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Characterization on Specific Wear Rate of Al Composite Reinforced with nano-Al_2O_3 Using Taguchi's Technique

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ABSTRACT

The aim of the investigation was to study and predict wear properties of nano-Al_2O_3 reinforced Al composite fabricated by a two-step stir casting method. A pin-on-disc wear device was used to study the wear characteristics. An L9 Orthogonal array was selected as per Taguchi's method to analyze the results and ANOVA was used to examine the impact of applied force, sliding speed, and duration on specific wear rates with "smaller the better" as selection criteria. As per the investigation, applied load significantly influences the particular specific wear rate. Sliding duration is the second most important factor, whereas sliding speed is the factor that has the lowest impact on a given specific wear rate. We created a regression equation with R^2 and adj R^2 of 99.85% and 99.76% respectively that can estimate the specific wear rate of nano-Al_2O_3 reinforced Al composite. An apple-to-apple comparison between experimental and projected values was built using a regression equation and revealed an error limits of 2.1% and 6.6%. The worn-out surfaces of the cylindrical pins with the lowest and highest specific wear rates were examined using a scanning electron microscope and identified with oxidation and cracks.

Keywords: Stir casting, Wear properties, Microstructure, Taguchi's technique, ANOVA.

1. INTRODUCTION

Due to the aerospace industry's rapid development, particularly in the last 20 years, research focus has shifted from base materials to composites due to the desire for environmentally friendly, lightweight, and highly wear-resistant materials on a global scale. The most used material is aluminum (Al), which has a low density and high availability [1]. Pure aluminum, however, is subject to a variety of limitations because of how aeronautical applications. Aluminum composites are becoming more widely accepted in these many industries to get over these limitations [2]. Additionally, aluminum and its alloys exhibit poor wear characteristics. To achieve excellent wear qualities, aluminum and its alloys contain a variety of reinforcements, including SiC, ZnO, Al_2O_3, TiC, and others [3]. Among various reinforcements, Al_2O_3 is reported to be one of the most effective ingredients influencing wear properties in composites [4]. Al composites can be created using a variety of manufacturing processes, including stir casting, ultrasonic casting, powder metallurgy, etc. [5]. Among the alternatives, stir casting method is relatively simple and cost-effective for manufacturing Al composites [6]. Al composites with up to 30% volume of reinforcing particles can be made via stir casting [7]. Due to variances in density and the development of porosity, the dispensation of the reinforcement materials into a metal matrix composite may not be completely homogenous, which is one of the downsides of this casting method [8]. These conditions lessen the property of Al composite which can be minimized by a multistage step stir casting method [9]. Considering these factors, the fabrication technique, reinforcement particle, and reinforcement size that has been selected for the development of Al composite is respectively two-step stir casting method and 2.5% Al_2O_3 having 20 nanometers (nm). Since the poor wear resistance of aluminum and its alloy is one of the most encountered challenges in the aerospace industry and wear is governed by excessive frictional stress, characterization of different wear properties of Al composites is continuously investigated by researchers globally [10-12].

In the current study, an Al composite having a composition of 2.5 wt. % of Al_2O_3 with 97.5 wt. % of Al was fabricated by a two-step stir casting method. The Impact Charpy test was carried out as per ASTM E23-18 and the Impact toughness was obtained as 13.47J. The Flexural test was carried out as per ASTM D790-17. The ultimate flexural stress and Elastic Modulus were obtained as 291.51 MPa and 81.36 GPa. The Vickers micro hardness test was carried out as per ASTM E92-17 and obtained as 35.72 HV with a 500 gm load for 10 seconds duration. The Rockwell hardness was carried out as per ASTM standard E10-18 where a 1.58 mm diameter hardened steel ball was subjected to a load of 100kg and the Rockwell hardness number was obtained as 24.33 RHN. The fabricated Al MMC exhibited superior mechanical properties in comparison with pure Al as-casted condition [13].The heat treatment of 2.5 wt. % of Al_2O_3 reinforced Al composite was carried out at solution temperatures of 510°C, 530°C and 550°C and thermal aging at 140°C, 160°C, 180°C, 200°C and 220°C for studying the influence of heat treatment on hardness & electrical conductivity. As per the study, we observed the highest improvement of 25.92% and 9.57% respectively in hardness and electrical conductivity at a solution temperature of 530°C followed by thermal aging of 180°C in comparison to as casted condition [14].

