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Wear Test Parameters Optimization for Tribological Characteristics of AZ91D Magnesium Metal Matrix Composite Reinforced with Boron Carbide and Zirconia

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Abstract:

The wear behaviour of a stir cast hybrid magnesium matrix composite reinforced with nano zirconia (1 to 3 wt%) and 2 weight percent of nano boron carbide particles was examined using a pin-on-disk type tribometer at room temperature. Taguchi design based design of experiment was used to conduct the wear test. The variance analysis (ANOVA) was used to determine the impact of individual factor on composite wear performance. The wear characteristics were observed to be substantially influenced by the weight percent of reinforcements, load, and speed. The response surface methodology was used to create a mathematical model for wear and Coefficient of Friction, which were then validated by doing an experiment at the optimal level.

Keywords **—**AZ91D/B_4C/ZrO_2Hybrid composite, Boron Carbide, Zirconia, Taguchi Analysis, Optimization, Response Surface Methodology**.**

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I. INTRODUCTION

The automotive and aerospace sectors continuous quest for lighter materials has reawakened interest in low-density magnesium-based composites. Low density, enhanced specific strength, effective damping nature and better dimensional stability are all advantages of magnesium. However, Magnesium's poor wear resistance, intrinsic brittleness and poor thermal stability have restricted its use in piston-cylinder liners, as well as in a variety of real-time applications. The reinforcing particles particularly of nano-scales, are desired to increase the wear resistance of Mg matrix. Because a material's wear resistance is governed by its plastic deformation, nano-sized particles can develop strength and hardness, causing increased wear resistance. Several particles, including silicon carbide, alumina, titanium carbide, silicon nitride, boron nitrides and carbides, carbon fibers and nano tubes, graphite and others, can be fortified in Mg-matrix depending on the needs. The advancement of zirconia particle reinforcement has been the subject of extensive investigation. When associated to composites with other reinforcements, zirconia reinforced composites have a comparatively enhanced refractoriness, chemical resistance and abrasion proofed. Plastic deformation is not feasible in most magnesium composites. This is a constraint that can be circumvented by using nano-scale

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reinforcements. After investigating the effect of hybrid reinforcement on ductility and strength, several researchers have concentrated on it [1-3]. Atthisugan et al. employed a stir casting method to include graphite and boron carbide into AZ91D Magnesium Material, and discovered that this significantly improved the wear resistance of the nanocomposite [4]. To make the AZ91/ZrSiO4 composite, V. Mohanavel et al (2020) used the stir casting method. The mechanical characteristics and tribological behaviour are examined. Micro hardness was determined using a diamond indenter with a 2 second dwell period. A 10mm diameter specimen was employed in a pin-on-disk wear test. When compared to the AZ91 base alloy, the AZ91 alloy with 8% ZrSiO4 composite had a maximum tensile strength of 183 MPa, a high hardness of 71 HV, and improved wear resistance [5]. Madhusudhan M et al. looked into the effect of fortification of ZrO_2 particles on the mechanical characteristics of AA7068 aluminium alloy composites manufactured through stir casting. An increase in the weight percentage of Zirconia particles in composites resulted in a significant upgrading in the tensile strength and hardness [6]. J. Udaya Prakash et al. (2018) optimised the wear parameters of 413 Aluminum Alloy reinforced with 3%, 6%, and 9% B_4C using a taguchi-based grey relation analysis approach. The stir casting technique was implemented for the fabrication of composite. A dry sliding wear test was performed by means of a pin-on-disc testing equipment. Sliding distance and speed were the most important factors in determining the friction coefficient and wear rate. The Taguchi L27 orthogonal array was used in this work. ANOVA was used to examine the Grey Relation Grade. As the weight fraction of reinforcement rose, the matrix grain size shrank. The addition of carbides increased the hardness of the material [7]. Amandeep Singh et al. (2017) used a typical stir casting method to create a magnesium metal matrix composite reinforced with 3 to 12 percent B_4C. A steel disc with square cross-section pins was used to conduct a pin-on-disk wear test. The dispersion hardening generated by the carbide particles was discovered to be the explanation for the composite's improved wear resistance. Abrasion and adhesion were the main wear processes [8]. Due to the aggregation criteria of nanoparticles, fabricating nanocomposite is a tough task. Although powder metallurgy is more widespread, the fundamental issue with the ultimate product is porosity. In-situ salt route techniques and spray casting are also commonly used. Stir casting is becoming increasingly standardised due to its flexibility, ease of use and enormous production capabilities. This involves, melting the actual metal in a furnace and mixing it with the reinforcements, which are pre-heated. The liquefied slurry is then poured into the required shape. The foundation metal for this investigation is AZ91D magnesium alloy, which is one of the most common alloy groups among Mg alloys. Although this alloy has improved specific strength, good castability and stiffness, its wear properties are not sufficient. As a result, this alloy contains Boron carbide and Zirconia nanoparticles to improve wear resistance. A thorough analysis of the literature reveals that there are few publications on improving the wear properties of hybrid magnesium nanocomposite manufactured by stir casting. As a result, optimising the wear properties of Mg-ZrO_2-B_4C manufactured by stir casting is significant.

