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# OPTIMIZATION OF THE PROCESS PARAMETERS FOR DRY-SLIDING WEAR OF AN Al 2219-$SiC_p$ COMPOSITE USING THE TAGUCHI-BASED GREY RELATIONAL ANALYSIS

# OPTIMIRANJE PROCESNIH PARAMETROV PRI SUHI OBRABI Z DRSENJEM KOMPOZITA Al 2219-$SiC_p$ S TAGUCHIJEVO SIVO RELACIJSKO ANALIZO

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This article focuses on an approach based on the Taguchi method with grey relational analysis for optimizing the process parameters for the dry-sliding wear of Al 2219-SiC particulate composites with multi-performance characteristics. The grey relational grade obtained with the grey relational analysis is used to optimize the process parameters. The optimum process parameters can then be determined with the Taguchi method using the grey relational grade as the performance index. The composite was fabricated via a powder-metallurgy route with the mass fractions of (10, 15 and 20) % and precipitated at (500, 550 and 600) °C. The dry-sliding-wear test was conducted on a pin-on-disc wear-testing machine for the normal loads of (10, 20 and 30) N and at disc speeds of (400, 500 and 600) r/min. The performance indicators of the wear test were the wear rate, the coefficient of friction, the friction force and the temperature rise of the pin. Further, optimization of the process parameters was performed using the Taguchi-based grey relational analysis followed by ANOVA to determine the percentage contributions of the process parameters to the wear performance of the composites. An $L_9$ orthogonal array was used for the optimization study. The influences of individual process parameters on the wear performances of the composites are analyzed and presented in this study.

Keywords: optimization, grey relational analysis, wear rate, temperature rise of the pin

Članek obravnava približek, ki temelji na Taguchijevi metodi sive relacijske analize za optimiranje procesnih parametrov pri obrabi s suhim drsenjem zrnatega kompozita Al 2219-SiC z več zmogljivostmi. Za optimiranje procesnih parametrov so bile uporabljene sive relacijske stopnje, dobljene iz sive relacijske analize. Optimalne procesne parametre je mogoče določiti s Taguchijevo metodo z uporabo sive relacijske stopnje kot indeksom zmogljivosti. Kompozit je bil izdelan po postopku prašne metalurgije z masnim deležem (10, 15 in 20) % in izločenem pri (500, 550 in 600) °C. Preizkus obrabe pri suhem drsenju je bil izvršen na napravi "pin on disc" za preizkušanje obrabe pri obremenitvah (10, 20 in 30) N in hitrosti vrtenja plošče s (400, 500 in 600) r/min. Indikatorji zmogljivosti pri preizkusu obrabe so: hitrost obrabe, koeficient trenja, sila trenja in naraščanje temperature preizkušanca. Nadaljnja optimizacija parametrov procesa je bila izvršena s Taguchijevo sivo relacijsko analizo, ki ji je sledila ANOVA za določanje deleža parametrov procesa na vedenje kompozita pri obrabi. Ortogonalna namestitev $L_9$ je bila vzeta za študij optimiranja. V tej študiji je predstavljen vpliv posameznih parametrov procesa na vedenje obrabe kompozita.

Ključne besede: optimiranje, siva relacijska analiza, hitrost obrabe, narastek temperature preizkušanca

