Taguchi's Orthogonal Array Approach to Study the Wear Behavior of Aluminium Alloy/Soda Lime Glass Composites

M.R. Shivakumar[1], N.V.R. Naidu[2]
[1]Assistant Professor, [2] Professor and Head
Department of Industrial Engineering and Management,
M.S.Ramaiah Institute of Technology, Bangalore-560054, India.

Abstract

Aluminium alloy based composites find applications, particularly where weight saving is mandated. This investigation aimed at developing and characterizing one such novel composite. Stir casting technique was adopted to produce soda lime glass powder reinforced LM6 alloy (Al-Si eutectic) metal matrix composites (MMCs). The pre-heated glass particles of average size 75, 125, and 210 micron, at three different levels (1.5, 3.0 and 4.5 wt %) were added as reinforcement to LM6 alloy to produce the composite test castings. Taguchi's orthogonal array approach was used to design the experiments. Wear property was evaluated for this class of composites. The significant factors influencing the weight loss in wear were identified. A regression analysis was employed to establish correlations between reinforcement parameters and the weight loss in wear.

Keywords: *Composite materials, glass particles, Al-Si alloy, Taguchi's orthogonal array.*

1. Introduction

The demand for materials possessing enhanced properties has been increase in the automotive and other sectors. As alloy development has almost reached saturation, the above demands have to be met by newer materials such as light metals based metal matrix composites. In metal matrix composites, tailoring of specific properties is achieved by incorporating a controlled amount of ceramic filler particles or fibres within a base metal matrix. A number of material combinations have been attempted and documented in the literature. Applications of metal matrix composites range from structural components to electronic packaging.

Aluminium and its alloy always are the first choices when weight reduction is called for. However, aluminium and its alloys suffer from the limitations of inadequate yield strength, low wear resistance and poor thermal properties. Substantial development work has been carried out on aluminium based MMCs with ceramics (silicon carbide, alumina, zirconia, silica and graphite) as the reinforcement [1]. However, the use of non-refractory materials such as glass powder as the reinforcement in MMCs has not been attempted extensively [2]. Compared to the other reinforcing materials in use, glass offers several advantages, in particular on the fronts of availability and cost. Likewise, several aluminium alloys have been investigated by previous workers as the matrix, but the most versatile cast alloy viz., Al-Si eutectic (LM 6 alloy) has not been exploited so much. Therefore, there seems to be ample scope and need to undertake an experimental investigation to produce LM6 based, glass powder reinforced MMCs and to characterize the MMCs thus produced for physical, mechanical and micro-structural properties.

In order to optimize the processing route in the shortest time, Design of Experiments (DOE) procedure can be readily adopted. The basic idea is that among all possible combinations of parameters, only some need to be actually tried, leading to significant reduction in number of tests and cost [3].

2. Experimental details

2.1 Materials

LM6 alloy was the matrix and soda lime glass powder was added as the reinforcement for the present investigation. The soda lime glass powder of required fineness was obtained after crushing and sieving commercially available soda lime glass sheets. The compositions of the base alloy LM6 and soda lime glass are shown in Table 1 and 2 respectively.

Pre-treatment of reinforcement particles consisted of cleaning the particles with alcohol and drying them before pre-heating. Pre-treatment and pre-heating of reinforcement improved wetting and dispersion of particles in the matrix. In addition, a small amount of magnesium (0.50%) was added to the melt to promote wetting of glass powder by the liquid alloy.

2.2 Preparation of the composites

Optimization of the process parameters and procedure was required to produce composite materials with homogeneous distribution of reinforcement particles and to get composites with minimum level of micro-structural defects. Extensive trials showed that the temperature of the matrix alloy before the introduction of glass powder is one of the important parameters [4]. Furthermore, the rate of introduction of the particles, pre-treatment of reinforcement and stirring parameters are also important to achieve good quality composites.

