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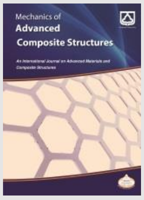

# Optimization of Wear Behaviour on Mg-$TiO_2$ Nanocomposite Using Taguchi Grey Relational Analysis

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**KEYWORDS**

Optimization;
Process parameters;
Wear;
ANOVA;
Grey relational grade.

**ABSTRACT**

In this research, the dry sliding wear behaviour of the Mg-$TiO_2$ nanocomposite is analyzed by conducting a wear test using a pin-on-disc wear testing machine under normal atmospheric conditions. The process parameters considered during the test are the weight fraction of $TiO_2$ nanoparticles, normal load, and sliding speed. The sliding distance and wear track diameter are maintained constant at 1500 m and 90 mm respectively during the test. The performance measures are cumulative wear and coefficient of friction. Taguchi-based Grey relational analysis is employed in this study to optimize the performance of the wear behaviour of the nanocomposite. The design of experiments considered in this study is L9 orthogonal array with each process parameter for three levels. Grey relational grade (GRG) is computed for each experiment and it was found that the maximum GRG of 0.825 is obtained for the process parameter combination A3B2C1 which corresponds to 5wt% $TiO_2$, 1 kg normal load and 1.5 m/s sliding speed respectively. The initial GRG estimated is compared with the predicted and experimental values for the optimum process parameters and it was found that there is an improvement in GRG by 2.2% and 0.77% respectively. ANOVA (Analysis of variance) is carried out to estimate the process parameter that influences the wear behaviour of the nanocomposite significantly and later concluded that the process parameter normal load is the most significant factor other than any other factors.

## 1. Introduction

Pure magnesium and magnesium-based metal matrix composites are emerging as a new class of engineering materials with applications in aerospace, automobiles, structural engineering, and biomedical. Magnesium alloys and composites have recently attracted much interest due to their specific characteristics, such as low density and high specific strength despite having low creep resistance, wear resistance, and modulus. [1] The reason for this is that adding appropriate reinforcements in the right form can considerably improve the material's above-mentioned qualities. For example, adding particle reinforcements such as Titanium oxide ($TiO_2$), Titanium carbide (TiC), Silicon carbide (SiC), Aluminum oxide ($Al_2O_3$), and others to pure Mg or Mg alloys may greatly improve the material's mechanical behaviour. [2-4] Due to magnesium's affinity for oxygen, the processing and manufacture of magnesium-based composites are thought to be more difficult. As a result, the initial cost of producing magnesium-based composites was raised. In order to solve this challenge, the powder-based fabrication method is preferred, which has become increasingly popular in recent years, as they are easier to fabricate and more cost-effective. When opposed to liquid-state processing processes, powder metallurgy has fewer oxidation and flammability concerns. Though magnesium-based composites have a number of drawbacks, low wear resistance has received increasing attention as a result of magnesium's use in vehicle and biomedical applications. [5] The wear behaviour of the material has a greater impact on performance in these applications than any other mechanical

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properties. Wear resistance can be greatly enhanced by combining strong ceramic reinforcements such as Titanium oxide ($TiO_2$), Titanium carbide (TiC), Silicon carbide (SiC), Aluminium oxide ($Al_2O_3$), and others with pure magnesium or magnesium alloys. [4-7] With these materials obtained for investigation, several researchers and scientists have put in a tremendous lot of effort. These studies have produced a number of scientific hypotheses, concepts, and empirical models related to the wear behaviour of magnesium composites. A few of the most well-known works of literature on magnesium wear studies, process parameter optimization using various optimization techniques, including Grey Relational Analysis (GRA), are reviewed in-depth for a better understanding of the scope and importance of reinforcement and processing conditions, and their impact on the material's wear performance. [8-11].

