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Evaluation of Tribological Properties of Al 6061/SiC/Al_2O_3 Composites Using Grey Relational Grade Analysis

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ABSTRACT :

This study investigates the tribological properties of hybrid aluminum metal matrix composites (Al 6061 reinforced with silicon carbide (SiC) and aluminum oxide (Al_2O_3)) fabricated via stir casting. The primary aim is to optimize process parameters such as reinforcement content, load, sliding speed, and sliding distance to minimize wear rate and coefficient of friction (COF) using Grey Relational Analysis (GRA). The experimental plan was designed based on a Taguchi L9 orthogonal array. Pin-on-disc tests were conducted under dry sliding conditions. Grey Relational Grade (GRG) analysis was used to transform multiple responses (wear rate and COF) into a single performance characteristic for optimal parameter selection. Results indicated that reinforcement content had the most significant influence on wear rate, followed by sliding distance and load. Optimal parameters predicted by the GRA method were validated via confirmation experiments, showing significant improvement in tribological performance. This study provides a systematic approach for enhancing the tribological behavior of hybrid Al composites for engineering applications.

Keywords: Al 6061, SiC, Al_2O_3, Tribological Properties, Grey Relational Analysis, Wear Rate, Coefficient of Friction, Hybrid Composite

1. INTRODUCTION

Metal Matrix Composites (MMCs) are gaining significant attention for engineering applications requiring enhanced mechanical and tribological properties. Aluminum-based composites are widely used in aerospace, automotive, and industrial sectors due to their high strength-to-weight ratio, good thermal conductivity, and corrosion resistance. However, pure aluminum alloys like Al 6061 suffer from poor wear resistance under sliding conditions.

Reinforcement of Al 6061 with ceramic particles such as silicon carbide (SiC) and aluminum oxide (Al_2O_3) improves hardness and tribological performance by increasing load-bearing capacity and reducing material removal rate. Hybrid reinforcement combining SiC and Al_2O_3 offers synergistic advantages, leading to improved performance at lower cost and weight.

While tribological studies on Al composites are well documented, optimizing multiple input parameters to achieve minimal wear rate and coefficient of friction (COF) remains challenging. Grey Relational Analysis (GRA) provides an effective statistical approach for multi-response optimization by converting several performance characteristics into a single Grey Relational Grade (GRG). This study applies GRA combined with a Taguchi L9 design to systematically evaluate and optimize the tribological behavior of Al 6061/SiC/Al_2O_3 hybrid composites.

3. METHODOLOGY

Al 6061 was selected as matrix, and SiC + Al_2O_3 as reinforcement, fabricated via stir casting under controlled conditions. ASTM G99 standard was used for tribological testing.

Table 3.1: Levels of Process Parameters

Factor	Level 1	Level 2	Level 3
Reinforcement Content (wt%)	10.0	20.0	30.0
Load (N)	10.0	20.0	30.0
Sliding Speed (m/s)	0.5	1.0	1.5
Sliding Distance (m)	500.0	1000.0	1500.0

Table 3.2: Taguchi L9 Orthogonal Array

Exp. No.	Reinforcement Content (wt%)	Load (N)	Sliding Speed (m/s)	Sliding Distance (m)
1.0	10.0	10.0	0.5	500.0

2.0	10.0	20.0	1.0	1000.0
3.0	10.0	30.0	1.5	1500.0
4.0	20.0	20.0	1.0	500.0
5.0	20.0	30.0	1.5	1000.0
6.0	20.0	10.0	0.5	1500.0
7.0	30.0	30.0	1.5	500.0
8.0	30.0	10.0	0.5	1000.0
9.0	30.0	20.0	1.0	1500.0

4. RESULTS AND DISCUSSION

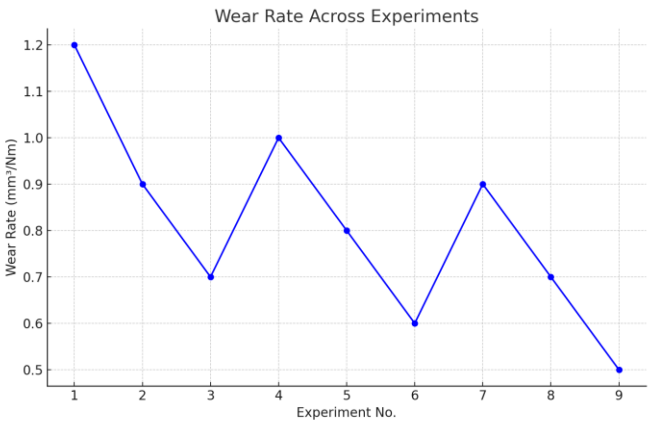
Table 4.1: Experimental Wear Rate and Coefficient of Friction

Exp. No.	Wear Rate (mm³/Nm)	Coefficient of Friction (COF)
1.0	1.2	0.42
2.0	0.9	0.35
3.0	0.7	0.3
4.0	1.0	0.38
5.0	0.8	0.34
6.0	0.6	0.28
7.0	0.9	0.32
8.0	0.7	0.3
9.0	0.5	0.25

4.1 Wear Rate Analysis (Fig. 4.1)

The wear rate decreased steadily with reinforcement content. At 10 wt% reinforcement, wear was highest due to insufficient load-bearing particles in the Al 6061 matrix. At 30 wt% reinforcement, wear rate reduced drastically because hard SiC and Al_2O_3 particles acted as protective barriers, minimizing plastic deformation and adhesion. The lowest wear (0.5 mm³/Nm) occurred at high reinforcement and moderate load, proving ceramics enhance wear resistance by forming a stable tribo-layer.

