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Optimization of Wear Performance of Al-Epoxy Composites Using Taguchi L9-Method

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ABSTRACT

Aluminum-epoxy composites have gained significant attention in various engineering applications due to their improved mechanical and tribological properties. This study focuses on investigating and optimizing the wear behavior of aluminum-epoxy composites. The composites were fabricated by incorporating aluminum particles into an epoxy matrix using a suitable manufacturing process. The wear characteristics of the composites were evaluated using a wear testing apparatus. Taguchi's method was employed to design the experiments and optimize the wear process parameters. The effects of key factors such as applied load, sliding speed, sliding distance, and percentage of aluminum particles on the wear performance were analyzed using an analysis of variance (ANOVA) table and regression analysis. The goal was to determine the optimal combination of process parameters that would minimize wear and enhance the wear resistance of the composites. Scanning electron microscopy (SEM) was used to examine the worn surfaces and investigate the wear mechanisms. The results indicated that the applied load, sliding speed, and percentage of aluminum particles significantly influenced the wear behavior of the composites. The optimized process parameters were determined to achieve the desired wear resistance properties. This study provides valuable insights into the wear behavior of aluminum-epoxy composites and offers an effective approach for optimizing the wear process parameters.

Keywords: Aluminum-epoxy composites, Wear behavior, Taguchi method, Optimization, Wear resistance, applied load, sliding speed, sliding distance, Aluminum particles, Scanning electron microscopy.

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1. INTRODUCTION:

The increasing demand for lightweight and high-performance materials has led to extensive research in the field of composite material systems. Aluminum and its alloys have gained significant attention due to their superior mechanical and tribological properties compared to base alloys. Among various aluminum-based composites, aluminum-epoxy composites have emerged as a promising choice due to their lightweight nature, high specific strength, excellent stiffness, and superior wear resistance. These composites find applications in a wide range of industries, including aerospace. To achieve the optimal combination of mechanical properties, formability, and strength, aluminum-epoxy composites manufactured through the stir casting technique have been preferred. Stir casting offers a simpler and cost-effective manufacturing method compared to alternative techniques. It involves the melting of aluminum in a furnace followed by the addition of solid epoxy particles through continuous stirring. This ensures a homogeneous distribution of particles in the molten aluminum matrix. This research focuses on investigating and optimizing the wear behavior of aluminum-epoxy composites. The study considers various parameters, such as particle size, weight percentage, sliding distance, and applied load. The effects of these parameters on wear response are analyzed using the Taguchi method, which is suitable for handling multiple variables in experimental design. Both experimental and analytical approaches are employed to enhance the mechanical properties and wear resistance of aluminum-epoxy composites. The coefficient of friction is determined through friction testing apparatus, and the impacts of applied load and sliding distance on wear behavior are studied. The findings from this research contribute to the understanding and development of aluminum-epoxy composites for a wide range of engineering applications. Polymer matrix composites (PMCs) have gained widespread popularity as matrix materials due to their unique properties and versatility. This is primarily attributed to the fact that polymers, as standalone materials, often lack the necessary mechanical properties required for structural applications. Polymers typically exhibit low strength and stiffness when compared to metals and ceramics. However, these limitations can be overcome by reinforcing polymers with other materials, resulting in improved mechanical properties. This research focuses on the development and utilization of polymer matrix composites to enhance the mechanical properties of structural materials. By incorporating high-strength reinforcing materials into a polymer matrix, the composite material achieves a synergistic combination of properties, addressing the shortcomings of polymers. The reinforcing materials, such as fibers, particles, or additives, significantly contribute to the strength, stiffness, and other desirable properties of the composite. The advantages of polymer matrix composites include their lightweight nature, corrosion resistance, design flexibility, and ability to be tailored for specific applications. The selection of appropriate reinforcement materials and their proper alignment within the polymer matrix is crucial to achieve the desired mechanical properties. Various manufacturing techniques, such as injection molding, pultrusion, and filament winding, are employed to fabricate polymer matrix composites with tailored properties. This research aims to investigate the mechanical behavior, including strength, stiffness, and toughness, of polymer matrix composites. Experimental characterization methods, such as tensile testing, flexural testing, and impact testing, are employed to evaluate the performance of the composites. Additionally, advanced analytical techniques, including finite element analysis, are utilized to understand the underlying mechanisms governing the mechanical properties of these composites. Figure 1 shows the Flow chart of PMC.

