

USE OF GREY BASED TAGUCHI METHOD IN BALL BURNISHING PROCESS FOR THE OPTIMIZATION OF SURFACE ROUGHNESS AND MICROHARDNESS OF AA 7075 ALUMINUM ALLOY

UPORABA GREY-TAGUCHIJEVE METODE PRI PROCESU GLAJENJA ZA OPTIMIZACIJO POVRŠINSKE HRAPAVOSTI IN MIKROTRDOTE ALUMINIJEVE ZLITINE AA 7075

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This study investigated the multi-response optimization of burnishing process for an optimal parametric combination to yield favorable surface roughness and microhardness using the Grey relational analysis and Taguchi method. Sixteen experimental runs based on an orthogonal array of Taguchi method were performed to derive objective functions to be optimized within experimental domain. The objective functions have been selected in relation of burnishing parameters; burnishing force, number of passes, feed rate and burnishing speed. The Taguchi approach followed by Grey relational analysis was applied to solve the multi-response optimization problem. The significance of the factors on overall quality characteristics of the burnishing process has also been evaluated quantitatively with the variance method (ANOVA). Optimal results were verified through confirmation experiments. This shows application feasibility of the Grey relation analysis in combination with Taguchi technique for continuous improvement in product quality in manufacturing industry.

Keywords: ball burnishing process, Grey relation analysis, Taguchi method

V tej študiji je raziskana večodgovorna optimizacija procesa glajenja z dosegom optimalnih kombinacij parametrov za ugodno površinsko hrapavost in mikrotrdoto z uporabo Greyjeve analize odvisnosti in Taguchijeve metode. Šestnajst eksperimentov v ortogonalni porazdelitvi po metodi Taguchi je bilo uporabljenih za razvoj objektivnih funkcij za optimizacijo v eksperimentalnem polju. Objektivne funkcije so bile izbrane v odvisnosti od parametrov glajenja; sila glajenja, število prehodov, hitrost podajanja in hitrost glajenja. Taguchijev približek in Greyjeva analiza odvisnosti sta bila uporabljena za rešitev večodgovornega problema. Kvantitativno je bil ocenjen tudi pomen dejavnikov kakovosti procesa glajenja z metodo variance (ANOVA). Optimalni rezultati so bili potrjeni s preizkusi. Delo dokazuje uporabnost Greyjeve analize odvisnosti in Taguchijeve tehnike za stalno izboljšanje kakovosti proizvodov v predelovalni industriji.

Ključne besede: krogelno glajenje, Greyjeva analiza odvisnosti, Taguchijeva metoda

1 INTRODUCTION

The function performance of a machined component such as fatigue strength, load bearing capacity, friction, etc. depends to a large extent on the surface as topography, hardness, nature of stress and strain induced on the surface region. Nowadays, about 50% of the energy supplied is lost in the friction of elements in relative motion^{1,2}. Roughness values less than 0.1 mm are required for good aesthetic appearance, easy mould release, good corrosion resistance, and high fatigue strength. During recent years, however, considerable attention has been paid to the post-machining metal finishing operations such as burnishing which improves the surface characteristics by plastic deformation of the surface layers^{2,3}.

Burnishing is considered as a cold-working finishing process, differing from other cold-working, surface treatment processes such as shot peening and sand blasting, etc. in that it produces a good surface finish and also induces residual compressive stresses at the metallic

surface layers⁴. Accordingly, burnishing distinguishes itself from chip-forming finishing processes such as grinding, honing, lapping and super-finishing which induce residual tensile stresses at the machined surface layers^{5,6}. Also, burnishing is economically desirable, because it is a simple and cheap process, requiring less time and skill to obtain a high-quality surface finish^{4,5}.

Beside producing a good surface finish, the burnishing process has additional advantages over other machining processes, such as securing increased hardness, corrosion resistance and fatigue life as a result of producing compressive residual stress. Residual stresses are probably the most important aspect in assessing integrity because of their direct influence on performance in service. Thus, control of the burnishing process (burnishing conditions) in such a way as to produce compressive residual stresses in the surface region could lead to considerable improvement in component life. A comprehensive classification of burnishing tools and their application has been given by Shneider⁷. A literature survey shows that work on the burnishing process

has been conducted by many researchers and the process improves also the properties of the parts, e.g. higher wear resistance^{2,8,9} increased hardness¹⁰⁻¹², surface quality^{2,3,14} and increased maximum residual stress in compression¹¹. The parameters affecting the surface finish are: burnishing force, feed rate, ball material, number of passes, workpiece material, and lubrication^{2,3}. It is necessary to find an optimal process condition capable of producing desired surface quality and hardness. However, this optimization should be performed in such a way that all the objectives should fulfill simultaneously. Such an optimization technique is called multi-response optimization¹⁵.

