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Optimization of dry sliding wear properties ofAZ91E/ nano Al_2O_3 reinforced metal matrix composite with grey relational analysis

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Abstract

The present paper examined the dry sliding wear behaviour of Al_2O_3-reinforced magnesium composites which are produced with semi solid stir casting method through a pin-on-disc sort of wear arrangement. The specimens of AZ91E - Al_2O_3 reinforced metal matrix composites (MMCs) are made to slip against a steel counterpart and have undergone dry sliding wear tests. So as to assess the dry sliding behaviour, the wear rate and friction force have been selected as responses and varied percentages of reinforcement, loads, sliding distances and velocities have been chosen as the control variables. The experimental design was carried out making use of an L9 orthogonal array. Grey relational analysis (GRA) was the method employed in the initial stages of the optimization of the dry sliding performance of the Al_2O_3-reinforced MMCs. For the whole grey relational grade, wear rate and friction force resulted as the optimum level parameters based on the GRA. To conclude, the SEM images (scanning electronic microscope) are taken to examine the wear surface morphology and wear mechanism of the composites. The analysis shows optimal parameter combination is determined as sliding velocity: 1m.sec^{-1}, sliding distance: 500m, applied load: 10N, and % of reinforcement: 1%.

Keywords: Magnesium , AZ91E, grey relational analysis, metal matrix composites, Al_2O_3 particulates, Taguchi.

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1. Introduction

Metals and alloys have been most widely exercised due to their functional and resourceful nature. Small percentage of decrease in wear probably is cost effective. Wear is one of the removals of materials from a surface, but wear system with few exceptions is the process of eliminating materials which has not been observed directly. Contrasting unreinforced metals MMCs acquire higher wear resistance. The level of improvement of wear resistance of MMCs is highly dependent on the type of reinforcement in addition to its volume fractions (Miyajima and Iwai, 2003). For the progress of the wear resistance of MMCs, particle reinforcement is most advantageous when compared to whiskers and fibers. Caused by enormous surface damage and material transfer to the counter face of composites, the wear rate along with the matrix alloy increases rapidly beyond a critical load. At the maximum sliding velocity, abrasion and adhesion were principal wear mechanisms with a transition to thermal softening (Zhang et al., 2010).

A continuous research analysis on the behaviour of wear on magnesium alloy matrix composites is in progress. It has also analyzed that its performance is related on the amount of reinforcement w.r.t. mechanical properties (Yao et al., 2010; Girish et al., 2015). It has been observed that the addition of Al_2O_3 to AZ91E matrix by semi solid stir casting method yielded improved properties than monolithic material, still the wear behaviour is an issue in overall product development (Sameerkumar et al., 2016). It is observed that more purposeful factors on mechanical as well as wear properties of composites are brought forth when reinforced with the same quantity of nano sized particles than micron ranged particles (Lim et al., 2005; Cao et al., 2008). Supplementation of Al_2O_3fibers in AM60 alloy may boost the wear resistance by converting it from slight to severe wear (Banerji et al., 2012).

Over the last two decades the study on Mg based MMCs was confined when compared to abundance Al MMC research, regardless of the potential of Mg based MMCs. There is need for further research on tribological properties of materials like Al MMCs. Numerous engineering applications encounter severe wear problems as for example in bearings, moving parts, engine parts, etc (Sameerkumar et al., 2015). There are several instances like piston -cylinder arrangement, steering rod and steering wheel interface under dry or lubricated circumstances magnesium alloys come in contact with other materials either by sliding or reciprocating. In engineering research Taguchi method is extensively used dominant tool to design a superior quality system.

A unique design of orthogonal array is used by the Taguchi method to examine the consequences of parameters through a minimum number of experiments. Now-a-day's Taguchi method is extensively used in enormous engineering applications, research projects and industrial areas. Taguchi technique is an effectual one in the exploration of the outcomes of many factors on performance as the time needed for experimental analysis can be radically minimized. It is also effective to decide the impact of various independent factors. For any testing procedure the determination of preferred testing parameters can be decided either by referring to a handbook or to personal experiences. However, the optimal testing parameters for a specific situation are not provided. The selection of appropriate testing or cutting conditions is grounded on several mathematical models based on statistical regression techniques (Sahin, 2003).