However, there is a research scope to study the wear properties of developed Al composite as it has many potential aerospace applications, including engine connecting rods and bearing housings. One of the most palatable statistical methods for examining the effects of numerous process parameters simultaneously is design of experiments (DOE) [15]. Using Taguchi's L9 orthogonal array, Suryakumari and Ranganathan (2018) investigated the wear behavior of an aluminum hybrid composite reinforced with 2.5% Al_2O_3 under applied loads ranging from 10 to 30 N and sliding velocities ranging from 500 to 1050 RPM [16]. Prakas et al. (2014) investigated the sliding wear behaviour of Al_2O_3-reinforced metal matrix composites with applied loads ranging from 15 N to 45 N and sliding speeds ranging from 390 RPM to 780 RPM [17]. Poovalingam Muthu (2020) used the Grey-Taguchi method to analyze the wear behavior of Aluminum MMCs while applying loads ranging from 10 N to 30 N and sliding between 780 RPM and 1050 RPM [18]. In the present study, the wear properties of developed Al composite were investigated at different parameters such as applied load varying from 20N to 50N, sliding duration from 5 to 15 minutes, and sliding speed at RPM of 100 to 200. Also, a Taguchi-based L9 orthogonal array was chosen for the prediction and optimization of those process parameters.

2. EXPERIMENTAL DETAILS

2.1 Materials Selection

Olympus' Vanta C Series XRF Analyzer was used to analyze the chemical composition of pure aluminum, the basic metal, and the results are shown in Table 1. Aluminum oxide (Al_2O_3) having a grain size of 20 nanometers was utilized as a reinforcing particle. The composition of manufactured aluminum composites reinforced with 97.5 wt. % aluminum and 2.5 wt. % Al_2O_3.

2.2 Casting Procedure

The Bangladesh Industrial Technical Assistance Center has provided casting support (BITAC). A gas-fired crucible furnace was used for the stir casting which can sustain up to 3500°C. The furnace was heated with natural gas. To provide enough air to maintain a constant temperature while burning gas, an external air blower was used. First, the furnace was heated to roughly 300 °C without using the blower while the aluminum metal was held in the crucible. The electric blower was turned on after 15 minutes and kept the base metal preheated for 60 minutes at a temperature of 500°C. Al_2O_3 particles were simultaneously preheated in an oven at 300°C for 120 minutes. The metal totally melts in over 60 minutes. The molten metal and Al_2O_3 were then thoroughly mixed for 5 minutes across two steps using the stirring machine. The finished metal was put into the empty sand mold. Al_2O_3 in the crucible was continuously mixed at a rate of 20 gm/ minute.

2.3 Experimental Setup

A pin-on-disc apparatus was utilized in the experiment, as depicted in Figure 1, and sample specimens were made in accordance with ASTM G99-17. The fabricated Al composite was used to create cylindrical pins with dimensions of 5 mm in diameter and 12 mm in height. The fabricated Al composite had a Brinell hardness of 139.32 and Vickers hardness of 35.72 respectively [13-14]. All of the pins were thoroughly cleaned and dried before the wear tests. The disc used for this experiment was of SS 309s material containing 60% Fe, 23% Cr, 14% Ni, 2% Mn, 0.84% Si, 0.08% C, 0.05% P, and 0.03% S as the counter-body. The hardness of the stainless steel disk was found on average