The majority of the research existing in literature on the effect of burnishing parameters on the burnished surface is of experimental nature and very few analytical models are available in the literature.

The Taguchi method is very popular for solving optimization problems in the field of production engineering.^{16,17} The method utilizes a well-balanced experimental design (allows a limited number of experimental runs) called orthogonal array design, and signal-to-noise ratio (S/N ratio), which serve as objective function to be optimized (maximized) within the experimental domain. However, traditional Taguchi method cannot solve multi-objective optimization problem. To overcome this, the Taguchi method coupled with Grey relational analysis has a wide area of application in manufacturing processes. This approach can solve multi-response optimization problem simultaneously^{15,18}.

Planning the experiments through the Taguchi orthogonal array has been used quite successfully in process optimization¹⁹⁻²⁴. Therefore, in this study the Taguchi L₁₆(4⁴) orthogonal array was applied to plan the experiments on burnishing process.

Four controlling factors including burnishing force (F), number of passes (N), feed rate (f) and burnishing speed (V) on the surface roughness (Ra) and microhardness (HV) with four levels for each factor were selected. The Grey relational analysis was then applied to examine how the burnishing parameters influenced the surface roughness and microhardness and an optimal parameter combination was then obtained. Through analyzing the Grey relational grade matrix, the most influential factors for individual quality targets of burnishing process can be identified. Additionally, the analysis of variance (ANOVA) was also utilized to examine the most significant factors for the surface roughness and microhardness in burnishing process.

2 GREY RELATIONAL ANALYSIS

In Grey relational analysis, experimental data i.e., measured features of quality characteristics are first normalized ranging from zero to one. This process is known as Grey relational generation. Next, based on normalized experimental data, Grey relational coefficient

is calculated to represent the correlation between the desired and actual experimental data¹⁵. Then overall Grey relational grade is determined by averaging the Grey relational coefficient corresponding to selected responses. The overall performance characteristic of the multiple response process depends on the calculated Grey relational grade. This approach converts a multiple response process optimization problem into a single response optimization situation with the objective function which is the overall Grey relational grade. The optimal parametric combination is then evaluated which would result in the highest Grey relational grade. The optimal factor setting for maximizing overall Grey relational grade can be obtained by Taguchi method¹⁵.

In Grey relational generation, the normalized Ra values corresponding to the smaller-the-better (SB) criterion which can be expressed as:

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1)$$

HV₁₀₀ should follow the larger-the-better (LB) criterion, which can be expressed as:

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

where $x_i(k)$ is the value after the Grey relational generation, $\min y_i(k)$ is the smallest value of $y_i(k)$ for the k^{th} response, and $\max y_i(k)$ is the largest value of $y_i(k)$ for the k^{th} response¹⁵. An ideal sequence is $[x_0(k) (k=1, 2, 3, \dots, 16)]$ for the responses. The definition of Grey relational grade in the course of Grey relational analysis is to reveal the degree of relation between the 16 sequences $[x_0(k) \text{ and } x_i(k), i=1, 2, 3, \dots, 16]$. The Grey relational coefficient $\xi_i(k)$ can be calculated as:

$$\xi_i(k) = \frac{\Delta_{\min} - \psi \Delta_{\max}}{\Delta_{0i}(k) + \psi \Delta_{\max}} \quad (3)$$

where $\Delta_{0i} = \|x_0(k) - x_i(k)\|$ the absolute value of the difference of $x_0(k)$ and $x_i(k)$; ψ is the distinguishing coefficient $0 \leq \psi \leq 1$; $\Delta_{\min} = \forall j^{\min} \in i \forall k^{\min} \|x_0(k) - x_j(k)\|$ is the smallest value of Δ_{0i} ; and $\Delta_{\max} = \forall j^{\max} \in i \forall k^{\max} \|x_0(k) - x_j(k)\|$ is the largest value of Δ_{0i} . After averaging the Grey relational coefficients, the Grey relational grade γ_i can be computed as:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \quad (4)$$

where n is the number of process responses. The higher value of Grey relational grade corresponds to intense relational degree between the reference sequence $x_0(k)$ and the given sequence $x_i(k)$. The reference sequence $x_0(k)$ represents the best process sequence. Therefore, higher Grey relational grade means that the corresponding parameter combination is closer to the optimal¹⁵. The mean response for the Grey relational grade with its

grand mean and the main effect plot of Grey relational grade are very important because optimal process condition can be evaluated from this plot¹⁵.

