OPTIMIZATION TECHNIQUE TO STUDY DRY SLIDING WEAR BEHAVIOR OF ALUMINIUM ALLOY 2218 BASED SELF LUBRICATING COMPOSITE MATERIALS

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ABSTRACT

The present work concentrates on the influence of addition of fly ash particulates as reinforcement on the tribological behaviour of aluminium matrix composites reinforced with Graphite (Gr) particulates. Use of graphite (Gr) reinforcement in aluminium matrix composites has been accounted to be good in reducing wear due to its solid lubricant property. Composites of aluminium alloy 2218 reinforced with 4% graphite particulate and (5%, 10% and 15%) fly ash particulate were produced by stir casting route. The wear and frictional properties of the hybrid metal matrix composites were studied by performing dry sliding wear test using a pin-on-disc wear tester. The experiments were directed as per the Taguchi design of experiment. The wear parameters chosen for the experiment were: sliding speed, applied load, time and sliding distance. Each parameter was assigned three points. The experiment consists of 27 tests according to the L 27 orthogonal array. The investigation was done to find the influence of applied load, sliding speed and sliding distance on wear rate, as well as the coefficient of friction during wearing process. Signal to noise ratio analysis has been carried out to determine optimal parametric condition, which yields minimum wear rate and frictional force. The confirmation experiments were conducted to verify the predicted model.

Keyword: - *AA 2218 alloy, Fly ash, Graphite, Stir casting route, Pin-on-disc, Wear Behaviour, Orthogonal array, Taguchi technique.*

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1. INTRODUCTION

Metal matrix composites have potential application in many fields because of their good physical and mechanical properties, such as high specific strength and stiffness, good wear resistance and low thermal expansion coefficient [1]. Aluminium is the matrix and reinforcement is usually non-metallic and commonly ceramic such as SiC, B_4C and Al_2O_3 [2]. Properties of AMCs can be tailored by varying the nature of constituents and their volume fraction. Aluminium alloys are widely used in the automotive industry because of their high strength to weight ratio as well as high thermal conductivity [3]. It is used particularly in automobile engines as cylinder liners as well as other rotating and reciprocating parts, such as the piston, drive shafts, brake rotors and in other applications in automotive and aerospace industries [1,3]. Aluminium and its alloys exhibit poor tribological properties leading even to seizure under adverse conditions. Hence, a strong drive to develop new materials with greater resistance to wear and better tribological properties led to the development of aluminum metal matrix composites [4]. The performance of metal matrix composite reinforced with ceramic particles has been reported to be superior to that of their unreinforced matrix alloy [4,5]. The addition of reinforcements significantly improves the wear resistance of aluminium alloy [6]. There has been an increasing interest in composites containing low density and low cost reinforcements [7]. Among various particulates used, fly ash is one of the least expensive and low density reinforcement available in huge quantities as solid waste by-product in thermal power plants [7,8]. It is therefore expected that the incorporation of fly ash particles in aluminium alloy has the potential for conserving energy intensive aluminium, and thereby reducing the cost of aluminium products, and at the same time causing a reduction in the weight of the products [9]. Researchers have also reported significant improvements in properties and higher wear resistance by the incorporation of fly ash in aluminium alloy [10,11]. Al 2219/15SiCp and Al 2219/15SiCp-3 graphite all fabricated by the liquid metallurgy route. Metal matrix composites (MMCs) based on AA2218 alloy have been successfully developed by stirring powder mix of TiO_2 particles along with Al_2O_3 particles prepared by milling into the alloy melt [12]. Self-lubricating composites provide engineers and project managers with simple, inexpensive solutions to certain tribological applications. Through the mechanisms of sacrificial wear and thin film transfer, the contact zone between a self-lubricating composite and a hard counterface can be lubricated without the need for traditional solid or liquid lubrication [13]. Within the space industry these materials are used as bushes, sliding interfaces, guides, ball-bearing cages, slip-rings, motor brushes, and gears. In certain applications under dry friction, the composites, containing small amount of solid lubricant, work very effectively. The addition of solid lubricant particles such as graphite along with fly ash as hybrid reinforcements effectively improves the tribological properties of the whole system under sliding wear conditions [13,14]. These hybrid graphitic aluminium metal matrix composites provided greater seizure resistance even under dry sliding conditions. Wear becomes more stable as the amount of graphite addition increases [15]. The graphite smears on the sliding pin surface and forms a layer which reduces wear [16]. From the study it is concluded that we can use fly ash for the production of composites and can turn industrial waste into industrial wealth [17]. Graphite exhibit high temperature and oxidizing atmosphere environments, whereas liquid lubricants typically will not survive. Among aluminium alloys Al 2xxx series alloys enjoy the highest strength to weight ratio, having wide applications in the automobile and aerospace industries. 2xxx series of Al-alloys have been used extensively as a matrix material for development of MMCs. However AA 2218 has the highest strength to weight ratio. And especially applicable for high temperature application, like engine cylinder liner, piston rod and cylinder head. However little amount of work has been carried out on AA 2218 alloy. Aluminium alloy reinforced with fly ash and Graphite hybrid composite act as a self-lubricating material which is applicable for high temperature applications. Based on the literature review, an attempt is made to study the influence of wear parameters such as applied load, sliding speed, and sliding distance on the dry sliding wear behaviour of the Al/Fly ash/graphite hybrid metal matrix composites using Taguchi design of experiment. Combined effect of the above mentioned parameters were also investigated by including their interactions using ANOVA technique.

