INVESTIGATION ON TRIBOLOGICAL PROPERTIES OF AZ61 MAGNESIUM ALLOY METAL MATRIX REINFORCED WITH BORON CARBIDE AND SILICON DIOXIDE

M.Sudheer[1], Dr.P.Prasanna[2]

[1]Post Graduate Student and [2]Associate Professor in Mechanical engineering

JNTUH University College of Engineering, Science and Technology, Hyderabad, India

[1]malrajusudheer6@gmail.com

[2]prajntu@jntuh.ac.in

ABSTRACT

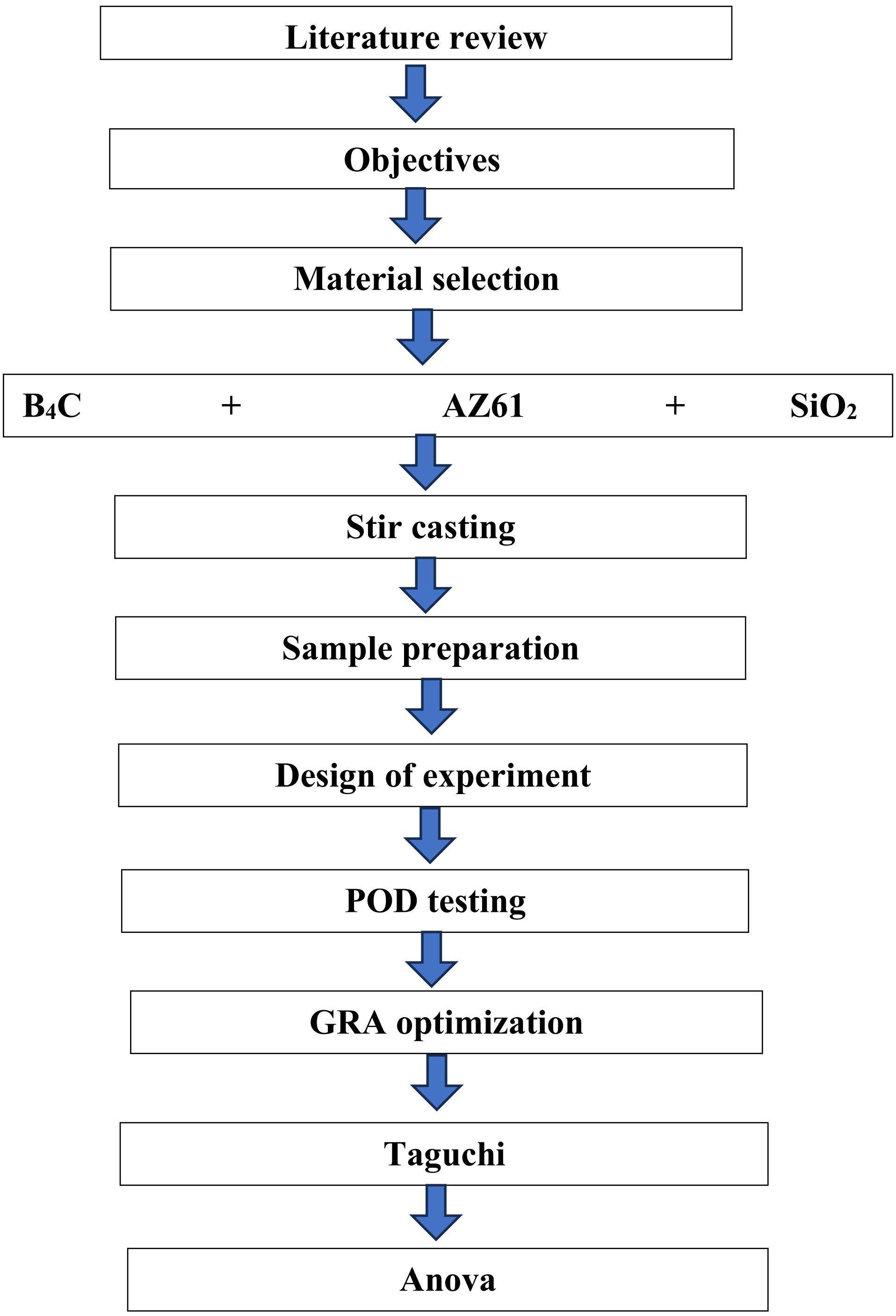
This study explores the tribological properties of AZ61 magnesium alloy composites reinforced with Boron Carbide (B_4C) and Silicon Dioxide (SiO_2). Magnesium alloys, known for their low density and high strength-to-weight ratio, are widely considered in aerospace, automotive, and biomedical applications. However, their poor wear resistance and corrosion vulnerability limit broader utilization. To overcome these limitations, a hybrid metal matrix composite was fabricated using the stir casting method. Four compositions were developed: (i) pure AZ61, (ii) AZ61 + 2% B_4C, (iii) AZ61 + 2% B_4C + 2% SiO_2, and (iv) AZ61 + 4% B_4C + 4% SiO_2. The composites were subjected to tribological evaluation using a pin-on-disc test (ASTM G99) at varying loads (0.5–2.0 kg) and sliding speeds (300–600 rpm). Wear rate and coefficient of friction (COF) were recorded and analyzed using statistical tools including Taguchi design, Grey Relational Analysis (GRA), and Analysis of Variance (ANOVA). Results reveal significant improvement in wear resistance and reduction in COF for reinforced samples compared to pure AZ61. The optimal composition (AZ61 + 2% B_4C + 2% SiO_2) exhibited balanced performance, while excessive reinforcement (4% B_4C + 4% SiO_2) led to particle agglomeration and decreased bonding strength. Findings confirm the potential of hybrid reinforcements in enhancing tribological behavior, with applications in lightweight structural, automotive, and biomedical engineering.

