OPTIMIZING WEAR BEHAVIOR OF HYBRID AL7075 COMPOSITES USING TAGUCHI TECHNIQUE

Ravi Kumar Nagula
[a]Research Scholar, Department of Mechanical Engineering, Jawaharlal Nehru Technological University Hyderabad, Hyderabad-500085, TS, India,

Dr. K. Vijaya Kumar Reddy
[b]Professor, Department of Mechanical Engineering, Jawaharlal Nehru Technological University Hyderabad, Hyderabad-500085, TS, India

Abstract- In the current investigation, an Al7075 alloy as the matrix, and different weight percentages of (Si3N4 by 2, 4 and 6 percent of wt) silicon nitride, snail shell powder (SSP by 2, 4 and 6 percent of wt), and a constant weight percentage of rice husk ash (RHA by 5 percent of wt) are used as the material for reinforcement. The manufacture of the composite matrix is carried out using a method known as stir casting. The hybrid composite that is produced as a result of this formation is referred to Hybrid Aluminium Metal Matrix Composite (HAMMC). To evaluate the tribological properties of composites, pin-on-disc testing machine is utilized. Taguchi method is utilised in the process of analysing the parameters in order to determine the friction co-efficient and wear rate. After that, the analysis is proceeded with the optimization of the testing conditions by making use of a L9 orthogonal array in (DoE) Design of Experiment. In an attempt to investigate the influential factors such as reinforcement in percentage, applied load in N, and sliding speed in RPM on the dry sliding wear rate and friction co-efficient of the selected composite samples, an Analysis of Variance (ANOVA) was developed, and equations in regression model are obtained through the use of MINITAB R17. Using the software, these equations were generated and used in the investigation. The morphology of wear surface and wear process of Samples are analysed with the assistance of an optical microscope. The outcomes of the wear tests are then correlated with the observations made by the microscope.

Keywords: Composite, specific Wear rate, coefficient of friction, Taguchi Technique, L9 Orthogonal Array, ANOVA.

I. INTRODUCTION

Metal matrix composites are a relatively new development that has sprung out in response to the ever-increasing need for materials that are light in weight, high in performance, environmentally friendly, resistant to wear and corrosion, and so on. Because of its superior mechanical qualities (and lower density), as compared with metals and alloys, Hybrid Aluminum Metal Matrix Composites (HAMMCs) are increasingly being put to use in a variety of applications, particularly those in which weight and strength are of the utmost importance [1, 2]. Appliances requiring attributes like great strength, damping, coefficient of thermal expansion, and thermal conductivity can benefit from HAMMCs, which have a lower density. In tribological and automotive sector applications, such as brake drums, pistons, brake discs, and cylinder blocks, HAMMCs' particular features make them an excellent choice [3-5].

Atmospheric pressure is used to spread reinforcing components such as metal nitrides, oxides, carbides, and borides in molten matrix alloy during the cast process. To produce MMCs having a higher reinforcement volume % at lower amount of pressure, a liquid processing approach has recently been devised [6]. According to the findings of recent research investigations, it is possible to achieve homogenous mixing by selecting suitable processes parameters such as molten metal temperature, stirring speed, and time, preheating mould temperature, and uniform particles feed rate [7, 8].

The intended type, reinforcement distribution, and quantity, as well as the alloy matrix and the use to which it will be put, are the primary considerations that guide the selection of an appropriate process engineering. Because of its superior formability properties and possibility of modifying the composites strength with heat treatment, 7075 is a popular choice among the various aluminium alloys for use as a matrix material in the preparation of composite metal matrix. This popularity can be ascribed to the detail that 7075 is one of the most suited aluminium alloys [9-12]. Because SiC particles are so hard, including them in an aluminium matrix allows for greater wear resistance thanks to the matrix's improved durability [13]. Particle reinforcement is applied to the matrix of HAMMCs that are particulate reinforced in order to enhance the bulk material's stiffness and strength [14-16]. When hard ceramic particles are added to traditional alloys, such as SiC, Al2O3, and B4C, amongst others, the resulting alloys have wear resistance improvement and a higher strength/weight ratio [17, 18]. The reinforcement selection, its fabrication method of manufacture, and its matrix chemical compatibility are the three most important factors in determining whether or not these qualities can be achieved.

The methods of heat treatment are extremely important in the engineering materials system, as they are responsible for increasing the properties of composite materials. The primary goal of heat treatment process is to produce a material that is both structurally and physically robust, making it suitable for use in engineering applications [19]. When aluminium alloys are subjected to heat treatment, the maximum concentration of the hardening solute in the alloy is more likely to dissolve into solution. By subjecting an alloy to a heat treatment at a temperature value at which there is only 1 solid phase present, it is possible to circumvent the need for this procedure. As a result of being subjected to this heat treatment process, solute atoms that are formerly a component of solid that existed in two phases are dissolved into solution, and the solid then originates (creates) as a single phase. After the sample are heated to necessary temperature for solutionizing, after that it is then cooled at such a faster rate that solute atoms do not have sufficient time for the solution to precipitate out before it is stopped. The quenching process has resulted in the formation of a solution that is Super saturated between the solute and the aluminium matrix. [20, 21].