II. Experimental Details

A. *Work piece material*

The base metal in this research is AZ91D, and the reinforcements are nano Zirconia and nano boron carbide particles. Table 1 shows the basic composition of the AZ91D magnesium alloy. Nanoparticles have an average particle size of 100 nm. Nano composites were created in this study using a liquid state stir casting process. A steel crucible was used to melt the AZ91D pieces in the furnace and the temperature is set to 750°C in this procedure. Figure 1 depicts the furnace. To prevent magnesium from oxidation, composite samples were created in an inert gas atmosphere. Meanwhile, reinforcement particles are weighed and loaded into a tiny furnace that is connected to the main furnace and is intended specifically for pre-heating reinforcements. For an hour, the reinforcements were pre-heated at 350°C. To form a vortex, molten

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AZ91D is mechanically agitated at 600 rpm for 10-12 minutes. To make the composite, pre-heated reinforcements are poured and combined with the molten AZ91D alloy. The temperature of the furnace was held at 750°C at the time, and continuous stirring was performed. The liquid was then placed into a long-lasting mould. This method was repeated for three weight percentages of Zirconia nano powder (1 percent, 2 percent, and 3%), while Boron carbide is held constant at 2%. The cast nano-composites were processed further in order to obtain the desired samples.

TABLE I
COMPOSITION of AZ91D MAGNESIUM ALLOY in WEIGHT PERCENT

Al	Mn	Zn	Si	Cu	Fe	Ni	Others
8.3-9.7	0.15-0.5	0.35-1	0.1	0.03	0.005	0.002	0.02

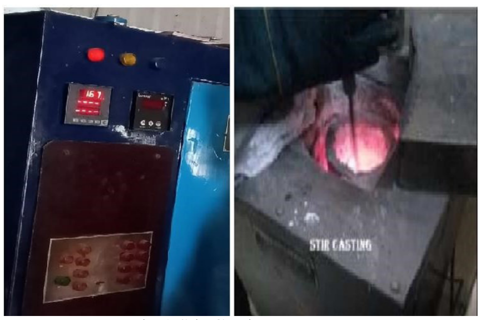

Fig 1 Stir Casting Furnace

TABLE II
DETAILS OF REINFORCEMENT

Sl.No.	AZ91D (%)	B_4C (%)	ZrO_2 (%)
1	100	0	0
2	97	2	1
3	96	2	2
4	95	2	3

B. Design of Experiment

Design of Experiment is a scientific method for obtaining the most conclusive knowledge from the least amount of data. The statistical approach plans the specifics of the experiment so that sufficient data may be collected, evaluated, and a legitimate conclusion can be formed. This method aids in determining the smallest number of parameter combinations and levels required to determine the main and interaction effects of chosen parameters on the output. Taguchi, grey relational analysis, Response surface approach, and more DOEs are available. Researchers will select an appropriate experiment design based on the circumstances. Taguchi design of experiments was employed in this study. Three input parameters at four levels were considered in this case. Table 3 summarises them.