In regular practice, dealing with highly associated multi-response problems seems to be difficult. Multi-objective optimization problems are unfeasible to resolve using the traditional Taguchi method. When grey relational analysis and Taguchi method are coupled this problem can be effortlessly sorted out. Earlier, to evaluate the best possible process parameters of a distinct quality feature Taguchi Method was employed, as it focused on optimizing a single quality response (Balasubramanian and Ganapathy, 2011). Sometimes, in processes products have many quality responses that are to be considered. The Taguchi method elementarily applies engineering verdict to determine most advantageous factor levels for multi-responses, which augments uncertainty while the process of decision-making which can be solved through the grey system theory by Deng (1989). To vary multiple quality characteristics, the assimilation of grey relational analysis and the Taguchi Method was suggested by Chen et al. (2000). This integrated method alters the characteristics of multiple quality into distinct grey relational grades. The relevant quality characteristic arrays are acquired in comparison with the computed grey relational grades.

Henceforth a feasible set of process parameters with response grades are preferred. This effort examines the optimum conditions of the dry sliding performances on Al_2O_3 -reinforced Mg-MMCs applying grey relational analysis. Nine dry sliding wear experiments were performed by altering control variables like Sliding Velocity (V), reinforcement percentage (R), sliding distance (D), and Applied Load (L). This research asserts to resolve the optimum blend of these control variables.

2. Experimental Set Up and Procedure

The casting methodology and the basic characterisation was reported in the earlier work (Sameerkumar et al., 2016; Tarasasanka et al., 2016). To determine the wear behaviour of the proposed composite,i.e design of experiments methodology is used in the present study. A detailed description of design of experiments along withtest set up to carry out the experimentation is discussed in this section.

2.1 Design of Experiments

According to the standard orthogonal array the tests are carried out. The choice of the orthogonal array rests up on the state that the degrees of freedom for the orthogonal array ought to be superior to or equal to the sum of those wear parameters (Tarasasanka and Ravindra, 2017). In the existing survey, an L9 orthogonal array is selected contains 4 columns and 9 rows which was described earlier in the paper of the authors (Tarasasanka and Ravindra, 2017). The parameters of wear opted for the testing are load (L), sliding distance (D), sliding velocity (V) and reinforcement percentage (R). Table 1, denotes the levels of the corresponding factors and the L_9 orthogonal array is shown in Table 2. The outcome to be observed is that the smaller amount of wear gives better objective (Ghetiya et al., 2016).

Table 1. Control factors and corresponding levels

Parameter	Symbol	Units	Level 1	Level2	Level 3
Sliding Velocity	*V*	m/sec	1	3	5
Sliding Distance	*D*	m	500	1000	1500
Applied Load	*L*	N	10	15	20
%of Reinforcement	*R*	%	1	2	3

Table 2.Layout of orthogonal array.

L_9 Orthogonal array								
	Independent Variables				Reflection of Parameters from Table 1			
Experiment No.	S	L	D	R	S	L	D	R
1	1	1	1	1	1	10	500	1
2	1	2	2	2	1	15	1000	2
3	1	3	3	3	1	20	1500	3
4	2	1	2	3	3	10	1000	3
5	2	2	3	1	3	15	1500	1
6	2	3	1	2	3	20	500	2
7	3	1	3	2	5	10	1500	2
8	3	2	1	3	5	15	500	3
9	3	3	2	1	5	20	1000	1

2.2Experimental Setup

A 40mm long and 6mm diameter samples (Figure 1) were machined out from castings using wire EDM are used for performing the tests. A pin-on-disc wear testing machine was shown in Figure 2 (M/s DUCOM, Bangalore, India) with a polished and hardened disc prepared of En-32 steel (HRC 62-65 hardness) was utilized as counterpart for testing wear.