Table 1: Chemical composition of LM6 alloy

Element	Wt.%
Si	11.24
Cu	0.08
Mg	0.1
Fe	0.46
Mn	0.14
Ti	0.16
Ni	0.01
Zn	0.01
Lead	0.01
Al	Balance

Table 2: Chemical composition of commercial soda lime glass

Constituent	Wt.%
SiO_2	71-73
Na_2O_2	14-15
CaO	8-10
MgO	1.5-3.5
Al_2O_3	0.5-1.5

Pre-treated soda lime glass particles were dispersed into molten LM6 alloy using the stir casting vortex method. The mixing equipment consists of a driving motor to which was attached a stainless steel impeller, a lifting mechanism for the rotation drive unit and stirrer assembly. Approximately 2 kg of LM6 alloy ingots were charged into a graphite crucible and melted in a resistance heated furnace. When the melt reached 720^{o}C, which is well above the melting temperature of LM6 alloy, about 10 gm of magnesium was added in order to improve wetting. Dross was skimmed from the surface of the melt after treating with degassing agent hexa-chloro-ethene.

Melt was positioned under the stirrer which was lowered into the crucible. The melt was stirred at a fixed stirring speed of 400 RPM to form a sufficiently large vortex. Pre-heated soda lime glass powder was added at the rate of 20 gm per min. to the vortex point. After adding the particles, impeller was driven for some more time till the temperature of the melt lowered to 640^{o}C. Soon after, the melt mixture was poured into the mould pre-heated to 200^{o}C.

LM6 alloy/soda lime glass particles composites with 1.5%, 3.0% and 4.5% (weight fraction), and 75, 125 and 210 micron (average particle size) at different pre-heated temperatures (260 ^{o}C, 380 ^{o}C and 500 ^{o}C) of soda lime glass powder were produced using the above methodology.

2.3 Study of wear behavior

A pin-on-disk test apparatus was used to determine the dry sliding wear characteristics of the composite. The pin-on-disk test apparatus consists of a driving spindle with revolving disk, a lever arm and attachments to hold the pin specimen. Machined composite specimen (pin of 8 mm diameter and 30 mm height) was made to rub against the rotating hardened steel disk under controlled load. Weight loss during each test was obtained by weighing the pin specimen before and after each test (using electronic weighing scale with an accuracy of 0.1 mg after proper cleaning with acetone solution).

2.4 Design of Experiments

In most of the experimentation, scientifically planned experimental design is useful to reduce the research efforts, budgets and time. Design of experiments is a powerful tool for analyzing the influence of control variables on performance output. Statistically planned Taguchi's approach to design experiments is easy to adopt and apply. Hence it has gained wide popularity in the engineering and scientific community. LM6 alloy/soda lime glass particulate composites in this work were prepared with the three control variables viz., weight fraction, particle size and pre-heat temperature of reinforcement, each at three levels listed in Table 3.

Taguchi's orthogonal array (OA) for three factors (each at three levels) was used in planning the experimentation based on the degrees of freedom on levels of factors, L_9 (3^4) OA was selected. The L_9 array of Taguchi for the test is shown in Table 4. The influence of reinforcement parameters on weight loss was evaluated using Signal-to-Noise ratio (SN ratio) analysis.

SN ratio for ***'smaller is the better'*** quality characteristic = $-10 \log_{10} (1/n) \Sigma(y_i^2)$……….. (1) ('n' is the number of observation and 'y' is the observed data).

Table 3: Levels of the reinforcement parameters

Control factor	Level		
	1	2	3
A: Weight Percent	1.5	3.0	4.5
B: Particle size (micron)	75	125	210
B: Pre-heat temperature(^oC)	260	380	500

Fig 1: Pin-on-disk wear test equipment

Table 4: Taguchi orthogonal array L_9 (3^4)

Test Run	A: Weight Percent	B: Particle size (micron)	C: Temperature (^0C)
1	1.5	75	260
2	1.5	125	380
3	1.5	210	500
4	3.0	75	380
5	3.0	125	500
6	3.0	210	260
7	4.5	75	500
8	4.5	125	260
9	4.5	210	380

3. Results and Discussions

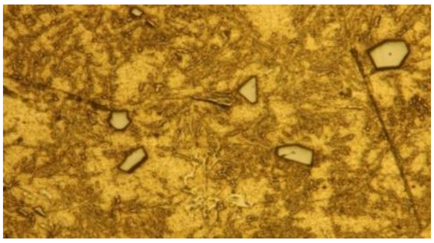
Nine samples of LM6 alloy/soda lime glass particles composites were produced using the design parameter combinations as per the L_9 (3^4) orthogonal array. The experimental runs were done each with three replications. Weight loss values were assessed and SN ratio was calculated for every run. Tests were carried out at a sliding speed of 7 m/s and sliding distance of 2100 m at three different load conditions viz. 10 N, 15 N and 20 N.