## 2. Experimentation

In the study, commercially available 99.9% pure Mg with an average particle size of 150 microns and hard ceramic reinforcement, $TiO_2$ nanoparticulate with an average particle size of a hydraulic press. In a microwave furnace, the green compacts are heat-treated using a two-stage hybrid sintering process. Finally, the heat-treated specimens are extruded and machined to the desired dimensions and good surface finish. Wear experiments on a pin-on-disc wear testing machine (provided by Ducom Instruments Pvt. Ltd., Bengaluru, India) were conducted to investigate the wear behaviour of Mg-$TiO_2$ nanocomposite in accordance with ASTM standard G99-055. The wear tests were conducted at room temperature in a dry running atmosphere. The wear test specimens have a diameter of 8 mm and a length of 30 mm. The wear testing machine used these specimens as pins, while the counter disc was a standard material oil-hardened non-shrinking die steel (OHNS) with a diameter of 160 mm and a thickness of 8 mm, and a hardness of 57-60 HRC. 21 nm was used. Powder metallurgy was used to create the necessary workpiece specimens. The steps in this procedure are as follows: Using a planetary-type ball mill, the pure Mg and tiny $TiO_2$ particles are first thoroughly mixed. For blending purposes, a mechanical alloying approach was used in a ball mill with a rotating speed of around 300 rpm. The mixed powders are then loaded into the die and compressed iso-statically with a 950 MPa iso-static pressure using a 100-ton The weight percent of reinforcement, sliding speed, and the normal load were chosen as input process parameters for the study. [5-10] Throughout the tests, the sliding distance and wear track diameter are kept constant at 1500 m and 90 mm, respectively. Cumulative wear (in microns) and coefficient of friction were the study's performance indicators. [5-10] Each experiment was done three times to confirm that the results were consistent. Table 1 lists the process parameters that were investigated in the study, as well as their levels. The L9 orthogonal array was chosen for the investigation because it has three elements, each with three levels. A flowchart in Fig. 1 depicts the step-by-step Taguchi Grey Relational Analysis (GRA) approach for improving the process parameters. [7-8] The L9 orthogonal array was chosen for the investigation because it has three elements, each with three levels.

**Table 1.** Process parameters and their levels

| Process parameter | Levels | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A - wt% of $TiO_2$ | 1.5 | 2.5 | 5 |
| B – Normal load (kg) | 0.5 | 1.0 | 2.0 |
| C - sliding speed (m/s) | 1.5 | 2.0 | 2.5 |
| Output measures–cumulative wear (μm) & coefficient of friction | | | |

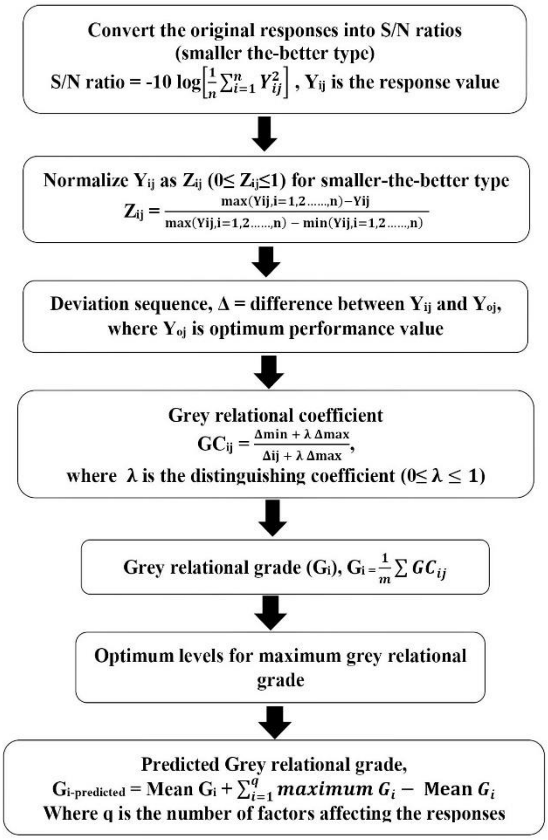

**Fig. 1.** Step-by-step procedure of Taguchi Grey Relational Analysis

## 3. Results and Discussions

Tables 2 and 3 provided the results of each trial, including S/N ratios, normalized S/N ratios, deviation sequence, grey relational coefficient, and grey relational grade. Table 2 also showed the grey relational grade, which was used to rank the investigations. As shown in Fig. 1, the different responses to this investigation, such as cumulative wear and coefficient of friction were combined into a single response, grey relational grade. Grey relational grade was the objective function in Taguchi-based Grey relational analysis (GRG). For this sliding wear behaviour, both cumulative wear and coefficient of friction were minimized in this work.

