grade.

The higher value of the Grey relational grade corresponds to an intense relational degree between the reference sequence $x_0(k)$ and the given sequence $x_i(k)$. The Grey relational coefficients and Grey relational grade are presented in Tab. 6 calculated by Eq. (4) and (8), respectively. The highest Grey relational grade is the rank of 1. Therefore, the experiment number 5 is the best combination of turning parameters for surface roughness and material removal rate among the nine experiments.

Table 6 Grey relational coefficient, Grey relational grade and corresponding *S/N* ratios

Exp. No.	Grey relational coefficient		Grey relational grade	Rank	*S/N* Ratio
	Ra	*MRR*			Larger-the-better
1.	1,0000	0,3333	0,66667	3	−3,5218
2.	0,5502	0,4545	0,50237	8	−5,9795
3.	0,3333	1,0000	0,66667	2	−3,5218
4.	0,6683	0,4000	0,53415	7	−5,4468
5.	0,6555	0,7273	0,69139	1	−3,2056
6.	0,3558	0,4000	0,37792	9	−8,4520
7.	0,6199	0,5263	0,57311	4	−4,8352
8.	0,7098	0,3774	0,54360	5	−5,2944
9.	0,3713	0,7143	0,54278	6	−5,3075

The multi-objective optimization problem has been transformed into a single equivalent objective function optimization problem using Grey relational analysis. Accordingly, optimal combination of process parameters is evaluated considering the highest Grey relational grade by using the Taguchi method.

3.4 Analysis of *S/N* ratios

Taguchi method recommends the use of the *S/N* ratio to measure the quality characteristics deviating from the desired values [19]. The signal-to-noise (*S/N*) ratio is a

measure of the magnitude of a data set relative to the standard deviation. In the Taguchi method, signal to-noise *S/N* ratio is used to represent a performance characteristic and the largest value of *S/N* ratio means the optimal level of the turning parameters.

There are three types of *S/N* ratio: the larger-the-better, the nominal-the better, and the smaller-the-better. Tab. 6 shows the *S/N* ratio based on the *larger-the-better* criterion for the overall Grey relational grade calculated using Eq. (9):

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right],\qquad(9)$$

where *n* is the number of measurements, and y_i is the measured characteristic value. The mean response for the Grey relational grade with its grand mean and the main effect plot of the Grey relational grade are very important because the optimal process condition can be evaluated from this plot, (shown in Fig. 1. and 2.). The dashed line is the value of the total mean of the *S/N* ratio and mean effect plot.
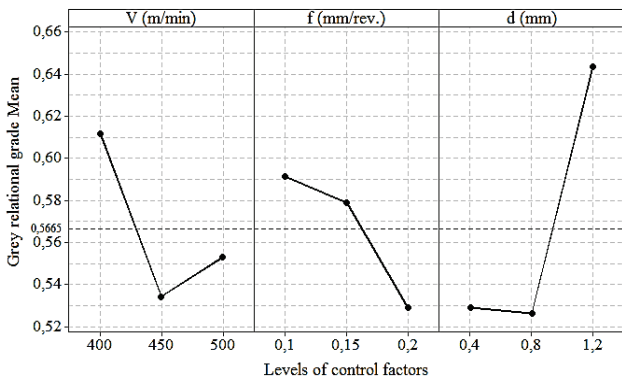

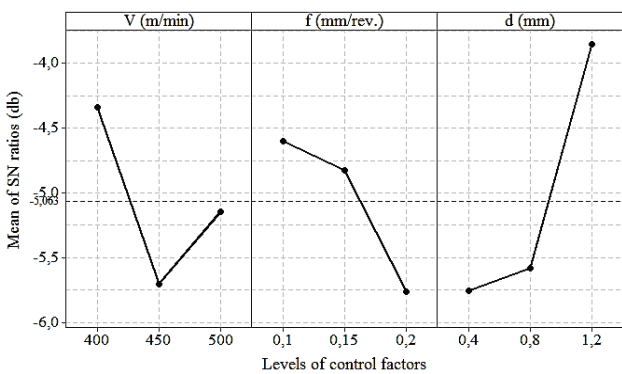**Figure 1** Mean plot for the Grey relational grade

Figure 2 S/N plot for the Grey relational grade

The means of the Grey relational grade for each level of turning parameters were calculated from Tab. 6 and summarized in Tab. 7. The larger the Grey relational grade, the better the multiple quality characteristics.

Table 7 Response table for the mean Grey relational grade

Parameter	Grey relational grade			
	Level 1	Level 2	Level 3	Delta
A (*V*)	**0,6119**	0,5345	0,5532	0,0774
B (*f*)	**0,5913**	0,5791	0,5291	0,0622
C (*d*)	0,5294	0,5264	**0,6437**	0,1173

Total mean value of the Grey relational grade = **0,5665**

As indicated in Fig. 1. and 2., the optimal parameter condition for turning of the C45 carbon steel regarding surface roughness and material removal rate multiple performance characteristics are levels: A-level 1, B-level 1, C-level 3. Namely, cutting speed of *V* = 400 m/min, feed rate of *f* = 0,1 mm/rev and depth of cut *d* = 1,2 mm.