3 EXPERIMENTAL DETAILS AND TEST RESULTS

3.1 Workpiece Material

In this study, high strength precipitation hardening 7XXX series wrought aluminum alloy AA 7075 was used. The strength and good mechanical properties make the AA 7075 aluminum alloy appropriate for the use in aerospace industry. The chemical composition and mechanical properties of the workpiece material is given in **Table 1**.

Table 1: Chemical composition and mechanical properties of AA7075 aluminum alloy

Tabela 1: Kemična sestava in mehanske lastnosti aluminijeve zlitine AA 7075

Chemical composition (%)	Al	Cu	Mg	Cr	Zn
	90.0	1.60	2.50	0.23	5.60
Mechanical properties	Tensile strength (MPa)	Yield strength (MPa)	Shear strength (MPa)	Fatigue strength (MPa)	Hardness (HV ₁₀₀)
	220	95	150	160	150

The workpiece material, as shown in **Figure 1**, was prepared with the diameter of 30 mm and 70 mm in length as a three part each having 20 mm length.

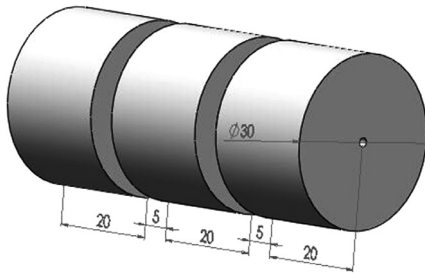


Figure 1: Dimensions of workpiece material²⁵

Slika 1: Mere preizkušanca

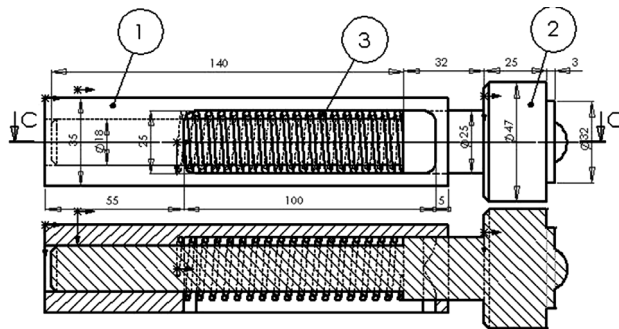


Figure 2: Detailed drawing of the ball burnishing tool: (1) casing; (2) adapter cover; (3) spring²⁵

Slika 2: Načrt gladilnega orodja: (1) ohišje; (2) prilagoditveni pokrov, (3) vzmet²⁵

3.2 Machines and Equipments

An 18 mm diameter ball was used for burnishing. The detailed drawing is shown in **Figure 2**. When the ball or roller is pressed against the surface of the metallic specimen, a pre-calibrated spring was compressed. This spring is being used mainly to reduce the possible sticking of the tool onto the surface²⁵.

The experiments were performed on a *FANUC GT-250B CNC* lathe. The burnishing tool was mounted on the CNC turret. Dry turning and burnishing were used in all the experimental work, but alcohol was used to clean the specimens before burnishing. Cleaning of the ball was carried out continuously in order to prevent hard particles from entering on the contact surface between the tool and the specimen, such hard particles usually leaving deep scratches, which may damage the burnished surface of the specimen²⁵.

Phynix TR-100 model surface roughness tester was used to measure the surface roughness of the burnished samples. Cut off length was chosen as 0.3 for each roughness measurement. Vickers microhardness tester with 100 g load (HV₁₀₀) was used for microhardness measurements²⁵. Six measurements of surface roughness and microhardness were taken from the samples and average of the values were used in the multi-criteria optimization.

3.3 Process Parameters and Test Results

In full factorial design, the number of experimental runs exponentially increases as the number of factors as well as their level increases. This requires huge experimentation cost and considerable time. So, in order to compromise these two adverse factors and to search the optimal process condition through a limited number of experimental runs Taguchi's L₁₆(4⁴) orthogonal array consisting of 16 sets of data was selected to optimize the multiple performance characteristics of surface roughness. The burnishing parameters used in this study are shown in **Table 2**.