## 1 INTRODUCTION

Particulate-reinforced aluminium metal-matrix composites are increasingly used in many areas. They are found in the automobile, mining, mineral, aerospace and other applications owing to their very good properties such as high specific stiffness, high specific modulus, low density, good corrosion resistance, wear resistance, etc.[1] Discontinuously reinforced aluminium metal-matrix composites (MMCs) have isotropic properties offering a higher specific stiffness than aerospace metal alloys.[2] Most of the aluminium MMCs have reinforcements such as SiC, alumina, fine graphite, etc.[3–5] An extensive research was done, both experimentally and analytically, on these materials to better understand their mechanical behavior and wear resistance. The presence of hard reinforced particulates has given these composites superior tribological characteristics.[6] The wear resistance, along with a good specific resistance, makes the composites suitable for the applications where a sliding contact is expected. As the wear resistance is a property of primary importance to assess the performance of such components, the tribological behavior of aluminium-alloy-based composites has received strong interest, and work on the sliding and abrasive wears of these materials was comprehensively reviewed by Deuis et al.[7,8] The effects of different parameters such as load, volume fraction, size of reinforcement, sliding distance and velocity on the dry-sliding wear of $SiC_p$-reinforced aluminium alloys have been studied. The sliding speed and load affect the wear mechanism and its rate. As the load and sliding speed increase, the wear rate increases,[9,10] and at high sliding speeds the composites with a higher reinforcement amount show a higher wear resistance.[11] During the wear experiments, the values of the wear rate may reach the minimum for the optimum values of the input variables. The goal of the optimization is to determine the optimum input values for obtaining the minimum or maximum values of the output variable. A successful optimization requires a cause-and-effect relationship (an input-output relationship) between the predictors and the response variables. In the literature several techniques like the Taguchi's approximation, artificial neural networks, genetic algorithms, etc., are described to construct a cause-effect relationship between the variables of a process to optimize the predictor variables. The Taguchi's approximation aims to determine the optimum choice of the levels of the controllable factors in a process of manufacturing a product. The principle of choosing the levels focuses, to a great extent, on the variability around the pre-chosen target for the process response.[12–14]

## 2 EXPERIMENTATION

The step-by-step procedure of the grey relational analysis is shown in **Figure 1**. **Table 1** shows the chemical composition of the Al 2219 alloy. The control factors considered and their levels are presented in **Table 2**. For conducting the experiments, an $L_9$ orthogonal array was chosen. Orthogonal arrays are a simplified method of putting together an experiment. It simplifies the number of experiments to be conducted. The $L_9$ orthogonal array was chosen from the standard array-selector table

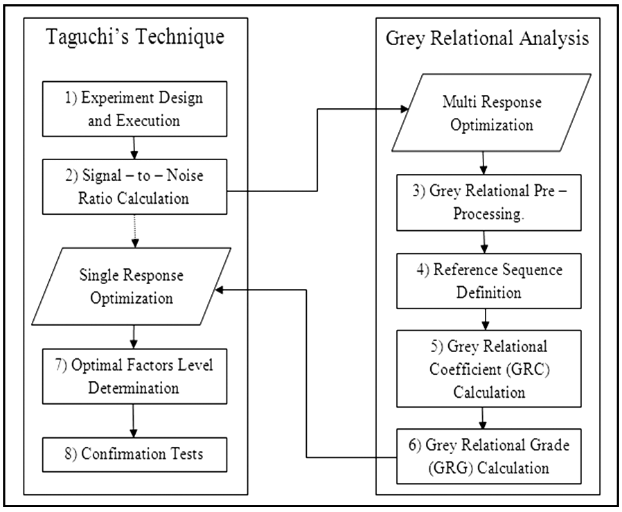


**Figure 1:** Step-by-step procedure of a grey relational analysis
**Slika 1:** Koraki postopka sive relacijske analize

**Table 1:** Chemical composition of the Al 2219 alloy in mass fractions, *w*/%
**Tabela 1:** Kemijska sestava zlitina Al 2219 v masnih deležih, *w*/%

| Alloy composition | Si | Cu | Mn | Zn | Ti | Mg | V | Zr | Al |
|---|---|---|---|---|---|---|---|---|---|
| | 0.20 | 6.00 | 0.30 | 0.10 | 0.10 | 0.02 | 0.05 | 0.10 | balance |

