Dry Sliding Wear Characteristics of Al6061-Zircon particulate Aluminium Matrix Composites Using Taguchi Technique

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Abstract-This paper investigates the sliding wear behaviour of zircon particle-filled aluminium matrix composites (AMCs). Zirconium Silicate was chosen as Reinforcement for the current study. The percentage reinforcement is varied from 6 to 12 wt% in steps of 3. For investigating the wear behaviour, factors such as applied normal load, speed and sliding distance are considered. Also Taguchi design of experimental technique is employed for the study and analysis of sliding wear. Findings showed that Al6061-Zircon particulate-reinforced AMNCs show better wear resistance than unreinforced Al6061 alloy. Also regression is used to develop a model to predict the wear rate of these composites. Analysis of variance (ANOVA) and S/N ratio at room temperature for both Specific Wear rate and COF were developed to study the most significant parameter on corresponding responses. Confirmation experiments were conducted to validate multi-linear regression model. Worn surfaces were examined using scanning electron microscope (SEM) to investigate wear characteristics. The developed material can be used to fabricate automobile components like cylinders and connecting rods.

***Index Terms*-Metal Matrix composites, Al6061, $ZrSiO_4$, Stir casting, Sliding wear, L27 array, Analysis of variance.**

I. INTRODUCTION

During the last three decades, there have been intensive efforts towards preparation and characterization of metal matrix composites (MMCs) due to the demand for properties like high strength and high performance of these composites in the field of aeronautical and automobiles [1-3]

In the current scenario, aluminium metal matrix composites (AMC) is preferred in most application due to lightness and cost effective. Generally, AMCs are fabricated with matrix as aluminium (Al) and reinforcement as ceramics. AMCs has been attributed inherent strength, high strength modules, and better wear resistance with customize properties of thermal due to the addition of ceramics. The reinforcements (ceramics) restricted the deformation of Al from load and distributed load uniformly throughout the base matrix with enhances the properties of composite. The combination of metal matrix together with ceramic reinforcements have shown good potential in the engineering field where the need of higher mechanical properties such as hardness, tensile strength and tribological properties like wear is felt. In case of wear properties, wear behaviour of the composite is a complex process involving not only mechanical but also thermal and chemical interaction of two contact surfaces. S Dhanalakshmi et.al, [4] suggested that wear resistance of the hybrid Al7075-Al_2O_3-B_4C composites increases with increasing weight percentage of reinforcement in the composite. E. Subba Rao et.al, [5] concluded that AA6061-MOS_2 composites were successfully fabricated by stir casting method and observed the uniform distribution of reinforcements (precipitates) in the developed composites. Madevan Nagaral et.al,[5] revealed that the Two step addition methods of reinforcements is adopted to introduce SiC and Graphite particulates into Al6061 matrix during melt stirring has contributed in homogeneous distribution of SiC and Graphite particulates with no clustering or agglomeration as evident from SEM microphotographs. Al 6061 alloy is the best selected one to get favorable mechanical properties, good formability and the strength. The stir casting method is found to be easier and the low-cost production method when compared to other processing methods, particularly when discontinuous reinforcements are used. Surendra Kumar Patel et.al,[6] concluded that the combination of reinforcement in LM-13 alloy composites 50 % SiC and 50 % zirconium silicate particles reinforced composite yields better tensile strength as compared to other combinations. An important factor for the use of this technique is adequate wettability between the matrix alloy and the reinforcement material. Taguchi technique is a better technique to deal with responses influenced by multivariable.

In the current work, we address the fabrication of Al 6061-Zircon composites using two step Stir casting method and also an attempt has made in this investigation to study the effect of applied load, sliding speed and sliding distance on dry sliding wear behaviour of the Al/$ZrSiO_4$ composites using Taguchi design of experiments. The analysis of variance was employed to find the percentage of influence of various factors and its interaction on dry sliding wear of the composites. Specific wear rate was calculated by considering density, load, sliding distance and the weight loss and by using Taguchi orthogonal design with the L27 Orthogonal array.