1.1 Taguchi Method

The design of experiments (DOE) approach using Taguchi technique has been successfully used by researchers in the study of wear behaviour of MMC's [2]. Taguchi method is a powerful tool for the design of high quality systems [10]. The Taguchi approach to experimentation provides an orderly way to acquire data and to analyze the effects of process and material parameters over some specific response [11]. Thus this method combines experimental and analytical concepts to determine the parameter with the strongest influence on the resulting response for a significant improvement in the overall performance. The plan of experiments is generated in Taguchi method by the use of standard orthogonal arrays. The experimental results are then analyzed by using analysis of mean and analysis of variance (ANOVA) of the influencing factors [18]. The major aim of the present investigation is to analyse the influence of parameters like load, sliding speed and fly ash content on dry sliding wear of aluminium fly ash-graphite hybrid metal matrix composites using Taguchi technique. A multiple linear regression model is developed to predict the wear rate of the hybrid composites.

2. EXPERIMENTAL WORK

AA 2218 has the highest strength to weight ratio. The main alloying element is copper. The second is magnesium, which is predominantly added to increase the wetting between matrix and reinforcement. The chemical composition of AA 2218 was tabulated in Table 1. In this present work, stir casting technique was used to fabricate AA 2218 alloy with varying weight percentages of fly ash (5, 10, and 15%) and a constant weight percentage of Gr (4%). In order to achieve good binding between the matrix and reinforcements, 2% of magnesium is added. The experimental setup was shown in figure 1. The fly ash and graphite particles with a size range of 53 to 75 μm were used. Fly ash particles being hard in to nature improve the hardness, strength and stiffness of the hybrid composite. Graphite imparts excellent self-lubricating property to the hybrid composite.

Table -1: Chemical Composition of AA 2218 in wt. %

Cu	Ni	Mg	Si	Fe	Ti	Al
3.87	1.90	1.47	0.51	0.16	0.02	Bal

Fig -1: Stir casting Setup

3. MECHANISM OF WEAR TEST

The composite specimens were rubbed against hardened steel. Dry sliding wear tests were carried out using pin -on-disc type wear tester at different parameters like sliding speed, applying load, Sliding time and percentage of reinforcement were varied in the range given in table 2.

Table -2: Process parameters and levels

Level	Speed (m/s)	Load (N)	Time (min)	Percentage of Reinforcement (%)
1	1.5	10	5	5
2	3	20	10	10
3	4.5	40	15	15

Figure 2 shows the complete pin-on-disc wear test experimental setup.