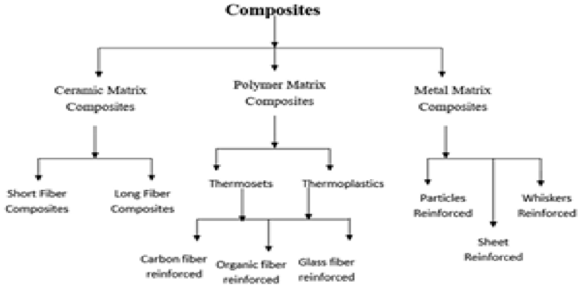

Figure 1: Flow chart of PMC

2. MATERIALS AND EXPERIMENTAL DETAILS

2.1 Matrix Material

A Epoxy systems are widely recognized as the primary composite material for low-temperature applications, typically below 200°F (93°C). These systems offer a range of beneficial properties that make them highly suitable for various industries and applications. One notable advantage of epoxy systems is their excellent chemical resistance. They demonstrate resistance to a wide range of chemicals, including acids, alkalis, solvents, and fuels. This property is particularly advantageous in applications where the composite material may come into contact with corrosive substances or environments. Furthermore, epoxy systems exhibit superior adhesion to fibers, making them ideal for use in composite materials. When combined with reinforcing fibers such as carbon fibers or glass fibers, epoxy composites can achieve high strength-to-weight ratios and excellent mechanical properties. The strong bond between the epoxy matrix and fibers contributes to the overall structural integrity and load-bearing capacity of the composite. Dimensional stability is another notable characteristic of epoxy systems. They offer minimal shrinkage during curing, resulting in composites with precise dimensional control and stability. This property is essential in applications where tight tolerances and dimensional accuracy are required, such as aerospace components or precision engineering. Additionally, epoxy systems can be tailored to meet specific application requirements through the incorporation of various additives and fillers. Figure 2 shows the Matrix (Epoxy LY556) and Hardener (HY951).

Figure 2: Matrix (Epoxy LY556) and Hardener (HY951)

To obtain accurate information about the hardener, it is recommended to refer to the technical data sheet or product specifications provided by the manufacturer or supplier of the epoxy resin and hardener. These documents typically contain precise information regarding the properties, handling instructions, and safety precautions for the product. Contacting the local industrial supplier in Chennai from whom you purchased the epoxy resin and hardener would be the best way to obtain the accurate specifications for Aradur HY951.

2.2 Filler Material

Bauxite is the primary source of aluminum. It is a sedimentary rock that contains a high concentration of aluminum hydroxide minerals, along with other impurities such as iron oxide, silica, and titanium dioxide. The Bayer Process is used to extract aluminum oxide (alumina) from bauxite. In this process, bauxite is crushed and mixed with sodium hydroxide (caustic soda) at high temperatures and pressures. This chemical reaction produces a solution of sodium aluminate, from which impurities are removed. The remaining solution is then cooled and aluminum hydroxide precipitates out. The precipitated aluminum hydroxide is calcined (heated) to produce alumina. Figure 3 shows the Aluminium Powder.

Figure 3: Aluminium Powder

Aluminum powder is available in different particle sizes, ranging from fine to coarse. The particle size distribution affects properties such as flowability, packing density, and reactivity Aluminum powder is highly reactive, especially when exposed to oxygen.