Keywords: Tribological properties , AZ61 alloy , Silicon dioxide , Boron carbide , Pin-on-Disc Test

1. INTRODUCTION

The growing demand for lightweight and high-performance materials has driven extensive research into magnesium alloys, particularly AZ series alloys. Among them, AZ61 is attractive due to its combination of strength, castability, and corrosion resistance. Despite these advantages, it suffers from poor wear resistance and limited formability due to its hexagonal close-packed crystal structure. Reinforcement with ceramic particulates such as Boron Carbide (B_4C) and Silicon Dioxide (SiO_2) has emerged as a promising approach to address these challenges. Metal Matrix Composites (MMCs) integrate ceramic reinforcements within a metallic matrix, significantly enhancing hardness, wear resistance, and mechanical stability. In this research, AZ61 was reinforced with B_4C and SiO_2 to develop hybrid composites with superior tribological properties. Literature review confirms that B_4C improves hardness and wear resistance, while SiO_2 provides thermal stability and dimensional accuracy. Together, these reinforcements offer potential for automotive, aerospace, and biomedical applications. The primary objective of this work is to investigate how varying reinforcement percentages affect the wear rate and coefficient of friction of AZ61 composites under dry sliding conditions, and to optimize processing parameters using statistical tools

2. METHODOLOGY



3. MATERIALS

AZ61 Alloy

A silvery-white metal, magnesium is frequently employed as an alloying element in non-ferrous metals including lead, zinc, and aluminum. Magnesium is used extensively in the manufacturing and engineering sectors because of its low density, high machinability, and ease of casting. AZ61 stands out from the other magnesium alloys due to its corrosion resistance and well-balanced mechanical characteristics. The structural performance of this alloy is improved by the addition of manganese, zinc, and aluminum to its magnesium core. A silvery-white metal, magnesium is frequently employed as an alloying element in non-ferrous metals including lead, zinc, and aluminum. Magnesium is used extensively in the manufacturing and engineering sectors because of its low density, high machinability, and ease of casting. AZ61 stands out from the other magnesium alloys due to its corrosion resistance and well-balanced mechanical characteristics. The structural performance of this alloy is improved by the addition of manganese, zinc, and aluminum to its magnesium core. According to studies, AZ61 can be strengthened with ceramic materials such as silicon dioxide (SiO_2) or boron carbide (B_4C) to significantly increase its hardness, tensile strength, and resistance to wear. This makes it a good material for structural and tribological applications. In the automotive industry, AZ61 is utilized in structural brackets, gearbox cases, and steering columns where strength and portability are crucial. It is used for non-load-bearing structures and interior parts in aerospace applications to assist lower total weight. Furthermore, reinforced AZ61 alloys are of interest for biomedical applications, such as bone fixation devices and temporary implants, due to their biocompatibility and degrading behavior. AZ61 is a high-performance material that can be used in industrial machinery, biomedical engineering, automotive, and aerospace with the right reinforcement.

