Optimization of Wear Properties in Bismuth-Reinforced Mg-Al/Mg2Si Composites Using Taguchi's Design of Experiments

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Abstract— This study investigates the dry sliding wear behavior of Mg-Al/Mg2-Si composites reinforced with varying percentages of Bismuth (0%, 0.7%, 1.4%, and 2%). Using the Design of Experiments (DOE) method and the Taguchi approach with an L9 orthogonal array, the influence of load, sliding speed, and sliding distance on wear loss was examined. Experimental results were analyzed using Analysis of Variance (ANOVA) to determine the significance of each parameter on wear behavior. The results indicate that for the composite with 0% Bismuth, load was the most significant factor influencing wear loss, with a contribution of 39.54%. For the composite with 0.7% Bismuth, sliding speed was found to be the most significant factor, contributing 64.4%. In the composite with 1.4% Bismuth, sliding distance was the most influential parameter, accounting for 46.3% of the variation in wear loss. Lastly, for the composite with 2% Bismuth, load again emerged as the most significant factor with a 43.2% contribution. The study concludes that the wear behavior of Mg-Al/Mg2-Si composites is significantly influenced by the applied load, sliding speed, and sliding distance, with their effects varying depending on the percentage of Bismuth reinforcement. These findings provide valuable insights into optimizing wear resistance in composite materials through tailored adjustments of wear parameters.

Index Terms- Magnesium Alloys, Mg2Si reinforcement, wear properties

I. INTRODUCTION

Recent emission norms have driven the demand for lightweight materials to reduce carbon dioxide (CO2) emissions and enhance fuel efficiency [1]. Magnesium alloys meet this need due to their low density; they weigh about 35% less than aluminum and are four times lighter than steel [3]. These alloys provide an attractive combination of properties for various applications [4]. However, their low hardness [5], high chemical reactivity, and low wear resistance limit their use [6]. Researchers focus on improving the microstructure of magnesium alloys to enhance their mechanical properties [[8], [9], [10], [11], [12]]. Srinivasa R. Bakshi et al. [13] fabricated aluminum/aluminum-silicon composite coatings via cold spraying. They found that increasing Al–Si content improved hardness but did not reduce wear loss due to intersplat delamination. Xiao-Feng Wu et al. [14] modified Al–Mg2Si composites with Nd, improving phase morphology and reducing wear rates. Makoto Hino et al. [15] observed that anodizing AZ91D magnesium alloy from phosphate solutions significantly reduced wear loss. J. Corrochanoa et al. [16] reported that ball milling and MoSi2 reinforcement enhanced wear resistance in Al-Mg-Si alloys by stabilizing the microstructure. R. L. Deuis et al. [17] reviewed aluminum composites, noting that load, sliding speed, and reinforcement properties affect wear performance. Hemanth Kumar T.R. et al. [18] used Taguchi methods to optimize tribological properties of Al-Cu-Mg composites, reducing wear rates and friction.

II. TAGUCHI TECHNIQUE IN WEAR BEHAVIOR ANALYSIS

Researchers use the Taguchi technique, a key part of the Design of Experiments (DOE) framework, to efficiently study the wear behavior of aluminum-based metal matrix composites. This technique reduces the number of experiments needed compared to full factorial designs. It identifies interactions between parameters through a structured approach that includes planning, conducting, and analyzing phases. During planning, researchers determine the combinations of factors and levels to gather essential data. They analyze the results using a signal-to-noise ratio to optimize process designs. By employing orthogonal arrays, Taguchi’s method evaluates the effects of multiple factors and applies analysis of means and variance to assess their influence. Researchers then develop a multiple linear regression model to predict wear rate.

III. MATERIALS AND PROCESSING

3.1 Raw Materials

Commercially pure magnesium ingot (99.3% pure), aluminum ingot (99.2% pure), and silicon powder (99.95% purity) were used as the primary materials to prepare the Mg-Al/Mg2Si composites. The magnesium and aluminum ingots were obtained from Jagada Industries, Virudhunagar, and cut into smaller pieces using a power hacksaw to facilitate melting within crucibles. The silicon powder, sourced from Jedee Enterprise, Mumbai, had a particle size of 23 microns.

3.2 Modification Material

Bismuth (Bi) powder, also obtained from Jedee Enterprise, Mumbai, with a particle size of 44 microns, was used to modify the Mg-Al/Mg2Si composites. Bismuth is characterized by its low melting point (271°C) and possesses self-lubricating properties during friction processes.

3.3 Processing of Mg-Al/Mg2Si Composites

The processing of Mg-Al/Mg2Si composites began with commercially pure magnesium ingots and silicon powder as the initial materials. The melting process was conducted in a steel crucible using a 2 kW electric resistance furnace under an argon gas protective atmosphere. Given magnesium's flammability in the presence of oxygen, all processing steps were carried out in an inert gas atmosphere. The furnace was equipped with bottom pouring arrangements and maintained an inert gas atmosphere throughout.

