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Study of Dry Sliding Wear Properties for AL-2024 based Metal Matrix Composites Fabricated by Stir Casting Method

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Abstract: Metal matrix composites possess significantly improved mechanical properties like high specific strength, specific modulus, damping capacity and good wear resistance compared to a Unreinforced alloys. Among various discontinuous dispersoids used, fly ash is one of the most inexpensive and low density reinforcement available in large quantities as solid waste by product during combustion of coal in thermal power plants. E-glass is another reinforcement used in this composite to enhance some of the mechanical properties of Al-2024. It is therefore expected that the incorporation of E-glass and fly ash particles in aluminium alloy will promote yet another use of this low-cost and moderate strength by stir casting method. The present investigation has been focused on the tribological properties and parameters are optimized by Taguchi method. Finally it is also validating and analysed by ANOVA.
Keywords: AL2024, Stir casting, ANOVA, Taguchi etc.

I. INTRODUCTION

Over the last thirty years composite materials, plastics and ceramics have been the dominant emerging materials. The volume and number of applications of composite materials have grown steadily, penetrating and conquering new markets relentlessly. Modern composite materials constitute a significant proportion of the engineered materials market ranging from everyday products to sophisticated niche applications.

There have been tremendous strides in engineering materials since 1950s. Several super alloys and heat resistance materials have been developed for various industrial applications, especially aerospace/aircraft and defense. Automotive, medical and sport equipment industries pushed advances in materials particularly having low density and very light weight with high strength, hardness and stiffness. One of these important advanced materials is composite. In Composite Metal Matrix Composites are composed of a metallic matrix (Al,Mg,Fe,Cu etc) and a dispersed ceramic (oxide, carbides) or metallic phase(Pb,Mo,W etc). Ceramic reinforcement may be silicon carbide, boron, Flyash, alumina, silicon nitride, boron carbide, boron nitride etc. whereas Metallic Reinforcement may be tungsten, beryllium etc . MMCs are used for Space Shuttle, commercial airliners, electronic substrates, bicycles, automobiles, golf clubs and a variety of other applications. Most MMCs are still in the development stage or the early stages of production and are not so widely established as polymer matrix composites. The basic advantages of MMCs are such as no significant moisture absorption properties, non-inflammability, low electrical and thermal conductivities and resistance to most radiations.

A. Aluminum Alloy Al2024

Aluminium and its alloys are generally resistant to corrosion in aqueous media due to the formation of a passive layer that protects them, except in solutions containing chloride ions which can break in the passive layer causing pitting corrosion damage. Due to low specific weight and mechanic properties aluminium alloys are commonly used to produce metallic foams. Aluminium alloy 2024 is one of the most extensively used of the 2xxx series aluminium alloys.

It was the first Al-Cu-Mg alloy to have a yield strength approaching 50,000-psi and generally replaced 2017-T4 (Duralumin) as the predominant 2XXX series aircraft alloy.

With its relatively good fatigue resistance, especially in thick plate forms, alloy 2024 continues to be specified for many aerospace structural applications. Metallic foams are part of a new family of materials called cellular metals. These materials are characterized by a unique combination of physical, chemical and mechanical properties such as hardness coupled with a low specific weight, or high permeability to gases with high mechanical strength.

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B. Fly Ash

Fly ash, also known as "pulverized fuel ash" , is a coal combustion product that is composed of the particulates(fine particles of fuel) that are driven out of coal-fired boilers together with the flue gases. Depending upon the source and makeup of the coal being burned, the components of fly ash vary considerably, but all fly ash includes substantial amounts of silicon dioxide (SiO_2) (both amorphous and crystalline), aluminium oxide (Al_2O_3) and calcium oxide(CaO), the main mineral compounds in coal-bearing rock strata. fly ash produced from coal combustion was simply entrained in flue gases and dispersed into the atmosphere. This created environmental and health concerns that prompted laws that have reduced fly ash emissions to less than 1% of ash produced. Worldwide, more than 65% of fly ash produced from coal power stations is disposed of in landfills and ash ponds. Fly ash majorly used in cement industries, Road sub-base, paints, metal casting etc, but still disposal of fly ash is major problem.