II. TAGUCHI TECHNIQUE

Taguchi technique is a powerful tool for the design of high quality systems which provides a simple efficient and systematic approach to optimize designs for performance, quality and cost. Taguchi parameter design can optimize the performance characteristics through the setting of design parameters. This method is multi-step process, which follow a certain sequence for the experiments to give an improved understanding of a product or process performance. This includes planning, designing, conducting, analysis and confirmation phases. Analysis of variance is a mathematical technique, which is based on a least square approach [7]. The results are analyzed by signal to noise ratio (S/N) values that are categorized into three types of quality characteristics such as Smaller the better (SB), higher the better (HB) and nominal the best (NB). This will be selected based on the response of the process, since here the response is specific wear rate and we have to minimize the value of response so LB characteristics need to be applied here[8].

With the help of S/N ratio and ANOVA analysis, optimal combinations of process parameters are obtained and confirmation test was performed to verify optimum process parameters

$$S/N = -10 \log 1/n \left(y1^2 + y2^2 + y3^2 + \dots\dots\dots + yn^2\right) \dots\dots\dots\dots\dots\dots\dots (1)$$

Where $y1$, $y2$, $y3 \dots yn$ are the response of sliding wear, n is the number of observations

III. EXPERIMENTAL DETAILS

3.1 Materials

In the present investigation Aluminium 6061 was chosen as the matrix material with the following chemical composition (%): Si = 0.5, Fe = 0.5, Cu = 0.30, Mn = 0.10, Mg = 0.9, Zn = 0.2, Ti = 0.10, Cr=0.25, Al = balance. Al6061 matrix was chosen as it provides excellent strength and wear resistance in automobile components. Zirconium Silicate was taken as Reinforcement in the powder form with a particle size of 60microns ZrO_2=67.22, SiO_2=30.85, HfO_2=1.39, Al_2O_3=0.11, Fe_2O_3=0.029, MgO=0.014 .Stir casting was adapted to fabricate the composites.

3.2 Development of composites

The quantity of Zircon particles were varied from 6 to 12 wt. % in steps of 3wt %. The stir casting technique has been used to prepare the Al6061-$ZrSio_4$ composites. The aluminium ingots Al 6061 was placed in a silicon carbide made crucible, which was placed in a furnace (electrical resistance) at an operating temperature of around 750 degree Celsius. Hexachloroethane (C_2Cl_6) was added to the melt to remove the unwanted gases in the melt. Zircon particulates of particle size of 60 microns in weighted quantity were inserted into the vortex of the melt at 750^0C .Before introducing The reinforcing particles pre- heated to a temperature of 200^0C and added to the melt by two stage reinforcement mixing method where half of the weight percentage of reinforcement added into the melt and stirred using mechanical stirrer for five minutes and later the temperature was brought down to 650^0C, at this stage remaining half of the reinforcement was added into the melt and it was stirred manually as it was in a solid state for five minutes and later the mixture heated to the pouring temperature 750^0C where at this stage the mixture was stirred using mechanical stirrer once again and later it was poured to permanent moulds with 150mm length and 20mm diameter. This method of two stage incorporation of reinforcement into Al6061 alloy matrix will increase wettability of the matrix and hard reinforcement. The prepared castings were machined and micro structural studies were carried out using SEM. Once the Zircon particles confirmed in the matrix, composites were subjected to the sliding wear test using pin-on-disc machine.

3.3 Plan of experiments

The experiments were conducted as per the standard orthogonal array. In the present study, an L_{27} orthogonal array was chosen. The wear parameters chosen for the experiment was (i) speed, (ii) load (iii) sliding distance (iv) percentage of reinforcement. Table 1 indicates the factors and their levels. The response to be studied was the wear with the objective of smaller is the better. The experiments were conducted as per the orthogonal array with level of parameters given in each array row. The wear test results were subject to the Analysis of Variance.