Using an apparatus of the pin-on-disc variety and a dry environment, Rao et al. [22] studied the influence of stress on the friction and wear of worn MMCs surfaces of. As a form of reinforcement, different amounts of TiC particulates, ranging from 2 to 10 weight percent, were mixed with AA7075. According to the findings of the study, increasing the load results in a greater rate of wear while simultaneously decreasing the (COF) coefficient of friction for both the composites and the matrix.

Ponugoti et al. were able to characterize the tribological behaviours of hybrid MMCs that were synthesised using Al6061 with 9 percent WC and Gr. [23]. A large part of an HMMC's performance is determined by its tribological abilities, such as friction coefficient and wear rate. The vortex-prepared reinforced aluminium matrix composite with short steel fibres tribological characteristics [24]. The coefficient of friction and wear rate are calculated by choosing pin on disc equipment by changing the load applied from 10-40 N with distance of sliding 2000 m and a constant velocity of sliding of 1.8 m/s. It was found that rise in volumetric wear rate with rise in load applied, and the shift from mild volumetric wear to strong wear rely on the pin material strength to the adjacent surface. This led to the conclusion that the cof and rate of wear are prominent factors in determining wear rate. When taken together, all of these considerations led to significant advancements in the research sector all over the world regarding the production of HAMMCs with enhanced mechanical, tribological, and physical properties [25, 26].

An experimentation planned to examine at once two or more elements that have the capability to alter the variability or subsequent average of specific process or product attributes. This can be done by comparing the results of multiple experiments. In the DOE, the chosen level of factors influencing should be primary focus. Observations are made regarding the outcomes of the various test combinations, and an examination of the aggregated results is supported out in order to ascertain the optimum amalgamation of the numerous influential aspects [27]. The purpose of test is to assess concurrently two or more variables that have probability to influence final variability or average of particular process or product characteristics. The preferred level of elements influencing has to be prioritised. The outcomes of various test sets are observed, and then whole set of results are studied, in order to ascertain the optimal amount of the many components that are impacting the test results. Taguchi optimization technique tool is used for problem solving the design [28]. When related with the full factorial DOE, the experiment number that are necessary to the response model function can be cut down by using this method by a significant amount. In addition to this, it is a methodical and straightforward strategy for optimizing the design characteristics, such as quality and cost [29]. To determine the possible ways in which the parameters interact with one another, this method involves a series of steps. This method is referred to as a factorial design strategy, and it results in an orthogonal standard array [30].

An orthogonal array, which is selected for Taguchi method, is applied to cut down on experiment numbers required to analyze the optimum test parameters once they have been set. The investigation of the experimental outcomes makes use of S/N ratios to enable identification of the most suited design process. It is also successfully applied for the analysis of sliding wear behaviour of composites [31].

The majority of research work that has been documented has been done on Al 7075 with a variety of reinforcements including silicon, silicon carbide SiC, titanium, boron carbide, alumina, and so on. However, very less has tried Al7075 with three different kinds of reinforcements such as Si3N4, SSP, or RHA. Based on what has been said so far, it is possible to draw the conclusion that there is not adequate data presented on wear resistance of three particle reinforced matrix alloys of Al7075. As a result, the purpose of this work is to fabricate Al7075/Si3N4/SSP/RHA composite matrix with varied percentage weights of reinforcement particles and to investigate the tribological properties of these metal matrix composites using brake drum as an application.

In addition, the Taguchi DOE optimization method is chosen for aforementioned work combination in order to study the effect of factors such as percentage of reinforcement, applied load, and sliding speed on the wear behaviour of the Al7075/Si3N4/SSP/RHA composites. This investigation was carried out for the purpose of determining how these factors influence wear behaviour of the Aluminium composites. In light of information presented above, an attempt is made to utilise ANOVA in order to calculate the percentage of influence that a number of different components and their relations have on the wear and friction coefficient of Aluminium composites.

II. MATERIALS SELECTION & PREPARATION OF THE COMPOSITE

The element composition of Al7075 alloy is presented in Table 1. This alloy is chosen as it exhibits excellent combination of strength/weight ratio and fracture tolerance at cryogenic and higher temperatures. The density and hardness value for alloy matrix are 2.614 g/cm3 and 66 HRB respectively. specimens Hardness is calculated using Rockwell hardness machine by applying a 100 kgf load and the hardness average from 5 different set of the tests is considered.