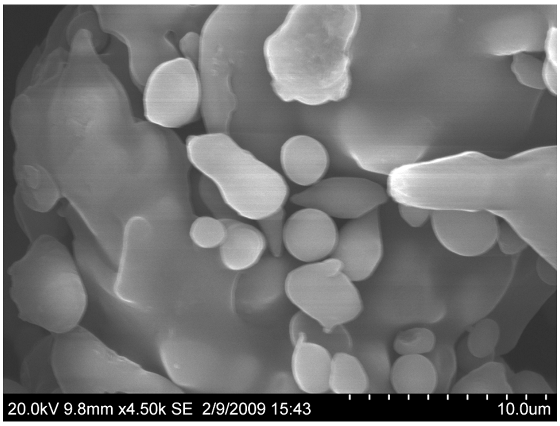


**Figure 2:** SEM micrograph of an unreinforced aluminium alloy
**Slika 2:** SEM-posnetek zrn aluminijeve zlitine brez dodatkov

based on the number of factors, their levels and degrees of freedom. The responses and *S*/*N* ratios are presented in **Tables 3** and **4**. The materials used for the experimentation were the Al 2219 alloy and SiC particulates (with the average particle size of 23 μm) of different mass fractions such as (10, 15 and 20) %. The workpieces were fabricated via a powder-metallurgy technique and the precipitation hardening of all the workpieces was carried out at different temperatures such as (500, 550 and 600) °C. A SEM (scanning electron microscope) image of Al 2219 is shown in **Figure 2**. The wear performance of the aluminum-matrix composites were studied by conducting a wear test using a pin-on-disc wear tester (Ducom, Bengaluru) under dry running conditions shown in **Figure 3**. The responses studied for evaluating the wear behavior of the composites were the wear rate, coefficient of friction, friction force and temperature rise of the pin. The process parameters during the wear test were optimized using the grey relational analysis. The grey relational analysis can effectively manage discrete data sets, uncertainty and multi-response characteristics.[9] The grey relational analysis is a method for measuring the absolute value of a data difference between sequences and it can be used to measure the approximate correla-

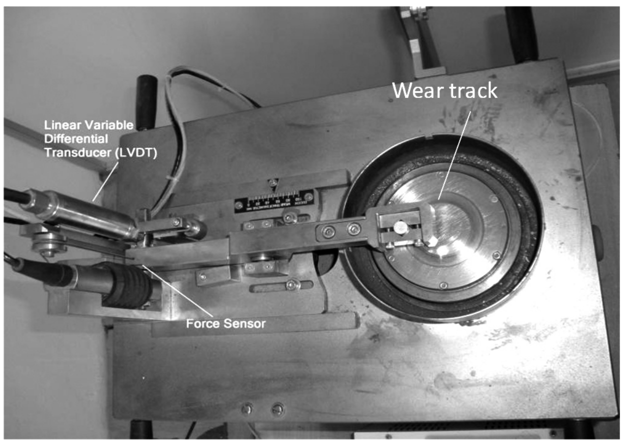


**Figure 3:** Photograph of a pin-on-disc wear-test set up
**Slika 3:** Posnetek naprave "pin-on-disc" za preizkus obrabe

tion between sequences.[10] In a grey relational analysis, the experimental observations of the wear rate, coefficient of friction, friction force and temperature rise of the pin are first normalized to be in the range of zero to one. This is called the data pre-processing[10] shown in **Table 5**. It is required because the range and the unit of observation differ from the other indicators. The grey relational coefficient is the measure of relevance between two systems or sequences. The calculated grey relational coefficients for different wear-test conditions are presented in **Table 6**. The grey relational grade is also calculated by taking the average value of the grey relational coefficients and it is presented in **Table 6**.

The signal-to-noise (*S/N*) ratios for the responses are calculated using the following equations:[15]

Nominal the better,

$$S/N \text{ ratio} = 10\lg_{10}\left(\frac{y^2}{s^2} - \frac{1}{n}\right) \tag{1}$$

Smaller the better,

$$S/N \text{ ratio} = -10\lg\frac{1}{\mathrm{n}}\sum_{i=1}^{n} y_i^2 \tag{2}$$

Higher the better,

$$S/N \text{ ratio} = -10\lg\frac{1}{\mathrm{n}}\sum_{i=1}^{n}\frac{1}{y_i^2} \tag{3}$$

where $n$ = the number of trials, $y_i$ = the signal factor or performance characteristic and $s^2$ = the noise factor. Noise factors are the factors that are impossible or too expensive to control during an experiment. The smaller-the-better criterion was used for the parameters of the wear rate and the temperature rise of the pin and the higher-the-better criterion was used for the parameters of the coefficient of friction and the friction force. The normalization process in the grey relational analysis was done using the following equations:[16]