C. E-Glass

E-Glass fibers are among the most versatile industrial materials known today. They are readily produced from raw materials, which are available in virtually unlimited supply. These glass fibers are derived from compositions containing silica. They exhibit useful bulk properties such as hardness, transparency, resistance to chemical attack, stability, and inertness, as well as desirable fiber properties such as strength, flexibility, and stiffness. Glass fibers are used in the manufacture of structural composites, printed circuit boards and a wide range of special-purpose products.

D. Stir Casting

it is a one economical process for the fabrication of aluminum based metal matrix composites. In this process some of the parameters which affect the final microstructure and mechanical properties of the composites. In our work, Al based alloy is reinforcement Fly ash and e glass composites at temperatures between (680 to 850 °C) and stirring periods (2 and 6 min). The higher stirring temperature (850 °C) also leads to improved ceramic incorporation. In some cases, shrinkage porosity and intensive formation of the metal/ceramic interface are also observed. Finally, the mechanical properties of the composites were evaluated, and their relation with the corresponding microstructure and processing parameters of the composites. It consists of some the flowing steps like melting, Pre heating, Slag removing, mixing and Pouring of molten metal matrix and reinforcement mixture to the die.

II. FABRICATION AND EXPERIMENTAL WORK

The purpose of the experimental investigation is to analyze the mechanical behavior of the composite under different compositions of the reinforcing materials. For this, fabrication of hybrid composite is carried out for various combinations of matrix and reinforcing materials. The matrix material used for this purpose is AL2024. The alloys have very good casting and machining characteristics. Typically they are used in the heat-treated condition. Corrosion resistance is excellent and it has very good weldability characteristics. Mechanical properties are rated excellent particularly if given a solution and aging treatment . Typically this alloy is used in castings for aircraft parts, pump housings, impellers, high velocity blowers and structural castings where high strength is required. It can also be used as a substitute for aluminum alloy 6061. The reinforcing materials used for the purpose are Fly Ash in powder form and E-Glass fibers less than 2mm length. Composites with different combinations of the Al2024, Flyash and E-Glass are prepared which are given below:
Specimen 1 (100% AL2024)
Specimen 2 (90% AL2024+2% E-glass+8% fly ash)
Specimen 3 (90% AL2024+1.5% E-glass +8.5% Fly ash)
Specimen 4 (90% Al2024+1% E-glass+9% fly ash)

A.Preperation Of Hybrid Composites

Fabrication of hybrid metal matrix composites is done using liquid melt technique. In liquid melt method, matrix metal is melted in a furnace and the reinforcements are introduced while stirring the molten metal. This is an effective and economic method for fabrication of metal matrix composites. Melting of aluminium 2024 alloy is carried out in a muffle furnace. The furnace is crucible type and electrically heated 3-phase resistance furnace of 12kw capacity. The range of the furnace is 12000C, with an accuracy of +/- 10 C.

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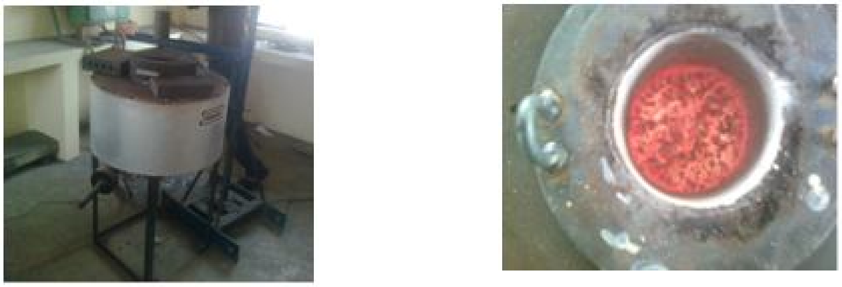

Figure 1: Furnace used for Melting Al2024

Prior to melting aluminium billets are cleaned thoroughly to remove any impurities present on the surface of the billet. A known quantity of Aluminium is charged into the furnace for melting which is shown in above Figure 1. The charging medium is a Graphite Crucible which is pre-heated to a temperature of 300-400^{o}C. Melting point of aluminium alloy lies between 660-730^{o}C. The aluminium alloy is superheated to a temperature of 780^{o}C and maintained at that temperature. This is because of two major reasons, first one is the slag formation is possible at higher temperatures then that of melting point of the metal, Secondly, to achieve the required fluidity until pouring of molten metal into the die, as there are several operations are to be performed before pouring such as degassing, mixing of reinforcements etc. Fly Ash and e-glass fibers are pre-heated to a temperature of 300-400^{0}C in a separate furnace before mixing into the molten metal pool. This is because, if not, addition of reinforcing materials can reduce the temperature of the molten metal by considerable amount and can cause problems during pouring. This will result in defects in the cast composite bar. Another reason is to remove the moisture content present in the reinforcing materials.