It readily oxidizes to form a thin layer of aluminum oxide on its surface, which provides corrosion resistance and stability. Table 1 shows the Properties of Aluminium powder.

Table 1: Properties of Aluminium powder

Materials	Density (g/cc)	Tensile strength (GPa)	Thermal Conductivity (W/m.K)	Tensile Modulus (GPa)	Bulk Modulus (GPa)
Al	2.68	0.3	70	237	76

3. TAGUCHI'S METHOD

Design of experiments (DOE) is indeed a powerful analysis tool for modeling and analyzing the influence of control factors on performance output. However, traditional experimental designs can be challenging to use, especially when dealing with a large number of experiments or when the number of machining parameters is increasing [8]. The selection of control factors is a crucial stage in the design of experiments [9]. To address these challenges, the Taguchi method, developed by Dr. Genichi Taguchi, is introduced as an experimental technique that reduces the number of experiments by utilizing orthogonal arrays and minimizing the effects of uncontrollable factors [8]. The Taguchi method involves designing a plan of experiments with the objective of acquiring data in a controlled manner. These experiments are then executed, and the data is analyzed to obtain information about the behavior of the given process. By using orthogonal arrays, the Taguchi method allows for the systematic exploration of multiple control factors and their interactions while minimizing the number of experiments required. The key idea behind the Taguchi method is to identify the most influential control factors and optimize their levels to achieve the desired performance output. The method emphasizes the concept of robust design, aiming to minimize the variation in performance caused by uncontrollable factors, such as environmental conditions or material variability. By reducing this variation, the Taguchi method helps improve the quality and reliability of products or processes. One of the advantages of the Taguchi method is its efficiency in terms of reducing the number of experiments needed compared to traditional experimental designs. This is achieved by carefully selecting orthogonal arrays, which provide a balanced and efficient arrangement of experiments to explore the factor space. Additionally, the method employs statistical techniques to analyze the experimental data and determine the optimal factor levels. Overall, the Taguchi method is a valuable approach for experimental design, particularly when dealing with a large number of control factors and aiming to minimize the effects of uncontrollable factors. It allows for efficient exploration of factor combinations, optimization of performance output, and improvement in product or process robustness. The Taguchi method is a statistical approach used in engineering and manufacturing to optimize product or process designs. It aims to minimize the variability in the performance of a product or process by identifying the optimal combination of design parameters.

One of the key advantages of the Taguchi method is its ability to consider both the mean performance (objective function) and the variability (noise sensitivities) of the system. By utilizing experimental data, the Taguchi method helps predict the optimal design parameter combination that minimizes the objective function while also meeting all constraints. Figure 4 shows the Process Flow of Taguchi Method.

