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MULTI-OBJECTIVE OPTIMIZATION OF TRIBOLOGICAL PARAMETERS OF HYBRID COMPOSITES USING GREY RELATIONAL ANALYSIS

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ABSTRACT

This paper presents an effective approach for the optimization of the tribological properties of hybrid aluminium matrix composites (356-B_4C_p-MoS_2) fabricated by stir casting technique, with multiple performance characteristics based on the grey relational analysis. In this study B_4C was kept constant at 6% for all three composites (356-6% B_4C, 356-6% B_4C-2% MoS_2 and 356-6% B_4C-4% MoS_2) and MoS_2 was varied from 0 to 4% with an increment of 2 wt%. Dry sliding wear tests were conducted using a standard pin on disc test setup following a well-planned experimental schedule based on Taguchi's orthogonal arrays. The input parameters such as sliding speed, sliding distance, load and reinforcement percentages are optimized with considerations of multiple performance characteristics: wear rate, specific wear rate and coefficient of friction. The optimal levels of input parameters were selected from response table and response graph from the grey relational grade. ANOVA was used to find the significance of the wear parameters.

Key words: Hybrid aluminium matrix composites, Stir casting, Taguchi design of experiments, Grey relational analysis, ANOVA.

INTRODUCTION

The development of metal matrix composites (MMCs) has set the stage for a new revolution in materials[1]. Aluminium matrix composites have a market potential for various applications, particularly in the automotive industry where the pressure to use lightweight materials has increased because of environmental issues. Examples of components that have been manufactured using metal matrix composites include pistons for diesel engines and

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connecting rods[2]. Hybrid MMCs are obtained by reinforcing the matrix alloy with more than one type of reinforcements having different properties[3]. Hybrid metal matrix composites (HMMCs) are second-generation composites where more than one type, shape, and size of reinforcements are used to obtain better properties[4]. Addition of ceramic reinforcements such as SiC, Al_2O_3, TiC, B_4C, and ZrO_2 to metal matrix improves hardness and thermal shock resistance[5]. Boron carbide is a nonmetallic reinforcement having a high hardness coupled with high wear resistance and high melting point thus possessing resistance to change due to the addition of chemicals. Hence reinforcing the aluminium composites with B_4C particles confers high specific strength, elastic modulus, good wear resistance and thermal stability[6]. Wear studies on Al-B_4C composites with varying weight percentage of B_4C (5, 10 and 15%) showed a linear increase in wear resistance with B_4C contents and the highest wear resistance was observed at 15 percentage reinforcement of B_4C[7]. Friction and wear behaviour of MoS_2, boric acid, graphite and TiO_2 has been compared under extreme boundary lubrication conditions. Results show that MoS_2 and graphite were 30–50% more effective than other two lubricants. Coefficient of friction shows a decreasing trend with increase in sliding speed due to increasing temperature and higher shear force. High coefficient of friction values were recorded for all the lubricants (0.2-0.5). This is due to predominating solid interactions during boundary lubrication conditions. Boric acid and TiO_2 were not much effective in lubrication[8]. Dry sliding metal-to-metal contact wear can be observed in cams, gears, bearings, clutches and other applications involving sliding contact or rolling contact[9]. The wear resistance is strongly dependent on the rotational speed and the hardness of the counter materials. The counter-face materials with a lower hardness have reduced the wear resistance due to the mutual abrasion between the counter material and the wear surface of the specimen[10]. Processing techniques such as stir casting process has proved to be relatively economical and easy to use. Improvement in mechanical and tribological properties was presented in this paper[11]. Taguchi technique is a powerful tool in experiment design. It provides a simple, efficient and systematic approach for optimization, quality and cost[12]. The basic idea of GRA is to find a grey-relational grade (GRG), which can be used for the conversion from a multi-objective case to a single-objective case. GRG was also used to estimate the parameter effects on the overall performance response[13]. A review of literatures indicates that the tribological study on Al/B_4C/MoS_2 composites is very limited. This study presented the optimization in tribological behaviour of Al/B_4C/MoS_2 composites to minimize the wear rate, specific wear rate and coefficient of frictionusing Taguchi DOE with grey relational analysis (TGRA) considering multiple performance characteristics. Nine experimental runs based on Taguchi orthogonal array were conducted to determine the best factor level combination. The influence of the control factors such as the mass fraction of MoS_2, sliding speed, sliding distance and load were studied by assessing the single weighted GRA.

