Wear performance optimization of stir cast Al-TiB$_2$ metal matrix composites using Taguchi design of experiments

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Abstract. The present study outlines the use of Taguchi parameter design to minimize the wear performance of Al-TiB$_2$ metal matrix composites by optimizing tribological process parameters. Different weight percentages of micro-TiB$_2$ powders with average sizes of 5-40 micron are incorporated into molten LM4 aluminium matrix by stir casting method. The wear performance of Al-TiB$_2$ composites is evaluated in a block-on-roller type Multitribo tester at room temperature. Three parameters viz. weight percentage of TiB$_2$, load and speed are considered with three levels each at the time of experiment. A L27 orthogonal array is used to carry out experiments accommodating all the factors and their levels including their interaction effects. Optimal combination of parameters for wear performance is obtained by Taguchi analysis. Analysis of variance (ANOVA) is used to find out percentage contribution of each parameter and their interaction also on wear performance. Weight percentage of TiB$_2$ is forced to be the most effective parameter in controlling wear behaviour of Al-TiB$_2$ metal matrix composite.

1. Introduction

Metal matrix composites (MMCs) are mainly composition of more than two or two phases which are discrete both chemically and physically and phases are distributed such a way that provides some important properties which cannot be achievable by individual phase [1]. In case of MMCs, generally a matrix phase is obtained using metal or metallic alloys and ceramic or metallic particulates are used as reinforcement. As matrix, aluminum, magnesium, titanium alloys are mainly used [2]. Among MMCs, aluminum (Al) based metal matrixes are more popular for usage as wear resistant components in automobile or components used in extremely abrasive, corrosive environment like chemical, aerospace industry [2-4]. In comparison to conventional base alloys or metals, MMCs also able to provide improved strength, high elasticity, high stiffness but fabrication of MMCs are mostly challenging and important part over others [5]. Challenges are getting compatibility between matrix phase and reinforced particulates and also in the unvarying distribution of particulates over total matrix phase. To fabricate Al-TiB$_2$ metal matrix composites, among many processes in-situ techniques are common which is based on solid-solid reaction process [6]. But, TiB$_2$ has agglomerating behavior and it reduces the chance of uniform distribution of TiB$_2$ particles over the matrix phase in case of in-situ techniques. This agglomeration of TiB$_2$ also has calamitous effects to the properties of as cast Al-TiB$_2$ composites due to segregation in the grain boundary by agglomerated TiB$_2$ particles [7-8]. Stir cast method under broad genre of liquid metallurgy techniques is most economical, competent to eradicate snags of in-situ techniques, simple and adaptable for large quantity production, outstandingly

productive for net-shaped or near-net shaped components compare to other fabrication routes for Al-TiB_2 composites [9-10]. LM4 is an alloy which shows good castability and LM4 is widely used for commercial purpose through casting. It contains some amount of copper and silicon and shows low fluidity, low wear resistance and low strength to weight ratio.

Reinforcement of ceramic particulates in aluminum alloy base metal is commonly and also for some cases commercially accepted practice as the reinforcement increases tribological properties, hardness, and stiffness like some other desired properties of the base alloy. SiC, TiB_2, B_4C, Al_2O_3, AlN, ZrB_2 are the most common ceramic reinforcement for aluminum alloy [11-12]. In many literatures, it is found that TiB_2 reinforced aluminum based metal matrix composites are acceptably good mechanical and tribological properties holder in comparison to aluminum based metal matrix composites reinforced with particulates other than TiB_2 [13]. TiB_2 is less reactive with molten aluminum which causes almost no brittle reaction product in the interface. As well as TiB_2 holds excellent properties like high Elastic Modulus, high hardness, low density, and high wear resistance. TiB_2 reinforced aluminum alloy MMCs are used as crucible in chemical industry, wear resistant parts in ceramic, aerospace industry. That's why wear resistant properties are very desirable for TiB_2 reinforced MMCs [14].

Wear is a specific property of material which is denoted by removal or loss of the material from surface due to relative motion between a surface and the contacting substance or substances. Wear test can be performed in dry as well as in lubricating conditions. Wear is an important characteristic of tribology and often determines service life of the device through its mechanism. Hence, except in some narrow and specific cases, wear is an undesired occurrence so it should be minimized. Sliding wear behaviour of TiB_2 reinforced Al matrix composites at elevated temperature and normal temperature was studied in 2009 [15]. In that same year sliding wear behavior of T6 treated A356-TiB_2 was studied [16]. Wear prediction of Al-TiB_2 metal matrix composites was also done in 2014 by using response surface methodology [17]. But study on wear behavior of stir cast Al-TiB_2 metal matrix composites and also on optimization of process parameters to minimize the wear performance is really scanty. Present study tries to find out the acceptable parameters for optimum wear performance of Al-TiB_2 composites by using the application of Taguchi method.