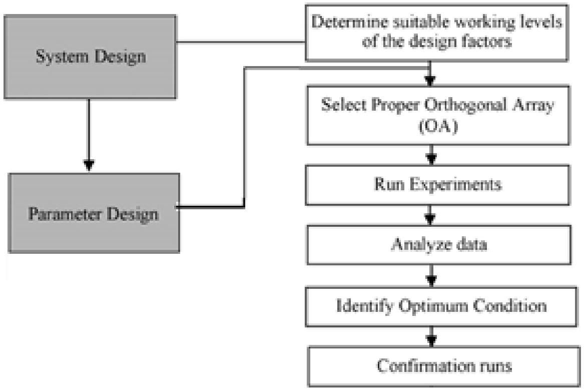

Figure 4: Process Flow of Taguchi Method

3.1 Wear experiment

The Ducom Pin-on-disc tribometer was employed to conduct the wear tests in the study. This tribometer is specifically designed to evaluate wear behavior under sliding conditions. The samples used in the tests had dimensions of 8 millimeters in diameter and 30 millimeters in height. During the tests, the samples were pressed against a rotating steel roller, which acted as the counterface material. The setup of the equipment ensured that the stationary plate served as the test sample. The loading lever of the tribometer was equipped with a counterweight at one end and a loading pan at the other end. The loading pan was used to apply the desired load by adding dead weight. To measure the applied load, a load sensor was positioned near the pivot point of the loading lever. This load sensor provided accurate readings of the load applied during the tests. The Ducom Pin-on-disc tribometer is a versatile instrument that allows for precise investigation of wear under sliding conditions. By utilizing this tribometer, the researchers were able to simulate and evaluate the wear behavior of the samples subjected to sliding contact with the rotating steel roller. The instrument provided valuable data and insights into the wear performance of the materials being tested. In the wear testing process using the pin-on-disc tribometer, the sliding occurs between an immovable pin and a rotating disc. Even as the contact surface of the pin wears away, it remains in contact with the disc due to the applied load. This continuous contact generates a signal that is used to determine the maximum wear. Additionally, the friction coefficient is continuously measured as wear progresses, providing insights into the wear behavior. To determine the maximum wear, the predicted level of wear is calculated based on the measured signals and data collected during the testing. The aim is to assess the extent of wear that the specimens can withstand under specific conditions. To measure the weight loss of each sample before and after the experiment, an electronic single-pan scale with a resolution of 0.0001 g is used. After each test, the specimens are thoroughly washed with an acetone solution to remove any debris or contaminants. The weight of the specimens before and after the experiment is recorded, allowing the calculation of the weight loss experienced by each specimen during the wear testing. By accurately measuring the weight loss, the researchers can quantify the extent of wear and evaluate the performance of the materials under study. This information is crucial for understanding the wear characteristics and durability of the tested specimens. Figure 5 shows the Ducom Pin-on-disc apparatus.

Figure 5: Ducom Pin-on-disc apparatus

Table 2 shows the Levels and process parameters.

Table 2: Levels and process parameters

Level	Load (N)	Speed (rpm)	Sliding distance (m)
1	15	250	550
2	25	450	1100
3	35	650	1650

In the L9 Orthogonal array, the factors or parameters being investigated (applied load, speed and sliding distance) are varied across three levels. Each level represents a specific value or setting for the respective parameter. The total number of experiments carried out is 9, as determined by the Taguchi model. The wear response, which is the focus of the model, is measured and recorded for each experiment. The goal is to analyze the effects of the different parameter levels on the wear behavior. After conducting the experiments, a tabulation of the responses is performed, which likely includes the wear measurements for each combination of parameter levels. The analysis of variance (ANOVA) is then applied to analyze the data and determine the significance of each factor and their interactions in influencing the wear response. Table in your report likely presents the L9 Orthogonal array with the wear response, displaying the specific combinations of parameter levels and the corresponding wear measurements obtained from the experiments. Table 3 shows the L9 Orthogonal array with wear.

Table 3: L9 Orthogonal array with wear

Exp. No.	Load (N)	Speed (rpm)	Sliding Distance (m)	Wear in Microns
1	15	250	550	80
2	15	450	1100	85
3	15	650	1650	100
4	25	250	1100	65
5	25	450	1650	69
6	25	650	550	88
7	35	250	1650	48
8	35	450	550	69
9	35	650	1100	75

Based on the S/N (signal-to-noise) response table generated using MINITAB 16.1 Software, the impact of each control component (load, speed, distance, and weight percentage) on wear was calculated. The S/N ratio represents the response variable in terms of signal (desired outcome) and noise (undesired variation). By analyzing the S/N ratios for wear, it is determined that load has the most significant impact on wear. This is followed by speed, sliding distance, and weight percentage (Wt. %) of the composites. The control factor with the largest delta value, which is the difference between the minimum and maximum S/N ratios, indicates the most significant disparity among the control factors. Furthermore, the table indicates that weight percentage has the least significant impact on wear among all the parameters studied. This suggests that variations in the weight percentage of the composites have a relatively smaller effect on the wear response compared to the other factors. Figure 6 shows the Main Effects Plot for SN ratio-Wear.