A composition of approximately 88.3 wt.% Mg and 9 wt.% Al was melted and superheated to 760°C. Silicon powder, preheated to 200°C and packed in aluminium foil, was added to the Mg-Al melt (2.7 wt.% Si). The melt was held at 760°C for 10 minutes and stirred at 600 rpm for 7 minutes to ensure complete dissolution of the silicon. Various amounts of bismuth powder (0.7 wt.%, 1.4 wt.%, and 2 wt.%), preheated to 200°C to eliminate moisture and gases, were then added. Finally, the composite melt was poured into preheated steel molds (dimensions: 3 mm × 5 mm × 120 mm) at 400°C.

IV. EXPERIMENTAL WORK

4.*1 Wear Testing*

We assessed wear behavior using a pin-on-disc testing machine with pin diameters ranging from 3 to 12 mm, a disc diameter of 165 mm, and sliding speeds between 5 and 10 m/s. We applied loads ranging from 60 to 100 N and sliding distances of 1800 to 3000 m. We cleaned and weighed the specimens, secured the disc and pin, applied the specified load, and conducted the test until we reached the desired number of revolutions. After the test, we inspected the specimens for wear and re-weighed them to ensure accuracy.

4.2 Experimental Design and Analysis

We conducted experiments using the L9 orthogonal array according to the standard procedure. We selected this array to ensure that the degrees of freedom exceeded or matched the total degrees of freedom required for our wear parameters. The chosen wear parameters were composition (C), sliding speed (S), and load (L). The L9 orthogonal array has 9 rows and 4 columns, covering all combinations of these parameters.

In the Taguchi method, we transformed experimental results into signal-to-noise (S/N) ratios to evaluate quality characteristics. For this study, we adopted the ‘lower-the-better’ criterion to assess the wear rate of magnesium hybrid composites, aiming for minimal wear rates. We computed the S/N ratios for each parameter level and conducted statistical analysis of variance to identify significant factors. This analysis allowed us to predict the optimal parameter combinations.

Table:1: Process Parameters

Level	load(N)	Speed(m/s)	Siding distance(m)
1	60	2	1800
2	80	3	2400
3	100	4	3000

Table 2: Orthogonal array L9 of Taguchi

Sl No	Load (N)	Speed (m/s)	Sliding distance (m)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

V. RESULTS AND DISCUSSION

The experiment aimed to determine the most influential factors affecting wear rate and their optimal combinations to minimize it. Using an orthogonal array, we evaluated the impact of composition (C), sliding speed (S), and normal load (L) on wear rate, which characterizes the tribological behavior of composites. We converted experimental results into signal-to-noise (S/N) ratios to quantify each parameter's influence. Analysis indicated that load has the greatest effect on wear rate, followed by sliding speed, with composition being the least influential.

5.1 Mg-Al/Mg2-Si reinforced with 0% Bismuth

Table 3: Orthogonal array L9 of Taguchi

Sl NO	Load(N)	Sliding speed(m/s)	Sliding distance(m)	Weight loss (gm./min)
1	6	2	1800	0.00638
2	6	3	2400	0.00661
3	6	4	3000	0.00643
4	8	2	2400	0.00525
5	8	3	3000	0.00580
6	8	4	1800	0.00715
7	10	2	3000	0.002423
8	10	3	1800	0.004277
9	10	4	2400	0.00660

Table 4: ANOVA results

Source	DF	Seq SS	Adj SS	Adj MS	F	P	p%
Load	2	0.0000070	0.0000070	0.0000035	4.26	0.190	39.54
Speed	2	0.0000063	0.0000063	0.0000031	3.84	0.207	35.59
Distance	2	0.0000028	0.0000028	0.0000014	1.68	0.373	15.28
Error	2	0.0000016	0.0000016	0.0000008			9.040
Total	8	0.0000177					

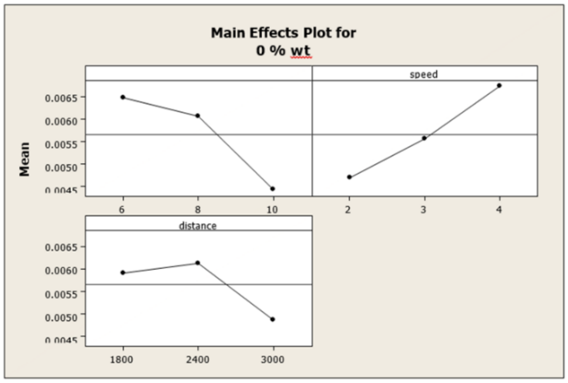

Fig 1: Main effects plot for means of weight loss

Table 4 reveals that the applied load significantly impacts wear loss, contributing 39.54% to the variation. This indicates that load is the most critical factor affecting wear behavior. In contrast, sliding speed and sliding distance contribute 35.59% and 2.09%, respectively, to wear loss, suggesting that their influence is less substantial. Thus, controlling the applied load is crucial for managing wear phenomena, while sliding speed and distance have a minimal effect.