Nominal the better,

$$Y(k) = \frac{\left|x_i^0(k) - x^0\right|}{\max x_i^0(k) - x_i^0(k)} \tag{4}$$

Smaller the better,

$$Y(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{5}$$

Higher the better,

$$Y(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{6}$$

where $Y(k)$ = the normalized value for the $k^{\text{th}}$ trial, $x_i^0\,(k)$ = the value of the output parameter for the $k^{\text{th}}$ trial, min $x_i^0\,(k)$ = the smallest value of the output parameter $x$ for the $k^{\text{th}}$ trial and max $x_i^0\,(k)$ = the largest value of the output parameter $x$ for the $k^{\text{th}}$ trial. The grey relational coefficient (*GRC*) for any output parameter can be calculated using the following formula:

$$\delta j = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{oi} + \zeta\Delta_{\max}} \tag{7}$$

where $\delta j$ = the *GRC* for the $j^{\text{th}}$ output parameter,
$\Delta_{oi} = \left|x_i^*(k) - x_i^0(k)\right|$ = the deviation sequence,
$x_0^*\,(k)$ = the reference sequence,
$\Delta_{\min} = \min\left|x_i^*(k) - x_i^0(k)\right|$
$\Delta_{\max} = \max\left|x_i^*(k) - x_i^0(k)\right|$ and
$\zeta$ = the mass coefficient. The grey relational grade (*GRG*) is calculated using the following equation:[17]

$$GRG = \frac{1}{\mathrm{n}}\sum_{i=1}^{n}\delta j \tag{8}$$

where $n$ = the number of output parameters.

**Table 2:** Control factors and their levels
**Tabela 2:** Kontrolni faktorji in njihovi nivoji

| S. No. | Control factor | Coding | Level |
|---|---|---|---|
| 1 | Mass fraction, % | A | 10, 15 & 20 |
| 2 | Precipitation temperature, °C | B | 500, 550 & 600 |
| 3 | Normal load, N | C | 10, 20 & 30 |
| 4 | Speed of disc, r/min | D | 400, 500 & 600 |

**Table 3:** $L_9$ orthogonal array and the values of responses
**Tabela 3:** Ortogonalna namestitev $L_9$ in vrednosti odzivov

| A | B | C | D | Wear rate (μm/s) | Coefficient of friction | Friction load (N) | Temperature rise of pin (°C) |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 0.0741 | 0.449 | 2.339 | 4.6 |
| 1 | 2 | 2 | 2 | 0.1489 | 0.4512 | 8.55 | 10.2 |
| 1 | 3 | 3 | 3 | 0.1243 | 0.3292 | 10.746 | 13.4 |
| 2 | 1 | 2 | 3 | 0.1708 | 0.5452 | 9.775 | 14.2 |
| 2 | 2 | 3 | 1 | 0.1833 | 0.486 | 18.62 | 13 |
| 2 | 3 | 1 | 2 | 0.1027 | 0.5699 | 6.545 | 7.8 |
| 3 | 1 | 3 | 2 | 0.173 | 0.5727 | 15.312 | 16.6 |
| 3 | 2 | 1 | 3 | 0.0812 | 0.6435 | 6.405 | 12.2 |
| 3 | 3 | 2 | 1 | 0.1864 | 0.5412 | 10.292 | 12.4 |