These findings provide valuable insights into the relative importance of each control component in influencing the wear behaviour of the studied composites. Table 4 shows the Response Table for Signal to Noise Ratio.

Table 4: Response Table for Signal to Noise Ratio

Response Table for Signal to Noise Ratio			
Smaller is better			
Level	LOAD	SPEED	SLIDING
1	-38.88	-35.98	-37.91
2	-37.31	-37.38	-37.45
3	-35.97	-38.8	-36.8
Delta	2.92	2.82	1.11
Rank	1	2	3

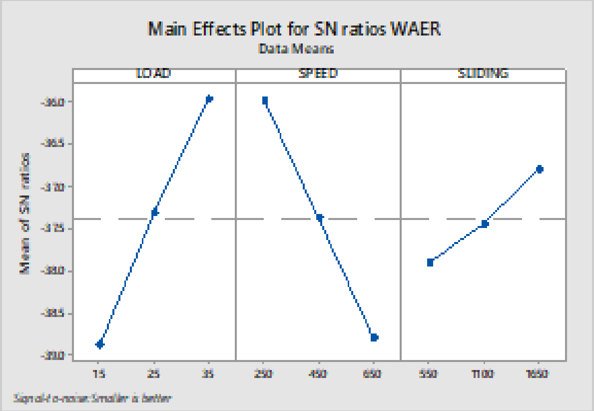

Figure 6: Main Effects Plot for SN ratio-Wear

3.2 ANOVA (Analysis of Variance)

It is a statistical technique commonly used to analyze the variation and significance of factors or variables in a study. It helps determine the contribution and significance of individual process parameters in influencing the response variable, in this case, the wear rate of aluminium. when conducting ANOVA using software like Minitab, the ANOVA table provides important statistical information for each factor, including: Sum of Squares (SS): The sum of squared deviations from the overall mean. It represents the variation attributed to each factor. Mean Squares (MS): The sum of squares divided by the corresponding degrees of freedom. It represents the average amount of variation explained by each factor. Degrees of Freedom (DOF): The number of independent pieces of information available for estimating the factor's effect. P-value: The probability of observing a test statistic as extreme as the one computed, assuming the null hypothesis is true. It indicates the significance of the factor. F-value: The ratio of mean squares of the factor to the mean square error. It is used to test the null hypothesis that the factor has no effect. Percentage Contribution: The percentage of variation in the response variable explained by each factor. It provides an indication of the relative importance of the factors. By examining the ANOVA table, you can identify which process parameters have a significant impact on the wear rate of aluminum based on their P-values and F-values. Factors with low P-values (typically less than a chosen significance level, such as 0.05) and large F-values are considered statistically significant and have a significant contribution to the response variable. Additionally, the percentage contribution provides insight into the relative importance of each factor in explaining the variation in the response variable. Factors with higher percentage contributions are considered more influential. The interpretation of the ANOVA results should be done in conjunction with other statistical analyses and considerations specific to your study. It's recommended to consult statistical resources, literature, or seek expert advice for a comprehensive understanding and interpretation of your ANOVA result. Table 5 shows the Analysis of Variance for Specific Wear Rate.

Table 5: Analysis of Variance for Specific Wear Rate

Source	DoF	Seq. SS	Adj. SS	Adj. MS	F	P-value	Cont. (%)	Remarks
Load	2	1787.33	1787.33	297.89	19.29	≤0.005	54.56	Significant
Speed	2	897.56	897.56	448.89	29.06	≤0.003	38.94	Significant
Sliding distance	2	822.2	822.22	411.11	26.62	0.033	3.47	Significant
Load Speed	4	67.56	67.56	33.78	2.19	0.036	0.62	Insignificant
Load Sliding distance	4	30.89	30.89	15.44	0.28	0.314	0.08	Insignificant
Error	2	17.96	17.96	10.92			2.33	
Total	16	3623.5					100	