Taguchi technique has been established as a robust tool for the design of high quality systems. In Taguchi method, robust parameter design is used to get quality improvement. Noise is an uncontrollable phenomena in many of the systems so system should be sensitive towards noise which can be achieved by minimizing variation and it is attained by installing robust parameter design which includes product and process design altogether. Optimal condition is obtained through Taguchi method by observing the reduction in variation of the results and the results are obtained within a specific trial condition which is determined by orthogonal array system. The sensitivity of a system to give output without significant variation is termed as quality characteristics and to identify this, Taguchi method uses the Signal to Noise (S/N) ratio by taking into account the variation of results for applied engineering problems [18].

In this study, wear performance is measured using Taguchi orthogonal design with three design parameters viz. Weight percentage (wt %) of TiB_2, Load and Speed. A block on roller type multitribotester is used to find out the coefficient of friction. Taguchi analysis is applied to find out the optimum combination of parameters that yields optimum (minimum) wear. Analysis of variance is carried out to observe the level of significance of individual factors and their interactions. The worn surface morphology is studied using SEM to observe the wear mode

2. Experimental Procedure

LM4 is used in this study as the base metal and the details of the composition are given in Table 1. Average size of TiB_2 particles varies from 5μm to 40μm. In this study stir casting method is used to fabricate composites. In this method, LM4 ingots are placed inside the chamber of Electric Resistance Arc Furnace. Then, ingots are heated to 800 C. TiB_2 particles are preheated at 600 C in a separate muffle furnace. Molten LM4 is stirred by a mechanical stirrer which is connected with furnace and

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stirring is performed for 5 minutes. The rotational speed of stirrer is determined at fixed speed through use of a controller. Fixed speed for stirring is held at 500 rpm. TiB_2 powder is preheated before adding it to the vortex of the molten alloy manually. Stirring process is responsible for creating this vortex. At the time of mixing, the temperature is kept stable around 800$^{°}$ C. After adding of preheated TiB_2 powder to the molten metal, metal is stirred for 15 minutes at 500 rpm rotational speed to ensure the homogenous nature of mixture. The mixture is then cooled at room temperature after pouring into a proper mould. This procedure is repeated for various weight percentages of TiB_2 particles (wt %) (1%, 2.5%, 4%, and 5.5%). Total four different composites are prepared with four different weight composition of TiB_2.

Table 1. Chemical composition of LM4 alloy.

Element	Wt%
Cu	3.2
Si	6
Mg	0.05
Fe	0.6
Mn	0.4
Ni	0.2
Zn	0.15
Al	remaining

Design parameters are such factors in an engineering problem which can be varied as well as controlled suitably to obtain the desired performance. The tribological performance of the fabricated Al-TiB_2 metal matrix composites can be controlled by a quality number of factors. A survey of the current literature reveals that the testing parameters viz. wt% of TiB_2 (A), load (B) and speed (C) (Table 2) can be easily controlled and are also popular among researchers to govern the tribological performance of specified composites. Based on Taguchi method an orthogonal array (OA) is assigned for performing experiment in a reduced number to find out optimal condition. In the present case each interaction is associated with four degree of freedoms. Therefore the total degree of freedoms for a three level design with three main parameter and three interactions is equal to eighteen. Total number of experiments must be greater than total degree of freedoms. So, in this study (Table 2) L27 OA has been used for experiment.

Table 2. Design factors and their levels.

Design factors	Unit	Level1	Level2	Level3
Wt% of TiB_2 (A)	%	2.5	4	5.5
Load (B)	N	25	50	75
Speed (C)	Rpm	400	500	600

In air at room temperature dry wear tests are performed (25°C) in a block-on-roller Multi-tribotester (TR 25, DUCOM, India). Dimensions of used test specimens are 20mm×20mm×8mm. A dead-weight system is used for loading of the composite block with previously mentioned dimensions against the roller. The specimens and disc are washed properly before operation to confirm that the wear tests are carried out under proper dry condition. The roller material is EN8 steel. The hardness of the roller material is comparatively much larger than the specimens for testing which leads to neglect the wear of the roller surface. Wear is measured in terms of displacement (microns).

After performing tests, a polynomial model is generated; statistical analysis of variance (ANOVA) is performed. Taguchi method is applied to find out the optimal combination of parameters and their levels. The statistical analysis is performed using MINITAB 14 statistical software package.