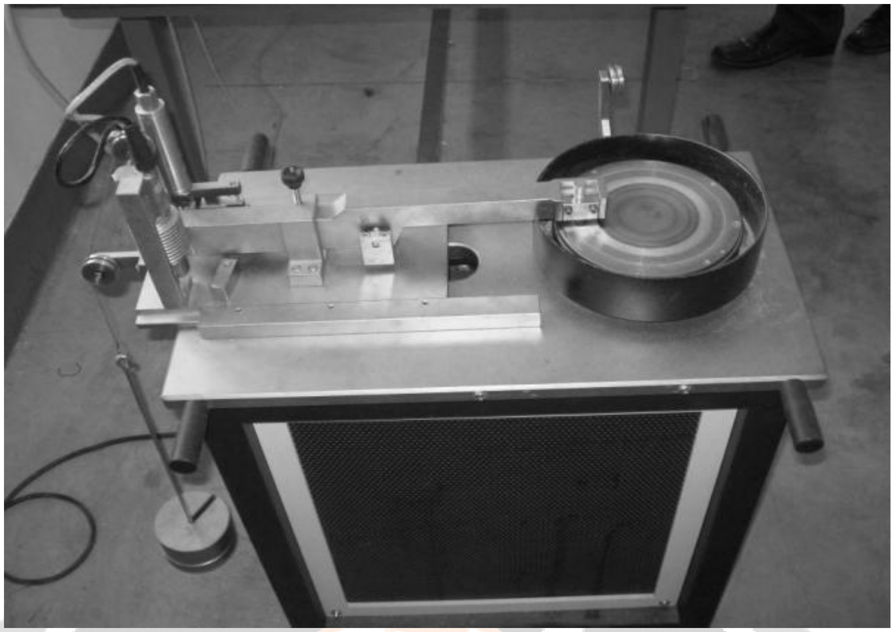

Fig -2: Pin on Disc Wear test Apparatus

3.1 Plan of Experiments

The experiments were conduct as per the standard orthogonal array. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than or at least equals sum of those of wear parameters. In the present investigation an $L_{27}(3^{13})$ orthogonal array which has 27 rows corresponding to the number of tests (20 degrees of freedom) and 13 columns at three levels and four factors, as shown in table 3.

Table -3: Orthogonal Array L_{27} (3^{13}) of Taguchi Method

$L_{27}(3^{13})$	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3

19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

4. RESULTS AND DISCUSSIONS

4.1 Hardness

Chart 1 shows an increase in hardness with the increase in the percentage of fly ash, when compared with the unreinforced eutectic AA 2218 alloy. The hardness was found to be 60 BHN for 5% fly ash, 68 BHN for 10% fly ash and 76 BHN for 15% fly ash.

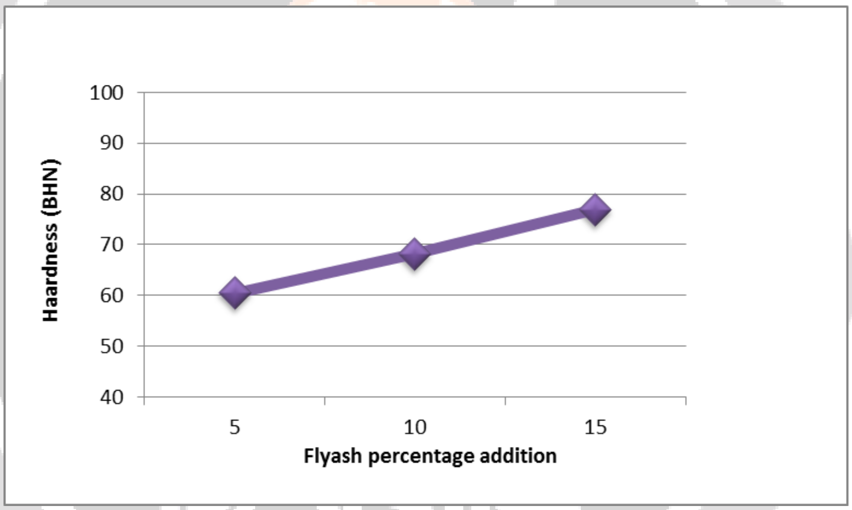

Chart -1: Hardness vs percentage of fly ash addition

It has been reported that addition of ceramic particles increases the hardness of composites. The increase in hardness is expected because of the presence of ceramic reinforcements which are very hard, and act as barriers to the movement of dislocations within the matrix and exhibit greater resistance to indentation. This trend is also observed in our study.