Element	Si	Cu	Mn	Zn	Mg	Cr	Al
Weight %	0.05	1.62	0.01	5.83	2.76	0.19	Balance

TABLE 1 Element Composition of Al7075

Stir-cast technique set up shown in Fig.1 is utilized to prepare composite samples. In this method, matrix alloy (Al7075) is superheated firstly above its melting temperature and then heated gradually below liquids temperature to retain the semi-solid state of matrix alloy. At this current temperature, preheated of varying weight percentage of Si3N4 (2%, 4% and 6%), SSP (2%, 4% and 6%) and constant weight percentage RHA (5%) in addition to 1% magnesium (Mg) particles are introduced into molten slurry and mixed. The composite molten slurry temperature is raised to total liquid state and automatic ultrasonic stirring is followed for 15 min at 1500 rpm average speed of stirring. The melt is then superheated over liquids temperature and lastly transferred into the Graphite crucible as per required dimensions [32]. The test samples are machined to make cylindrical pins having 10 mm diameter and 100 mm height. The sample faces are polished metallographically.

Fig.1: Stir Casting Unit

III. WEAR TEST SETUP AND PROCEDURE

A pin-on-disc experimental setup is utilized to investigate the wear rate and coefficient of friction of the sample composites. The slider disc is made up of mild steel disc, plain and hardened with a 200 mm diameter. A 185.72 mm sliding track diameter is considered in all the experimentation. The Hybrid Aluminium Metal Matrix Composite (HAMMC) specimens are machined as per ASTM G99 standard pins as per dimensions mentioned above. It is vital to confirm that test sample’s surface of contact is flat and polished prior to wear testing by following metallographic methods. Conventional polishing methods of aluminium alloy are employed to prepare the contact surfaces of the monolithic composite sample ready for wear experiments.

The experiments are performed by applying loads as 9.81, 19.62 and 29.43 N at a maximum constant sliding distance of 3500 m at different sliding speeds such as 200, 300 and 400 RPM. The specific wear rates of specimens are derived in weight units by weighing the sample before and after the experiment and at last changed into volumetric wear loss. The samples lost wear are obtained using electronic weigh balance (accuracy 0.001g). The difference in lost weight of each test specimens is calculated before and after individual wear experiment considering dry condition. Using this weight loss data, the composite’s specific wear rate is calculated. Friction force is obtained by the sensor provided and using it coefficient of friction is evaluated. At last, an optical microscope is utilised in order to carry out the microstructural study on the worn surfaces.

IV. DESIGN OF EXPERIMENTS

The specimens are tested following the techniques described in journal documents [33-35]. The experiments are conducted considering the standard L9 orthogonal array (OA). The evaluated results are investigated applying the MINITAB R17 software explicitly used for DOE applications. The factors selected for the method are percentage of reinforcement (%), applied load (N), sliding speed (RPM). Each factor is allotted to three levels as shown in following Table 2. The standard L9 orthogonal array comprises of nine iterations as in the Table 3. The 1st column is allotted to percentage of reinforcement, 2nd column is allotted to applied load, 3rd column is allotted to sliding speed. The response to be studied is specific wear rate,and coefficient of friction with the objective of smaller as the better. The results of sliding wear trial are further optimized following ANOVA.

Level	Reinforcement R (%)	Load L (N)	Speed S (RPM)
1	2	9.81	200
2	4	19.62	300
3	6	29.43	400

Table 2 Process Parameters and Levels

Ex.No	Reinforcement (%) R	Load (N) L	Speed (RPM) S	Specific Wear Rate (mm3/N.mm)	Coefficient of Friction (Cof)
1	2	9.81	200	0.00004456	0.1732925586
2	2	19.62	300	0.00025359	0.0968399592
3	2	29.43	400	0.00428717	0.6557934081
4	4	9.81	300	0.00056420	0.9887869521
5	4	19.62	400	0.00692725	0.6727828746
6	4	29.43	200	0.00010502	0.1427115189
7	6	9.81	400	0.01120341	0.6523955148
8	6	19.62	200	0.00008879	0.2650356779
9	6	29.43	300	0.00052817	0.1834862385

Table 3 Taguchi Method- L9 Orthogonal Array

V. RESULTS AND DISCUSSIONS

The effect of the tribological trial factors such as percentage of reinforcement (%), applied load (N), and sliding speed (S) on specific wear rate and friction coefficient is optimised and assessed by means of the Taguchi method, with suitable Signal-to-Noise ratio (S/N) and ANOVA values. This has resulted in specific wear rate and friction coefficient being determined by ANOVA. The composite performance is influenced and determined by these design factors, which are one-of-a-kind and inherent features of the manufacturing process. The rank, obtained from the difference between the maximum to minimum value (delta) of the mean of S/N ratios, is assessed to determine the factors that have a significant impact on the specific wear rate and the coefficient of friction. These parameters are expected to have a strong bearing on the specific wear rate and the coefficient of friction.