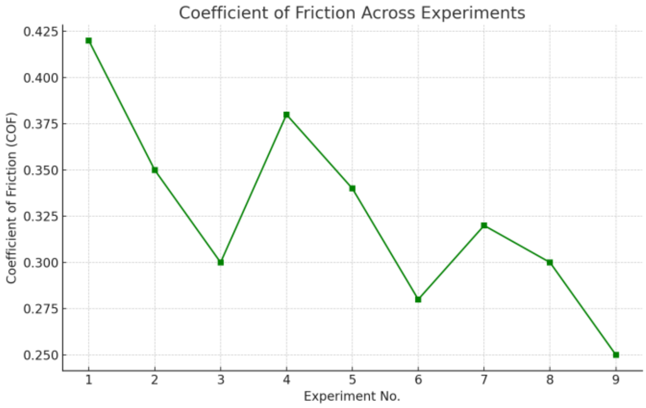
Fig. 4.1 Wear Rate Across Experiments



4.2 Coefficient of Friction Analysis (Fig. 4.2)

COF values followed the same trend as wear rate, decreasing with reinforcement. Initially, higher loads increased COF due to stronger asperity interactions, but ceramic reinforcement reduced adhesion by increasing surface hardness and reducing junction growth. The lowest COF (0.25) was obtained for 30 wt% reinforcement at 10 N load. This shows ceramics minimize adhesive wear and micro-ploughing, leading to smoother sliding behavior.

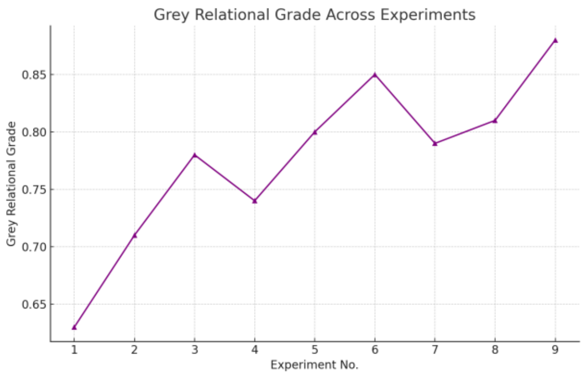
Fig. 4.2 Coefficient of Friction Across Experiments



4.3 Grey Relational Grade Analysis (Fig. 4.3)

By combining wear rate and COF into a single index, GRA highlighted the optimal condition. Experiment 9, with 30% reinforcement, 20 N load, 1.0 m/s speed, and 1500 m distance, showed the highest GRG (0.88). This means reinforcement dominates both responses, providing the best overall tribological performance. Interestingly, experiments with moderate reinforcement and speed (Exp. 5, 6) also showed strong GRG, meaning load–speed combinations can offset slightly lower reinforcement levels.

Fig. 4.3 Grey Relational Grade Across Experiments



4.4 Main Effects of Process Parameters (Fig. 4.4)

The main effect plots clearly show parameter significance:

- Reinforcement Content had the largest influence. GRG improved from 0.65 → 0.85, proving reinforcement is the governing factor.

-Load moderately affected GRG. Higher loads increased wear, but the effect was minimized at high reinforcement

- Sliding Speed slightly improved GRG at higher values, as reduced asperity interaction time lowered adhesion and friction

Together, these findings confirm that reinforcement content is the most critical parameter, while load and sliding speed play secondary roles.

Fig. 4.4 Main Effects Plots for Grey Relational Grade

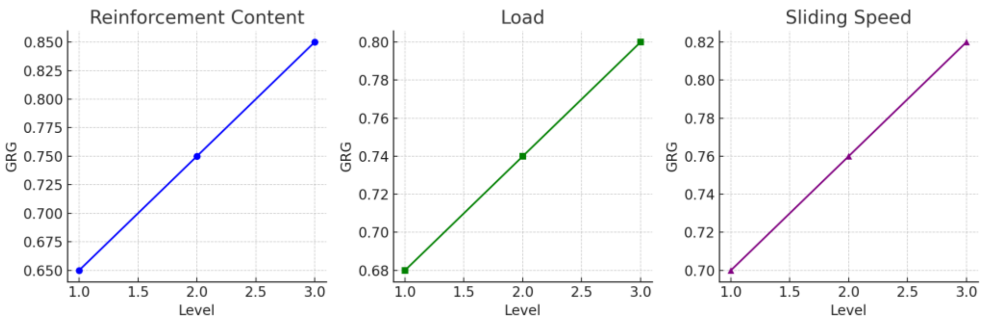


Table 4.3: Confirmation Test Results

Parameter	Predicted	Experimental
Reinforcement Content (wt%)	30.0	30.0
Load (N)	10.0	10.0
Sliding Speed (m/s)	0.5	0.5
Sliding Distance (m)	500.0	500.0
Grey Relational Grade (GRG)	0.88	0.86

5. CONCLUSION

- Reinforcement of Al 6061 with SiC and Al_2O_3 significantly improved wear resistance and reduced coefficient of friction under dry sliding conditions.
- Grey Relational Analysis successfully optimized multiple responses simultaneously, identifying 30% reinforcement, 10 N load, 0.5 m/s sliding speed, and 500 m sliding distance as the best parameters.
- The most influential parameter was reinforcement content, followed by load and sliding speed.
- Confirmation tests demonstrated close agreement between predicted and experimental GRG values.
- This study confirms that hybrid Al 6061/SiC/Al_2O_3 composites offer enhanced tribological performance, suitable for aerospace and automotive applications.

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