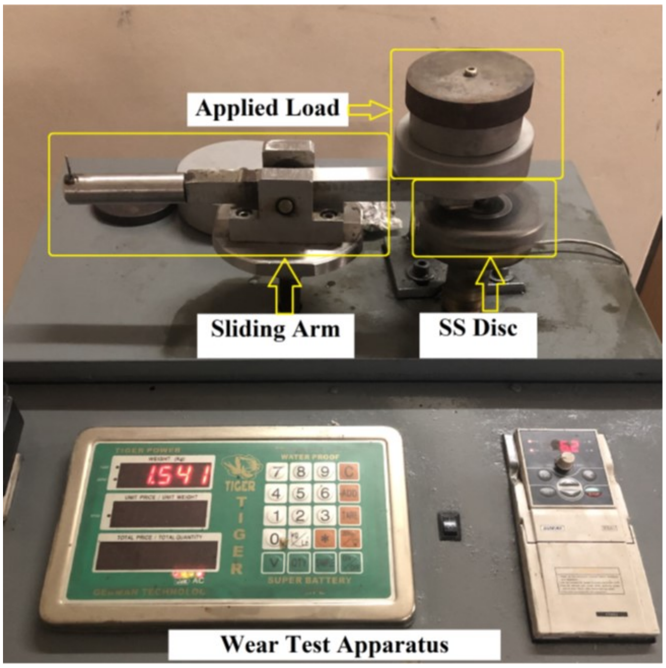


Figure 1: Pin-on-Disc wear setup

Table 1: Composition of Pure aluminum

Element	Al	Si	Fe	Cu	Zn	Zr	Pb
Percentage (%)	99.052	0.614	0.323	0.002	0.008	0.0007	0.0009

Table 2: Parameters and their levels for L9 orthogonal arrays of Taguchi's approach

Level	Applied Load (L)	Sliding Speed (N)	Sliding Duration (t)	Sliding Distance (SD)
Units	N	RPM	Minutes	Meter
1	20	100	5	77
2	35	150	10	231
3	50	200	15	462

Table 3: Specific Wear Rate, Signal-to-noise ratio and Mean Using Taguchi's Technique

Applied Load (N)	Sliding Speed (RPM)	Sliding Duration (Mins)	Specific Wear Rate (mg/Nm)	Signal to noise Ratio	MEAN
20	100	5	2.3377	7.38	2.34
20	150	10	2.7706	8.85	2.77
20	200	15	3.2035	10.11	3.20
35	100	10	5.4545	14.74	5.45
35	150	15	5.6566	15.05	5.66
35	200	5	5.4545	14.74	5.45
50	100	15	8.4416	18.53	8.44
50	150	5	7.7922	17.83	7.79
50	200	10	8.4416	18.53	8.44

as 168 HV made of stainless steel having a diameter of 0.049m [19]. The pin and disk weights were calculated using an electronic balance with a 0.001 mg accuracy for the wear test.

3. DESIGN OF EXPERIMENTS (DOE)

DOE can examine the effects of numerous process parameters simultaneously. For monitoring the results of those tests, each experiment requires a combination of the process parameters and their levels. For determining the impact of those process parameters, the Taguchi technique uses the process parameters in specified orthogonal arrays. The planning stage, conducting stage, and analysis stage are the three key phases that make up the DOE. By analyzing the results of the experiments, the S/N ratio is utilized to identify the process parameters that would produce the best results.

The purpose of the current work was to determine the minimum specific wear rate as much as possible. In this experiment, the Diameter of the sliding disc (D) was kept fixed at 0.049m. Sliding Distance (SD) and Specific Wear Rate (WR) were determined respectively using Equation (1) and Equation (2).

$$\boldsymbol{Sliding\ Distance\ (SD) = \pi \times D \times N \times t} \quad (1)$$

Where,
D= Diameter of the sliding disc (m),
N= Sliding speed (RPM)
T= Sliding Duration (Minutes)

$$\boldsymbol{Specific\ wear\ rate\ (WR) = \frac{\Delta W}{SD \times L}} \quad (2)$$