**Table 2**. S/N and normalized S/N of responses

| S. No. | Factors | | | Responses | | S/N of responses | | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | Cumulative wear (μm) | Coefficient of friction | Cumulative wear (μm) | Coefficient of friction | Cumulative wear (μm) | Coefficient of friction |
| 1 | 1.5 | 0.5 | 1.5 | 11.33 | 0.52 | -21.085 | 5.680 | 0.880 | 0.000 |
| 2 | 1.5 | 1 | 2 | 25.33 | 0.38 | -28.073 | 8.404 | 0.460 | 0.667 |
| 3 | 1.5 | 2 | 2.5 | 29.33 | 0.32 | -29.346 | 9.897 | 0.340 | 0.952 |
| 4 | 2.5 | 0.5 | 2 | 14.67 | 0.41 | -23.329 | 7.744 | 0.780 | 0.524 |
| 5 | 2.5 | 1 | 2.5 | 40.67 | 0.37 | -32.185 | 8.636 | 0.000 | 0.714 |
| 6 | 2.5 | 2 | 1.5 | 37.33 | 0.34 | -31.441 | 9.370 | 0.100 | 0.857 |
| 7 | 5 | 0.5 | 2.5 | 7.33 | 0.47 | -17.302 | 6.558 | 1.000 | 0.238 |
| 8 | 5 | 1 | 1.5 | 25.33 | 0.31 | -28.073 | 10.173 | 0.460 | 1.000 |
| 9 | 5 | 2 | 2 | 20 | 0.33 | -26.021 | 9.630 | 0.620 | 0.905 |

**Table 3.** Grey Relational Grades and ranks of responses

| S. No. | Factors | | | Deviation Sequences | | Grey Relational Coefficient | | Grey Relational Grade, Gi | Rank |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | Cumulative wear (μm) | Coefficient of friction | Cumulative wear (μm) | Coefficient of friction | | |
| 1 | 1.5 | 0.5 | 1.5 | 0.120 | 1.000 | 0.893 | 0.500 | 0.696 | 8 |
| 2 | 1.5 | 1 | 2 | 0.540 | 0.333 | 0.649 | 0.750 | 0.700 | 7 |
| 3 | 1.5 | 2 | 2.5 | 0.660 | 0.048 | 0.602 | 0.955 | 0.779 | 4 |
| 4 | 2.5 | 0.5 | 2 | 0.220 | 0.476 | 0.820 | 0.677 | 0.748 | 5 |
| 5 | 2.5 | 1 | 2.5 | 1.000 | 0.286 | 0.500 | 0.778 | 0.639 | 9 |
| 6 | 2.5 | 2 | 1.5 | 0.900 | 0.143 | 0.526 | 0.875 | 0.701 | 6 |
| 7 | 5 | 0.5 | 2.5 | 0.000 | 0.762 | 1.000 | 0.568 | 0.784 | 3 |
| 8 | 5 | 1 | 1.5 | 0.540 | 0.000 | 0.649 | 1.000 | 0.825 | 1 |
| 9 | 5 | 2 | 2 | 0.380 | 0.095 | 0.725 | 0.913 | 0.819 | 2 |

The initial ideal combination of process parameters for the maximum grey relational grade is A3B2C1, according to the rank determined for the grey relational grade presented in tables 4 and 5. Using the relationship presented in Fig. 1, the anticipated grey relational grade for this combination of optimum design parameters was 0.8438. This was taken a step further by putting it to the test. The computed grey relational grade was 0.8314, which was almost identical to the projected value, based on the testing findings of the optimum design parameters. In terms of original design parameters, the improvement in grey relational grade in predicted and experimental were 2.2 % and 0.77 %, respectively.

**Table 4.** Ranks for factors at all levels

| Factors | 1 | 2 | 3 | Delta | Rank |
|---|---|---|---|---|---|
| A | 0.725 | 0.696 | 0.809 | 0.113 | 1 |
| B | 0.742 | 0.721 | 0.766 | 0.045 | 2 |
| C | 0.74 | 0.755 | 0.734 | 0.021 | 3 |

**Table 5.** GRG for initial and optimum design parameters

| Confirmation Experiment | Initial Design Parameters | Optimum Design Parameters | |
|---|---|---|---|
| | | Predicted | Experimental |
| Setting level | A3B2C1 | A3B3C2 | A3B3C2 |
| Grey Relational Grade (GRG) | 0.825 | 0.8438 | 0.8314 |
| Improvement in GRG | | 2.2% | 0.77% |

The grey relational grades for all factors at all levels and all the experiments are shown in Fig. 2 and 3 respectively. The numerous performance features of the wear behaviour of the Mg-$TiO_2$ nanocomposite were greatly enhanced, as evidenced by the improvement in grey relational grade. The analysis of variance (ANOVA) was used to look into the important process parameters that affected the composite's wear behaviour The ANOVA results for output performance characteristics like cumulative wear and coefficient of friction are shown in tables 6 and 7 respectively. The residual plots for the performance measures cumulative wear and coefficient of friction were shown in Fig. 3 and 4. The estimated R-Sq. for cumulative wear and coefficient of friction are 77.08% and 64.11% respectively. The residual plots complement the results of R-Sq. It was observed from the ANOVA tables that, the most influencing factor was the normal load for both the performance measures. The contribution of the normal load is 68.9% in the case of cumulative wear, whereas 27.4% is for a coefficient of friction. The subsequent influencing factor on the output measures was sliding speed. The Highest F-ratio and P-value in the ANOVA tables of performance measures support the justification for the contribution made by the most influencing process parameter of the study. [12-15]