Regression analysis is a statistical technique used to model the relationship between a dependent variable (in this case, wear) and one or more independent variables (control factors such as load, speed, sliding distance, and weight percentage of reinforcement). It allows for making predictions or projections about the wear based on the values of these control factors. The regression equation is derived from the analysis and represents the mathematical relationship between the dependent variable (wear) and the independent variables. It can be used to estimate or predict the wear for different combinations of control factor values. The normal probability graph, also known as a normal quantile plot or Q-Q plot, is a graphical tool used to assess the normality of the residuals (errors) in a regression analysis. It plots the observed wear values against the expected values assuming a normal distribution. If the points on the graph align closely to a straight line, it indicates that the errors are normally distributed and the assumptions of the regression model are satisfied. Based on the description, Figure 6 shows that the points in the normal probability graph for wear are closer to the line, indicating that the errors associated with the experiments are negligible. This suggests that the regression model provides a good fit to the data and the assumptions of the model are reasonable. It's important to interpret the regression results and assess the model's goodness of fit and statistical significance to ensure the reliability of the predictions and conclusions. The normal probability graph is one of the tools used to evaluate the assumptions of the regression model.

Regression Equation

The Regression Equation is given as below.

WEAR IN MICRON= 80.78 + 0.0 LOAD_15- 14.33 LOAD_25- 24.33 LOAD_35
+ 0.0 SPEED_250+ 10.00 SPEED_450
+ 23.33 SPEED_650+ 0.0 SLIDING_550- 4.00 SLIDING_1100
- 6.67 SLIDING_1650.

3.3 Surface morphology

Scanning electron microscopy (SEM) serves as an invaluable tool in the realm of materials science and engineering, widely employed for investigating the microstructure and chemical composition of a diverse range of materials. SEM enables researchers to delve deep into the internal structures of materials, allowing for a thorough understanding of their properties and behavior. However, when it comes to the behavior of materials subjected to erosion wear, categorization into distinct groups of "ductile" or "brittle" wear behavior, while common, is not always clear-cut. It provided passage discusses the use of some form of microscopy or analysis to examine the morphology of epoxy coatings. It also highlights a key distinction between two different coatings based on the size of nanoparticle agglomerates. Figure 8 shows the SEM images of the surface morphology of Al-epoxy composite. Figure 8 shows the SEM images of the surface morphology of Al-epoxy composite