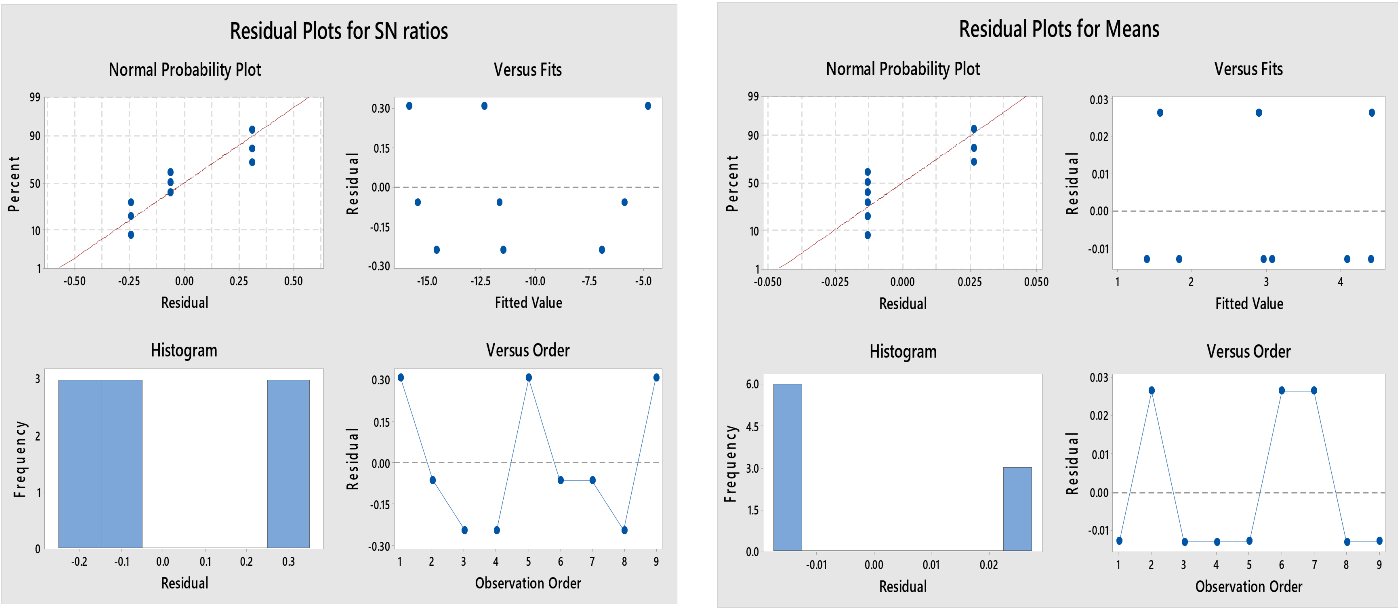
Where,
WR= Specific Wear Rate (mg/Nm)
ΔW= Wear Loss (mg)
SD= Sliding Distance (m)
L= Applied Load.

In the current investigation, the L9 orthogonal arrays of Taguchi's approach were used to create the experimental plan as per selected process parameters and their levels are shown in Table 2. The ANOVA method was used to analyze these process parameters.

A total of 09 experiments were conducted as shown in Table 3 as per L9 orthogonal arrays of Taguchi's approach for different process parameters. The Specific wear rate was determined using equation (2). Signal-to-noise (SN) ratio and mean are given from the experimental outcomes of Taguchi's approach. Residual plots for SN ratio and mean are shown in Figures 2(a) and 2(b).

3.1 Analysis of Variance (ANOVA)

ANOVA was used to assess the experimental results and the effects of the process parameters that were taken into consideration, such as the applied load, sliding speed, and sliding time, which have a significant impact on the particular wear rate. This investigation was carried out using a 95% confidence level and a significance level of 5%. Response for Signal to noise ratio and Means were ranked and shown in Table 4 and Table 5.



(a) (b)

Figure 2: Residual Plots for (a) Signal-to-Noise Ratios; (b) Mean values

Tables 4 and 5 show that the applied load is the process variable that has the greatest impact on the particular wear rate of Al_2O_3 reinforced Al composite. Bhuvanesh and Radhika (2017) found that the dominating factor was applied load to the wear rate [20] in their experimental study on the tribological properties of nitride-reinforced aluminum metal matrix composites. Consequently, our research supports Bhuvanesh and Radhika's findings (2017).

3.2 Regression Analysis

A regression model that illustrates the link between the independent variable and the response variable was produced by the statistical program "MINITAB 18". Equation (3) illustrates the interaction between applied stress, sliding speed, and distance on specific wear rate through ANOVA analysis. As per the analysis, the R^2 and adj R^2 values for this model are 99.85% and 99.76%, respectively. The combination settings of applied load, sliding speed, and duration have behavioral patterns described as the values of R^2 achieved 99.85%. Figure 3 represents the residual plot for specific wear rates.