Figure 1.Wear Specimen machined by EDM

Figure 2. Wear and friction measuring machine

The illustration shown in Figure 3 points out the procedure used to estimate the dry sliding wear. The sample initially weighs with the lowest count of 0.001 g when measured in an electronic weighing machine. While conducting the test the pin was pressed hardly against steel disc by applying the load. After, a continued constant sliding distance, the specimens were separated, washed with acetone, dried out and measured to find out the loss of weight due to wear. The result regarding the variation in the measured weight earlier and later the test indicates the wear of the specimen, further the volume loss was estimated. Depending on the function of applied load, sliding velocity, sliding distance, percentage of reinforcement of wear of the composites was examined.

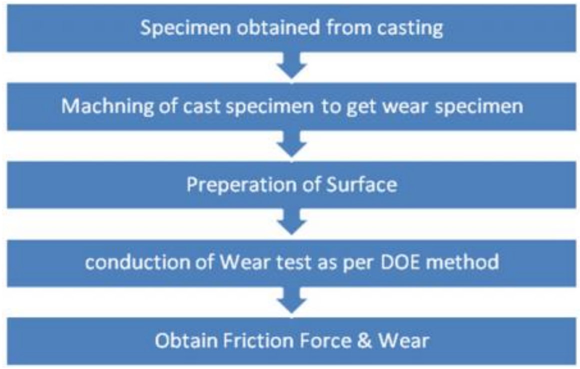

Figure 3. Procedure to estimate dry sliding wear.

3. Grey Relational Analysis

Grey relation analysis describes the importance of a particular parameter over other parameters in a given system and was an efficient tool for multi responses. Since Taguchi method focuses on single response optimisation, it was coupled with Grey relation analysis for multi response system. Initially experimental results (wear and friction force) were normalized in grey relational analysis, later the approximation of grey relational coefficient was taken from the normalized experimental data to illustrate the correlation between preferred and actual experimental data. The calculation of grey relational grade was done by maintaining an average of grey relational coefficient equivalent to every process response. The grey relational grade is totally assessed by several process responses. As a consequence, the conversion of optimization of complex multiple process responses becomes optimization of single grey relational grade. In addition, grey relational grade is considered as total estimation of investigational data for the multi response process. At the utmost grey relational grade, optimization of a factor is the best level. The detailed steps involved in

Taguchi's Grey Relational Analysis are as follows:

Step 1: The primary step was conversion of S-N Ratio values from the original response values. In this step the Equation (1) of "smaller the better" is used. On the ground of these S/N ratio values successive analysis was done. The Table3 displays S/N ratio values

$$\text{S/N ratio} = -10 \log_{10}[\frac{1}{n}\sum y^2] \tag{1}$$

Here n is 1 (wear) 2(friction force) & y is response value (wear/ friction force value).

Table 3: S/N Ratio analysis values

Expt No	Sliding Velocity (m.sec^{-1})	Load (N)	Sliding Distance (m)	% of Reinforcement (%)	Wear (mm^3.Km^{-1})	Friction Force (N)	SNRA1 (Wear)	SNRA2 (Friction force)
1	1	10	500	1	175	1.9	-44.8608	-5.57507
2	1	15	1000	2	425	3.2	-52.5678	-10.103
3	1	20	1500	3	567	4.3	-55.0717	-12.6694
4	3	10	1000	3	283	1.9	-49.0357	-5.57507
5	3	15	1500	1	571	3.1	-55.1327	-9.82723
6	3	20	500	2	293	2.9	-49.3374	-9.24796
7	5	10	1500	2	332	1.7	-50.4228	-4.60898
8	5	15	500	3	278	2.9	-48.8809	-9.24796
9	5	20	1000	1	416	3.7	-52.3819	-11.364

Step 2: In the next step of the grey relational analysis (Ghetiya et al., 2016), for normalizing the unprocessed data pre-processing of the data was first carried out for analysis. This is presented in Table 4. To control the effect of accepting different units Yij is normalized in addition to reduce the variability by the subsequent Equation (2) as Z_{ij} ($0 \le Z_{ij} \le 1$)). The normalized output parameter equivalent to the lower-the-better criterion can be expressed as

$$Z_{ij} = \frac{\min(Y_{ij}, i = 1,2,..,n) - Y_{ij}}{\min(Y_{ij}, i = 1,2,..,n) - \max(Y_{ij}, i = 1,2,..,n)} \tag{2}$$