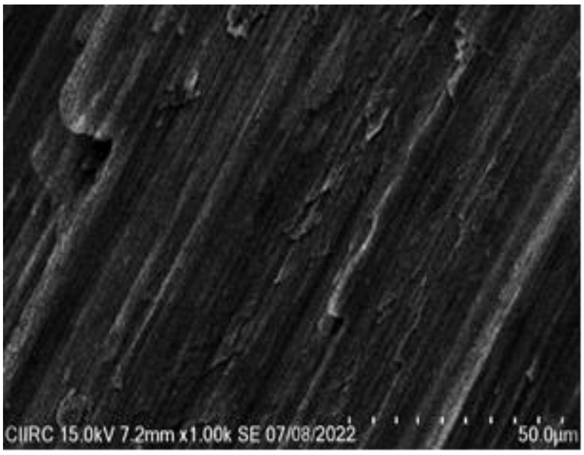

Figure 8: SEM images of the surface morphology of Al-epoxy composite

The passage attributes these morphological differences between the two coatings to the compatibility of the aluminum nanoparticles with the epoxy resin. This suggests that the interaction and compatibility between the nanoparticles and the resin play a crucial role in determining how they cluster or agglomerate within the coating. In the case of Al-epoxy coatings, the nanoparticles and epoxy resin appear to have better compatibility, leading to finer dispersion and smaller agglomerates. These morphological distinctions between coatings can have implications for the coating's properties and performance, including mechanical strength, adhesion, and surface characteristics, which are influenced by the arrangement of nanoparticles within the resin matrix. On the top surface of the composite, the micrograph shows that epoxy particles are scattered throughout. This suggests that the epoxy resin is uniformly distributed within the composite material. The distribution of epoxy particles appears to be relatively consistent. This implies that, in general, the epoxy resin is evenly dispersed throughout the material. However, it's important to note that there may be variations in this distribution. In some areas, tiny clusters of epoxy particles may be observed, indicating regions where epoxy particles have come together in small groups. Conversely, there may be areas with larger clusters where epoxy particles have aggregated more densely. The micrograph provides insights into the microstructure of the eroded composite surface, highlighting the presence of epoxy particles scattered across the surface. The distribution of these epoxy particles appears to be generally uniform, although small and large clusters may be visible in certain regions. This information is crucial for understanding how the composite material responds to erosion and wear, as the distribution of particles can influence its mechanical properties and wear resistance.

3.4 Confirmation of Experiment

The Confirmation of Experiment is shown in the below Table 6.

Table 5: Confirmation of Experiment

Exp. no.	Load (N)	Speed (rpm)	Distance (m)	Experimental Wear in Microns	Regression	Error %
1	15	650	550	85	82.3	3.22
2	25	450	1100	80	74.99	3.51
3	35	250	1650	75	75.54	2.09

The outcomes of the experiments that were carried out to validate the optimal amounts of the selected parameters are summarized and analyzed. These experiments were conducted using the chosen mix of factors and level settings that were determined earlier in the design of experiments (DOE) process. The results obtained from these experiments provide valuable information on the performance of the system under the optimized conditions. They allow for the evaluation of the effectiveness of the selected parameter values in achieving the desired outcomes, such as minimizing wear or maximizing performance. The summarized outcomes may include quantitative measurements of wear rates, wear depths, or any other relevant wear-related metrics. These results can be compared to the predicted values from the regression analysis or the initial screening experiments to assess the accuracy and reliability of the optimization process.

The results of the confirmatory tests indicate that the errors associated with the experimental wear measurements in microns and the regression model equation for wear are negligible. This suggests that the regression model accurately predicts the wear behavior of the composite material based on the chosen parameters and their levels. When the errors associated with the experimental wear measurements are negligible, it means that the observed wear values closely align with the predicted values from the regression equation. This indicates a good agreement between the experimental data and the model, validating the accuracy and reliability of the regression analysis. The negligible errors imply that the regression model provides a precise estimation of the wear performance based on the selected parameters. This is an important finding as it confirms the validity of the model in predicting wear characteristics and supports the optimization of the composite material for specific applications.

4.0 CONCLUSION

The following conclusions are drawn from the present study.

1. Successful adaptation of stir vacuum casting was achieved to fabricate pure aluminium composites. Stir vacuum casting is a manufacturing process that involves the combination of pure aluminium with other materials or reinforcements to create composite materials.
2. The scanning micrographs provide visual evidence of the successful incorporation and uniform distribution of zircon particles in the Al epoxy composites, confirming the effectiveness of the fabrication process.
3. The presence of these defects and excessive porosity in the Al samples suggests that the temperature reached in the homemade oven is only slightly higher than the melting temperature of Al. This indicates that the casting process may not have provided optimal conditions for solidification, leading to the formation of irregular structures.
4. Based on the response table and the analysis of variance, it is evident that the load parameter has the most significant impact on wear, followed by the sliding distance, speed and load of composites. The load parameter contributes to approximately 54.86 percent of the observed wear, indicating its strong influence on the wear behavior. The speed parameter accounts for around 38.94 percent of the wear, highlighting its significant contribution as well.
5. The regression equation derived in this investigation serves as a predictive tool for estimating the coefficient of friction in composites under intermediate conditions. By utilizing the established equation, it is possible to make reasonably accurate predictions of the coefficient of friction with an acceptable level of accuracy.

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