Table 1. Factors considered and their Levels

SI.NO.	LOAD (N)	SPEED (Rpm)	SLIDING DISTANCE (m)	PERCENTAGE OF REINFORCEMENT (%)
1	10	200	500	6
2	20	400	1000	9
3	30	600	1500	12

Table 2. Experimental design of L27 Orthogonal Array and responses of the wear test

Sl. No.	**LOAD**	**SPEED**	**SLIDING DISTANCE**	**PERCENTAGE OF REINFORCEMENT**	**SPECIFIC WEAR RATE (mm^3/N-m)**	**WEAR in Microns**
1	10	200	500	6	6.729	85
2	10	200	1000	9	3.189	79
3	10	200	1500	12	1.914	72
4	10	400	500	9	6.451	94
5	10	400	1000	12	2.55	88
6	10	400	1500	6	1.905	82
7	10	600	500	12	4.397	105
8	10	600	1000	6	2.279	108
9	10	600	1500	9	1.1947	112
10	20	200	500	6	3.2925	67
11	20	200	1000	9	1.577	64
12	20	200	1500	12	0.76	56
13	20	400	500	9	3.333	80
14	20	400	1000	12	1.24	74
15	20	400	1500	6	0.78	67
16	20	600	500	12	2.234	86
17	20	600	1000	6	1.21	89
18	20	600	1500	9	0.812	92
19	30	200	500	6	2.29	55
20	30	200	1000	9	1.05	51
21	30	200	1500	12	0.559	49
22	30	400	500	9	2.15	67
23	30	400	1000	12	0.8274	61
24	30	400	1500	6	0.555	56
25	30	600	500	12	1.13	77
26	30	600	1000	6	0.59	73
27	30	600	1500	9	0.4619	70

3.4 Experimental set up with procedure

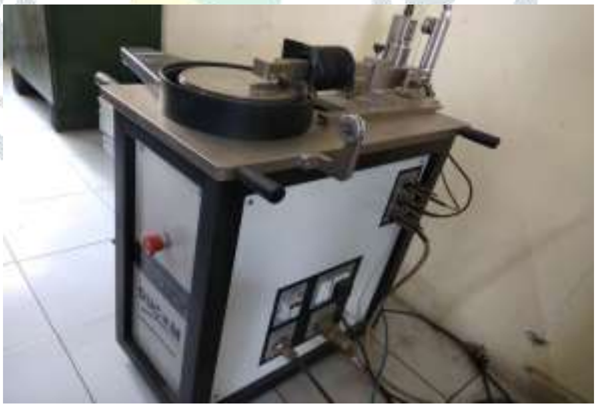


Fig 1.Pin on disc apparatus for the wear test

A pin-on-disc test apparatus shown in Fig.1 was used to conduct the dry sliding wear characteristics of the composite as per ASTM G99 standards. The wear specimen with 8 mm of diameter and 30 mm height was cut from as-cast samples and machined using the CNC machines. The initial weight of the specimen was measured in a single pan electronic weighing machine with least count of 0.0001 g. During the test the pin was pressed against the counterpart rotating against EN32 steel disc with hardness of 65 HRC by applying the load. After running through a fixed sliding distance, the specimens were removed, cleaned with acetone, dried and weighed to determine the weight loss due to wear.