4.2 Density

Chart 2 shows a decrease in density with the increase in the percentage of fly ash addition. The density of the base alloy was found to be 2.82 g/cm^3. The densities of the cast composites, at various percentages of fly ash are shown in Figure 8.2. It is observed that the density decreases as the percentage of fly ash increases, when compared with the unreinforced AA 2218 alloy. The density of the composite was found to be 2.8 g/cm^3 for 5% fly ash. Similarly, the density for 10% fly ash was 2.75 g/cm^3 and 2.65g/cm^3 for 15% addition of fly ash. Several investigators have reported a similar trend with the addition of particulates like fly ash.

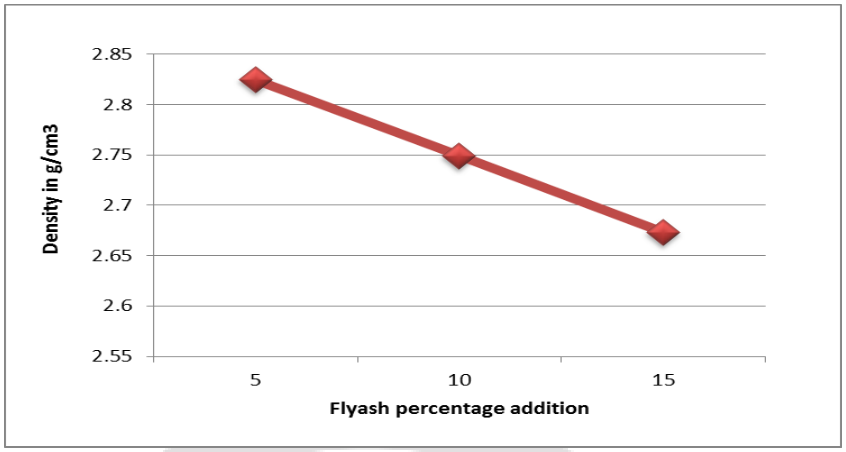

Chart -2: Density vs percentage of fly ash addition

4.3 Wear and Friction Behaviour

The aim of the experimental plan is to find the important factors and combination of factors influencing the wear process to achieve the minimum wear rate and coefficient of friction. The experiments were developed based on an orthogonal array, with the aim of relating the influence of sliding speed, applied load, time and percentage of reinforcement. These design parameters are distinct and intrinsic feature of the process that influence and determine the composite performance. Taguchi recommends analysing the S/N ratio using conceptual approach that involves graphing the effects and visually identifying the significant factors.

The above mentioned pin on disc test apparatus was used to determine the sliding wear characteristics of the composite. Experimental values of wear rate and coefficient of friction and the calculated values of signal to noise ratio for a given response using Equation 1, and are listed in table 4. The Taguchi's technique suggested that the analysing of signal to noise ratio using conceptual approach that involves graphing the special effects and visually making out the significant aspects.

Table -4: Results of L_{27} orthogonal array for HMMC's

Input Factor					Output Factor	
Serial No	Speed in m/s	Load in N	Time in sec	% Reinforcement	Wear rate in mm^3/m	Coefficient of friction
1.	0.785	10	300	5	0.0017641	0.290000
2.	0.785	10	600	10	0.0016888	0.220000
3.	0.785	10	900	15	0.0015562	0.189000
4.	0.785	20	300	10	0.0032176	0.140000
5.	0.785	20	600	15	0.0024843	0.121000
6.	0.785	20	900	5	0.0052136	0.175000
7.	0.785	30	300	15	0.0033124	0.101000
8.	0.785	30	600	5	0.0059102	0.153333
9.	0.785	30	900	10	0.0043627	0.110000
10.	1.570	10	300	10	0.0048176	0.370000
11.	1.570	10	600	15	0.0014743	0.340000
12.	1.570	10	900	5	0.0068247	0.530000