**Table 4:** *S/N* ratio of responses
**Tabela 4:** Razmerje odzivov *S/N*

| A | B | C | D | Wear rate | Coefficient of friction | Friction force | Temperature rise of pin |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 22.60364 | –6.95507 | 7.380604 | –13.2552 |
| 1 | 2 | 2 | 2 | 16.54211 | –6.91262 | 18.63932 | –20.172 |
| 1 | 3 | 3 | 3 | 18.11058 | –9.6508 | 20.62494 | –22.5421 |
| 2 | 1 | 2 | 3 | 15.35024 | –5.26888 | 19.80234 | –23.0458 |
| 2 | 2 | 3 | 1 | 14.73675 | –6.26727 | 25.39959 | –22.2789 |
| 2 | 3 | 1 | 2 | 19.76859 | –4.88403 | 16.31819 | –17.8419 |
| 3 | 1 | 3 | 2 | 15.23908 | –4.84146 | 23.70064 | –24.4022 |
| 3 | 2 | 1 | 3 | 21.80888 | –3.82903 | 16.13038 | –21.7272 |
| 3 | 3 | 2 | 1 | 14.59108 | –5.33284 | 20.25 | –21.8684 |

**Table 5:** Normalized values and deviation sequences of responses
**Tabela 5:** Normalizirane vrednosti in deviacijske sekvence odzivov

| Exp. number | Normalized values of responses | | | | Deviation sequences | | | |
|---|---|---|---|---|---|---|---|---|
| | Wear rate (μm/s) | Coefficient of friction | Friction load (N) | Temperature rise of pin (°C) | Wear rate (μm/s) | Coefficient of friction | Friction load (N) | Temperature rise of pin (°C) |
| 1 | 1.0000 | 0.3812 | 0.0000 | 1.0000 | 0.0000 | 0.6188 | 1.0000 | 0.0000 |
| 2 | 0.3339 | 0.3882 | 0.3815 | 0.5333 | 0.6661 | 0.6118 | 0.6185 | 0.4667 |
| 3 | 0.5530 | 0.0000 | 0.5164 | 0.2667 | 0.4470 | 1.0000 | 0.4836 | 0.7333 |
| 4 | 0.1389 | 0.6872 | 0.4567 | 0.2000 | 0.8611 | 0.3128 | 0.5433 | 0.8000 |
| 5 | 0.0276 | 0.4989 | 1.0000 | 0.3000 | 0.9724 | 0.5011 | 0.0000 | 0.7000 |
| 6 | 0.7453 | 0.7658 | 0.2583 | 0.7333 | 0.2547 | 0.2342 | 0.7417 | 0.2667 |
| 7 | 0.1193 | 0.7747 | 0.7968 | 0.0000 | 0.8807 | 0.2253 | 0.2032 | 1.0000 |
| 8 | 0.9368 | 1.0000 | 0.2497 | 0.3667 | 0.0632 | 0.0000 | 0.7503 | 0.6333 |
| 9 | 0.0000 | 0.6745 | 0.4885 | 0.3500 | 1.0000 | 0.3255 | 0.5115 | 0.6500 |

**Table 6:** Grey relational coefficient and grey relational grade
**Tabela 6:** Sivi relacijski koeficient in siva relacijska stopnja

| Experiment number | Grey relational coefficient | | | | Grey relational grade |
|---|---|---|---|---|---|
| | Wear rate (μm/s) | Coefficient of friction | Friction load (N) | Temperature rise of pin (°C) | |
| 1 | 1.0000 | 0.4469 | 0.3333 | 1.0000 | **0.6951** |
| 2 | 0.4288 | 0.4497 | 0.4470 | 0.5172 | 0.4607 |
| 3 | 0.5280 | 0.3333 | 0.5083 | 0.4054 | 0.4438 |
| 4 | 0.3674 | 0.6152 | 0.4793 | 0.3846 | 0.4616 |
| 5 | 0.3396 | 0.4994 | 1.0000 | 0.4167 | 0.5639 |
| 6 | 0.6625 | 0.6810 | 0.4027 | 0.6522 | 0.5996 |
| 7 | 0.3621 | 0.6894 | 0.7111 | 0.3333 | 0.5240 |