3.5 Analysis of variance (ANOVA)

The purpose of the analysis of the variance (ANOVA) is to investigate which turning parameters significantly affect the quality characteristic. By using the Grey relational grade value, ANOVA is indicated for identifying the significant factors. In addition to degree of freedom (*DF*), mean of squares (*MS*), sum of squares (*SS*), *F*-ratio and contribution (*C*) associated with each factor was presented. The higher the percentage contribution was, the more important the factor was for affecting the performance characteristics. The results of ANOVA for the Grey grade values are represented in Tab. 8. The results of the ANOVA indicate that the percentage contribution of cutting speed (*V*), feed rate (*f*) and the depth of cut (*d*) influencing the multiple performance characteristics were 12,63 %, 8,41 % and 34,62 %, respectively. From the percentage contribution of the ANOVA, the cutting speed and depth of cut were two parameters significantly influencing the Grey relational grade. And the depth of cut was the most effective factor on the performance.

3.6 Confirmation experiment

After the optimal level of turning parameters has been identified, a verification test needs to be carried out in order to check the accuracy of analysis. The estimated Grey relational grade $\hat{\gamma}$ is used to predict the improvement of the performance characteristic by using optimum combination of turning parameters. The estimated Grey relational grade $\hat{\gamma}$ can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o}(\overline{\gamma}_i - \gamma_m),\qquad(10)$$

here γ_m is the total mean Grey relational grade, $\overline{\gamma}_i$ is the mean Grey relational grade at the optimal level, and *o* is the number of the machining parameters significantly affect the multiple performance characteristics.

The A1B1C3 was an optimal combination of turning parameters by the Grey relational analysis. Therefore, the A1B1C3 optimal combination parameters were regarded as the confirmation test.

Tab. 9 shows the comparison of the estimated Grey relational grade with the actual Grey relational grade obtained in verification experiment using the optimal cutting parameters. Namely, surface roughness *Ra* was improved from 2,01 μm to 1,11 μm and the material removal rate *MRR* was also improved from 36 cm³/min to 48 cm³/min considering initial cutting conditions. In conclusion, it is clearly shown that the multiple performance characteristics in turning C45 carbon steel were significantly improved by increase in Grey relational grade of 0,1835.

Table 8 ANOVA results of turning process parameters

Main control factors	Symbol	Degree of freedom DF	Sum of squares (SS)	Mean of squares (MS)	F-ratio	Contribution, C (%)
Cutting speed V	A	2	0,009792	0,004896	0,28	12,63
Feed rate f	B	2	0,006515	0,003258	0,19	8,41
Depth of cut d	C	2	0,026836	0,013418	0,78	34,62
Error	-	2	0,034371	0,017186	-	44,34
Total	-	8	0,077515	-	-	100

Table 9 Results of confirmation test

Factor levels	Initial factor settings	Optimal process condition	
		Prediction	Experiment
Factor levels	A2B3C1	A1B1C3	A1B1C3
Ra (µm)	2,01	-	1,11
MRR (cm^3/min)	36	-	48
S/N ratio of overall Grey relational grade	−8,4520	−2,67106	−5,01424
Overall Grey relational grade	**0,37792**	**0,713898**	**0,56142**
Improvement in Grey relational grade = **0,1835**			

4 Conclusions

In this study, the Grey-based Taguchi method was applied for the multiple performance characteristics of turning operations.

Multi-response optimization of turning process has been used to obtain optimal parametric combination that provides the minimum surface roughness (Ra) with the maximum material-removal rate (MRR). The application of the Grey relational analysis based on the Taguchi method directly integrates the multiple quality characteristics into a single performance characteristic called Grey relational grade. Optimal combination of process parameters is evaluated considering the highest Grey relational grade by using the Taguchi method.

By applying the Taguchi method the number of experiments is drastically reduced. A L$_9$ (3^4) Taguchi orthogonal array, the signal to noise (S/N) ratio and the analysis of variance (ANOVA) were used for the optimization of cutting parameters considering Grey relational grade. According to the analysis the optimal parameter combination for turning of the C45 carbon steel regarding surface roughness and material removal rate multiple performance characteristics were levels: A-level 1, B-level 1, and C-level 3. Namely, cutting speed of V = 400 m/min, feed rate of f = 0,1 mm/rev and depth of cut d = 1,2 mm.

The results of the ANOVA indicate that the percentage contribution of cutting speed, feed rate and the depth of cut influencing the multiple performance characteristics were 12,63 %, 8,41 % and 34,62 %, respectively. From the percentage contribution of the ANOVA, the cutting speed and depth of cut were two parameters significantly influencing the Grey relational grade. And the depth of cut was the most effective factor on the performance.

Effectiveness of this method was verified by the test experiment. The Grey relational grade of the multiple performance characteristics was significantly improved by 0,1835 through this method. Namely, surface roughness Ra was improved from 2,01 µm to 1,11 µm and the material removal rate MRR was improved from 36 cm^3/min to 48 cm^3/min considering initial cutting conditions.

Therefore, the optimization of the complicated multiple performance characteristics of the processes can be greatly simplified by using the Grey-based Taguchi method. The performance characteristics of the turning operations, such as the material removal rate and the surface roughness are greatly enhanced by using this method.

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6 References

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