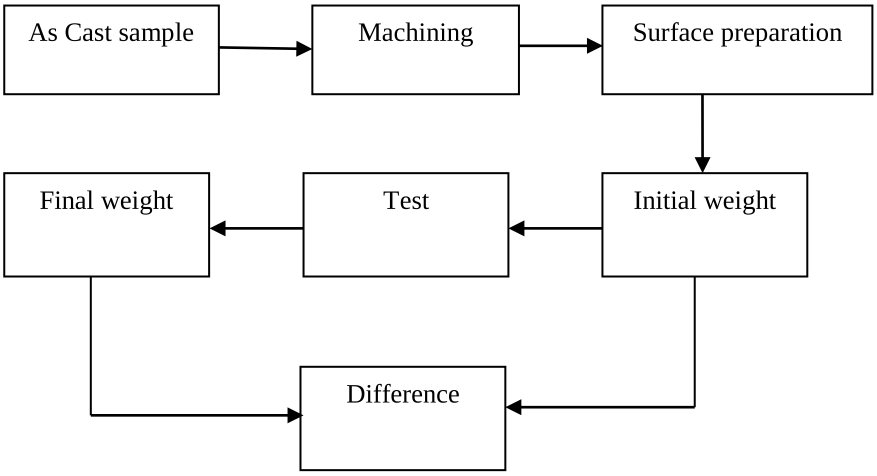
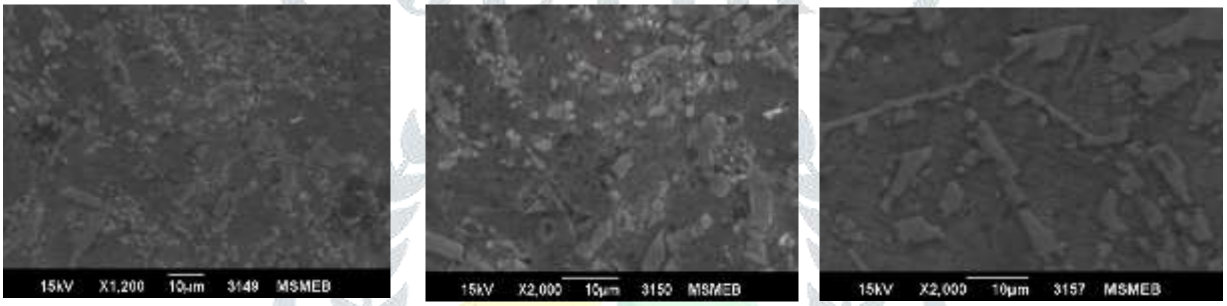


Fig. 2 Step-by-Step procedure used to evaluate the dry sliding wear of composites

IV. RESULTS AND DISCUSSIONS

4.1 Microstructural Studies



(a) (b) (c)

Fig.2. The SEM micrograph of composites with a) 6% of zircon b) 9% of zircon c) 12% of Zircon

Fig. 2 (a) shows the microstructure of Al6061-6 wt. % composite. The Micrograph shows the refined microstructure and homogeneous distribution of particles in the alloy matrix. Refined microstructure and absence of dendritic morphology can be attributed to the two-step stir casting process adopted here in which prolonged time of mixing and stirring. Zirconium silicate particles provide effective site for nucleation and also restricts the growth of dendrite and modifies the matrix with more refined structure leading to improvement in strength. Fig. 2 (b) shows microstructure of Al 6061- 9 wt. % which represents Zirconium silicate depicts the refinement of microstructure where the Clustering of particles is observed at some places. Fig.3 (c) indicates distribution is more refined and morphology has changed from finer to coarse distribution.

4.2 Statistical analysis

The experiments were conducted with an intention to relate the influencing factors like Speed (S), Applied load (L) sliding distance (D), percentage of reinforcement with dry sliding wear of composites under the current study. On conducting the experiments as per the orthogonal array, the dry sliding wear results for various combinations of parameters were obtained. The purpose of the statistical analysis of variance (ANOVA) is to investigate which design parameter that significantly affects the wear characteristic. Based on ANOVA the optimal combinations of the process parameters are predicted. This analysis is carried out for level of significance of 5% (i.e., the level of confidence 95%) Tables 3 and 4 shows the responses for Specific wear rate and Co-efficient of friction for Zircon reinforced composite materials.

Table 3.Resonse table for Specific Wear rate (mm^3/N-m)

Level	Load	Speed	Sliding distance	Wt. %
1	-9.3062	-5.1959	-9.8123	-4.0733
2	-3.2132	-4.4419	-3.0039	-4.5310
3	0.8636	-2.0179	1.1604	-3.0515
Delta	10.169	3.1780	10.9727	1.4795
Rank	2	3	1	4

Table 4 Response table for wear (microns)

Level	Load	Speed	Sliding distance	Wt. %
1	-39.15	-36.01	-37.87	-37.40
2	-37.39	-37.31	-37.46	-37.72
3	-35.76	-38.99	-36.98	-37.19
Delta	3.39	2.99	0.89	0.52
Rank	1	2	3	4

The Delta value in Table 3 and 4 indicates the variation in mean within the levels and delta value is computed by subtracting the smallest mean value from largest mean value of S/N ratio. When there is larger variation between the mean values, the delta value will be high. The parameter with the largest delta value has greater significance on wear rate. The rank of parameters is decided from this delta value. From the delta values in Table 3 it is observed that sliding distance has the major significance on specific wear rate followed by load, speed and weight percentage has the major significance on Specific wear rate.