B_4C

Boron carbide (B_4C) is a great ceramic material with exceptional hardness, low density, and significant wear resistance. It is one of the hardest known materials, with a Mohs hardness of roughly 9.5, only surpassed by diamond and cubic boron nitride. Boron carbide is widely used as reinforcement in metal matrix composites (MMCs) t improve abrasion resistance, strength, and hardness without significantly increasing weight due to its remarkable mechanical and thermal properties. Because of its high melting point (~2450°C), excellent chemical stability, and neutron absorption capacity, B_4C is also useful in abrasives, nozzles, armor plates, and nuclear shielding.

SiO_2

Silica, or silicon dioxide (SiO_2), is a naturally occurring substance made of silicon and oxygen. It is frequently found in sand, quartz, and other kinds of rocks and is one of the most prevalent elements in the Earth's crust. Because of its superior mechanical, thermal, and chemical qualities, SiO_2 which may be found in both crystalline and amorphous forms is extensively utilized in many different industries. It has strong thermal insulation qualities, is extremely wear-resistant, and is chemically stable. Because of these characteristics, silicon dioxide is used in many different fields, such as electronics, glassmaking, ceramics, and as a reinforcing filler in metal matrix composites and polymer materials.

4. STIR CASTING

Stir casting is a commonly employed method for producing metal matrix composites, favored for its simplicity and cost-effectiveness, which makes it ideal for mass production. In this technique, a mechanical stirrer creates a vortex in the molten metal, helping to uniformly distribute the reinforcement particles within the metal matrix. A standard stir casting system includes a furnace, a mechanical stirrer, and a feeder for the reinforcement material.

5. PIN-ON-DISC TESTING

The main goal of the test is to investigate how different load conditions, disc speeds, and reinforcement levels influence the material's wear resistance and frictional response. These tests aim to reveal how the addition of reinforcements affects tribological performance across various operating conditions, helping identify the optimal composition and processing parameters for enhanced wear resistance.

Standard (ASTM G99)

Pin size: Diameter: 3, 4, 6, 8, 10 & 12 mm; 25 to 30 mm load

Disc size: Diameter: 165 mm, 8 mm thick
Wear track: Diameter: 50 to 100 mm
Disc rotation: 200 – 2000 rpm
Sliding speed: 0.5 to 10 m/s
Normal load: 5 to 200N
Temperature: Ambient 36°C

The use of the L_{16} array allows the experimental design to effectively incorporate all combinations of load (0.5, 1, 1.5, and 2 kg), disc speed (300,400,500 and 600 rpm), and reinforcement percentage (0%+0%, 2%+0% 2%+2%, and 4%+4%). This comprehensive coverage enables a clear analysis of the individual and combined effects of these parameters on the material's wear performance. The approach ensures that the results are statistically sound, repeatable, and reliable, leading to more precise conclusions about the optimal conditions for enhancing wear resistance.

6. ANALYSIS OF VARIANCE

1) General Linear Model: COF Vs Reinforcement %, Load, Speed.
2) General Linear Model: wear rate Vs Reinforcement %, Load, Speed.