Table 2: Process parameters and their limits

Tabela 2: Parametri in omejitve procesa

Parameters	Notation	Unit	Levels of factors			
			1	2	3	4
Burnishing force	F	N	58.86*	117.72	176.58	235.44
Number of passes	N	-	1*	2	3	4
Feed rate	f	mm/min	0.1*	0.2	0.3	0.4
Burnishing speed	V	rpm	200*	300	500	700

*Initial factor settings

Table 3 shows the selected design matrix based on Taguchi L₁₆(4⁴) orthogonal array consisting of 16 sets of coded conditions and the experimental results for the

responses of Ra and HV₁₀₀. All these data were utilized for the analysis and evaluation of optimal parameter combination required to achieve desired surface quality within the experimental domain.

Table 3: Orthogonal array L₁₆(4⁴) of the experimental runs and results
Tabela 3: Ortogonalna porazdelitev L₁₆(4⁴) preizkusov in rezultati

Run no	Process parameters				Experimental results	
	F	N	f	V	Ra (μm)	HV ₁₀₀
1	1	1	1	1	0.61	160
2	1	2	2	2	0.57	167
3	1	3	3	3	0.53	173
4	1	4	4	4	0.59	187
5	2	1	2	3	0.36	165
6	2	2	1	4	0.18	178
7	2	3	4	1	0.25	181
8	2	4	3	2	0.20	193
9	3	1	3	4	0.20	172
10	3	2	4	3	0.22	187
11	3	3	1	2	0.08	196
12	3	4	2	1	0.23	210
13	4	1	4	2	0.30	191
14	4	2	3	1	0.15	199
15	4	3	2	4	0.14	205
16	4	4	1	3	0.19	212

4 PARAMETRIC OPTIMIZATION OF BURNISHING PROCESS

4.1 Evaluation of Optimal Process Condition

First, by using Eqs. (1) and (2), experimental data were normalized to obtain Grey relational generation¹⁵. The normalized data and Δ_{0i} for each of the responses are given in **Table 4** and **Table 5** respectively. For Ra smaller-the-better (SB) and for HV larger-the-better (LB) criterion has been selected.

Table 4: Grey relational generation of each performance characteristics

Tabela 4: Generacija Greyjeve odvisnosti za karakteristike vsake performance

Run no	Ra	HV
	<i>Smaller-the-better</i>	<i>Larger-the-better</i>
Ideal sequence	1	1
1	0.000	0.000
2	0.043	0.075
3	0.250	0.151
4	0.519	0.038
5	0.096	0.472
6	0.346	0.811
7	0.404	0.679
8	0.635	0.774
9	0.231	0.774
10	0.519	0.736
11	0.692	1.000
12	0.365	0.717
13	0.596	0.585

14	0.750	0.868
15	0.865	0.887
16	1.000	0.792

Table 5: Evaluation of Δ_{0i} for each of the responses

Tabela 5: Ocena Δ_{0i} za vsak odgovor

Run no	Ra	HV
Ideal sequence	1	1
1	1.000	1.000
2	0.957	0.925
3	0.750	0.849
4	0.481	0.962
5	0.904	0.528
6	0.654	0.189
7	0.596	0.321
8	0.365	0.226
9	0.769	0.226
10	0.481	0.264
11	0.308	0.000
12	0.635	0.283
13	0.404	0.415
14	0.250	0.132
15	0.135	0.113
16	0.000	0.208

Table 6 shows the calculated Grey relational coefficients (with ψ_{Ra} = 0.67, ψ_{HV} = 0.33) of each performance characteristic using Eq. (3).

Table 6: Grey relational coefficient of each performance characteristics (ψ_{Ra} = 0.67, ψ_{HV} = 0.33)

Tabela 6: Greyjeve odvisnostni koeficient za karakteristike vsake performance (ψ_{Ra} = 0.67, ψ_{HV} = 0.33)

Run no	Ra	HV
Ideal sequence	1	1
1	0.333	0.333
2	0.343	0.351
3	0.400	0.371
4	0.510	0.342
5	0.356	0.486
6	0.433	0.726
7	0.456	0.609
8	0.578	0.688
9	0.394	0.688
10	0.510	0.654
11	0.619	1.000
12	0.441	0.639
13	0.553	0.546
14	0.667	0.791
15	0.788	0.815
16	1.000	0.707

The Grey relational coefficients, given in **Table 7**, for each response was accumulated by using Eq. (4) to evaluate Grey relational grade, which is the overall representative of all the features of burnishing quality. Thus, the multi-criteria optimization problem was transformed into a single equivalent objective function optimization problem using the combination of Taguchi

approach and Grey relational analyses. Higher is the value of Grey relational grade, the corresponding factor combination is said to be close to the optimal.