STATISTICAL ANALYSIS OF EXPERIMENTS

The experiment was carried out in accordance with the Orthogonal Array, which allowed for the collection of data on a wide variety of parameter combinations. The results of the measurements were examined with MINITAB R17, especially designed for use in DOE-related endeavours. The L9 Orthogonal array for the composite is presented here in Table 3. For the purpose of evaluating the quality of the features, the test values are converted into a S/N ratio. The S/N ratio table of response is considered to assess the effect that regulate factors having on particular wear rate and COF. These control parameters included the % reinforcement, load, and speed. The response tables 4 and 6 for composite each include a ranking of the process factors based on the S/N ratios that are achieved for several factor levels for specific wear rate and COF. The tables of response 5 and 7 of composite each include a ranking of the process factors consider on the means that were achieved for numerous factors levels for specific wear rate and COF. These results were acquired for a variety of parameter values. It is shown that the speed has a leading influence on specific wear rate and COF, tailed by the % reinforcement and speed. The control factors are statistically significant in the Signal to Noise ratio. Graphic representation of the influence that process factors have on specific wear rate and friction coefficient may be found at figure (2-5). The evaluation of these experimental findings by means of the S/N ratio reveals the parameters that should be used in order to achieve the lowest possible friction coefficient and rate of wear. R1, L2, and S1 constitute the optimal settings for determining the rate of wear and the friction coefficient.

Level	Reinforcement R	Load L	Speed S
1	68.76	63.67	82.54
2	62.58	65.38	67.48
3	61.86	64.16	43.19
Delta	6.90	1.71	39.36
Rank	2	3	1

TABLE 4 Table of Response for SN Ratio- Smaller is better (Specific Wear Rate)

Level	Reinforcement (%) R	Load L	Speed S
1	0.001528	0.003937	0.000079
2	0.002532	0.002423	0.000449
3	0.003940	0.001640	0.007473
Delta	0.002412	0.002297	0.007393
Rank	2	3	1

TABLE 5 Table of Response for Means (Specific Wear Rate)