From the delta values in Table 4 it is observed that Load has the major significance on wear followed by speed, sliding distance and weight percentage has the major significance on Wear.

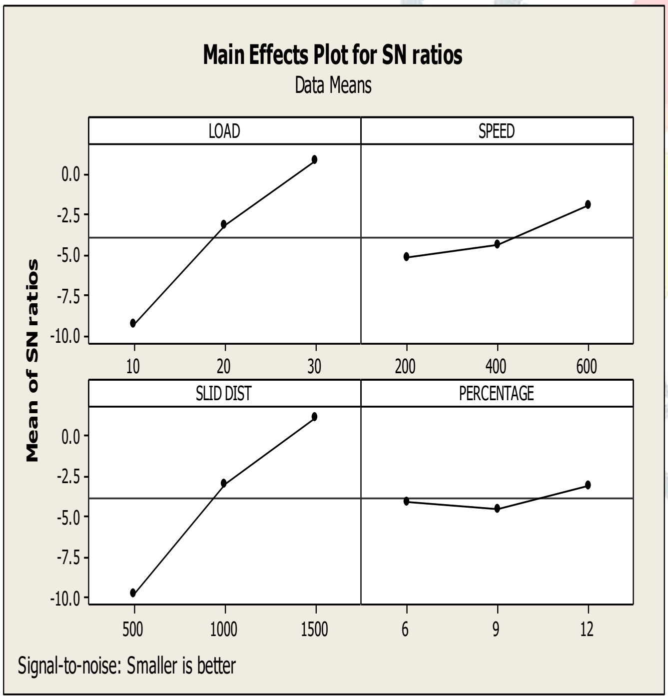


Figure 3: Effect of control factors on specific wear rate (*S/N* ratio)

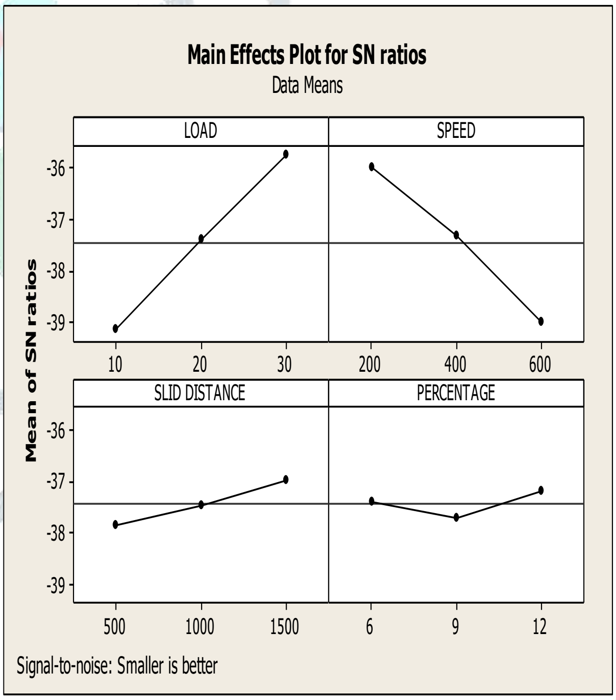


Figure 4: Effect of control factors on wear (microns (*S/N* ratio)

The above graphs have been plotted based on the Smaller is better concept due to the response of wear behavior. Generally this graphs will indicates the optimized levels of each parameter. From the Figure 3 it is observed that as the load, speed and sliding distance increases, there is increase in Specific wear rate But whereas increase in weight percentage of reinforcement the wear rate has been decreased from level-1 to level-2 and increased at level-3. The optimum mean response value for Specific wear rate was found to be level-1 in load, level-1 in speed, level-1 in sliding distance and level-2 in Wt. % of reinforcement. Also from the Figure 4 it is evident that as load, sliding distance increases there is an increase in Co-efficient of friction, but in the weight percentage of reinforcement the Co-efficient of friction has been decreased from level-1 to level-2 and increased at level-3.