3. Results and Discussions

Taguchi method takes account the variability within the trial condition so outputs are converted into S/N ratios as a value for evaluation characteristics. S/N ratio is also a statistical measure of performance for Taguchi method. The idea is to maximize the S/N ratios so that effects of random factors will be minimized. In this study, as wear performance has to be minimum, smaller is better type criterion is used for calculating S/N ratios. Equation used for calculation of S/N ratio is expressed below.

$$S/N = -10\log\left(\sum y^2/n\right) \tag{1}$$

Here in this equation (1), y is the observed data. Total number of observation is denoted by n. Table 3 represents the values of wear according to the design matrix and their S/N ratios.

Table 3. Experimental results and S/N ratios

Serial No	Wear (micron)	S/N ratio
1	124.611	-41.9111
2	132.245	-42.4276
3	147.124	-43.3537
4	135.127	-42.6148
5	151.247	-43.5937
6	168.471	-44.5305
7	149.528	-43.4945
8	173.673	-44.7946
9	202.476	-46.1275
10	194.763	-45.7901
11	219.411	-46.8252
12	235.785	-47.4503
13	211.679	-46.5136
14	238.124	-47.5361
15	272.145	-48.6960
16	234.431	-47.4003
17	284.147	-49.0709
18	302.145	-49.6043
19	212.516	-46.5478
20	248.625	-47.9109
21	264.033	-48.4332
22	239.458	-47.5846
23	278.679	-48.9021
24	302.547	-49.6159
25	288.245	-49.1952
26	310.214	-49.8332
27	342.324	-50.6887

Difference of the largest value from the lowest from among the values in each column is termed as delta values. Table 4 represents the delta values of S/N ratios for each factor and their levels. It is found from table 4 that wt% of TiB_2 holds highest delta value which directs that it has the greater influence on wear performance of composites over others.

The influence of each design factor on the wear behavior can be analyzed with the main effects plot and interaction plot. Best combination of the factors and their levels can also be easily evaluated from these plots. If the line for a design factor is nearly horizontal in the main effects plot, than that factor has a little contribution in the output. If line for any factor has the highest inclination, that factor has greater effect on output. Optimal combination of factors and their levels are also determined from the table 4. The optimum combination is level 3 (5.5%) of wt%, level 1 (25N) of load and level 1 (400 rpm) of speed as the S/N ratios of these combinations are minimum.

Table 4. Response table for S/N ratios

Level	Wt%	Load (N)	Speed (rpm)
1	-48.75	-45.63	-45.67
2	-47.65	-46.62	-46.71
3	-43.65	-47.8	-47.61
Delta	5.10	2.17	1.94
Rank	1	2	3

Figure 1 shows the main effects plot for S/N ratio of the parameters effecting wear performance of the composites. In case of main effects plot for S/N ratio, highest point for each factor will show the best level. It is evident from the figure that wear decreases with the increase in weight percentage, but increases with load. From the inclination of the graph in figure 1, it is easily said that rotational speed and load has less contribution in the output in comparison to weight percentage of TiB_2. Weight percentage has highest contribution as the inclination is the highest. The reason behind decreasing wear with increasing wt% of TiB_2 may be due to maximum work hardening experienced by the Al-matrix in the composite with higher amount of TiB_2 particles. When load increases, wear in case of each specimen increases. In this case reason is obvious that more force is applied on the specimen. The relationship observed between rotational speed of the roller and wear is like the relationship of load. With more rotational speed of roller more wear observed.
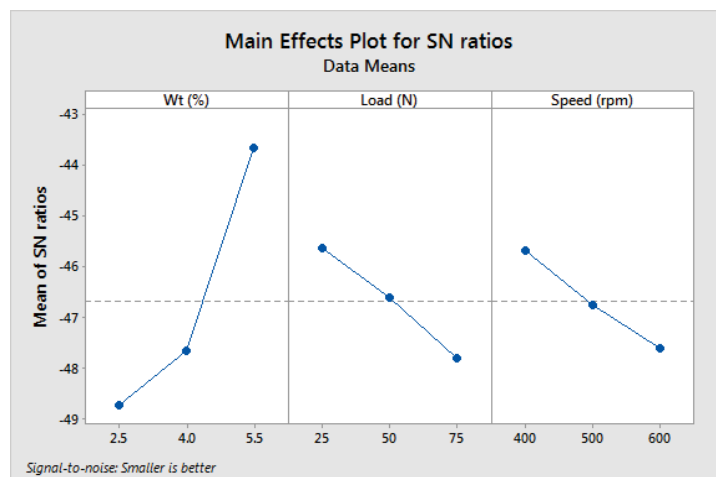