According to the results of the ANOVA and regression analysis, speed has no discernible impact on the coefficient of friction (COF), but reinforcing weight percentage and load do. Speed (p = 0.297) is not statistically significant, according to the ANOVA, while reinforcement % (p = 0.001) and load (p = 0.000) are extremely important variables. With a 97.22% adjusted R-squared, the regression model explains nearly all of the variance in the COF and offers a precise equation for predicting it. The greatest reduction in COF is achieved with an 8% reinforcement weight percentage, however raising the load from 4.905 N to 14.715 N has a mixed impact, increasing COF at lower loads while decreasing it at higher loads. COF is not greatly affected by speed, indicating that it has little bearing on this model. Furthermore, observation 1 appears to be a possible outlier based on its significant residuals and impact values. With a strong predictive power (R-sq. = 98.89%) and overall robustness, the model offers important insights into how load and reinforcement impact COF in the experiment.

Both load and reinforcement weight percentage (w%) have a statistically significant impact on the wear rate, according to the ANOVA and regression analysis, but speed has zero effect. The extremely low p-values for load (p = 0.000) and reinforcement (p = 0.000) demonstrate this, demonstrating their great importance, however the p-value for speed (p = 0.363) indicates it is not statistically significant. The load variable has the greatest F-value (248.15) of the three, making it the one that has the biggest impact on wear. With an adjusted R-squared of 98.23%, a projected R-squared of 94.97%, and an R-squared value of 99.29%, the regression model is extremely accurate, demonstrating its potent predictive power. The calculations show that the wear rate is considerably decreased by raising the reinforcement to 4% or more. In a similar vein, loads of around 14.715 N lessen wear more efficiently than lower or greater values. On the other hand, as indicated by its modest coefficients and high p-values, the speed variable has little effect. All things considered, the model accurately measures the effects of reinforcement and load on wear behavior, making it a trustworthy instrument for maximizing material performance in wear-critical applications.

7. GRA OPTIMIZATION

1) Data Pre-processing
2) Normalization
3) Deviation Sequence Calculation
4) Grey Relational Coefficient Determination
5) Grey Relational Grade Calculation

7.1. GRA OPTIMIZATION TABLE

Original values			Normalizing values		Deviation sequence		Grey Relation Coefficient		GRG	Rank
S. No	COF (μ)	Wear Rate (μm)	COF	Wear Rate	COF	Wear Rate	COF	Wear Rate		
1	0.44	0.045	0.000	0.000	1.000	1.000	0.333	0.333	0.333	16
2	0.305	0.030	0.500	0.500	0.500	0.500	0.500	0.500	0.500	12
3	0.235	0.024	0.759	0.700	0.241	0.300	0.675	0.625	0.650	9
4	0.215	0.021	0.833	0.800	0.167	0.200	0.750	0.714	0.732	7
5	0.375	0.039	0.241	0.200	0.759	0.800	0.397	0.385	0.391	14
6	0.25	0.025	0.704	0.667	0.296	0.333	0.628	0.600	0.614	10
7	0.2	0.020	0.889	0.833	0.111	0.167	0.818	0.750	0.784	5
8	0.17	0.016	1.000	0.967	0.000	0.033	1.000	0.938	0.969	2
9	0.318	0.033	0.452	0.400	0.548	0.600	0.477	0.455	0.466	13
10	0.22	0.021	0.815	0.800	0.185	0.200	0.730	0.714	0.722	8
11	0.18	0.018	0.963	0.900	0.037	0.100	0.931	0.833	0.882	4
12	0.171	0.015	0.996	1.000	0.004	0.000	0.993	1.000	0.996	1
13	0.378	0.039	0.230	0.200	0.770	0.800	0.394	0.385	0.389	15
14	0.26	0.026	0.667	0.633	0.333	0.367	0.600	0.577	0.588	11
15	0.21	0.020	0.852	0.833	0.148	0.167	0.771	0.750	0.761	6
16	0.175	0.017	0.981	0.933333333	0.019	0.067	0.964	0.882	0.923	3
MAX	0.44	0.045	1	1	1	1				
MIN	0.17	0.015	0	0	0	0	ZETA=.5			