The regression equation of specific wear rate can be expressed as follows:

$$WR = -1.863 + 0.18182\ L + 0.002886\ SD + 0.05724\ t \qquad (3)$$

Table 4: Response for signal-to-noise ratios with smaller is better

Level	Load	Speed	Duration
1	5.872	10.595	10.360
2	11.857	10.947	11.072
3	15.296	11.482	11.592
Delta	9.424	0.887	1.232
Rank	1	3	2

Table 5: Response for means

Level	Load	Speed	Duration
1	1.594	2.923	2.790
2	2.978	2.912	2.978
3	4.302	3.039	3.107
Delta	2.708	0.127	0.316
Rank	1	3	2

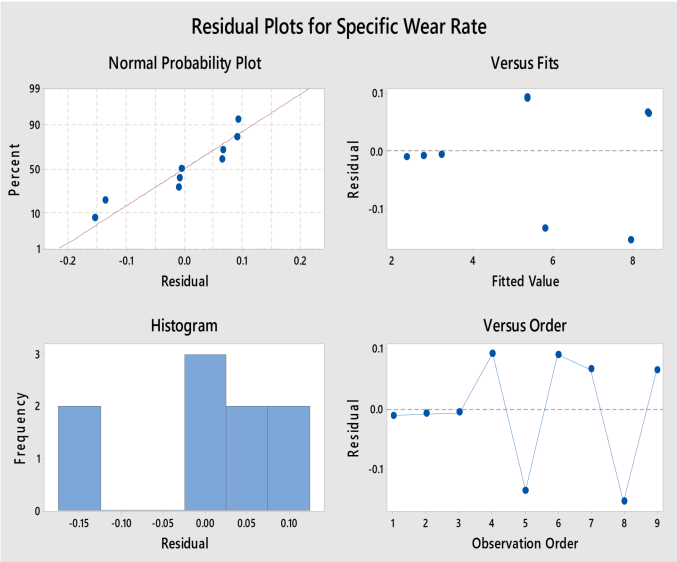


Figure 3: Residual plots for specific wear rate

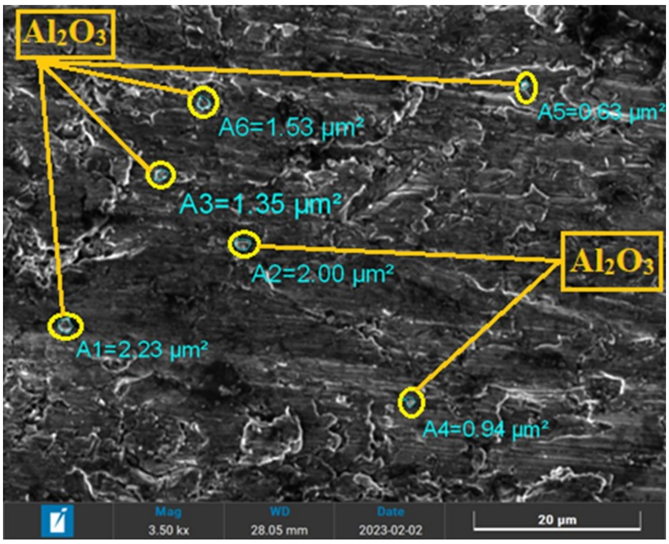
3.3 Study of Variance

Table 6 displays the significance of terms related to this model at a 5% significance level and a 95% confidence level. The significance of several aspects, including the regression model, terms, and lack of fit, is investigated using this analysis. By looking at the P-value, it is possible to assess whether or not the model's results are statistically significant.

4. CONFIRMATION TEST

In this current work, the confirmation test was carried out by choosing the process parameters as given in Table 7. The tests were carried out and the outcomes were compared with the predicted value given by the regression equation (3). The comparison between the experimental and predicted value is exhibited in Table 7.