The sample surface plots shown in Fig. 6 and 7 generated for the output measures against normal load and weight fraction of the reinforcement keeping the sliding speed at the constant of about 2 m/s. The level of influence discussed previously was confirmed through these surface plots also.

The higher-order regression model for the responses is given below:

*Cumulative wear =*

$$35.85+0.8216A+9.01B+1.39C+0.0542AB-1.43AC-0.6914BC-2.32A^2-14.75B^2+1.33C^2$$

*Coefficient of friction =*

$$0.3708-0.0058A-0.0476B+0.0094C$$

**Table 6.** ANOVA for the response – cumulative wear

| Source | DOF | Adjusted Sum of squares | Adjusted mean of squares | F-ratio | P-value | Percentage of contribution |
|---|---|---|---|---|---|---|
| A | 2 | 92.94 | 46.468 | 3.27 | 0.092 | 2.27 |
| B | 2 | 1390.15 | 695.073 | 48.91 | 0.0001 | 68.93 |
| C | 2 | 56.96 | 28.478 | 2.00 | 0.197 | 3.57 |
| A X B | 4 | 27.97 | 6.993 | 0.49 | 0.742 | -0.33 |
| A X C | 4 | 108.06 | 27.016 | 1.90 | 0.204 | -0.65 |
| B X C | 4 | 300.37 | 75.093 | 5.28 | 0.022 | 8.26 |
| Error | 8 | 113.69 | 14.211 | | | 17.93 |
| Total | 26 | 2090.13 | | | | 100 |

**Table 7.** ANOVA for the response – coefficient of friction

| Source | DOF | Adjusted Sum of squares | Adjusted mean of squares | F-ratio | P-value | Percentage of contribution |
|---|---|---|---|---|---|---|
| A | 2 | 0.0146 | 0.0073 | 6.99 | 0.018 | 10.60 |
| B | 2 | 0.0398 | 0.0199 | 18.96 | 0.001 | 27.46 |
| C | 2 | 0.0116 | 0.0058 | 5.53 | 0.031 | 7.30 |
| A X B | 4 | 0.0155 | 0.0038 | 3.70 | 0.054 | 7.11 |
| A X C | 4 | 0.0018 | 0.0004 | 0.43 | 0.781 | -2.70 |
| B X C | 4 | 0.0479 | 0.0119 | 11.42 | 0.002 | 30.28 |
| Error | 8 | 0.0084 | 0.0010 | | | 19.92 |
| Total | 26 | 0.1398 | | | | 100 |