13.	1.570	20	300	15	0.0049685	0.224000
14.	1.570	20	600	5	0.0075191	0.270000
15.	1.570	20	900	10	0.0058134	0.245000
16.	1.570	30	300	5	0.0077383	0.216667
17.	1.570	30	600	10	0.0066385	0.190000
18.	1.570	30	900	15	0.0065695	0.100600
19.	2.355	10	300	15	0.0078442	0.510000
20.	2.355	10	600	5	0.0082033	0.714000
21.	2.355	10	900	10	0.0070389	0.541000
22.	2.355	20	300	5	0.0098043	0.412000
23.	2.355	20	600	10	0.0081026	0.335000
24.	2.355	20	900	15	0.0079215	0.304000
25.	2.355	30	300	10	0.0094383	0.252333
26.	2.355	30	600	15	0.0086137	0.220000
27.	2.355	30	900	5	0.0129543	0.303333

4.4 Results of Statistical Analysis of Experiments

The influence of controlled process parameters such as sliding speed, applied load, sliding time and percentage of reinforcement has been analyzed and the rank of involved factors like wear rate and coefficient of friction which supports signal to noise response is given in tables 5 and 6.

Table -5: Response for Signal to Noise Ratio- Smaller Is Better (Wear Rate)

Level	Speed (Db)	Load (Db)	Time (Db)	% Reinforcement (Db)
1	50.63	48.87	45.77	43.66
2	45.44	44.97	46.62	45.83
3	41.16	43.37	44.84	47.74
Delta	9.47	5.50	1.79	4.07
Rank	1	2	4	3

Table -6: Response for Signal to Noise Ratio- Smaller Is Better (Coefficient Of Friction)

Level	Speed (Db)	Load Db)	Time (Db)	% Reinforcement (Db)
1	16.034	8.445	12.019	10.371
2	11.974	12.743	12.059	12.386
3	8.570	15.389	12.500	13.821
Delta	7.464	6.944	0.481	3.449
Rank	1	2	4	3

It is evident from the tables that, among these parameters, load is a dominant factor on the wear rate and percentage of reinforcement for coefficient of friction. The influence of controlled process parameters on wear rate and coefficient of friction are graphically represented in figures 3-6.