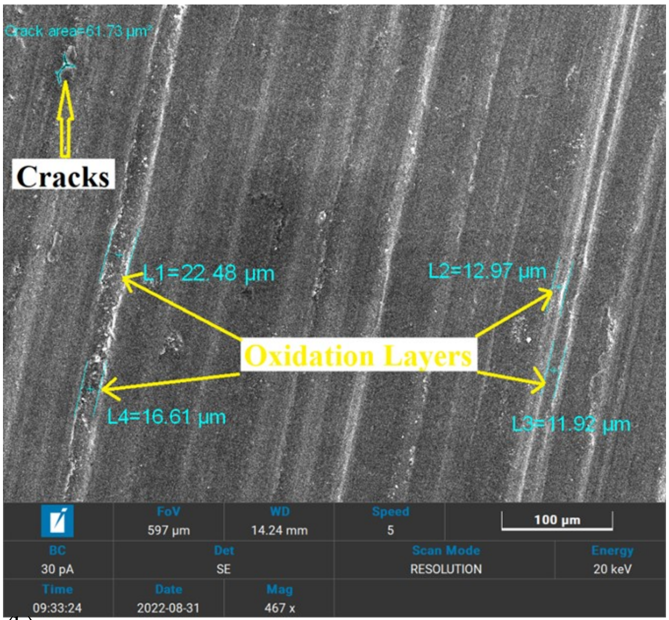
As per Table 7, we observed a 2.1% error between experimental and predicted values for the applied load of 30 N, sliding speed of 125 RPM for a duration of 12 minutes. Also, 6.6% error between experimental and predicted values for the applied load of 40 N, sliding speed of 180 RPM for a duration of 20 minutes. Rajesh et al. (2013) performed a confirmation test during their MOORA -Based tribological studies on red mud-reinforced aluminum metal matrix composites and observed a 4.2% difference between initial parameter and optimal parameters settings [21].



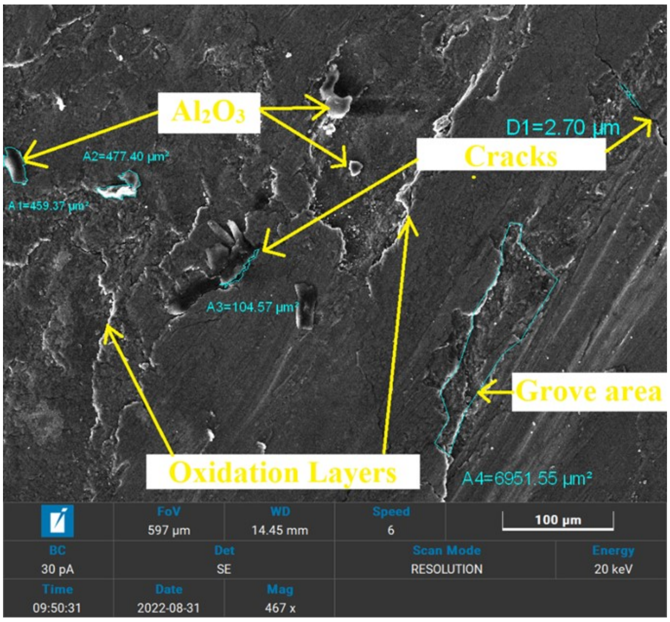
(a)

5. MICROSTRUCTURE OBSERVATION

After the preparation of Al composite by two-step stir casting, microstructure observation was carried out by



(b)



(c)

Figure 4: Microstructure observation of (a) Material with reinforcement dispersion and grain size; (b) worn-out surfaces of the cylindrical pin at applied load: 20 N, sliding speed: 100 RPM and sliding duration: 5 mins; (c) worn-out surfaces of the cylindrical pin at applied load: 50 N, sliding speed: 200 RPM and sliding duration: 10 mins

Table 6: Regression coefficients for specific wear rate

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-1.863	0.208	-8.96	0.000	
Applied Load	0.18182	0.00317	57.33	0.000	1.00
Sliding Speed	0.002886	0.000951	3.03	0.029	1.00
Sliding Duration	0.05724	0.00951	6.02	0.002	1.00

Table 7: Confirmation test of specific wear rate with % of Error

Applied Load (N)	Sliding Speed (RPM)	Sliding Duration (Mins)	Experimental	Prediction	Error (%) Calculation
			Specific Wear Rate (mg/Nm)	Specific Wear Rate (mg/Nm)	
30	125	12	4.5455	4.64	2.1%
40	180	20	6.6378	7.07	6.6%

Scanning Electron Microscope (SEM) in order to confirm the mixing of reinforcement particles (Al_2O_3) into a base material (99% Al). A sample of Al-Al_2O_3 with a dimension of 05mm×05mm×05mm was prepared for microstructure observation by Scanning Electron Microscope (SEM), Model: TESCAN VEGA 4.