Figure 1. Main effects plot for S/N ratios for wear performance

Figure 2 represents the two way interaction plot for coefficient of friction. If the lines on the interaction plot are non parallel, interaction happens. If the lines of interaction cross each other, strong

interaction occurs between factors. So, in figure 2, plot shows that lines are non-parallel but they are not crossing each other. It can be said that interaction happens but effect of interaction on wear performance is small.
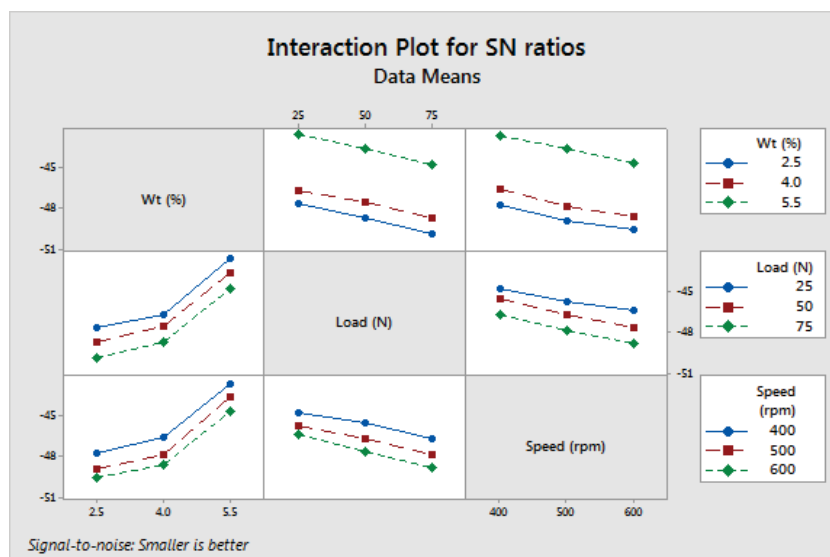

Figure 2. Interaction plots for wear behavior.

To find out the significance of each individual process parameters and their interactions on the system response, an efficient statistical tool is used which is named as ANOVA. In the present study, ANOVA is applied by considering an objective which is to evaluate the significance of parameters and their interactions on the wear performance of composites. Table 5 shows the result of ANOVA with the wear performance of as cast composites. Percentage contribution of each factor is showed in the last column of the table. Weight percentage (72.5%) and load (14.45%) are the main controlling factors on the wear behaviour. Contribution of speed (11.14%) as design factor is also significant. But in the case of interactions, they have very little contribution in the outputs. This behaviour of interactions is also seen in the case of interaction plot graphs (figure 2) previously.

Table 5. Results of ANOVA

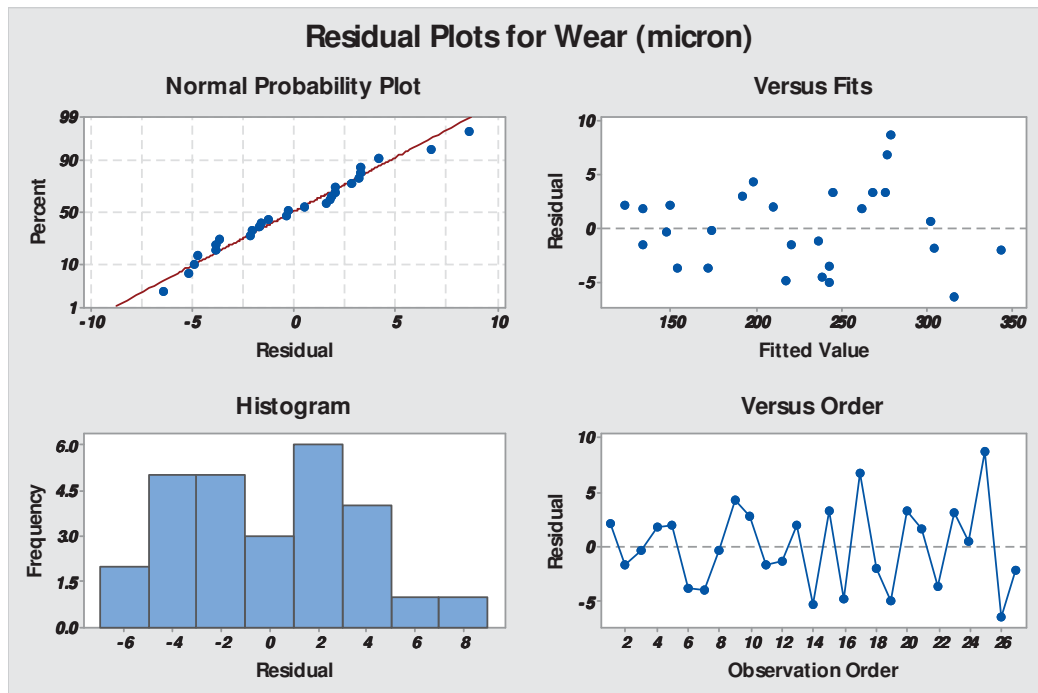| Source	Dof	Adj SS	Adj MS	F-value	Contribution
Wt%	2	72378.7	36189.3	782.59	72.5%
Load (N)	2	14435.1	7217.5	156.08	14.45%
Speed (rpm)	2	11123.2	5561.6	120.27	11.14%
Wt% * Load (N)	4	736.8	184.2	3.98	0.73%
Wt% * Speed (rpm)	4	468.9	117.2	2.54	0.46%
Load (N) * Speed (rpm)	4	319.5	79.9	1.73	0.32%
Error	8	369.9	46.2		
Total	26	99832.1			