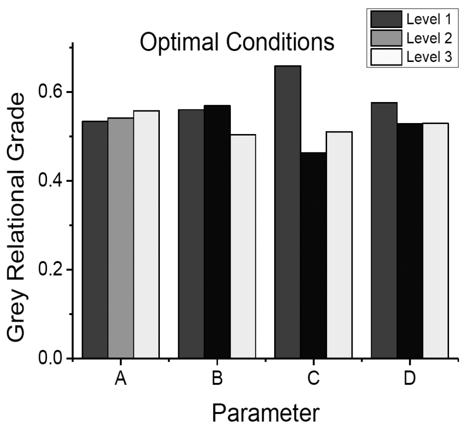


**Figure 4:** Grey relational grades for optimal conditions
**Slika 4:** Sive relacijske stopnje pri optimalnih razmerah

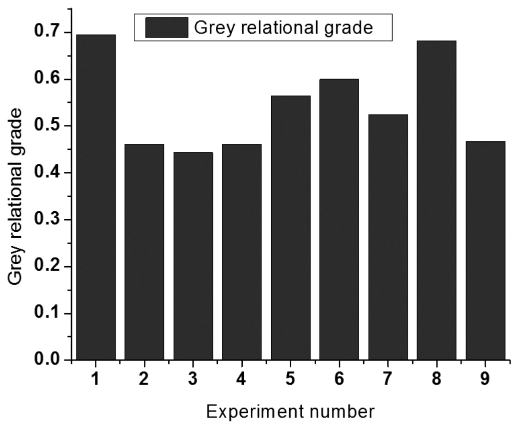


**Figure 5:** Grey relational grade versus experiment number
**Slika 5:** Siva relacijska stopnja proti številki preizkusa

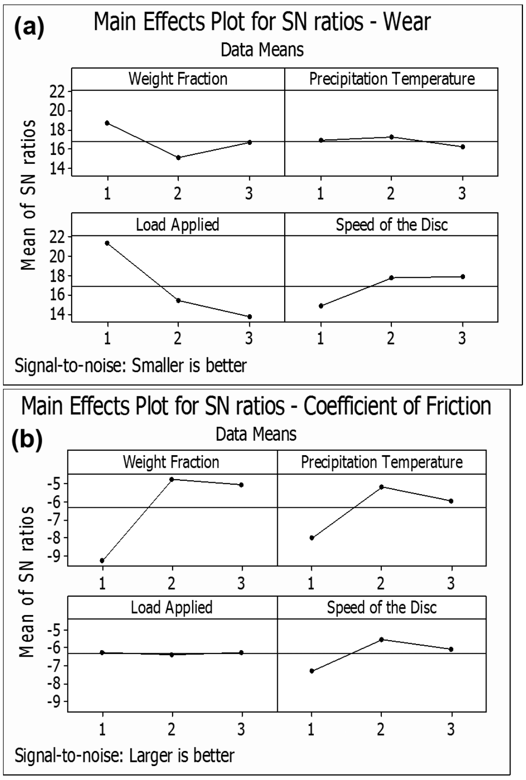


**Figure 6:** Main effects plot for *S/N*: a) wear, b) coeffition of friction
**Slika 6:** Glavni učinki razmerja *S/N* na: a) hitrost obrabe in b) koeficient trenja

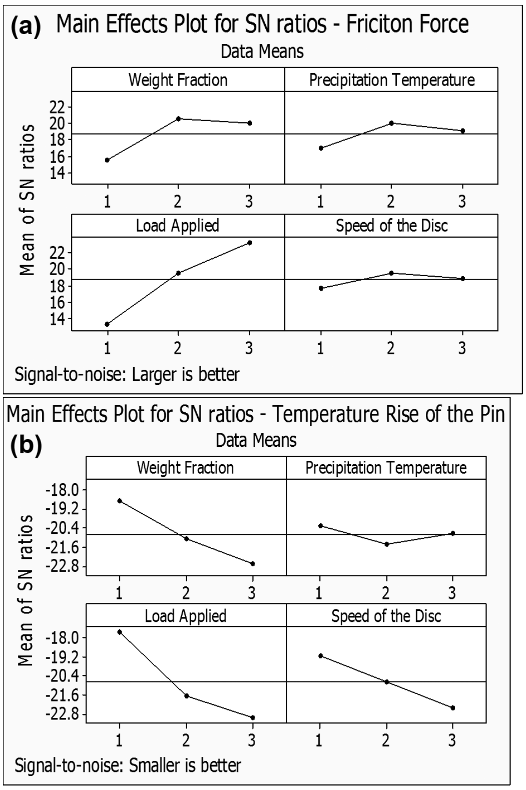


**Figure 7:** Main effects plot for *S/N* ratios of: a) friction force and b) temperature rise of pin
**Slika 7:** Glavni učinki razmerja *S/N* na: a) silo trenja in b) dvig temperature vzorca