Table 5 ANOVA table for Specific Wear Ratex10^{-13} (mm^3/N-m)

SOURCE	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
LOAD	2	26.2479	26.2469	13.1239	157.14	0.000	36.82
SPEED	2	3.0464	3.0469	1.5232	18.24	0.003	4.27
SLIDING DISTANCE	2	32.187	32.1877	16.0938	192.70	0.000	45.155
PERCENTAGE	2	1.3972	1.3972	0.6986	8.36	0.018	1.96
LOAD*SPEED	4	0.7131	0.7131	0.1783	2.13	0.194	1.00
LOAD*SLIDING DISTANCE	4	7.0475	7.0475	1.7619	21.10	0.001	9.88
LOAD*PERCENTAGE	4	0.1390	0.1390	0.0348	0.42	0.792	0.19
ERROR	6	0.5011	0.5011	0.0835			0.70
TOTAL	26	71.2800					100

Table 6 ANOVA table for Wear (microns)

SOURCE	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
LOAD	2	3952.30	3952.30	1976.15	110.24	0.000	52.22
SPEED	2	3092.07	3092.07	1546.04	86.25	0.000	40.86
SLIDING DISTANCE	2	200.07	200.07	100.04	5.58	0.043	2.643
PERCENTAGE	2	96.52	96.52	48.26	2.69	0.146	1.275
LOAD*SPEED	4	70.15	70.15	17.54	0.98	0.484	0.927
LOAD*SLIDING DISTANCE	4	6.81	6.81	1.70	0.10	0.980	0.0899
LOAD*PERCENTAGE	4	41.70	41.70	10.43	0.58	0.688	0.55
ERROR	6	107.56	107.56	17.93			1.42
TOTAL	26	7567.19					100

[Note:DF=Degrees of freedom; Seq SS=Sequential sum of squares; Adj SS=Adjusted sum of squares, Adj MS=Adjusted Mean Squares, F=Fisher values]

Table.5 shows the ANOVA results of Specific wear rate wear in reaction to the factors .Sliding distance having high significance with 45.155% of contribution followed by load , speed and percentage of reinforcement. Thus this factor shows the excellent improvement in the results.

Table.6 shows the ANOVA results of wear in reaction to the factors. Load having high significance with 52.22 % of contribution followed by speed, sliding distance and percentage of reinforcement. Thus this factor shows the excellent improvement in the results.

4.3 Regression analysis

Regression analysis is used to calculate the data based on the properties of developed composites. The regression equation are used to forecast the wear considering the factors used. The correlation between the control factors (load, speed, sliding distance and weight percentage of reinforcement) on the specific wear rate and COF was obtained by multiple linear regression technique and represented as follows.

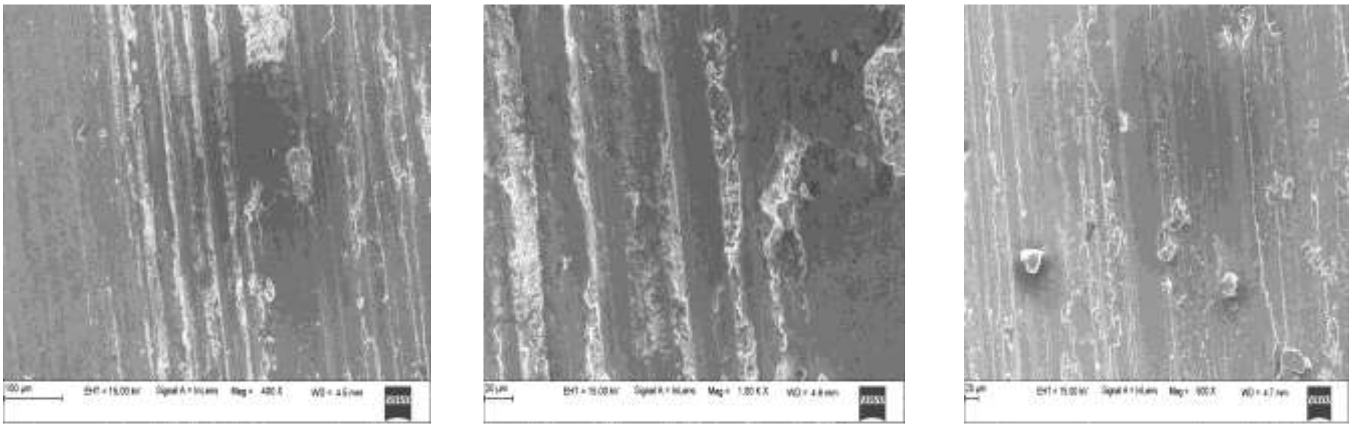
$$\text{Specific Wear Rate x}10^{-13} = 8.40 - 0.117\ \text{Load} - 0.00196\ \text{Speeds} - 0.00256\ \text{Slid Distance} - 0.0744\ \text{Percentage}\ldots \quad (2)$$