EXPERIMENTAL

Materials and methods

Materials used

356 Aluminium alloy is mainly used where good mechanical properties are required in castings of a shape or dimensions requiring an alloy of excellent castability in order to achieve the desired standard of soundness. The alloy is also used where resistance to corrosion is an important consideration particularly where high strength is also required. The aluminium 356 cast alloy has high copper and nickel content to decreases the ductility and provide resistance to corrosion. The percentage of iron content decreases the strength and ductility. Materials have been selected based on the physical and mechanical properties. The chemical omposition of 356 cast alloy are given in Table 1.

Table 1: Chemical composition of aluminium alloy

Constituent	Cu	Si	Fe	Mg	Mn	Ti	Ni	Zn	Al
Weight %	0.13	7.08	0.49	0.39	0.03	0.06	0.01	0.02	Balance

Boron carbide (B_4C) particles of average size 63 microns were used as one of the reinforcement material. It has many attractive properties, such as low specific gravity, high hardness, high elastic modulus and neutron absorption, which help B_4C to be widely used as cermets and armor materials. Boron carbide is uniquely suited for nuclear applications. The morphology of B_4C particles were shown in Fig. 1.

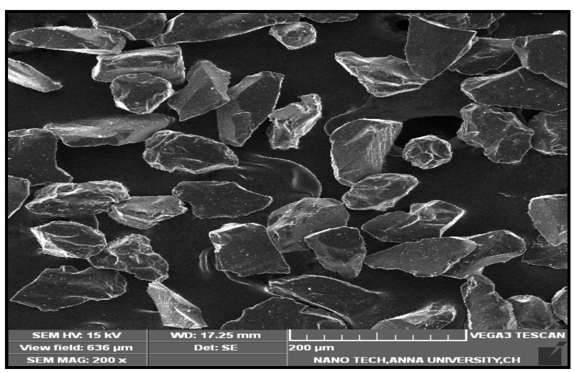

Fig. 1: Morphology of B_4C particles

Molybdenum disulphide (MoS_2) solid lubricant is used as a soft reinforcement in this research work. The low friction and easy cleavage of molybdenum disulfide is intrinsic to the material and a result of its crystal structure. The presence of condensable vapors is not required for molybdenum disulfide to exhibit low friction, as it is in the case of graphite, it has been established that condensable vapors play an important role in determining the friction and wear characteristics of a lubricant film of molybdenum disulfide. Special attentions have been given to relative amounts of solid lubricants in the metal matrix composites, since they affect the mechanical properties and tribological properties significantly.

Fabrication of hybrid composites

Stir casting technique was used for fabricating the hybrid aluminium matrix composites. Stir casting setup with furnace used for this project is shown in Fig. 2. The percentage of boron carbide added was kept constant as 6% by weight. The ingots of 356 aluminium alloy were taken in a graphite crucible and melted in an electric furnace to a temperature of 850^{o}C. The melt was degassed at 800^{o}C using a solid dry hexachloro ethane (C_2Cl_6, 1%wt) degasser. Potassium hexaflurotitanate (K_2TiF_6 1%wt) was added to the molten metal. The reason for the addition of titanium in the casting of Al/B_4C composite is to form a reaction layer on the interface that contains titanium carbide (TiC) and Titanium Boride (TiB_2) for increasing the wettability and interfacial bonding. With the addition of Titanium (Ti) in the form of K_2TiF_6, Potassium (K) and Fluoride (F) contribute to remove the oxide film on the aluminium surface. The molten metal was stirred to create a vortex and the preheated (200^{o}C) boron carbide particles and Molybdenum disulphide (0, 2, 4 wt%) were introduced in to the melt and the slurry was stirred at 350 rpm for 5 min for producingthe three different hybrid composites (356/6%B_4C, 356/6%B_4C/2%MoS_2 and 356/6%B_4C/4%MoS_2). The stirred dispersed molten metal was poured into preheated (650^{o}C) cast iron moulds and cooled to room temperature.