The mean weight loss in wear and the corresponding SN ratios are listed in Table 5, 6 and 7 respectively for the 3 different loads employed.

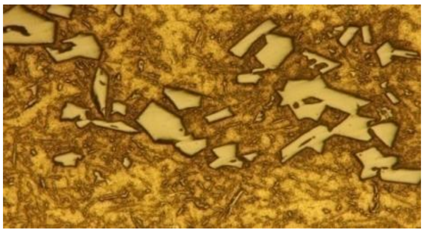
3.1 Microstructures

Micro-structural examination of the composite was conducted to confirm uniform distribution and interface bonding of reinforced glass particles in the LM6 alloy matrix. Typical microstructures are shown in Figs 2(a) and 2(b).

It may be inferred that glass particles are uniformly distributed in the LM6 alloy matrix. It may be observed that the cast microstructure of the LM6 alloy is not significantly affected by the presence of the reinforcing glass phase. In particular, no casting defect such as porosity was found at the interface between the glass particle and the matrix. This indicates that the glass particles are almost perfectly embedded inside the LM6 matrix without any interface de-bonding. This is due to adequate wettability between glass particles and LM6 alloy matrix.



(a) 1.5% glass reinforcement



(b) 4.5 % glass reinforcement

Fig 2: Microstructures of LM6 / glass composites, (100X)

3.2 Wear behavior

The results were analyzed using the commercial software MINITAB 14 specifically used for design of experiment applications. The influence of reinforcement of parameters on weight loss was then evaluated using SN ratio response table. The rankings of process parameters using SN ratios obtained for different parameter levels for weight loss are shown in Table 8, Table 9 and Table 10 respectively for 10 N, 15 N and 20N loads.

3.3 Main effect plot

Figures 3, 4 and5 show the main effects plots corresponding to the 3 loads viz., 10N, 15N and 20N. It may be seen that among all the factors, weight percent of glass powder is the most significant one, followed by particle size. Pre-heat temperature of the glass particle has the least or almost no significant influence on the weight loss. The weight loss of factor A is less at level 3 compared to levels 1 and 2. For factor B, at level 1, weight loss is minimum. The analysis of the responses based on SN ratio and means leads to the conclusion that factor combination A3B1C3 results in the least weight loss. The optimum combination of reinforcement parameter levels were selected by selecting the higher SN ratio values and the results are tabulated in Table 11. Results distinctly reveal that soda lime glass particles reinforcements do improve the wear resistance significantly.

Table 5: Experimental data with mean weight loss and SN ratio *(load: 10 N)*

Test Run	A	B	C	Observed values of Weight loss (g)			Mean Weight loss (g)	SN ratio (dB)
1	1.5	75	260	0.0041	0.0038	0.0041	0.0040000	47.9534
2	1.5	125	380	0.0040	0.0047	0.0042	0.0043000	47.3103
3	1.5	210	500	0.0044	0.0045	0.0043	0.0044000	47.1295
4	3.0	75	380	0.0045	0.0030	0.0024	0.0033000	49.3293
5	3.0	125	500	0.0035	0.0035	0.0036	0.0035333	49.0355
6	3.0	210	260	0.0034	0.0038	0.0042	0.0038000	48.3724
7	4.5	75	500	0.0020	0.0010	0.0015	0.0015000	56.1678
8	4.5	125	260	0.0010	0.0025	0.0022	0.0019000	53.9469
9	4.5	210	380	0.0012	0.0020	0.0031	0.0021000	52.9958