Figure 2: Solidification of Composites in Metallic dies

In casting metal matrix composites, particulate addition requires all the care. For the better properties it should be evenly distributed by some means. Stirring of liquid melt is also likely to improve the properties, as grain refinement is likely to occur. Once the degassing is completed, next step is to mix the liquid metal with required amount of Fly ash and E-Glass particles. The molten metal is placed under the mechanical stirrer. The stirrer steel blade is coated with aluminium which prevents the migration of ferrous particles into the aluminium melt. The stirrer is rotated at 550 rpm and the depth of immersion of the stirrer is maintained about two-thirds the depth of the molten metal. The rate of addition of the reinforcements is a critical parameter and it decides the uniform dispersion and distribution of the dispersed phase in the composites. When the Flyash particles and E- glass fibers are distributed evenly in the aluminum melt, next step is to pour the mixture in the permanent dies. In above figure 2 shows that die and it is preheated to a temperature of 400^{0}C to allow the uniform solidification of melt. Molten metal is manually poured into the pre-heated die with the help of tongs. Once the melt is completely solidified, the mold is split open and solidified, cylindrical castings are taken out for further processing.

III. MECHANICAL WEAR TESTING

This paper deals with the experimental study of wear characteristics on the fabricated composites. Composite specimens are fabricated with Flyash and E-Glass particles in different proportions in the aluminium alloy Al2024 matrix, which resulting in different composite specimens of Al2024 - Flash –E-Glass particle metal matrix composites. In the below table.1 show that the composition of these composite specimens.

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Table.1: composition of different composite specimens.

Sl. No.	Composite Designation	FlyASH Wt %	E-Glass Wt%
1	AL100%	0	0
2	AL8F2G	8%	2%
3	AL8.5F1.5G	8.5%	1.5%
4	AL9F1G	9%	1%

The fabricated composite materials are machined to prepare specimens for conducting various mechanical tests according ASTM G99 standard Specimen using CNC lathe and milling machine. Machined composite specimens were tested for any defects using the non destructive testing method. The ultrasonic flaw detector is used to check for any types of defects in the machined composite specimens.

A. Dry Sliding Wear Test

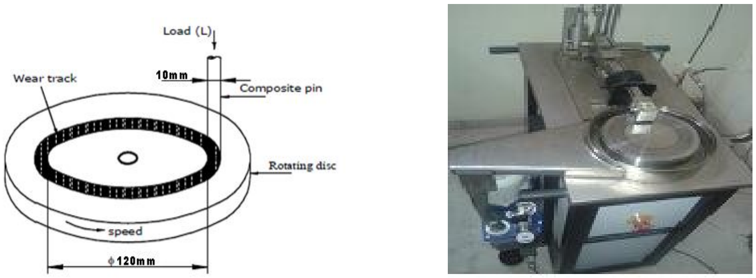

Figure 3: Pin-on-disc wear testing setup

The adhesive wear resistance of Al2024 alloy and its composites were studied by conducting dry sliding wear test. The wear testing specimen is prepared according to ASTM G99. A pin on disc wear testing configuration as shown in figure 3, is used to check dry sliding wear properties of composite specimen. The specimen is rubbed against rotating hard steel disc without any lubricant. Tests were conducted for different variables such as speed ranging from 200 to 500 rpm, normal load from 20 N to 60 N in steps of 20 N, and for a sliding time of 5-10 minutes. Common track diameter of 120 mm is used to test the specimen. After testing, the specimen is removed from the machine and weighed. The difference in initial and final weight gives the loss of material in turn wear rate of the material. The specimen is weighed using electronic balance. Tests are conducted at normal room temperature.