TABLE III
WEAR TEST PARAMETERS AND THEIR LEVELS

Variables	Levels
Reinforcement (Wt.% of ZrO_2)	0, 1, 2, 3
Load (N)	4.905, 9.81, 14.715, 19.62
Speed (RPM)	200, 300, 400, 500

C. Experimental Set-up

At ambient temperature, dry sliding wear test of the developed Mg-B_4C-ZrO_2 composites was conducted on a Pin-on-Disk type triboteter (JNTUHCEH, Hyderabad, India). Figure 2 shows the Pin-on-Disk tribotester in operating order. Wear test was conducted on samples of 12 mm in diameter and 120 mm in length each. The samples were meticulously cleansed to ensure that the studies were conducted in a dry environment. This test uses a steel disc as the counter surface. Because the hardness of the disc material is substantially higher than that of the composite. The wear on the disc was ignored. To induce the desired load to the sample, a dead weight was put on the pan. All samples are subjected to the same wear test, with wear assessed by the dislocation of material from the test samples surface.

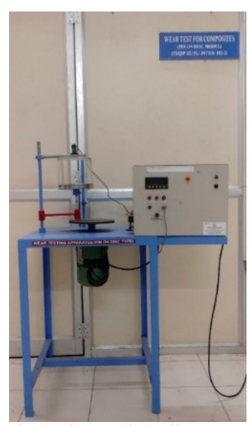
Fig. 2 Pin-on-disk tribotester

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III. RESULTS AND DISCUSSION

The experiments were conducted according to the Design of Experiments as suggested by Taguchi technique. The time period of each experiment was kept constant at 15 minutes and wear track radius was also kept constant at 0.070 meters. Subsequently, the average linear wear was 0.55, 0.3925, 0.18 and 0.3125 microns for 0%, 1%, 2% and 3% of ZrO_2 respectively. While the average COF was 0.4777, 0.4709, 0.4122 and 0.4262 for 0%, 1%, 2% and 3% of ZrO_2 respectively. The average linear wear improved by 62.27% while the Coefficient of Friction improved by 13.71% for (2% B_4C + 2% ZrO_2) compared to AZ91D magnesium alloy.

TABLE IV
OBSERVATION (L16 ORTHOGONAL ARRAY)

S.No	Specimen Material %Wt-B_4C	Load on Pin N	Speed RPM	Coefficient of Friction	Linear Wear μm
1	0	4.905	200	0.8000	0.51
2	0	9.810	300	0.4370	0.52
3	0	14.715	400	0.3760	0.53
4	0	19.620	500	0.2980	0.64
5	1	4.905	300	0.7900	0.35
6	1	9.810	200	0.4300	0.31
7	1	14.715	500	0.3390	0.44
8	1	19.620	400	0.3247	0.47
9	2	4.905	400	0.5410	0.14
10	2	9.810	500	0.4700	0.16
11	2	14.715	200	0.3010	0.19
12	2	19.620	300	0.3370	0.23
13	3	4.905	500	0.6200	0.30
14	3	9.810	400	0.4500	0.33
15	3	14.715	300	0.3600	0.25
16	3	19.620	200	0.2750	0.37

D. *Analysis of Variance*

To statistically assess the experimental outcomes and develop an effective regression model, ANOVA is used. MINITAB 19 was used to do ANOVA in this investigation. The results of the ANOVA analysis are shown in Table 4.

TABLE V
ANALYSIS OF VARIANCE FOR WEAR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Ref	3	0.287225	87.74%	0.287225	0.095742	75.59	0.000
Load	3	0.026925	8.22%	0.026925	0.008975	7.09	0.021
Speed	3	0.005625	1.72%	0.005625	0.001875	1.48	0.312
Error	6	0.007600	2.32%	0.007600	0.001267		
Total	15	0.327375	100.00%				

TABLE VI

MODEL SUMMARY

S	R-sq	R-sq(adj)
0.0355903	97.68%	94.20%

TABLE VII
ANALYSIS OF VARIANCE FOR COEFFICIENT OF FRICTION

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Ref	3	0.01262	3.11%	0.01262	0.004208	0.80	0.539
Load	3	0.35081	86.33%	0.35081	0.116938	22.16	0.001
Speed	3	0.01129	2.78%	0.01129	0.003763	0.71	0.579
Error	6	0.03166	7.79%	0.03166	0.005276		
Total	15	0.40638	100.00%				

TABLE VIII

MODEL SUMMARY

S	R-sq	R-sq(adj)
0.0726375	92.21%	80.52%

From the analysis of variance, it is observed that reinforcement and load are more influencing the wear and coefficient of friction respectively. The contribution of error was very limited.