Table 4 Normalized S/N ratios

Expt No	Sliding Velocity (m.sec^{-1})	Load (N)	Sliding Distance (m)	% of Reinforcement (%)	Normalized S/N Ratios	
					Wear	Friction Force
1	1	10	500	1	0	0.119857
2	1	15	1000	2	0.750297	0.681607
3	1	20	1500	3	0.994056	1
4	3	10	1000	3	0.406443	0.119857
5	3	15	1500	1	1	0.647395
6	3	20	500	2	0.435807	0.575528
7	5	10	1500	2	0.541474	0
8	5	15	500	3	0.39137	0.575528
9	5	20	1000	1	0.732198	0.838056

Step 3: The grey relational coefficient (Ghetiya et al., 2016) is estimated to present the association between the ideal (best) and specific normalized experimental results. Before the experiment was conducted, for the reference the deviation sequence and comparability sequence were traced out. The grey relational coefficient is displayed in Table 5.

$$\Delta x_i(k) = | x_0(k) - x_i(k) | \tag{3}$$

The absolute difference of the compared series and the referential series should be acquired by using Equation (3) and the maximum and the minimum difference should be found. The distinctive coefficient p is between 0 and 1. Generally, the distinctive coefficient p is set to 0.5. Grey relational coefficient is illustrated as follows

$$x_i(k) = \frac{\Delta \min + p\Delta \max}{\Delta x_i(k) + p\Delta \max} \tag{4}$$

Table 5 Grey relational Coefficients

Expt No	V	L	D	R	Normalized S/N Ratios		Grey Coefficients	
					Wear	FF	Wear	FF
1	1	10	500	1	1	0.880143	1	0.806638
2	1	15	1000	2	0.249703	0.318393	0.399905	0.423152
3	1	20	1500	3	0.005944	0	0.33466	0.333333
4	3	10	1000	3	0.593557	0.880143	0.551607	0.806638
5	3	15	1500	1	0	0.352605	0.333333	0.43577
6	3	20	500	2	0.564193	0.424472	0.534298	0.464888
7	5	10	1500	2	0.458526	1	0.480089	1
8	5	15	500	3	0.60863	0.424472	0.560934	0.464888
9	5	20	1000	1	0.267802	0.161944	0.405779	0.373677

Step 4: The determination of grey relational grade was done by averaging the grey relational coefficient which is related to every performance characteristic (Ghetiya et al., 2016). It is shown in Table 6 Estimated grey relational grade is the basis for the performance characteristic of multi response process. The grey relational grade can be denoted as

$$¥_i = \frac{1}{n}\sum_{k=1}^{n} ¢_i(k) \tag{5}$$

Where, Y_i is the grey relational grade for the jth experiment and k is the number of performance characteristics

Table 6 Grey Relational Grade

Expt No	V	L	D	R	Grey relation grade	Rank
1	1	10	500	1	0.903319	1
2	1	15	1000	2	0.411529	6
3	1	20	1500	3	0.333996	9
4	3	10	1000	3	0.679122	3
5	3	15	1500	1	0.384552	8
6	3	20	500	2	0.499593	5
7	5	10	1500	2	0.740044	2
8	5	15	500	3	0.512911	4
9	5	20	1000	1	0.389728	7

Step 5: Determination of combination Level for Optimal Factor: As the experimental design is orthogonal, it is feasible to detach the result of every parameter on the grey relational grade at various levels. To cite, mean of grey relational grade for the Sliding velocity at 1, 2 and 3 stages were estimated by taking average of grey relational grade for the experiments 1 to 3, 4 to 6, and 7 to 9 respectively the. Table 7 represents the mean of grey relational grade for every stage of the précised machining parameters.