Figure 1 displays the main effects plot for wear loss, highlighting the impact of various parameters on composite wear. The plot, created using MINITAB-15 software and data from Table 3, shows that sliding speed has the most pronounced effect on wear loss, evident from its steep slope. In contrast, load and sliding distance have smaller impacts. Increasing the load reduces wear loss because higher loads increase friction and contact area, leading to more wear debris and accelerated wear. On the other hand, increasing the sliding speed raises wear loss. Sliding distance initially increases wear up to 2400 meters before causing a decrease, indicating that wear intensifies with distance initially but eventually stabilizes or reduces.

5.2 Mg-Al/Mg2-Si reinforced with 0.7% Bismuth

Table 5: Orthogonal array L9 of Taguchi

Sl NO	Load(N)	Sliding speed(m/s)	Sliding distance(m)	Weight loss (gm/min)
1	6	2	1800	0.00279
2	6	3	2400	0.004842
3	6	4	3000	0.00809
4	8	2	2400	0.000696
5	8	3	3000	0.002489
6	8	4	1800	0.00108
7	10	2	3000	0.00120
8	10	3	1800	0.00229
9	10	4	2400	0.00378

Table 6 ANOVA results

Source	DF	Seq SS	Adj SS	Adj MS	F	P	p%
Load	2	0.00000137	0.00000137	0.0000069	1.25	0.444	15.3
Speed	2	0.0000576	0.0000576	0.0000288	5.25	0.160	64.4
Distance	2	0.0000072	0.0000072	0.0000036	0.65	0.65	8.05
Error	2	0.0000110	0.0000110	0.0000055			12.30
Total	8	0.0000894					

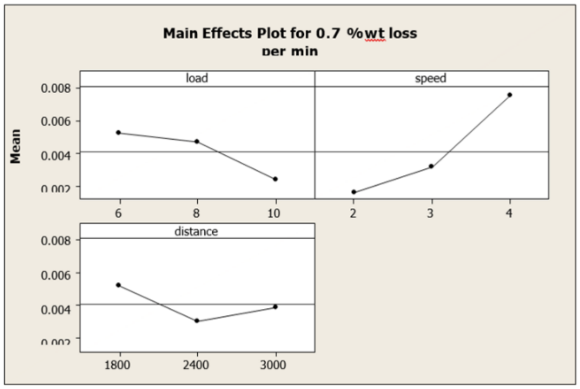

Fig 2: Main effects plot for means of weight loss

Figure 2 presents the main effects plot for wear loss, illustrating how different parameters affect the composite's wear behavior. The plot, generated using MINITAB-15 software and data from Table 5, shows that sliding speed has the most significant effect on wear loss, evident from its pronounced slope. In contrast, load and sliding distance have relatively lesser influences. As the load increases, wear loss decreases. Increasing sliding speed leads to a reduction in wear loss, while wear loss increases with sliding distance.

5.3 Mg-Al/Mg_2-Si reinforced with 1.4% Bismuth

Table 7: Orthogonal array L9 of Taguchi

Sl NO	Load(N)	Sliding speed(m/s)	Sliding distance(m)	Weight loss (gm/min)
1	6	2	`1800	0.003690
2	6	3	2400	0.002801
3	6	4	3000	0.001980
4	8	2	2400	0.001510
5	8	3	3000	0.00276
6	8	4	1800	0.002616
7	10	2	3000	0.001379
8	10	3	1800	0.004813
9	10	4	2400	0.00501

Table 8: ANOVA results

Source	DF	Seq SS	Adj SS	Adj MS	F	P	p%
Load	2	0.00000137	0.00000137	0.0000069	1.25	0.444	15.3
Speed	2	0.0000576	0.0000576	0.0000288	5.25	0.160	64.4
Distance	2	0.0000072	0.0000072	0.0000036	0.65	0.65	8.05
Error	2	0.0000110	0.0000110	0.0000055			12.30
Total	8	0.0000894					

Table 8 shows that the sliding distance has the most significant influence on wear loss, with a contribution of 46.3%. Therefore, distance is a crucial factor to consider during wear phenomena. Following distance, sliding speed has a smaller impact at 26.33%, while the applied load affects wear loss the least, contributing only 12.6%.