Fig. 2: Stir casting setup

Wear test

The wear tests were conducted using pin on disc wear testing machine. The wear specimen (pin) of 6 mm diameter and 50 mm height was machined from as cast samples, and then polished metallographically. The initial weight of the specimen was measured in a single pan electronic weighing machine with least count of 0.0001 g. The pin was pressed against the AISI 4140 steel disc with hardness of 55HRC by applying the load. After running through a fixed sliding distance, the specimens were cleaned with acetone, dried and weighed to determine the weight loss due to wear. The difference in the weight measured before and after the wear test of the composites specimen is the weight loss and then the wear rate, specific wear rate and coefficient of friction was calculated using the standard formulae.

Design and analysis of experiments

Plan of experiments

The experimental plan is designed to find the factors influencing the wear process for achieving minimum WR, SWR and COF. The experiments were developed based on an orthogonal array, with the aim of relating the influence of sliding speed, sliding distance, load and weight percentage reinforcement of the material. The process parameters and their levels are shown in Table 2.

Table 2: Process parameters and their levels

Level	Sliding speed, S (m/s)	Sliding distance, D (m)	Load, L (N)	Reinforcement, R (wt%)
1	1	500	15	0
2	1.5	1000	30	2
3	2	1500	45	4

Taguchi design of experiments

Design of experiments is one of the important and powerful statistical techniques to study the effect of multiple variables simultaneously. This method drastically reduces the number of experiments that are required to model the response function compared with the full factorial design of experiments. The Taguchi technique is devised for process optimization and identification of optimal combination of the factors for a given response.

The overall objective of the method is to produce high quality product at low cost. The L_9 orthogonal array used for this work is shown in Table 3.

Table 3: L_9 Orthogonal array

S. No.	Sliding speed, S (m/s)	Sliding distance, D (m)	Load, L (N)	Reinforcement, R (Wt%)
1	1	500	15	0
2	1	1000	30	2
3	1	1500	45	4
4	1.5	500	30	4
5	1.5	1000	45	0
6	1.5	1500	15	2
7	2	500	45	2
8	2	1000	15	4
9	2	1500	30	0

Grey relational analysis

Grey theory is one of the important theories and can be used for analyzing the uncertainty, multi-input and discrete data. A grey system has a level of information between black and white. The grey relational analysis is a measurement of the absolute value of the data difference between sequences, and is also used to measure an approximate correlation between sequences. It is an effective means of analyzing the relationship between the sequences with less data and can analyze many factors.

Analysis approach

The experiments were conducted according to Taguchi's L_9orthogonal array using 9 different experiments. For GRA, these 9 experiments became 9 subsystems. The influence of these subsystems on the response variables were analyzed by using GRA. The wear tests (system) were assessed by conducting 9 experiments (subsystems) and each experiment was termed as comparability sequence. The parametric conditions corresponding to the highest weighted GRG gave minimum values of the wear rate, specific wear rate and coefficient friction. In this manner, the multi-objective problem was converted into single objective optimization using GRA technique.

RESULTS AND DISCUSSION

The wear tests were conducted to study the effect of process parameters over the output response characteristics. The GRG of the response characteristics for each variable at different levels were calculated from experimental data. The main effects of process variables of GRG were plotted. The response graphs are used for examining the parametric effects on the response characteristics. The analysis of variance (ANOVA) of GRG is carried out to identify the significant variables and to quantify their effects on the response characteristics. The most optimal settings of process variables are established by analyzing the response graphs and the ANOVA tables. The experimental results along with their grey relational coefficients and GRG were given in Table 4.

Table 4: Experimental results of composites

S. No.	SWR* E-3	WR* E-3	COF	GRC SWR	GRC WR	GR COF	GR Grade
1	0.163	2.446	0.226	0.396	0.592	0.333	0.440
2	0.122	3.663	0.182	0.477	0.46	0.519	0.485
3	0.092	4.151	0.179	0.559	0.422	0.539	0.507
4	0.122	3.663	0.172	0.477	0.46	0.595	0.511
5	0.127	5.714	0.144	0.465	0.333	1	0.599
6	0.080	1.199	0.208	0.601	0.842	0.391	0.611
7	0.016	0.733	0.187	1	1	0.488	0.829
8	0.269	4.029	0.152	0.333	0.43	0.836	0.533
9	0.106	3.175	0.181	0.518	0.506	0.526	0.517

In this study all the designs, plots and analysis have been carried out using Minitab statistical software. Fig. 3 shows that the GRG increases with increase in sliding speed and load and, decreases with increase in sliding distance. When the pin is sliding over the disc the pin wears initially and then a mechanically mixed layer is formed and this resists the wear rate of the composite pin.