Table 7 Main Effects of parameters on Grey relational Grade

Factors	V	L	D	R
Level 1	0.549615*	0.774162*	0.638608*	0.559199*
Level 2	0.521089	0.43633	0.49346	0.550389
Level 3	0.273781	0.407772	0.486197	0.508677

The higher the grey relational grade, indicates the improvement in the multiple performance characteristics. Though, the comparative significance among the machining parameters for several performance characteristics yet demands more research, so that the best possible grouping of machining parameter levels may be determined more precisely. With the aid of Table 4 the optimal parameter grouping is determined as $V_1L_1D_1R_1$ i.e. Sliding velocity: 1m.sec^{-1}, Applied load: 10N, Sliding distance: 500m and percentage of reinforcement: 1%.

4. Confirming Results

The proof test for the optimal parameters was carried out to analyse the performance characteristics. Table 5 displays uppermost grey relational grade, representing the primary process parameter set of $V_1L_1D_1R_1$ for the finest compound performance characteristics among the experiments. Table 8 shows the assessment of the experimental outcomes for optimal conditions ($V_1L_1D_1R_1$) with forecasted results for optimal ($V_1L_1D_1R_1$) parameters. The anticipated values were achieved by (Sahin, 2003)

$$\bar{¥} = ¥_m + \sum_{i=1}^{q} (\bar{¥}_i - ¥_m) \tag{6}$$

Where $\bar{¥}_i$ is the total mean of grey relation grade, $¥_m$ mean of grey relation grade at optimum level and q is the number of parameters.

Table 8 Confirmation Results

	Optimal process Parameters	
	Predicted	Experimental
Level	$V_1L_1D_1R_1$	$V_1L_1D_1R_1$
Grey Grade	0.903319	0.903319

5. Morphology of Wear Surfaces

The wear behaviour of composites comprising various percentages of Al_2O_3 particles was determined and compared to that observed in the base alloy. The final wear rate was obtained by taking average of three pin specimens at each specified load, which are presented graphically in Figure 4. The wear rate of unreinforced alloy is also plotted along with the composites for comparison. It is found from the graph that the wear rate of both the unreinforced alloy and composites increase with an increase in load. However, the wear rate of the composite specimens is significantly lower than that of the base alloy.

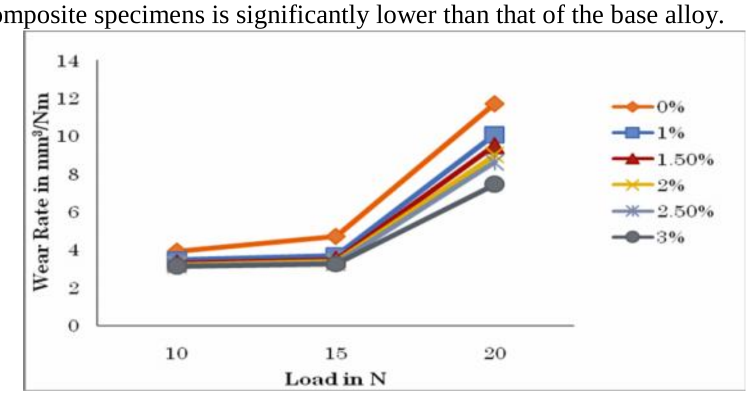

Figure 4. Effect of load and % of reinforcement on wear rate at sliding velocity of 5m/sec

It is evident from the graph that there exists a transition phenomenon at which there is a sudden increase in the wear rate of both reinforced and unreinforced materials. However, the transition loads for the composites were much advanced than that of the loads observed at base alloy. In addition, the transition load amplified with an increase in reinforcement content. Figure 5 and Figure 6 illustrates the SEM image of wear surface at different loading conditions, decent wear tracks and plastic deformation of material was observed. It also disclose that Al_2O_3 plays a significant role in increase of wear rate.