Table 7: Grey relational grade

Tabela 7: Greyjeva stopnja odvisnosti

Run no	Grey relational grade	Rank
1	0.333	16
2	0.348	15
3	0.380	14
4	0.397	13
5	0.443	12
6	0.629	6
7	0.558	10
8	0.651	5
9	0.591	8
10	0.606	7
11	0.874	1
12	0.573	9
13	0.548	11
14	0.750	4
15	0.806	2
16	0.803	3

When the Taguchi experimental design is carried out, a function would be offered (efficiency evaluation) about one design factor as the standard to evaluate the efficiency and to understand the experiment efficiency. While Taguchi experimental design took the quality loss as the base, it would design one statistic to evaluate efficiency, which is called the S/N ratio. In this section we had one quality characteristic that is grey relational grade for Taguchi analysis²⁶. **Table 8** shows the S/N ratio based on the larger-the-better criterion for overall Grey relational grade calculated by using Eq. (5).

$$S/N = -10 \lg \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \quad (5)$$

where n is the number of measurements, and y_i is the measured characteristic value.

Table 8: S/N ratio for overall Grey relational grade

Tabela 8: Razmerje S/N za splošno Greyjevo odvisnostno stopnjo

Run no	S/N
1	-9.54
2	-9.16
3	-8.40
4	-8.02
5	-7.07
6	-4.02
7	-5.06
8	-3.72
9	-4.57
10	-4.34
11	-1.17
12	-4.83
13	-5.21

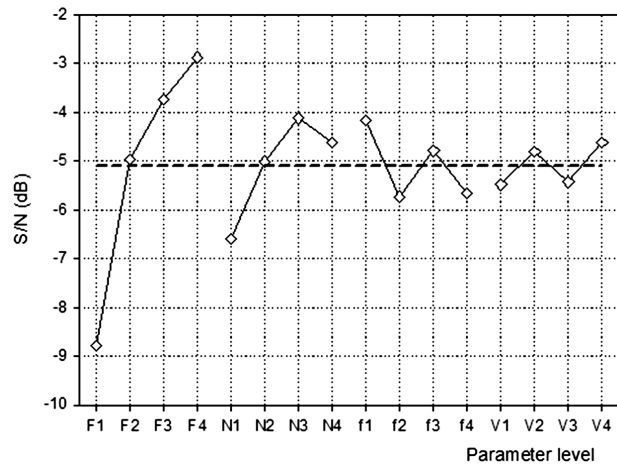


Figure 3: S/N ratio plot for the overall Grey relational grade

Slika 3: S/N razmerje za splošno Greyjevo stopnjo

14	-2.50
15	-1.87
16	-1.90

Graphical representation of S/N ratio for overall Grey relational grade is shown in **Figure 3**. The dashed line is the value of the total mean of the S/N ratio.

As indicated in **Figure 3**, the optimal condition for the burnishing of AA7075 aluminum alloy becomes $F_4N_3f_1V_4$. **Table 9** shows the mean Grey relational grade ratio for each level of the process parameters.

Table 9: Response table for the mean Grey relational grade

Tabela 9: Tabela odgovorov za povprečno Greyjevo odvisnostno stopnjo

Factors	Grey relational grade				
	Level 1	Level 2	Level 3	Level 4	Max-Min
F	0.36	0.57	0.66	0.73	0.37
N	0.48	0.58	0.65	0.61	0.17
f	0.66	0.54	0.59	0.53	0.13
V	0.55	0.61	0.56	0.61	0.06

Total mean Grey relational grade= 0.58

4.2 Analysis of Variance (ANOVA)

The purpose of the analysis of variance (ANOVA) is to investigate which burnishing parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each burnishing parameters and the error. Thus;

$$SS_T = SS_F + SS_e \quad (6)$$

where

$$SS_T = \sum_{j=1}^p (\gamma_j - \gamma_m)^2 \quad (7)$$

and

- SS_T Total sum of squared deviations about the mean
- γ_j Mean response for j^{th} experiment
- γ_m Grand mean of the response
- p Number of experiments in the orthogonal array
- SS_F Sum of squared deviations due to each factor
- SS_e Sum of squared deviations due to error

In addition, the F test was used to determine which burnishing parameters have a significant effect on the performance characteristic. Usually, the change of the burnishing parameter has a significant effect on the performance characteristics when the F value is large. ANOVA for overall Grey relational grade is shown in **Table 10**.