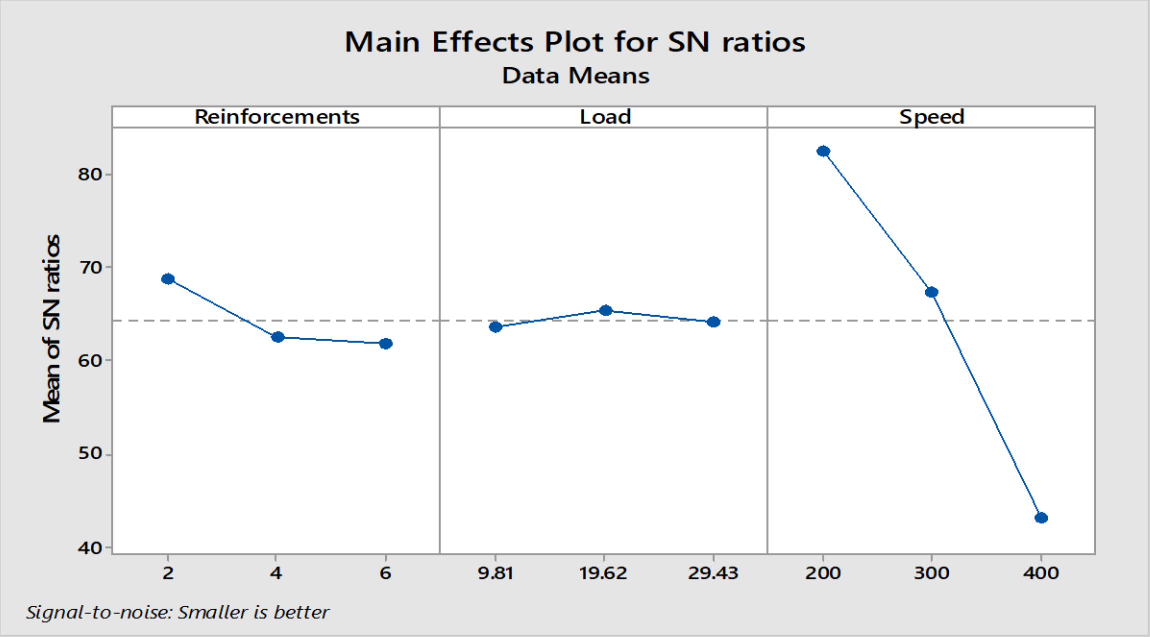

Figure 2. Main Effects plot for S/N ratio – Specific Wear rate

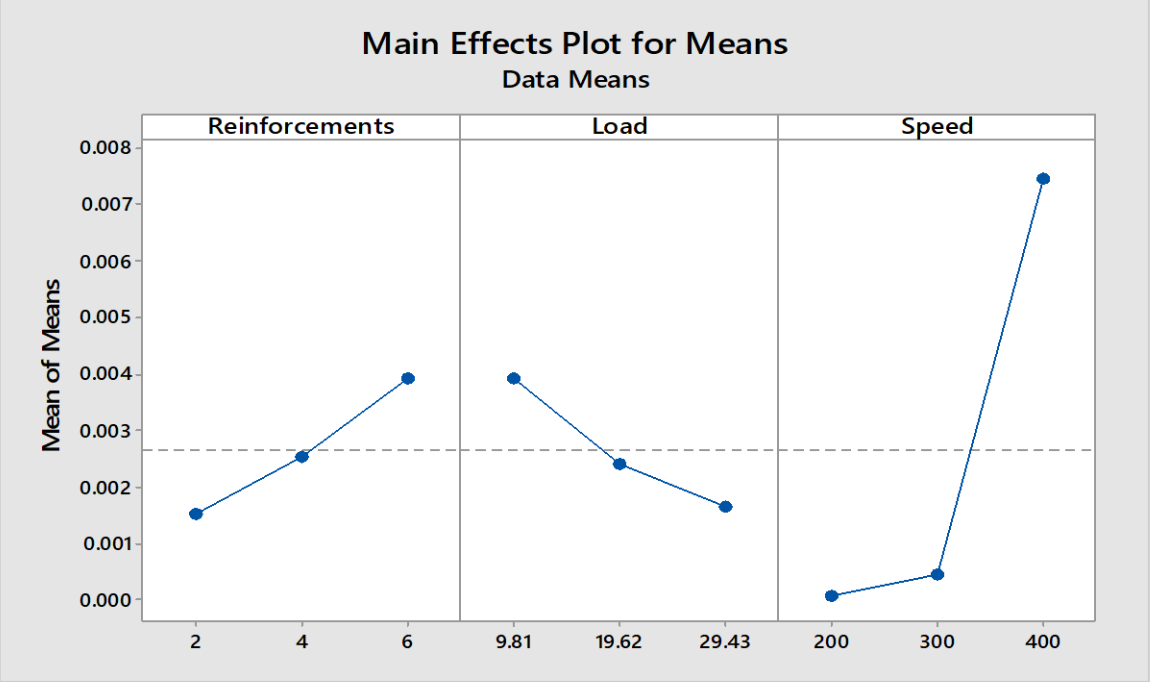

Figure 3. Main Effects plot for Means – Specific Wear rate

Level	Reinforcement (%) R	Load L(N)	Speed S (m/s)
1	13.056	6.344	14.556
2	6.817	11.752	11.702
3	9.991	11.768	3.606

Delta	6.239	5.424	10.951
Rank	2	3	1

TABLE 6 Table of Response for SN Ratio- Smaller is better (Friction Co-efficient)

Leve l	Reinforcement (%) R	Load L (N)	Speed S (m/s)
1	0.3086	0.6048	0.1937
2	0.6014	0.3449	0.4230
3	0.3670	0.3273	0.6603
Delta	0.2928	0.2775	0.4666
Rank	2	3	1

TABLE 7 Table of Response for Means (Friction Co-efficient)