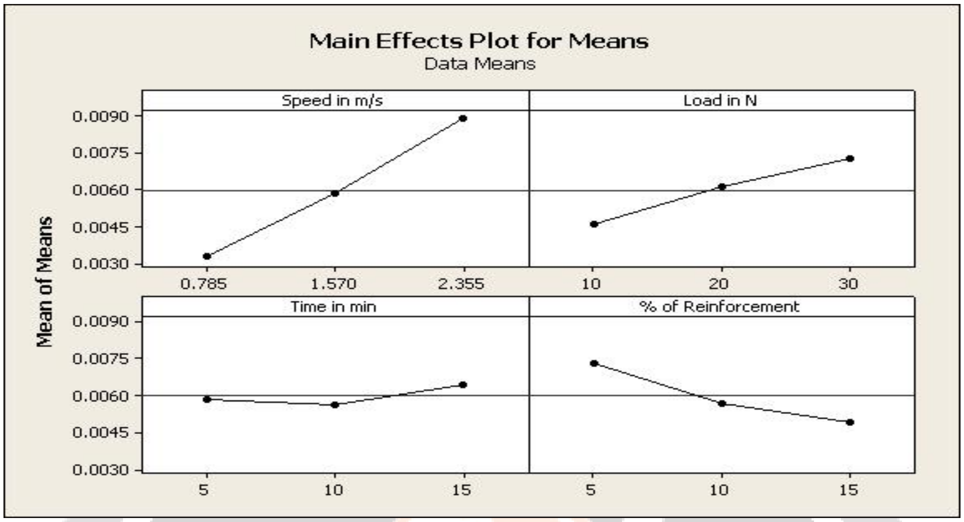

Fig -3: Main Effects Plot for Means – Wear Rate

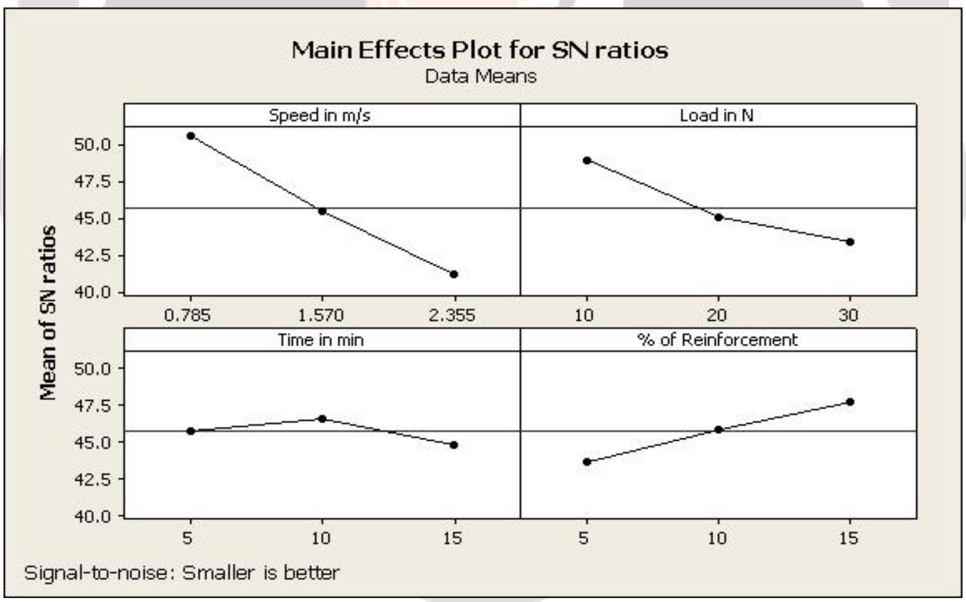

Fig -4: Main Effects Plot for S/N Ratios – Wear Rate

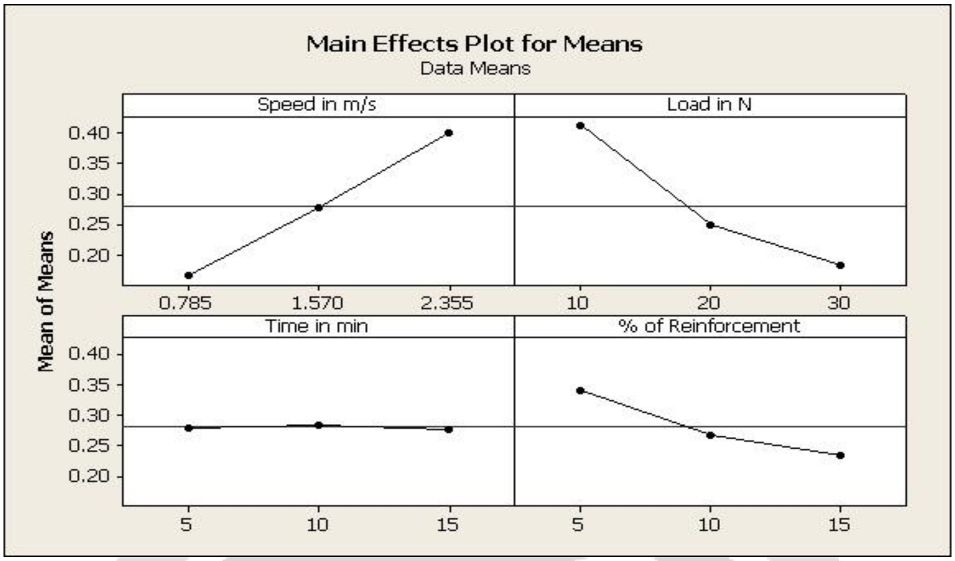

Fig -5: Main Effects Plot for Means – Coefficient of Friction

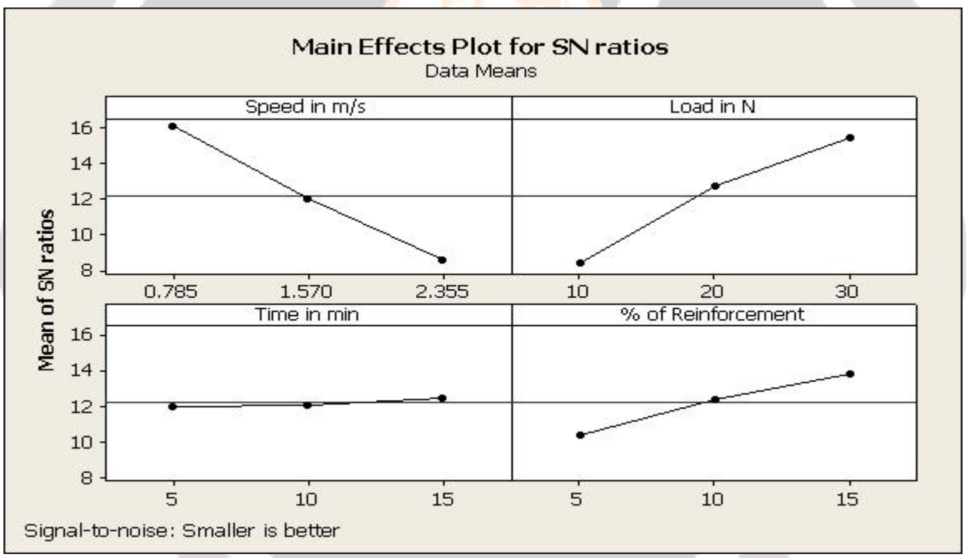

Fig -6: Main Effects Plot for S/N Ratios – Coefficient of Friction

Based on the analysis of these experimental results with the help of signal to noise ratio, the optimum conditions resulting in wear rate and coefficient of friction are shown in figures 4 and 6. The figures clearly indicate that the third level of sliding speed, first level of load and third level of both sliding time and percentages of reinforcement are the optimum points, but these optimum conditions are not available in L_{27} orthogonal array. Hence the optimum conditions tested separately and the results are given in table 7.

Table -7: Analysis of Variance for Wear Rate

Ex. No	Speed (m/s)	Load (N)	Time (sec)	Reinforcement %	Wear Rate mm^3/m	S/N Ratio for Wear (db)	Coefficient of Friction	S/N Ratio for Coefficient of Friction (db)
1	0.785	10	600	15	0.001556	56.158	______	_____
2	0.785	30	900	15	_____	_____	0.10100	20.000

Table 8 shows the results of the analysis of variance on the wear rate for fly ash and Gr particulates reinforced Al-6061 alloy matrix composite. This analysis is carried out at a level of 5% significance that is up to a confidence level of 95%. The last column of the table indicates the percentage of contribution (Pr) of each factor on the total variation indicating the degree of their influence on the results.