Figure 3. Residual plots for wear depth (micron)

The coefficient of determination (R^2) for wear behaviour is 99.63%. A relationship between all three factors also has been found. Figure 3 shows the residual plots of wear behaviour which determines the adequacy of the model). The difference between experimental values and predicted values is called as residuals. Points randomly scattered in residual versus fitted value graphs determine that errors are negligible having constant variance [19]. In the graph of normal probability plot points are very close to the line which means errors are negligible and also in residual versus fitted value, points are randomly scattered. These two points are sufficient to show the adequacy of the mathematical model.

SEM micrograph of the worn surface after wear testing is shown in figure 4. In the figure, there are debris also and the nature is like abrasive wear. The same trend in SEM images is observed for other combinations of parameters within same experimental condition considered in this study.

4. Conclusions

Wear tests are performed on Al-TiB_2 composites fabricated through stir cast process. Weight percentage of TiB_2 reinforcement, applied load, and rotational speed of the roller are the three factors under which wear behavior are tested in multi-tribotester machine. Statistical analysis has been done on the experimental outputs and following conclusions have been drawn.

- Wear of Al-TiB_2 composites decreases with the increase of weight percentage of TiB_2 as reinforcement and increases with load. With increase of speed, wear increases.
- Taguchi method is applied to evaluate the wear behavior of composite. A model has been developed with coefficient of determination value (R^2) 99.63% so that wear values can be predicted with the same condition.
- Based on ANOVA results and Taguchi analysis, weight percentage of TiB_2 is the most effective parameters for controlling wear behavior. It has 72.5% contribution in the total variance of the result. Next significant factor is load for controlling output. It shows 14.45% contribution. Speed has 11.14% contribution and in significance it is last among three.

Interaction of all three factors and their effect on wear behavior is negligible compare to individual factors.
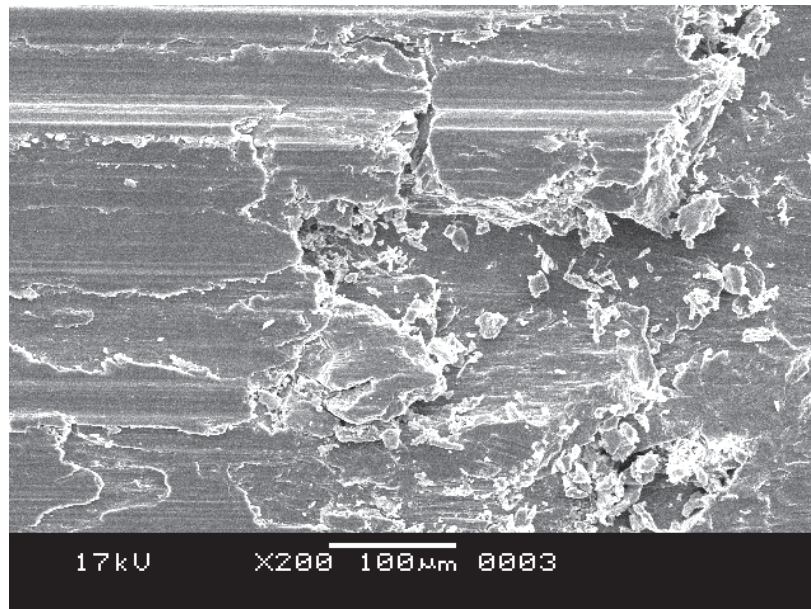

Figure 4. SEM images of the worn out surface of the composite.

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