Table 10: ANOVA results

Tabela 10: ANOVA rezultati

Parameter	Degree of Freedom	Sum of Square	Mean Square	F	Contribution (%)
F	3	0.300	0.100	19.00	71.59
N	3	0.066	0.022	4.20	15.75
f	3	0.043	0.014	2.72	10.26
V	3	0.009	0.003	0.63	2.14
Error	3	0.001	0.005		0.23
Total	15	0.419			100

According to this analysis, the most effective parameters with respect to surface roughness and microhardness are burnishing force, number of passes, burnishing feed and burnishing speed. Percent contribution indicates the relative power of a factor to reduce variation. For a factor with a high percent contribution, has a great influence on the performance. The percent contributions of the burnishing parameters on the surface roughness and microhardness are shown in **Table 10** and **Figure 4**. Burnishing force (71.59%) was found to be the major factor affecting surface roughness and microhardness, whereas number of passes (15.75%), burnishing feed (10.26%) and burnishing speed (2.14%) were found to be the second, third and fourth ranking factor respectively.

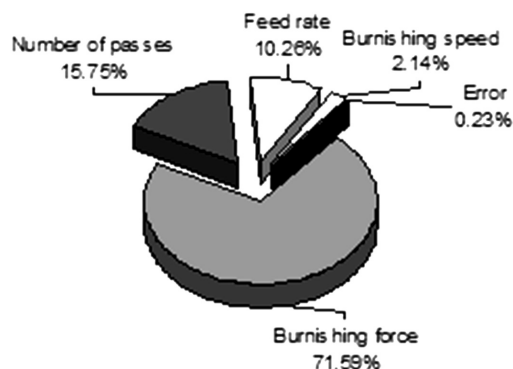


Figure 4: Contribution percentage of the burnishing parameters
Slika 4: Odstotna porazdelitev parametrov glajenja

4.3 Confirmation Test

After evaluating the optimal parameter settings, the next step is to predict and verify the enhancement of quality characteristics using the optimal parametric combination. The estimated Grey relational grade $\hat{\gamma}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^o (\bar{\gamma}_i - \gamma_m) \quad (8)$$

where γ_m is the total mean Grey relational grade, $\bar{\gamma}_i$ is the mean Grey relational grade at the optimal level, and o is the number of the main design parameters that affect the quality characteristics. **Table 11** indicates the comparison of the predicted surface roughness and microhardness with that of actual by using the optimal burnishing conditions; good agreement between the actual and predicted results was obtained. Also, improvement in overall Grey relational grade was found to be as 0.65.

Table 11: Results of confirmation test

Tabela 11: Rezultati potrditvenih preizkusov

Factor levels	Initial factor settings	Optimal process condition	
		Prediction	Experiment
	$F_1N_1f_1V_1$	$F_4N_3f_1V_4$	$F_4N_3f_1V_4$
Ra	0.61		0.12
HV ₁₀₀	160		200
S/N ratio of overall Grey relational grade	-9.54	-0.51	-0.80
Overall Grey relational grade	0.33	0.91	0.98

Improvement in Grey relational grade=0.65

In Taguchi method, the only performance feature is the overall Grey relational grade and the aim should be to search a parameter setting that can achieve highest overall Grey relational grade. The Grey relational grade is the representative of all individual performance characteristics. In this study, objective functions have been selected in relation to parameters of surface roughness and microhardness. The weight calculations were done by using Analytic Hierarchy Process (AHP) and the weights were found to be as 0.67 and 0.33 for the responses of surface roughness and microhardness respectively. The results showed that using optimal parameter setting ($F_4N_3f_1V_4$) caused lower microhardness together with higher surface roughness.

5 CONCLUSIONS

Taguchi method is a very effective tool for process optimization under limited number of experimental runs. Essential requirements for all types burnishing processes are smoother surface with higher surface hardness. This study has concentrated on the application of Taguchi method coupled with Grey relation analysis for solving

multi criteria optimization problem in the field of burnishing process. Experimental results have shown that surface roughness and microhardness of burnished aluminum alloy are greatly improved by using Grey based Taguchi method.

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