IV. RESULTS AND DISCUSSION

The purpose of the experimental investigation is to analyze the mechanical behavior of the composite under different compositions of the reinforcing materials. For this, fabrication of hybrid composite is carried out for various combinations of matrix and reinforcing materials. The tests were repeated for sliding speeds of 1.05 m/s, 1.83 m/s and 2.62 m/s, and it was found that the sliding speed has a direct impact on the wear rate of the composite material. At a sliding speed more than 3 m/s, high wear rate of composite material was observed and it was mainly because of localized melting of the composite pin due to high frictional temperature. At a sliding speed of 4 m/s, the composite pins were melted and found adhered to the disc as flakes.

A. Effect of Normal load (n) on The Composite

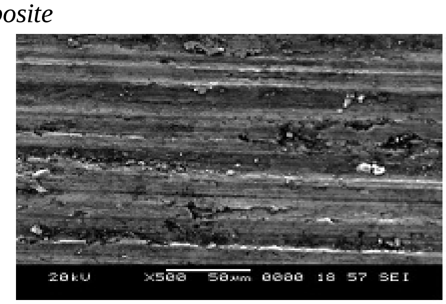

Figure 4 : SEM of the worn surface of the composite after testing at 20N Load indicating oxidation wear mechanism

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At higher applied loads, high wear rates are observed. The wearing surface is characterized by a significant transfer of material between the sliding surfaces. A de-lamination wear mechanism has been observed at higher loads. At very high loads, the near-surface temperature generated is high enough to reduce the shear strength in the sub-surface layer promoting extensive material transfer from the matrix alloy to the steel counter face. Figure 4 shown the SEM image showing a delamination wear mechanism which is observed with a wear specimen tested at 60 N load.

B. Effect of Sliding Speed

At lower sliding speeds, the wear mechanism is observed as wear due to the formation of oxide tribo layer which acts as a barrier to the wear of the MMC. The formation of microgrooves indicates that the predominant wear mechanism is wear due to abrasion. Grooving and scratching appear more severe at higher load and sliding speeds and less severe at lower load and sliding speeds. Such features characteristics of abrasion, in which hard asperities of the steel counterface, or hard reinforced particles in between the contacting surfaces, plough or cut into the pin, causing wear by the removal of small fragments of material.

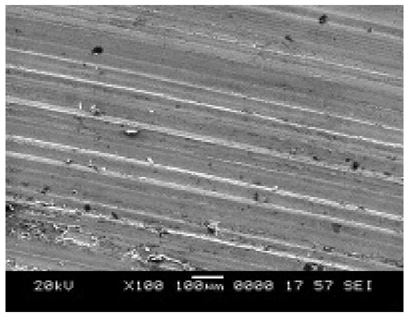

Figure.5 : SEM of the worn surface of the composite after testing at a sliding speed of 1.83 m/s indicating groove formation due to abrasion wear

The abrasion is extensive in this composites tested, due to the presence of Flyash and E-Glass, that become trapped in the sliding interface gets embedded in the counterface, contributing to abrasive wear. Figure.5 shows the SEM micrographs of the worn surface of the MMC which clearly shows the wear groove formation, indicating abrasion wear mechanism.

C. Effect of wt% of Reinforcements

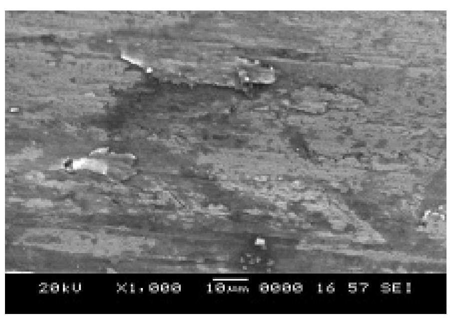

Figure.6: SEM micrographs of worn surfaces showing the wear mechanism due to thermal softening and adhesion

It can be observed from the SEM micrographs that the primary wear mechanism causing wear for the unreinforced alloy is due to adhesion of the matrix alloy due to thermal softening and as the wt% of reinforcements are increased the wear mechanism causing wear of the MMC is due to abrasion and delamination. This indicates that the increase in wt% of the reinforcement results in increased hardness of the MMC and is responsible for lower wear rate of the composites. Figure.6 shows the SEM micrographs of the worn surface of the composite specimens at higher wt% of reinforcements.