As shown in Figure 4(a), the morphology of Al_2O_3 particles is mainly irregular. The Al_2O_3 particles were uniformly distributed in the Al-Al_2O_3. The elliptical area immersed by the reinforcements (Al_2O_3) in Al composite is approximately 5.45 µm² and 6.29 µm² which is investigated through image processing as shown in Figure 4(a). Also, a few clustering or agglomerations of Al_2O_3 particles were perceived in the Al/ Al_2O_3 matrix composite.

The microstructure of the worn-out surface of the cylindrical pins having the lowest and highest specific wear rates was also examined by SEM with a diameter of 5 mm as shown in Figure 4(b) and Figure 4(c) respectively. The process parameters of the pin having the lowest specific wear rate were 20 N as applied load, 100 RPM as sliding speed, and 5 minutes as sliding duration. The process parameters of the pin having the highest specific wear rate were 50 N as applied load, 200 RPM as sliding speed, and 10 minutes as sliding duration.

In Figure 4(b), worn-out surface was observed with minor grooves developed for adhesive wear. The minor grooves and adhesive wear marks were due to the selected process parameters. We identified a minor crack of 51.73 µm² and a few grooves lines measured through SEM image processing denoted as L1 to L4 in Figure 4(b).

In Figure 4(c), the delamination overserved at the worn-out surface of the pin having maximum specific wear rate was for the selection of process parameters such as 50 N as applied load, 200 RPM as sliding speed, and 10 minutes as sliding duration. As per SEM, we observed deep grooves along with the surface level. The transition from minor grooves to deep grooves increased because of increasing applied load from 20N to 50 N, sliding speed from 100 RPM to 200 RPM, and sliding duration from 05 minutes to 10 minutes. As shown in Figure 4 (c), we identified 02 cracks at the worn surface of the pin, one having a width of 2.70 µm and another one having 104.57 µm². We also observed a few chips of surface whose area measured as 477.40 µm² (A1) and 459.437µm² (A2). One of the deep grooves measured 6951.55µm².

Rajesh et al. (2013) performed a tribological study on red mud-reinforced aluminum metal matrix composites. At the applied load of 20N load and a constant sliding distance of 3000 m, they identified formation of reinforcement particles at the surface which reduces the specific wear rate of the composite [21]. As shown in Figure 4(b), we also observed a similar formation of reinforcement particles on the worn-out surface of the pin for which the specific wear rate was minimum at the applied load of 20 N, sliding speed of 100 RPM, and duration of 5 minutes. Natrayan and Kumar (2019) investigated the wear behavior on AA6061/Al_2O_3/SiC metal matrix composite. As per their investigation, it was perceived that the increase in applied load and sliding speed increases the wear rate of the composites due to the formation of larger grooves on the worn surfaces. They observed cavities and a few dimples formed for the applied load of 30N and at the sliding speed of 200 RPM for a sliding distance 1200 m [22]. As per Figure 4(c), we also observe similar wear conditions for the process parameters such as 50 N as the applied load, 200 RPM as the sliding speed, and 10 minutes as the sliding duration. Therefore, we understand that our fabricated Al composite reinforced with Al_2O_3 has less abrasive wear.

6. RESULT AND DISCUSSION

6.1 Effect of Applied Load on Specific Wear Rate

The escalation of specific wear rate is observed with the increase of load from 20 N to 50 N nearly in linear proportion as shown in Figure 5. This trend in the plot is due to an increase in touching pressure between the composite pin and the disc which is the basis of greater surface damage. When the given load increases up to 35 N, wear is developed because of rubbing between cylindrical pins and SS disc. Also, acute wear is developed for adhesion when the applied load escalates from 35 N to 50 N and a similar pattern is observed by Radhika et al. (2014) at an applied load of 30N, sliding speed of 286 RPM for a sliding distance of 1500m [20]. Prasat et al. (2011) observed that at low load and sliding speed, the worn pin surface showed shallow grooves in the direction of sliding [23]. However, at higher loads and sliding speed, the alumina particles get fractured and these particles act as sharp asperities to remove more material from the wear surface [24] which is a similar finding as per the present microstructure observation shown in Figure 4(b) and Figure 4(c).