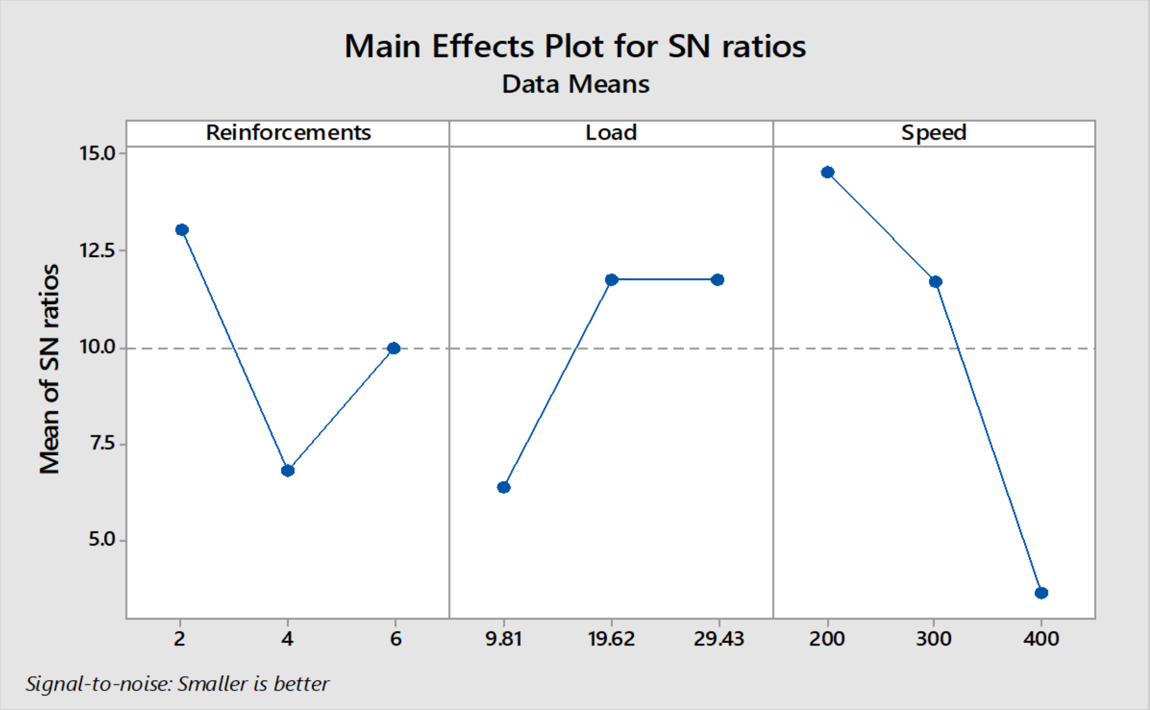

Figure 4. Main Effects plot for S/N ratio – Coefficient of friction

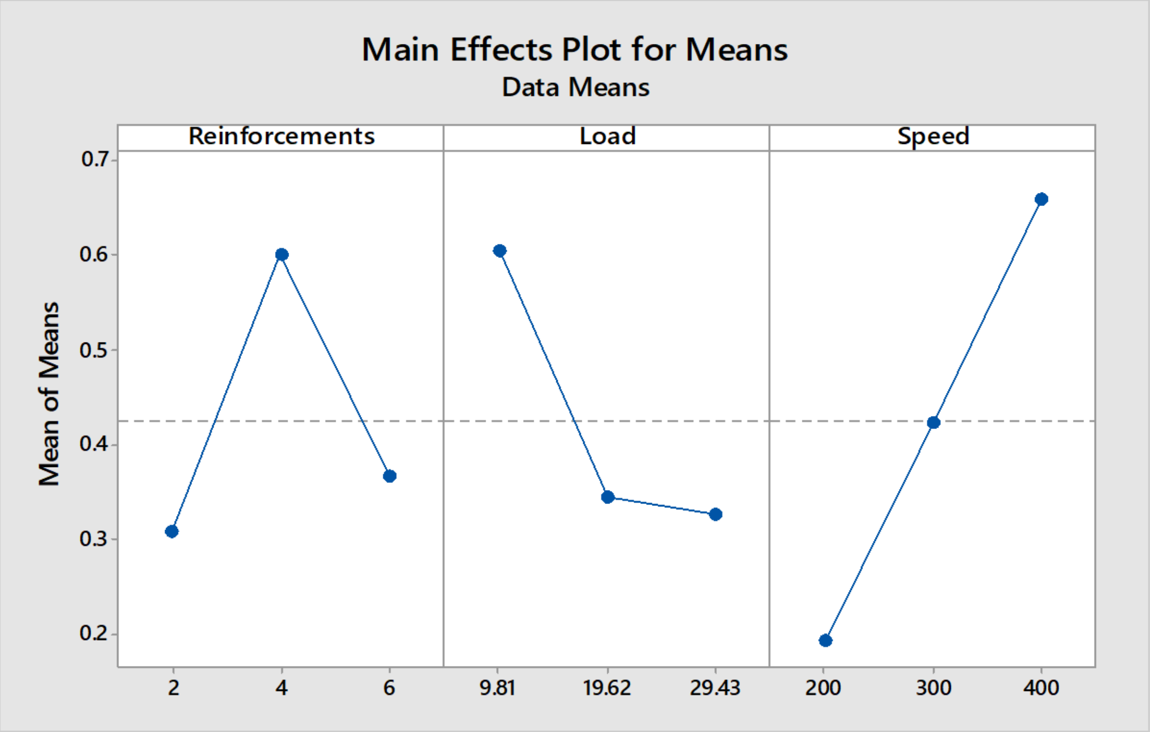

Figure 5. Main Effects plot for Means – Coefficient of friction

ANALYSIS OF VARIANCE (ANOVA)

The findings from experiment were examined using ANOVA, which is a statistical technique that examines the influence of the wear factors, namely the % of reinforcement, the applied load, and the sliding speed, which have a significant impact on the performance measurements. By carrying out an ANOVA, it is possible to identify the independent variable that predominates over the others and to evaluate contribution percentage that is made by each individual independent variable. The findings of the ANOVA for the specific wear rate and friction coefficient for three components that each had three levels of variation as well as the interactions between those factors are presented in Tables 8 and 9.