7.2 TAGUCHI DESIGN USING L16 ORTHOGONAL ARRAY

1.Reinforcement Effect
2.Load Effect:
3.Speed Effect

Level	Reinforcement (Mean GRG)	Load (Mean GRG)	Speed (Mean GRG)

1	0.5539	0.3948	0.6882
2	0.6894	0.6061	0.662
3	0.7666	0.7692	0.6683
4	0.6654	0.9051	0.6568
Delta	0.2127	0.5104	0.0314
Rank	2	1	3

8. REULTS

Levels	Initial Parameters	Optimal Parameters	
R2 L1 S2		Predicted	Experimental
Setting Level	R2 L1 S2		R3 L4 S2
Coefficient of Friction	0.25		0.171
Wear rate	0.025		0.015
Grey Relational Grade	0.614	0.8247	0.996
Improvement in GRG =	62.23%		

9.CONCLUSION

Using the stir casting technique, AZ61 reinforced with B_4C and SiO_2 hybrid metal matrix composites were manufactured. For the initial sample, just the standard magnesuim alloy was utilized. In the second sample, the alloy was supplemented with 2% boron carbide and 0% silicon dioxide. 2% boron carbide and 2% silicon dioxide made up the third sample, 4% boron carbide and 4% silicon dioxide and made up the fourth, and the remaining proportion was made up of AZ61 alloy. The proportion of reinforcement varied across all samples. The examination of these composites led to the following results.

1. The wear resistance properties of the samples reinforced with 2% boron carbide and 2% silicon dioxide were better to those of the base alloy and the remaining samples made for this project.
2. According to the Grey Relational Analysis approach, the 12th trial with

process parameters of 19.62N Load, 2% boron carbide and 2% silicon dioxide and speed of 400 RPM was ranked first; in other words, R3, L4, and S2 are the best options.

3. The impact of the input process factors is shown by the major effect graphs for the grey relational grade (GRG). The best outcome for GRG, which represents the ideal parameter choices, is indicated by the highest value at each level.

10.REFERENCES

[1] Y. Sun, W. Ding, “Magnesium-based composites for structural applications,” Journal of Magnesium and Alloys, vol. 8, no. 1, pp. 1–19, 2020.
[2] M. Gupta, N. M. L. Sharon, “Magnesium, Magnesium Alloys, and Magnesium Composites,” John Wiley & Sons, 2011.
[3] A. Atrens et al., “Review of recent developments in corrosion of magnesium alloys,” Journal of Magnesium and Alloys, vol. 6, no. 3, pp. 205–241, 2018.
[4] H. Friedrich, S. Schumann, “Research for a ‘new age of magnesium’ in the automotive industry,” Journal of Materials Processing Technology, vol. 117, pp. 276–281, 2001.
[5] B. D. Saravanan et al., “Tribological behavior of hybrid metal matrix composites,” Materials Today: Proceedings, vol. 27, pp. 1572–1576, 2020.
[6] C. S. Goh et al., “Magnesium composites reinforced with nano-SiC,” Composites Science and Technology, vol. 67, no. 8–9, pp. 1505–1511, 2007.
[7] C. Shoba et al., “Wear properties of AZ31 Mg alloy reinforced with Al_2O_3,” Materials and Design, vol. 58, pp. 207–213, 2014.
[8] R. Singh, A. Chauhan, “Characterization of B_4C reinforced magnesium composites,” Journal of Alloys and Compounds, vol. 639, pp. 62–69, 2015.
[9] S. Rajan, K. Manoj, “Influence of SiO_2 reinforcement on Mg composites,” International Journal of Engineering Science and Technology, vol. 23, no. 2, pp. 145–152, 2019.
[10] N. Manoharan, P. Kannan, “Tribological performance of AZ91 hybrid composites,” Materials Today: Proceedings, vol. 22, pp. 879–884, 2020.