D. Statistical Analysis of Wear Test

The Taguchi technique is a powerful design of experiment tool for acquiring the data in a controlled way and to analyses the influence of process variable over some specific variable which is an unknown function of these process variables and for the design of high quality systems. This method was being successfully used by many researchers in the study of the wear behavior of aluminium metal matrix composites. The Taguchi method, which is effective to deal with responses, was influenced by multivariables. This method drastically reduces the number of experiments that are required to model the response function compared with the full factorial design of experiments. This technique creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiments. The experimental results are analysed using analysis of means and variance to study the influence of factors.

Table 2: Factors and their levels

Symbol	Factor	Level 1	Level 2	Level 3
L	Normal Load N	20	40	60
S	Sliding Speed m/s	1.05	1.83	2.62
F	Flyash & E-glass content Wt%	4 SPs	4 SPs	4 SPs

In the present investigation, an L27 orthogonal array was selected. In the study of prediction of wear rate of the composite materials is carried out by selecting load (L), sliding speed (S) and wt% of Flyash and E-Glass (F) as control variables. The control variables and their levels are shown in table 2 and the standard L27 orthogonal array. The response variable to be studied is wear rate. The experiments were conducted based on the rank order generated by Taguchi model and the results were obtained. The analysis of the experimental data was carried out using MINITAB 15 software, which is specially used in DOE applications. The experimental results were transformed into a Signal-to-Noise (S/N) ratios. Where, *y* is the observed data (wear rate) and *n* is the number of observations. The above S/N ratio transformation is suitable for minimization of wear rate. The experiments were conducted as per orthogonal array and the wear rate results obtained for various combinations of parameters are shown in Table 3. The S/N ratio obtained from all the experiments are shown in Table 3.

Table 3: Wear rate and S/N ration obtained as per Taguchi's L27 Orthogonal Array

Sl. No.	Load, N(L)	Speed, m/s (S)	Flyash & EGlass wt%(F)	Wear Rate Kg/m x 10-5	S/N Ratio
1	20	1.05	Specimen 2	4.3221	-12.7139
2	20	1.05	Specimen 3	4.2548	-12.5777
3	20	1.05	Specimen 4	4.2467	-12.5611
4	20	1.83	Specimen 2	5.4929	-14.7960
5	20	1.83	Specimen 3	5.0214	-14.0164
6	20	1.83	Specimen 4	4.8204	-13.6616
7	20	2.62	Specimen 2	5.7068	-15.1279
8	20	2.62	Specimen 3	5.0277	-14.0273
9	20	2.62	Specimen 4	4.9241	-13.8465
10	40	1.05	Specimen 2	5.8757	-15.3812
11	40	1.05	Specimen 3	5.0686	-14.0977
12	40	1.05	Specimen 4	4.4106	-12.8900
13	40	1.83	Specimen 2	6.5615	-16.3401
14	40	1.83	Specimen 3	5.9511	-15.4920
15	40	1.83	Specimen 4	5.1044	-14.1588
16	40	2.62	Specimen 2	6.8274	-16.6850
17	40	2.62	Specimen 3	6.4797	-16.2310
18	40	2.62	Specimen 4	5.7960	-15.2625
19	60	1.05	Specimen 2	6.8034	-16.6545
20	60	1.05	Specimen 3	5.9539	-15.4960
21	60	1.05	Specimen 4	5.8150	-15.2911
22	60	1.83	Specimen 2	7.6529	-17.6765
23	60	1.83	Specimen 3	6.8746	-16.7449
24	60	1.83	Specimen 4	6.5706	-16.3521
25	60	2.62	Specimen 2	7.7599	-17.7971
26	60	2.62	Specimen 3	7.5801	-17.5935
27	60	2.62	Specimen 4	6.7334	-16.5646

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E. S-N Ratio Analysis

The influence of control parameters such as load, sliding speed and Alumina content on wear rate has been evaluated using S/N ratio response analysis. The control parameter with the strongest influence was determined by the difference between the maximum and minimum value of the mean of S/N ratios.