Si3N4, SSP, and RHA reinforced particles Al 7075 alloy aluminium matrix composite's specific wear rate is analysed using ANOVA. This research is done at a 5% significance level, which corresponds to a 95% level of confidence. It was determined that a source had made a statistically significant contribution to metrics performance if its P-value that is lower than 0.05. In the tables for the Analysis of Variance, contribution percentage (Pr) of each factor on the total variation is presented in fourth column. This indicates the degree to which each parameter had an impact on the final result. Sliding speed has a bigger impact on wear rate, as may be seen in Table 8 (below) (81.00 %). As a result, the sliding speed must be considered into account during the wear calculation. Reinforcement percentage (6.37 %) and applied load are next in line (6.85 %). Table 9 clearly presents that sliding speed component is the greatest effect on the friction coefficient (39.89 percent) compared to the other parameters studied in this study. Consequently, the sliding speed factor must be taken into account when calculating the friction coefficient. Applied load (17.69 %) and the percentage of reinforcement follow (17.60 %). Rate of wear and friction Coefficient are influenced most by factor sliding speed, according to results from the Analysis of Variance. Hence while the wear evaluation, sliding speed is a critical control component.

Factor	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Reinforcements	2	0.000009	6.85%	0.000009	0.000004	1.18	0.458
Load	2	0.000008	6.37%	0.000008	0.000004	1.10	0.476
Speed	2	0.000104	81.00%	0.000104	0.000052	14.01	0.067
Error	2	0.000007	5.78%	0.000007	0.000004		
Total	8	0.000129	100.00%				

TABLE 8 ANOVA for Wear Rate (mm3/N.mm)

Factor	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Reinforcements	2	0.1441	17.60%	0.1441	0.07205	0.71	0.585
Load	2	0.1449	17.69%	0.1449	0.07244	0.71	0.584
Speed	2	0.3267	39.89%	0.3267	0.16333	1.61	0.384
Error	2	0.2032	24.82%	0.2032	0.10162		
Total	8	0.8189	100.00%				

TABLE 9 ANOVA for friction co-efficient

MULTIPLE LINEAR REGRESSION MODEL

The software MINITAB R17 is used to create multi linear regression models for rate of wear and friction of coefficient. By suitable linear equation to the detected data, this model determines correlation between a predictor and a response variable. Based on an ANOVA analysis, significant terms such as % of reinforcement, applied load, and sliding speed have been linked in a Regression equation.

The following is the regression equation used to estimate the composite's wear rate:

Wear Rate = -0.00854 + 0.000603 Reinforcements - 0.000117 Load + 0.000037 Speed ----Eqn (1)

Equation to estimate friction Coefficient for the composite is:

Coefficient of friction = -0.055 + 0.0146 Reinforcements - 0.0141 Load + 0.00233 Speed ----Eqn (2)

Rate of wear and friction coefficient related to load (L) have found to be negative, indicating that rate of wear and friction coefficient of composite lowers with load rise. There is a positive correlation between % of reinforcement and sliding speed that indicates that as sliding distance and sliding speed rise, rate of wear and coefficient of friction increase.

To put it another way, when the % of reinforcement and the factor sliding speed increases, rate of wear and friction coefficient likewise increases. This is due to proportion of reinforcement and sliding speed increase, so does the temperature at the disc-to-pin interface.

OPTICAL MICROSCOPE EXAMINATION

Micrographs of worn surfaces of reinforced samples are shown in Figure 6 (Trial 1 - Trial 9). By using an optical microscope, wear rates can be determined by the presence of carbide phases in the matrix. Machine markings are visible on the steel disc and on the pin's whole surface during the sliding process. For this surface, the parameters were established, such as the percentage of reinforcement of 2%, the applied load of 19.62 N, and the sliding speed of 200 RPM, among other things. Speed and Reinforcing particles have a major role in creating grooves. More and more groves are formed, reinforcements protrude surface owing to the ploughing effect between pin and counter face, and debris by wear is formed. All of these phenomena increase in frequency and severity as the sliding speed rises. Some of the ceramic particles are fractured and lifted from the surface, while others are located inside cavities. Adhesive wear can be identified by the presence of pits or prows in the worn surfaces. Reinforcement causes the volume of prows to shrink.