**Table 7:** Optimum conditions of control factors
**Tabela 7:** Optimalne razmere kontrolnih faktorjev

| Factor | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Mass fraction | 0.5332 | 0.5417 | **0.5577** |
| Precipitation temperature | 0.5602 | **0.5689** | 0.5035 |
| Load | **0.6590** | 0.4631 | 0.5106 |
| Speed | **0.5753** | 0.5281 | 0.5292 |
| Average value = **0.5442** | | | |

**Table 8:** ANOVA for control factors
**Tabela 8:** ANOVA za kontrolne faktorje

| Testing parameter | Degrees of Freedom | Sum of squares | Mean sum of squares | Percentage contribution |
|---|---|---|---|---|
| Mass fraction, % | 2 | 0.0010 | 0.0005 | 0.0144 |
| Precipitation temperature, °C | 2 | 0.0149 | 0.0074 | 0.2197 |
| Load, N | 2 | 0.0485 | 0.0242 | 0.7160 |
| Disc speed, r/min | 2 | 0.0034 | 0.0017 | 0.0499 |
| Error | 72 | 0.0000 | 0.0000 | 0.0000 |
| Total | 80 | 0.0677 | | |

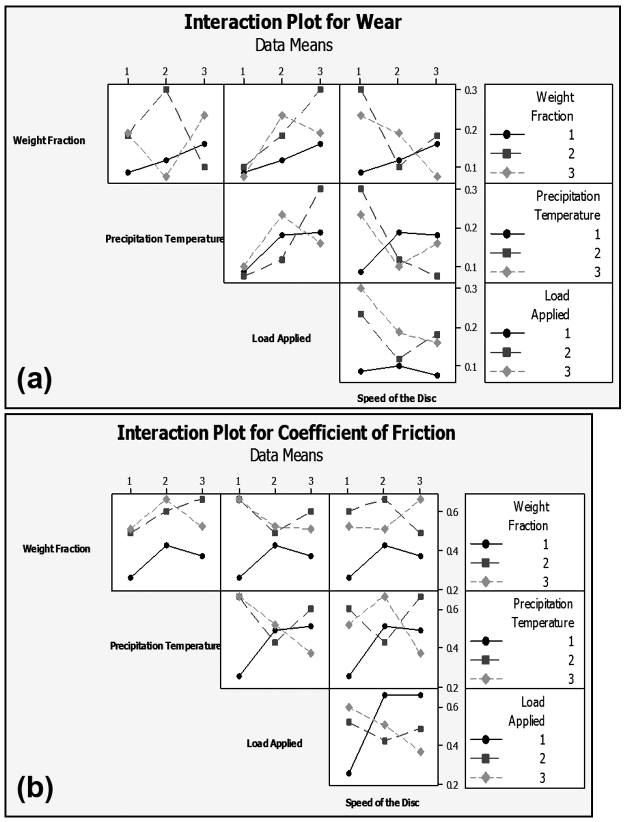


**Figure 8:** Interaction plot for data means of: a) wear rate and b) coefficient of friction
**Slika 8:** Prikaz interakcije glavnih podatkov na: a) hitrost obrabe in b) koeficient trenja