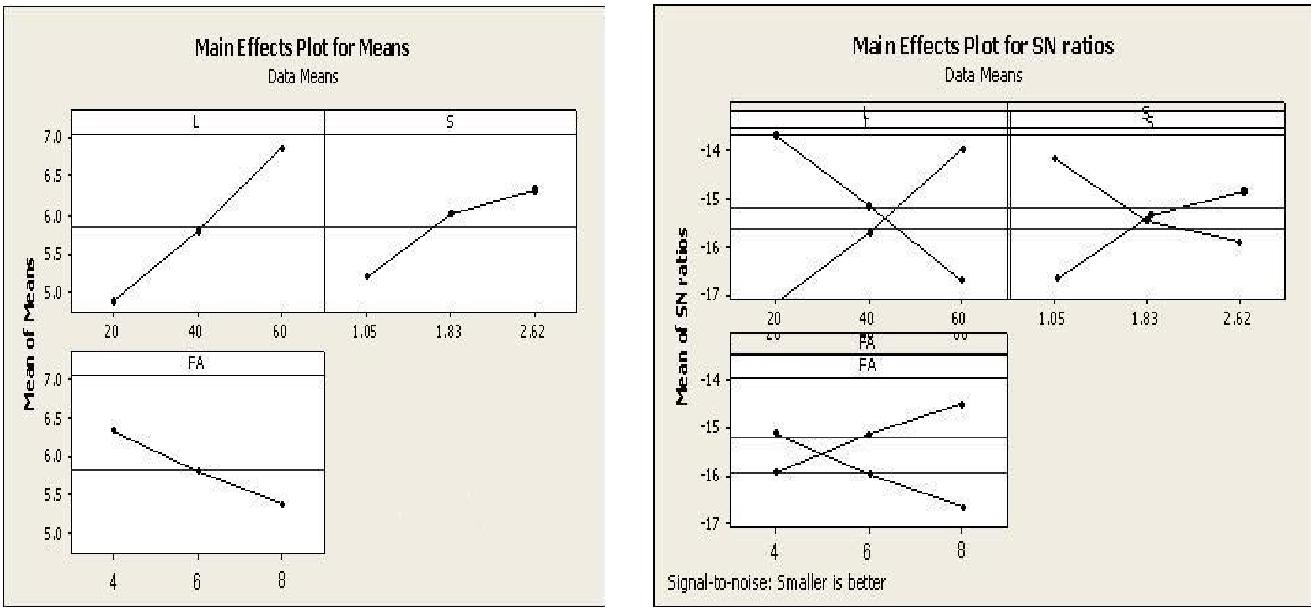

Figure.7: Main Effects plot for Means & Main Effects plot for S-N Ratios.

Table 4: Response table for S/N ratios - smaller is better (wear rate)

Level	Load	Speed	SiC
1	4.869	5.195	6.334
2	5.786	6.006	5.801
3	6.86	6.315	5.38
Delta	1.992	1.12	0.953
Rank	1	2	3

Higher the difference between the mean of S/N ratios, the more influential was the control parameter. The S/N ratio response analysis, presented in Table 4 shows that among all the factors, load was the most influential and significant parameter followed by sliding speed and Reinforcement content. Figure.7 shows the mean of wear rate graphically and figure 7 depicts the main effects plot for means of S/N ratio for wear rate. From the analysis of these results, it can be inferred that parameter combination of L = 20 N, S = 1.05 m/s and F = 9% gave the minimum wear rate for the range of parameters tested.

F. ANOVA and Effects of Parameters on Wear Rate

Analysis of Variance (ANOVA) was used to determine the design parameters significantly influencing the wear rate (response). The table shows the results of ANOVA for wear rate. This analysis was evaluated for a confidence level of 95%, that is for significance level of α=0.05. The last column of Table 5 shows the percentage of contribution (P %) of each parameter in the response, indicating the degree of influence on the result.

Table 5: ANOVA Results for Wear Rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
Load, N (L)	2	17.8907	17.8907	8.9454	209.230	0.000	61.38
Speed, m/s (S)	2	6.0266	6.0266	3.0133	70.480	0.000	20.68
Flyash & EGlass wt%(F)	2	4.1097	4.1097	2.0549	48.060	0.000	14.10
L X S	4	0.1298	0.1298	0.0325	0.760	0.580	0.45
L X F	4	0.5551	0.5551	0.1388	3.250	0.073	1.90
S X F	4	0.0919	0.0919	0.0230	0.540	0.713	0.32
Residual Error	8	0.3420	0.3420	0.0428			
Total	26	29.146					