The response Table 5 shows the average of each response characteristic for each level of each factor. The table includes ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest average for each factor. Ranks are assigned based on delta values; rank 1 to the highest delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. The ranks and the delta values show that sliding speed has the greatest effect on GRG and is followed by load, percentage of reinforcement and sliding distance in that order. It can be seen from Fig. 3 that the 3 level of sliding speed, 1 level of sliding distance, 3 level of load and 2 level of reinforcement provide maximum GRG.

Table 5: Response table

Level	Sliding speed, S (m/s)	Sliding distance, D (m)	Load, L (N)	Reinforcement, R (wt%)
1	0.4773	**0.5933**	0.5280	0.5187
2	0.5737	0.5390	0.5043	**0.6417**
3	**0.6263**	0.5450	**0.6450**	0.5170
Delta	0.1490	0.0543	0.1407	0.1247
Rank	1	4	2	3

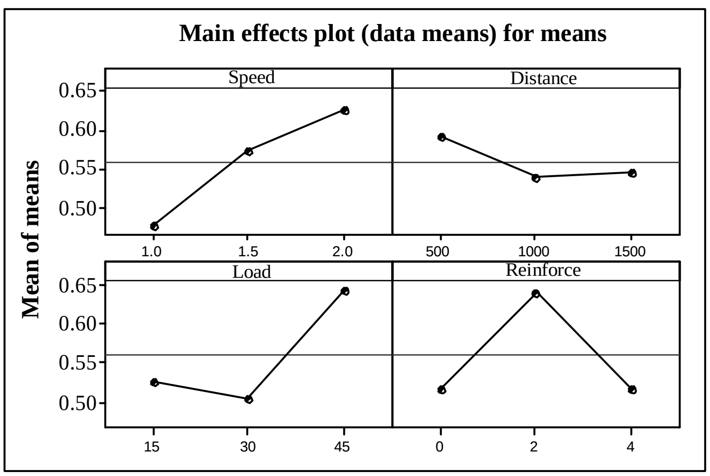

Fig. 3: Response graphs

In order to study the significance of the process variables towards GRG, analysis of variance was performed. From ANOVA Table 6 we see that Sliding speed, load and reinforcement were most influential for obtaining maximum GRG. Whereas Sliding distance has very less significance on GRG.

Table 6: ANOVA of GRG

Source	DOF	Sequence sum of square	Mean sum of square	Contribution (%)
Sliding speed	2	0.0343	0.0171	32.88
Sliding distance	2	0.0053	0.0027	5.08
Load	2	0.03404	0.0170	32.63
Reinforcement	2	0.03067	0.0153	29.40
Total	8	0.1043		100.00

Confirmation experiment

Experimental results are analyzed for identifying the optimum parameters. From Fig. 3 and response Table 5 the factors at level S3, D1, L3, R2 that is Sliding Speed 2 m/s, Sliding Distance 500 m, Load 45 N and 2% MoS_2 reinforcement are the optimum parameters for obtaining minimum wear rate, specific wear rate and coefficient of friction. The optimum parameters are used for conducting the confirmation experiment and also for predicting the wear rate, specific wear rate and coefficient of friction using Taguchi Design of Experiments. The predicted GRG and experimental value of GRG were same. So the optimization technique holds good for this research work.

CONCLUSION

The following conclusion can be drawn from the analysis of tribological behavior of these composites.

(i) Sliding speed is the parameter that has the highest statistical influence on GRG of the composites (32.88%) followed by load (32.63%), reinforcement (29.40%), and sliding distance (5.08%).

(ii) Optimum values of sliding speed is 2 m/s, sliding distance is 500 m, load is 45 and reinforcements is 2% MoS_2 added hybrid composites.

(iii) The tribological properties of 356/6%B_4C/2%MoS_2 composites are better than 356/6%B_4C and 356/6%B_4C/4%MoS_2 composites.

(iv) B_4C improves the hardness of materials. MoS_2 is improves the machinability.

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