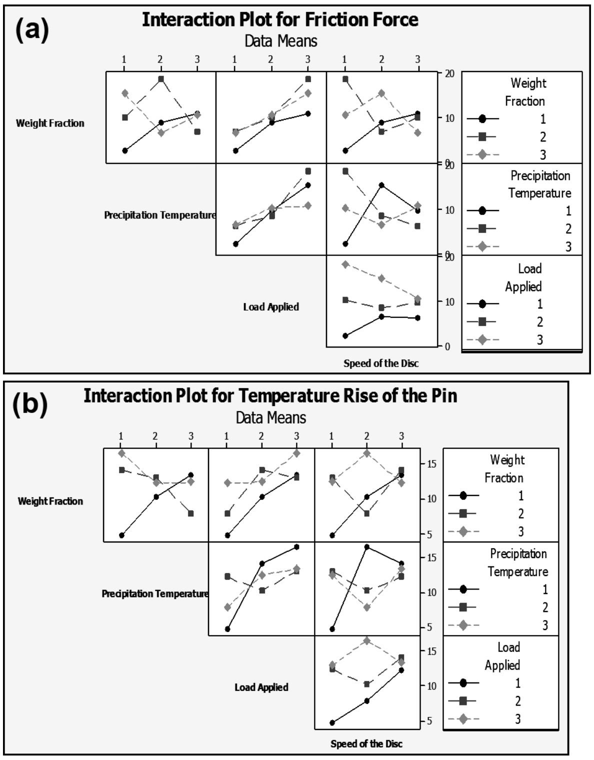


**Figure 9:** Interaction plot for data means of: a) friction force and b) temperature rise of pin

**Slika 9:** Prikaz interakcije glavnih podatkov na: a) silo trenja in b) dvig temperature vzorca

## 3 RESULTS AND DISCUSSIONS

Typically, a low wear rate, high coefficient of friction and friction force and a low temperature rise of the pin are desirable for a good wear-resistant material. According to the grey relational analysis, the experiment exhibiting the highest grey relational grade has the optimum experimental conditions.[16] From **Table 6**, it is clear that experiment number 1 (A1B1C1D1) had the most optimum condition with regard to the orthogonal array. From **Table 7**, we find that the optimum conditions, with regard to the entire experiment, were provided in the case of A3B2C1D1, i.e., the samples with 20 % mass fraction, precipitated at 550 °C, run at an applied load of 10 N and a speed of 400 r/min satisfy the given optimization conditions. The optimum conditions are also illustrated in **Figure 4**. The grey relational grades for the nine experiments are illustrated in **Figure 5**. The purpose of using ANOVA is to find which process parameter significantly affects the wear performance of the composites. ANOVA for the *GRG* is shown in **Table 8**. It has been observed that the normal load acting on the pin significantly influences the wear performance, followed by the precipitation temperature. The mass fraction of the reinforcement and the disc speed are less significant. This may be attributed to the fact that a finer particle size (600 mesh or 23 μm) of the reinforcement eliminates the effect of the mass fraction on the wear characteristics. Usually, fine-particle reinforcement has a good bonding strength with the matrix with all mass fractions, but it may lose it when the precipitation temperature is changed. This is in agreement with the results shown in ANOVA. The main effect plots of the output parameters such as wear, coefficient of friction, friction force and temperature rise of pin are illustrated in **Figures 6a, 6b 7a** and **7b**. The optimum conditions are also easily determined from these figures. The interaction plots for the output parameters are shown in **Figures 8a, 8b**, **9a** and **9b**. All these plots agree with the above arguments.

## 4 CONCLUSIONS

A grey relational analysis was used for optimizing the process parameters during a dry-sliding wear test of aluminium MMCs. The recommended levels of the process parameters for a better wear performance of the composites are the mass fraction of 20 %, the precipitation temperature of 550 °C, the applied load of 10 N and the speed of the disc of 400 r/min. Of the four process parameters considered during the study, only two factors, the normal load acting on the pin and the precipitation temperature, significantly influence the wear performance, much more than the mass fraction of the reinforcement and the disc speed. This is due to the particle size of the reinforcement (23 μm). A finer particle size leads to a good bonding with the matrix for all mass fractions and, therefore, the performance is the least influenced by the mass fraction. The grey relational analysis was more convenient for optimizing the process parameters as it simplifies the optimization procedure.

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