Table 6: Experimental data with mean weight loss and SN ratio (*load: 15 N)*

Test Run	A	B	C	Observed values of Weight loss (g)			Mean Weight loss (g)	SN ratio (dB)
1	1.5	75	260	0.0038	0.0045	0.0040	0.0041000	47.7220
2	1.5	125	380	0.0047	0.0047	0.0044	0.0046000	46.7407
3	1.5	210	500	0.0048	0.0047	0.0047	0.0047333	46.4962
4	3.0	75	380	0.0040	0.0035	0.0030	0.0035000	49.0599
5	3.0	125	500	0.0038	0.0035	0.0040	0.0037667	48.4680
6	3.0	210	260	0.0045	0.0044	0.0040	0.0043000	47.3197
7	4.5	75	500	0.0020	0.0021	0.0023	0.0021333	53.4040
8	4.5	125	260	0.0025	0.0026	0.0025	0.0025333	51.9246
9	4.5	210	380	0.0026	0.0032	0.0029	0.0029000	50.7212

Table 7: Experimental data with mean weight loss and SN ratio (*load: 20 N*)

Test Run	A	B	C	Observed values of Weight loss (g)			Mean Weight loss (g)	SN ratio (dB)
1	1.5	75	260	0.0040	0.0052	0.0046	0.0046000	46.6959
2	1.5	125	380	0.0062	0.0045	0.0043	0.0050000	45.8962
3	1.5	210	500	0.0050	0.0052	0.0058	0.0053333	45.4424
4	3.0	75	380	0.0043	0.0044	0.0036	0.0041000	47.7117
5	3.0	125	500	0.0043	0.0041	0.0041	0.0041667	47.6020
6	3.0	210	260	0.0045	0.0048	0.0042	0.0045000	46.9229
7	4.5	75	500	0.0025	0.0030	0.0030	0.0028333	50.9241
8	4.5	125	260	0.0030	0.0033	0.0031	0.0031333	50.0730
9	4.5	210	380	0.0035	0.0031	0.0036	0.0034000	49.3529

Table 8: Response Table - S/N Ratios for weight loss (10N load)

Level	A	B	C
1	47.46	51.15	50.09
2	48.91	50.10	49.88
3	54.37	49.50	50.78
Delta	6.91	1.65	0.90
Rank	1	2	3

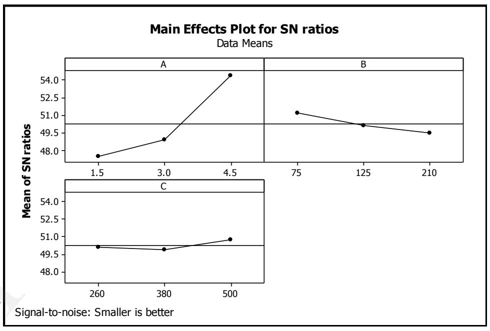


Fig 3: Main Effects Plot (Data Mean) for SN ratios (Load: 10 N)

Table 9: Response Table- S/N Ratios for weight loss (15N load)

Level	A	B	C
1	46.99	50.06	48.99
2	48.28	49.04	48.84
3	52.02	48.18	49.46
Delta	5.03	1.88	0.62
Rank	1	2	3

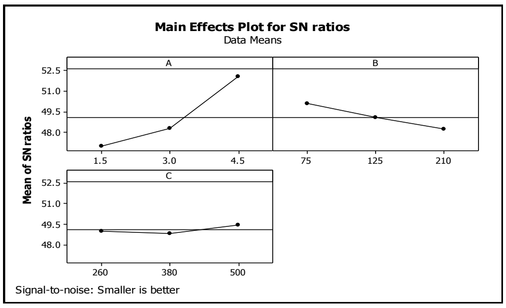


Fig 4: Main Effects Plot (Data Mean) for SN ratios (Load: 15 N)

Table 10: Response Table -S/N Ratios for weight loss (20N load)

Level	A	B	C
1	46.01	48.44	47.90
2	47.41	47.86	47.65
3	50.12	47.24	47.99
Delta	4.11	1.20	0.34
Rank	1	2	3