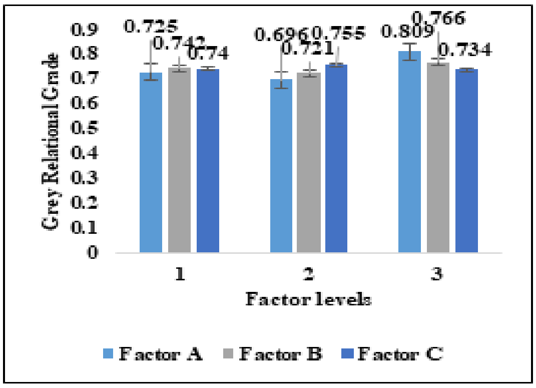

**Fig. 2.** Grey Relational Grades for the factors at all levels

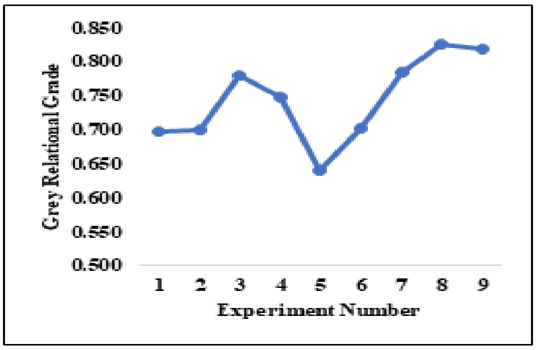

**Fig. 3.** Grey Relational Grades for all experiments

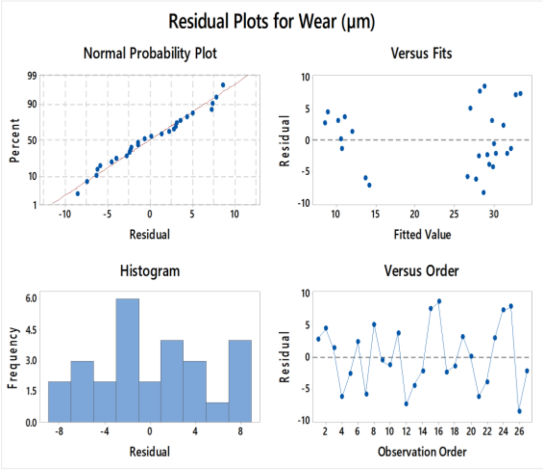

**Fig. 4.** Residual plots for cumulative wear

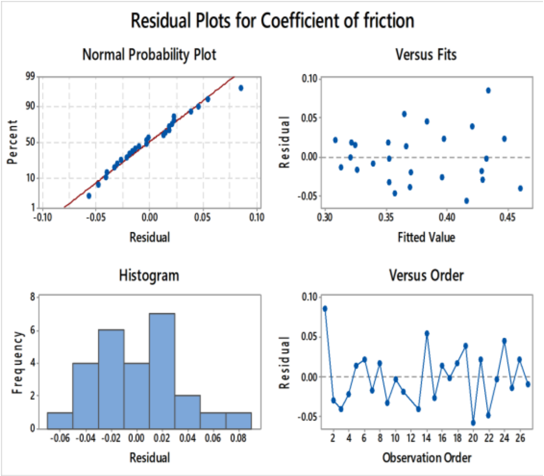

**Fig. 5.** Residual plots for the coefficient of friction

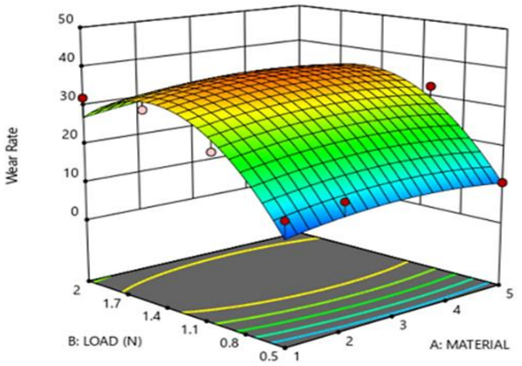

**Fig. 6.** Surface plot at 2 m/s sliding velocity for cumulative wear

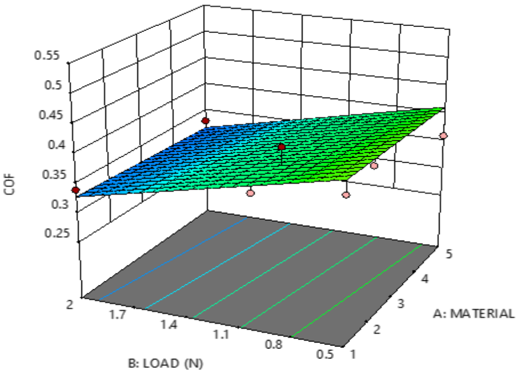

**Fig. 7.** Surface plot at 2 m/s sliding velocity for the coefficient of friction

## 4. Conclusions

In this study, Taguchi-based Grey relational analysis was used to optimize the wear behaviour of Mg-$TiO_2$ nanocomposite's numerous performance aspects. This optimization technique combines numerous performance criteria into a single grey relational grade performance metric. The highest grey relational grade obtained for an experiment depicts the best process parameter settings, which were further confirmed through experimentation. The investigation came up with the following conclusions.

- The process parameter combination A3B2C1, which corresponds to 5 wt% $TiO_2$, 1 kg normal load, and 1.5 m/s sliding speed, yields a maximum GRG of 0.825.
- For the optimum process parameters, the estimated GRG of 0.825 corresponding to A3B2C1 was compared to the predicted GRG of 0.8438 corresponding to A3B3C2 and the experimental GRG of 0.8314 corresponding to A3B3C2, and it was noticed that the GRG improved by 2.2 % and 0.77%, respectively.
- An analysis of variance (ANOVA) was utilized to identify which process parameters have a significant impact on the wear behaviour of the nanocomposite.

For performance metrics such as cumulative wear and coefficient of friction, it was discovered that normal load has the highest proportion of the contribution of around 68.9% and 27.4%, respectively.

## Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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