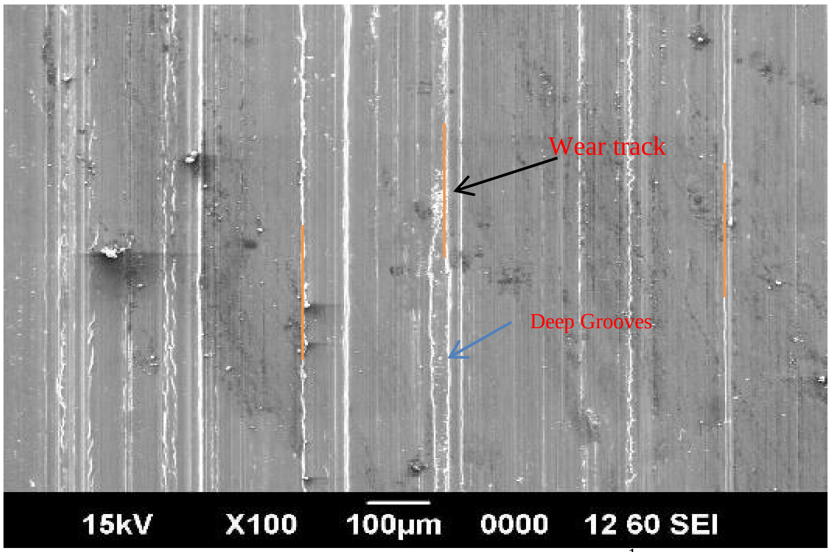

Figure 5. SEM image of wear specimen with 2% Al_2O_3 tested at a velocity of 5m.sec^{-1} and a sliding distance of 1.5 km at 20N load

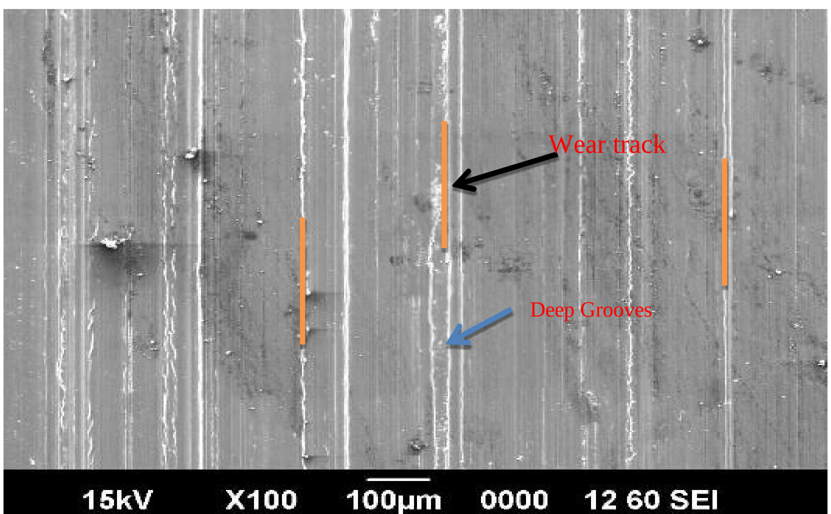

Figure 6. SEM image of wear specimen with 2% Al_2O_3 tested at a velocity of 5 m.sec^{-1} and a sliding distance of 1.5 km at 10N load

Due to the frictional heat generated on the sliding surface white patches were formed which shows the plastic flow of the material. Smoother surfaces were observed at lower loading condition. In these figures, the difference in the height of wear track was witnessed which may be due to direct contact of reinforced particles with the disc. Figure 5, which is at higher load shows some more plastic flow of material and distortion. The directional path of wear was revealed by straight lines.

6. Conclusions

In the current work, AZ91E/nano-Al_2O_3 Mg-MMCs were processed by the semi-solid stir casting process and the consequence of various parameters on wear properties was examined. The succeeding conclusions are perceived from current investigation

- The key role in improving the wear resistance of the composites is due to the reinforcement particles. It was established that the conversion load rises with arise in percentage of reinforcement and the decrease in wear rate of the composite was observed than that of the base alloy.

- Dry sliding wear behaviour of composites can be successfully evaluated using Taguchi based Grey relational analysis. This method provides a simple, systematized and proficient methodology for the optimization of control factors.
- The analysis shows optimal parameter combination is determined as V1L1D1R1 i.e. Sliding velocity: 1m.sec^{-1}, Sliding distance: 500m, Applied load: 10N, and % of reinforcement: 1%.

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