Table -8: Analysis of Variance for Wear Rate (mm^3/m)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr (%)
Speed (M/S)	2	0.000142	0.000142	0.000071	113.46	0.0000025	71.5266548
Load (N)	2	0.000033	0.000033	0.000017	26.51	0.0000016	12.1270829
Time (Secs)	2	0.000003	0.000003	0.000002	2.73	0.092	0.49502937
% Reinforcement	2	0.000026	0.000026	0.000013	21.04	0.000012	9.95846730
Residual Error	18	0.000011	0.000011	0.000001			5.892766
Total	26	0.000216					100

From table 8, one can easily observe that the sliding speed factor has greater influence on wear rate (Pr-S = 71.5266548 %). Hence applying sliding speed is an important control process parameter to be taken into account while wear process. Applied sliding speed is further followed by applied load (Pr-L = 12.1270829 %), percentage of reinforcement (Pr-R = 9.95846730 %) and sliding time (Pr-T= 0.49502937%).

4.5 Analysis Of Variance for Coefficient Of Friction

Table -9: Analysis of Variance for Coefficient of Friction

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr (%)
Speed (m/s)	2	0.243474	0.243474	0.121737	38.93	0.000013	34.35091233
Load (N)	2	0.249984	0.249984	0.124992	39.98	0.000019	36.64501295
Time (secs)	2	0.000253	0.000253	0.000127	0.04	0.960	0.776581413
% Reinforcement	2	0.053138	0.053138	0.026569	8.50	0.003	21.00759538
Residual Error	18	0.056280	0.056280	0.003127			7.219898
Total	26	0.603130					100

From table 9, one can clearly infer that the sliding speed and applied load have a greater control on coefficient of friction (Pr-S = 34.35091 %) and (Pr-L = 36.64501295 %)than the other factors. This parameter is then followed by percentage of reinforcement (Pr-R = 21.00759538 %) and Time (Pr-T = 0.77658 %).