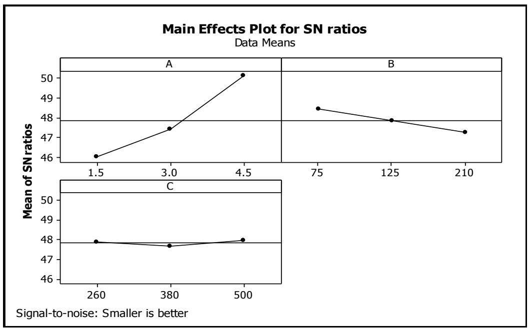


Fig 5: Main Effects Plot (Data Mean) for SN ratios (Load: 20 N)

Table 11: Optimum level of reinforcement parameters for weight loss.

Sl. No.	Load (N)	A: Weight Percent	B: Particle size (micron)	C: Temperature (^0C)
1	10	4.5	75	500
2	15	4.5	75	500
3	20	4.5	75	500

3.4 Regression Analysis

The weight percent, particle size and temperature of glass particles were considered in the development of mathematical models for weight loss. The correlation between factors and weight loss on LM6 alloy/soda lime glass composite was obtained through multiple linear regressions. The standard commercial statistical software package MINITAB was used in the model.

The regression equation developed (for 10 N load):
Weight loss (g) = 0.00526 - 0.000800 A + 0.000004 B - 0.0000001 C
[R^2 = 94.2%]

The regression equation developed (for 15 N load):
Weight loss (g) = 0.00501 - 0.000652 A + 0.000005 B - 0.0000001 C
[R^2 = 95.5%]

The regression equation developed for 20 N load:
Weight loss (g) = 0.00536 - 0.000619 A + 0.000004 B + 0.0000001 C
[R^2 = 97.8%]

In multiple linear regression analysis, R^2, the regression coefficient has values > 0.94 in all the models. This indicates that the fit of the experimental data is highly satisfactory. From the regression equation, it is observed that the weight percent of glass particles plays an important role in controlling weight loss, followed by glass particles size. The negative value of the co-efficient of the weight percent of glass particles indicates that increase in weight percent of glass particles decreases the weight loss.

3.5 Confirmation Experiment

The experimental confirmation test is the final steps in verifying the results drawn based on Taguchi's design approach. Accordingly, a confirmation experiment was conducted on LM6/soda lime glass composite prepared with optimal levels of the reinforce parameters obtained from the analysis (viz., A3B1C3). The pin-on-disk wear test was carried out at the sliding speed of 7 m/s for a sliding distance of 2100 m with the load of 10 N, 15 N and 20 N. Table 12 shows the results obtained from the regression equation and experimental results. The weight loss in the optimal levels of parameters of composite is minimal as compared to the other combinations of reinforcement parameters. The experimental value of weight loss compares well with the weight loss calculated using the regression equation (the percentage variation is only less than 7%).

Table 12: Comparison of confirmation experiment and Regression equation

Sl. No.	Load (N)	Experimental weight loss (g)				Regression model Weight loss(g)	% Error
		Observed values			Mean		
1	10	0.0020	0.0016	0.0018	0.00180	0.00191	-6.1
2	20	0.0021	0.0021	0.0026	0.00227	0.00240	-5.7
3	30	0.0025	0.0030	0.0027	0.00273	0.00292	-7.0

4. Conclusions

1. Successful fabrication of glass particles reinforced LM6 alloy MMC is possible by stir-casting techniques.
2. Taguchi's SN ratio approach, adopted to analyze the effect of the reinforcement parameters, has lead to reliable results on wear loss of the MMCs.
3. Soda lime glass particles reinforcement considerably improves the wear resistance of the base alloy.
4. Identification of the optimum combination of reinforcement parameters (in order to realize minimum weight loss) has been proved to be a possibility.
5. Confirmation tests carried out to validate the accuracy of the analysis justify the outcome of the investigation.

6. Regression equations developed in this work predict the wear loss of the MMCs corresponding to varying reinforcement parameters with reasonable accuracy.

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