$$\text{Wear} = 88.8 - 1.48\ \text{Load} + 0.0650\ \text{Speed} - 0.00667\ \text{Slid Distance} - 0.259\ \text{Percentage}\ldots\ldots \quad (3)$$

Fig.5.a shows the residual plots of wear which will help to determine adequacy of the model generated .The residuals are the difference between experimental values and predicted values and in residual versus percent, points are randomly scattered and in Fig 6.b it shows the residuals v/s the observations order where the curve move above and below the mean line for the corresponding samples.

4.4 Morphology of worn surfaces

The morphological changes on the worn out surface of the fabricated Al 6061/$ZrSiO_4$ composites developed are clearly observed through SEM images.



(a) (b) (c)

Fig 5. SEM image of the surface after wear test

SEM image of worn out surface after tests for wear is shown in Fig.5(a),(b) and (c) indicates the composites which were tested by pin-on-disc for 6,9 and 12% of Zircon .During sliding, the entire surface of the pin has contact with the surface of the steel disc and machine marks can also be observed. As the sliding speed increases, the number of grooves also increases and the reinforcements are projecting out from the pin surface due to ploughing action between counterface and pin and formation of wear debris was also observed.

4.5 Confirmation Experiment

This the final stage in Design of Experiment (DOE) which is to validate the optimum levels of factors chosen. Confirmatory experiment was conducted with the combination of factors and the levels selected. The results of the experiments carried out is shown in the below Table.8.

Table.7 Results of Experiment

EXP.NO	Load (N)	Speed (rpm)	Distance (m)	Percentage of reinforcement (%)
1	25	225	800	6
2	35	450	1600	9
3	45	900	2400	12

The results of the confirmatory test are tabulated in Table.8.

Table.8. Results of Confirmation Test

EXP NO	Experimental Specific wear rate(mm^3/N-m)x10^{-13}	Regression model Specific wear rate (mm^3/N-m)x 10^{-13}	Error(%)	Experimental Wear in microns	Regression model Wear in microns	Error(%)
1	2.40	2.53	5.13	97	104	6.73
2	1.22	1.34	8.95	51	54	5.55
3	5.42	5.66	4.24	58	62	6.45

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VI. CONCLUSIONS

From the present study the following conclusions drawn

- Stir casting with 2 step mixing was successfully adapted to develop the Al6061-6% Zircon, Al6061-9% & Al6061-12% composites.
- Introducing the Zircon particles into Al6061 matrix increases the wear resistance of composites.
- From the response table for the Specific wear rate it can be concluded that sliding distance (45.15%) is the influencing factor followed by load, Speed and weight percentage.
- From the response table for the Wear it can be concluded that Load (52.22%) is the most significant factor followed by Speed, Sliding Distance and weight percentage.
- Regression equation generated for the current study and was used to predict the Specific wear rate and Wear in the developed composites for intermediate conditions with reasonable accuracy.
- Analysis of worn surfaces revealed that at lower load, oxidation was the dominant wear mechanism, whereas at higher load, delamination and adhesion were found to be dominant for the alloys. It was found that mild wear occurs at lower applied load, whereas severe wear occurs at higher applied load.

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