4.6 Multiple Linear Regression Models

Statistical software MINITAB R16 is used for developing a multiple linear regression equation. This developed model gives the relationship between independent / predictor variable and a response variable by fitting a linear equation to the measured data.

- The regression equation for Wear rate in mm^3/m,
  = - 0.000552 + 0.00357 Speed in m/s + 0.000135 Load in N + 0.000059 Time in min - 0.000235 % of Reinforcement ---------- Equation 1

  R-Sq = 93.1%
- The regression equation for COF,
  = 0.385 + 0.148 Speed in m/s - 0.0114 Load in N - 0.00020 Time in min - 0.0106 % of Reinforcement -------------Equation 2

  R-Sq = 87.7%

5. CONFIRMATION EXPERIMENT

Confirmation test is the last step in the plan process. Table 10 indicates the values used for conducting the dry sliding wear test and Table 11 shows the results of confirmation experiment and their comparison with regression model which helps to identify the optical parameter values from the experimental analysis.

Table -10: Confirmation Experiment for Wear Rate and Coefficient of Friction

Level	Speed (m/s)	Load (N)	Time (sec)	Percentage of Reinforcement (%)
1	0.89	10	240	5
2	1.41	20	480	10
3	2.19	30	720	15

Table -11: Result of Confirmation Experiment and Their Comparison with Regression Model

Exp.	Exp. Wear	Reg. Model wear	% Error	Exp.	Reg. Model	% Error
1	0.00303273	0.002850147	6.40609	0.348772	0.34	2.58
2	0.00531441	0.005027521	5.70637	0.258524	0.245	5.52
3	0.00852786	0.007949122	7.28053	0.206904	0.203	1.92315

The mathematical model was developed with the help of regression equations (1&2) and also the comparison result values obtained experimentally were analyzed. From the analysis, the actual wear rate and co-efficient of friction are found to be varying from the calculated one using regression equation and the error percentage ranges between 5.70637 % to 7.28053 % for wear rate and 1.92315 % to 5.52 % for co-efficient of friction. As these values are closely resembling the actual data with minimum error, design of experiments by Taguchi method was successful for calculating wear rate and co-efficient of friction from the regression equation.

6. CONCLUSION

In the present investigation, the Al2218/fly ash/Gr hybrid composite was successfully fabricated by the stir casting route. The density, hardness and tribological behaviour were evaluated. The obtained results can be summarized as follows:

- Sliding speed (71.52%) has the highest influence on wear rate followed by load (12.12%) and percentage of reinforcement (9.95%) and for coefficient of friction, the contribution of sliding speed is 34.35%, load is 36.64% for AA 2218/Fly Ash/Graphite metal matrix composites.

- Hardness of composite samples increases (44.68, 51.06 and 58.36 BHN) while increase the volume fraction of reinforcements and density decreases upon increasing percentage of fly ash addition.
- Wear behaviour of the composites are better than that of unreinforced material. By increasing volume fraction, weight losses come closer to each other for all samples and then they decreases
- Increasing incorporation of Fly ash (5%, 10% & 15%) increases the wear resistance of composites by forming a protective layer between pin & counter face. The formation of a mechanically mixed layer seems to be a key factor controlling the wear behaviour of these composites.
- Better wear resistance was obtained and Coefficient of friction varies inversely with weight fraction of reinforcement, sliding speed and load. Coefficient of friction decreases with increase in percentage fly ash, load.
- Confirmation experiment was carried out & made a comparison between experimental values showing an error associated with dry sliding wear & coefficient of friction in both composites varying from 5.70637% to 7.28053 % and 1.92315% to 5.52% respectively. Thus design of experiments by Taguchi method was successfully used to predict the tribological behavior of composites.

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