6.2. Effect of Sliding Speed on Specific Wear Rate

The escalation of the specific wear rate was also noticed with the increase of speed from 100 RPM to 200 RPM as shown in Figure 5. As the sliding speed of the disc escalates up to 150 RPM, the reinforcement particles of nano Al_2O_3 develops a thin layer on the surface which withstands high stress, and therefore, it reduces the sliding wear up to a sliding speed of 150 RPM as shown in Figure 5. Poovalingam Muthu (2020) applied a sliding speed of 780 RPM to 1050 RPM and studied the wear behavior of Aluminum MMCs using the Grey-Taguchi method. As per their study, a similar thin oxidation layer developed on the surface which withstood high stress and reduced the sliding wear after a certain duration [18]. However, at higher sliding speeds, the temperature rise due to friction of the pin and SS disc. As a result, the material becomes soft and gets easily removed. Thus wear rate again increase at this condition which indicates a severe wear regime and delamination also becomes maximum at this condition [25].

6.3 Effect of sliding duration on Specific Wear Rate

We observe an escalation of specific wear rates with an increase in duration. Figure 5 exhibits a direct interrelation between the duration and specific wear rate. This phenomenon is for the presence of nano Al_2O_3 reinforcements that projects out of the pin surface and escalates the groove on the touching surface area. Tazari and Siadati (2019) observed the wear mechanism of material removal in an aluminum composite for 50 minutes and observed major adhesion and abrasion marks on the surface [26]. As per Figure 4(c), we also observe minor to major grooves for the duration from 5 minutes to 15 minutes which goes in line with the findings of Tazari and Siadati (2019).

7. CONCLUSION

The characterization on Specific Wear Rate of Al composite reinforced with nano Al_2O_3 indicated the following conclusions:

a. As per Taguchi's DOEs and ANOVA, the most effective parameter is the applied load which remarkably affects the specific wear rate. Next comes the sliding duration/distance and sliding speed can be considered as the least effective parameter for specific wear rate.

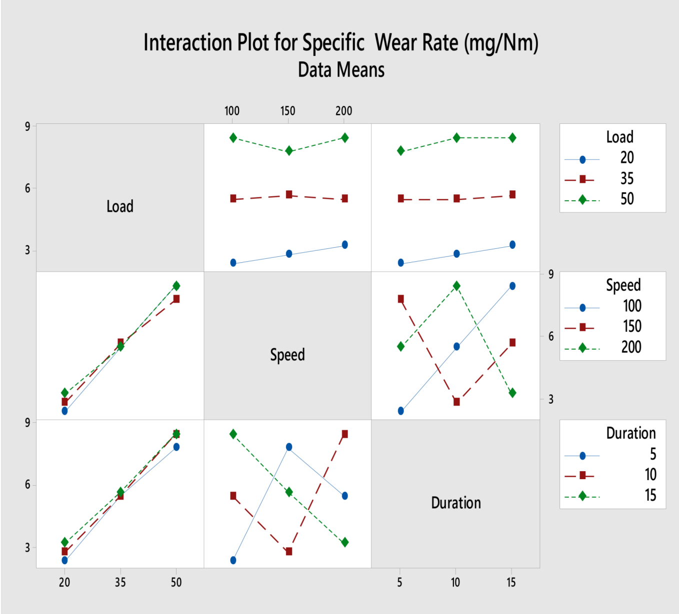


Figure 5: Interaction plot of Specific wear rate holding for a duration of 10 mins

b. A model has been developed as a regression equation to predict specific wear of nano-Al_2O_3 reinforced Al composite. As per the developed model, R^2 and adj R^2 are 99.85% and 99.76% respectively.

c. Two confirmation experiments were done and the outcomes of those experimental data were compared with the predicted value provided by regression equation (3). The comparison between the experimental and predicted values from two confirmation tests are showing an error of 2.1% and 6.6% respectively.

d. Microstructure has shown a distribution of Al_2O_3 in the metal matrix with fewer agglomeration. Also, the microstructure of worn-out surface has revealed narrow grooves and a minor crack on the surfaces for 20 N load, 100 RPM and 5 minutes duration. Conversely, microstructure of the worn-out surface having the highest specific wear rate displayed deep grooves and several cracks on the surfaces for the load of 50 N, sliding speed of 200 RPM and sliding duration of 10 minutes.

e. The effect of different sliding parameters on specific wear rate of fabricated Al composite will assist to identify the ideal wear resistance applications of fabricated Al composite to the aerospace industry.

DATA AVAILABILITY

The data used to support the findings of this study are included in the article.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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