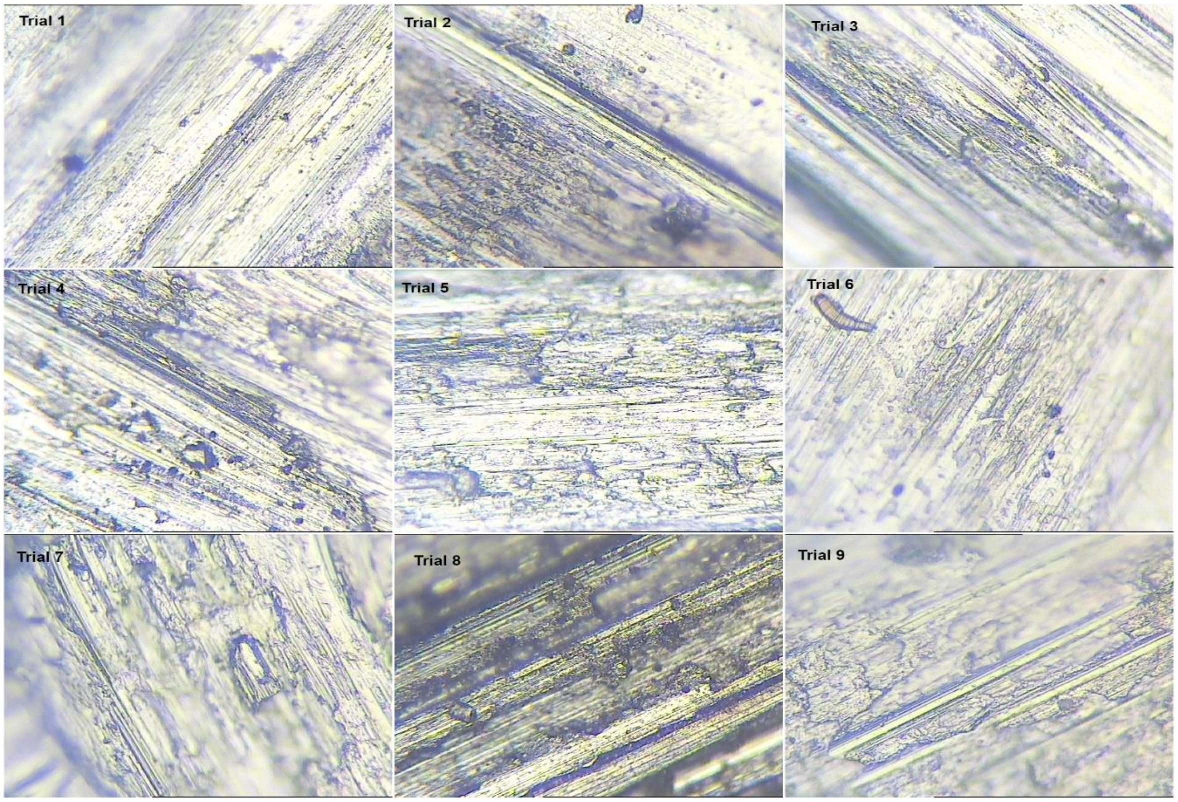

Fig 6. Worn Surfaces of specimens for Trial conditions 1 to 9.

VI. CONCLUSIONS

The following are the conclusions that may be considered from the study by applying the Taguchi method to determine which parameters for the composites' wear rate and friction coefficient are most optimal.

1. The stir-cast experimental setup was suitable for use in the production of Al 7075/Si3N4/SSP/RHA composites and could be utilised effectively.
2. The dry sliding wear rate and friction coefficient (cof) of composites have been effectively studied using the DoE by Taguchi approach and regression equation.
3. The ANOVA results demonstrate that distinct factors in the sequence of sliding speed, % of reinforcement, and applied load dominate the wear rate and friction co-efficient. While sliding speed, load applied, and the % of reinforcement all influence the friction coefficient.
4. Rate of Wear and friction coefficient are optimum for 2% percentage of reinforcement, 19.62 N load applied and 200 RPM sliding speed, respectively.
5. Sliding speed (81.00%) is the greatest effect on rate of wear followed by % of reinforcement (6.37 %) and applied load (6.85 %) and for friction co-efficient, the contribution by sliding speed (39.89 %), applied load (17.69 %), and percentage of reinforcement (17.60 %).
6. Sliding speed (81.00 %) has the greatest effect on rate of wear, followed by % of reinforcement (6.37 %) and applied load (6.85 %), while sliding speed (39.89 %), applied load (17.69 %), and percentage of reinforcement (17.60 %) have the greatest influence on co-efficient of friction.
7. It has been determined, through the use of regression equations, that the % of reinforcement and sliding speed have a positive association, but the applied load has a negative association with the Specific wear rate and the coefficient of friction.

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