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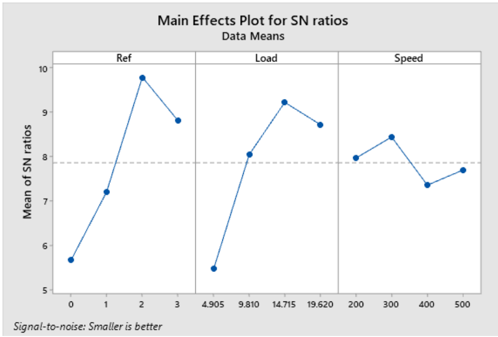

Fig. 3 Main effect plot for S/N ratio

From the Main effect plot for S/N ratio the highest values gives the optimal result. Consequently, reinforcement at 2 weight percent, Load at 14.715 N, and Speed at 300 RPM is the optimal level.

E. Development of Mathematical Models Using Response Surface Method

RSM uses statistical and regression techniques to objectively examine the system, analysing and optimising quantitative data gathered through a small number of tests. This method uses statistics to examine the relationship between input and output factors. This experimental technique is widely utilised in a variety of academic domains to statistically examine data. The response surface method was created primarily for the purpose of generating robust designs that are resistant to component variation and boosting output precision around a target value. Either a first or a second order model is considered while creating a regression model. The first order polynomial is used when a small region is chosen. When two independent variables are taken into account, a first order model is created.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i$$

The response of interaction terms from the first model is represented in the form of curvature. Depending on this, if the first order model is insufficient second order model is preferred.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j}^{k} \beta_{ij} X_i X_j$$

F. Mathematical models generated using Design Expert Software (RSM)

Wear=1.3165-0.155111xRef-0.10515xLoad-0.000416273xSpeed+0.00687587xRefxLoad+0.000169739xRefxSpeed+5.78746e-05xLoadxSpeed+0.00520625xRef^2+0.00213719xLoad^2-5.16875e^{-07}xSpeed^2

COF=0.74375-0.307841xRef-0.0250904xLoad-0.00079xSpeed+0.000463349xRefxLoad+2.72727e^{-05}xRefxSpeed+3.93847e^{-05}xLoadxSpeed+0.0725xRef^2+0.000727378xLoad^2+6.25e^{-07}xSpeed^2

For optimal level, the predicted Wear was 0.3308 microns. While, the predicted Friction Coefficient was 0.1729.

TABLE IX
VALIDATING THE MATHEMATICAL MODELS

	Predicted	Experimental	Error (%)
Coefficient of Friction	0.1729	0.1803	4.28
Wear Rate	0.3308	0.3410	3.08

According to the optimal level of parameters, confirmation experiment was conducted at 2% of ZrO_2 (2%ZrO_2+2%B_4C), 14.715 N Load, and 300 RPM Speed. The Coefficient of friction was found to be 0.1803, and Wear was found to be 0.3410 microns. The predicted value for coefficient of friction was 0.1729 while the Wear was 0.3308 microns respectively, which were calculated from the corresponding mathematical models developed using Response Surface Methodology in Design Expert 13 software.

An error of 4.28% was observed for COF while 3.08% error was observed for wear for experimental responses compared to the predicted parameters. This error might have been attributed due to the wobbling of disk, vibrations in the equipment, aging of the linear and frictional force sensors.

IV. CONCLUSIONS

The stir casting technique was used to create the AZ91D/B_4C/ZrO_2 hybrid metal matrix composite. The percentage of B_4C was kept constant for three test specimens while the percentage of ZrO_2 was varied. The subsequent conclusions were drawn from the experimental results. The reinforcement at 2 weight percent, Load at 14.715 N, and Speed at 300 RPM is the optimal combination of wear test parameters.The average linear wear improved by 62.27% while the Coefficient of Friction improved by 13.71% for (2% B_4C + 2% ZrO_2) compared to AZ91D magnesium alloy. Superior wear resistance was observe for the composite with 2% B_4C and 2% ZrO_2 reinforcements. The developed mathematical models were verified at the optimal level which showed very little deviation from the experimental results.

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