it can be observed from the results obtained in the Table 5, that load was the most significant parameter having the highest statistical influence (61.38%) on the dry sliding wear of composites followed by sliding speed (20.68%) and Reinforcement content (14.10%). When the P-value for this model is less than 0.5, then the parameter or interaction can be considered as statistically significant. This is desirable as it demonstrates that the parameter or interaction in the model has a significant effect on the response. From an analysis of the results obtained in Table 5, it is observed that the load (L), sliding speed (S), reinforcement content (F), the interaction effect of load with Reinforcement content (L x F) is significant model terms influencing wear rate of composites, since they have obtained the P - value < 0.5. Although the interaction effect of load with sliding speed (L x S) exerts some influence on the dry sliding wear, it may be considered statistically insignificant for its P-value is greater than 0.5, and hence it is neglected. When R2 approaches unity, a better response model results and it fits the actual data. The value of R2 calculated for this model was 0.988, i.e., very close to unity, and thus acceptable. It demonstrates that 98.8% of the variability in the data can be explained by this model. Thus, it is confirmed that this model provides reasonably good explanation of the relationship between the independent factors and the response.

G. Multiple Linear Regression Model

A multiple linear regression analysis attempts to model the relationship between two or more predictor variables and a response variable by fitting a linear equation to the observed data. Based on the experimental results, multiple linear regression models were developed using MINITAB 15. Regression equations thus generated establish correlation between the significant terms obtained from ANOVA, namely, load, sliding speed, Reinforcement content and their interactions. The regression equations developed for wear rate are: W2% GR = 2.97 + 0.0629 L + 0.713 S - 0.0719 F - 0.00218 L x F The regression coefficient (R2) obtained for the model was 0.953 for 9wt% Flyash and 1% E-Glass reinforcement particles, and this indicates that wear data was not scattered. The coefficient associated with load (L) in the regression equations is positive and it indicates that as the load increases, the wear rate of the composite also increases. The coefficient associated with sliding speed (S) in the regression equations is also positive and this suggests that the wear rate of the composite increases with increasing sliding speed. It can be inferred from the negative value of the coefficient associated with Filler content (F) in the regression equations that as the weight percentage of content E-Glass increases, wear rate of the composite reduces. The wear resistance of hybrid composite has increased due to the increase in the weight fraction of E-Glass. The increased area fraction of hard Flyash-E-Glass particles, improved the load carrying capacity and the abrasion resistance of composites. The specimen-4 with 9 wt% Flyash and 1% of E-Glass reinforced hybrid composite exhibit good wear resistance and the lowest wear rate at all loads and sliding speeds. The other interaction effects indicated in the equation was marginal.

H. The confirmation Test

In order to validate the regression model, confirmation wear tests were conducted with parameter levels that were different from those used for analysis. The different parameter levels chosen for the confirmation tests are shown in Table 6. The results of the confirmation test were obtained and a comparison was made between the experimental wear rate values and the computed values obtained from the regression model (Table 6). The error associated with the relationship between the experimental values and the computed values of the regression model for hybrid composites was very less (around error). Hence, the regression model developed demonstrates a feasible and effective way to predict the wear rate of the hybrid composites.

Table 6: Confirmation test results

Test No.	Experimental Wear Rate, kg/m x 10-5	Regression Model Predicted Wear Rate, kg/m x 10-5	Error, %
1	4.5631	4.4213	3.1
2	5.6891	5.5609	2.3
3	6.7845	6.4389	5.1

V. CONCLUSIONS

This chapter describes the analytical and experimental investigation on Al Based alloy composites (with Flyash and E-Glass variation) have led to the following specific conclusions.

A. The present work shows that successful fabrication of Al2024-Flyash-EGlass composites with different composition is possible by stir casting technique.

B. The wear rate increases with the increase in normal load. However, the composites have shown a lower rate of wear and good wear resistance (up to 9% Flyash, 1% E-Glass) as compared to that of other composition observed.

C. SEM analysis as done for different composition like 8, 8.5&9% of flyash and 2%, 1.5% &1% clearly observed at refined grain structure for respective composites.

D. The regression model developed demonstrates a feasible and effective way to predict the wear rate of the hybrid composites, and which is validated by confirmation test between experimental results and Regression Model results.

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