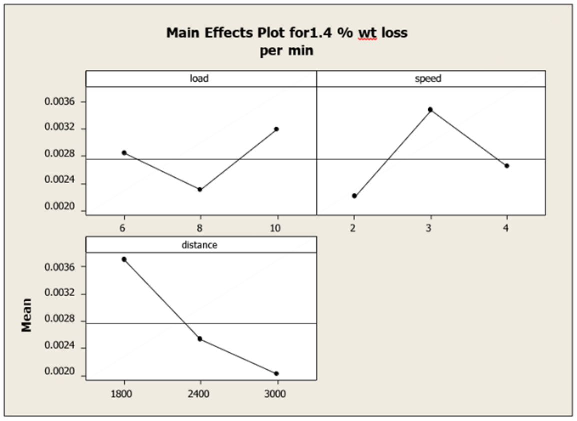

Fig 3: Main effects plot for means of weight loss

Figure 3 shows the influence of various factors on composite wear loss, using MINITAB-15 and data from Table 7. The load parameter has the most significant effect, initially reducing wear loss but causing it to rise later. The sliding speed impacts wear less noticeably: wear decreases at lower speeds, increases to a peak, and then decreases again.
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5.4 Mg-Al/Mg_2-Si reinforced with 2% Bismuth

Table 9: Orthogonal array L9 of Taguchi

Sl NO	Load(N)	Sliding speed(m/s)	Sliding distance(m)	Weight loss (gm/min)
1	6	2	1800	0.00132
2	6	3	2400	0.001984
3	6	4	3000	0.002066
4	8	2	2400	0.005430
5	8	3	3000	0.002250
6	8	4	1800	0.006248
7	10	2	3000	0.001575
8	10	3	1800	0.005250
9	10	4	2400	0.003455

Table 10: ANOVA results

Source	DF	Seq SS	Adj SS	Adj MS	F	P	p%
Load	2	0.0000122	0.0000122	0.0000061	2.22	0.311	43.2
Speed	2	0.0000021	0.0000021	0.00000010	0.38	0.725	7
Distance	2	0.0000084	0.0000084	0.0000042	1.53	0.395	29
Error	2	0.0000055	0.0000055	0.00000027			19.5
Total	8	0.0000282					

Table 9 reveals that the applied load has the greatest influence on wear loss, contributing 65.3%. Thus, load is a critical factor in wear phenomena. In comparison, sliding distance has a 10.2% impact, and sliding speed has a 20.4% impact, indicating that these factors are less significant.

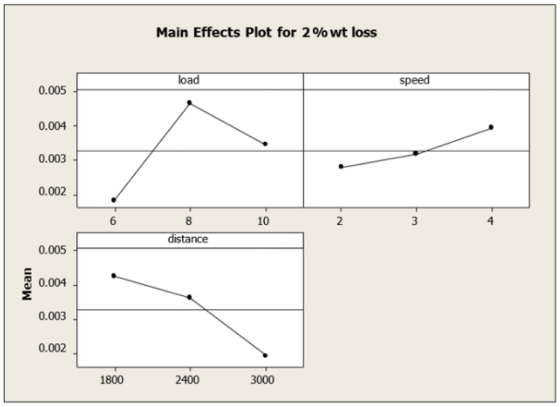

Fig 4: Main effects plot for means of weight loss

Figure 4 illustrates the main effects plot for wear loss, showing the influence of different parameters. In this plot, a nearly horizontal line indicates minimal effect, while a steeper incline signifies greater impact. Using MINITAB-15 software and data from Table 9, the analysis reveals that sliding speed significantly affects wear loss, with wear increasing as speed rises. The applied load initially increases wear loss up to 80 N but decreases at higher loads. In contrast, wear loss decreases as the sliding distance increases.

CONCLUSION

We assessed the dry sliding wear behavior of Mg-Al/Mg2-Si composites reinforced with various Bismuth percentages (0%, 0.7%, 1.4%, and 2%) using Taguchi's L9 orthogonal array. Our findings reveal that Bismuth content plays a crucial role in influencing the wear behavior of these composites. For composites without Bismuth, the applied load is the primary factor affecting wear loss, contributing 39.54% to the overall variation. Introducing 0.7% Bismuth shifts the significance to sliding speed, which accounts for 64.4% of wear loss variance. At 1.4% Bismuth, sliding distance becomes the key factor, responsible for 46.3% of wear loss. With 2% Bismuth, the applied load reemerges as the most influential factor, contributing 43.2% to wear loss. These results demonstrate that Bismuth content determines wear behavior in Mg-Al/Mg2-Si composites, with applied load generally being significant, while sliding speed and distance gain importance as Bismuth content increases. By adjusting wear parameters based on Bismuth levels, we can improve the wear resistance of these composites.

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