Influence of Process Parameters on Specific Wear Rate of nano Al 2 O 3 reinforced Al Composite Using Taguchi's Technique

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Abstract

Aluminum is widely used in many engineering fields for its exceptional qualities. However, aluminum has poorer wear characteristics. The aim of the investigation was to study the effect of process parameters on the 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 of an Al composite reinforced with nano-sized Al_2O_3. Based on Taguchi's method, tests were planned, and a L9 Orthogonal array was selected to analyze the results. We used ANOVA to examine the impact of applied force, sliding speed, and duration on certain wear rates. This model's goal was to assess the specific wear rate with "smaller the better" as the selection criteria. Out of all the process parameters, applied load has been found to be the one that most 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 recreated a regression equation with R^2 and adj R^2 of 99.85% and 99.76% respectively that was utilized to estimate the particular specific wear rate of nano Al_2O_3 reinforced Al composite. An apple-to-apple comparison between experimental and projected values was built using two confirmation tests. It revealed an inaccuracy of 2.1% and 6.6%, respectively, with a specific wear rate of Al composite. Using a scanning electron microscope, wornout surfaces of the specimen with the lowest and greatest specific wear rates were examined. As per the investigation, lowest specific wear rate obtained due to formation of fewer oxide layers at the worn out surface of specimen and highest specific wear rate obtained due to cracks and deep groves at the worn out surface of specimen.

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 a high availability [1]. Pure aluminum, however, is subject to a variety of limitations because of how aeronautical applications work. Aluminum composites are becoming more widely accepted in these many industries to get over these limitations [2]. Additionally, aluminum and its alloys exhibit poorer 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 the most effective parameter 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 its alternatives, the stir casting method is relatively simple and cost-effective for the manufacture of 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 our Al composite is respectively two-step stir casting method and 2.5% Al_2O_3 having 20nm. The poor wear resistance of aluminum and its alloy are one of the most encountered challenges in the aerospace industry. Wear is mainly governed by excessive frictional stress arising from adhesion and abrasion. Characterization of different wear properties of Al composites are continuously investigated by researchers globally [10–12]. In this current investigation, we fabricated an Al composite having a composition of 2.5 wt. % of Al_2O_3 reinforced with 97.5 wt. % of Al. The impact toughness, ultimate flexural stress, Vickers micro hardness and Brinell hardness of 2.5 wt. % of Al_2O_3 reinforced Al composite obtained respectively as 13.47J, 293.51 MPa, 35.72 HV and 139.32 BHN. The fabricated Al MMC exhibited superior mechanical properties in comparison with pure Al as casted condition. We also performed the heat treatment of 2.5 wt. % of Al_2O_3 reinforced Al composite 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 investigation of heat treatment effects on hardness & electrical conductivity. As per the investigation, 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. The effect of heat treatment on Al composite reinforced with 2.5 wt. % of Al_2O_3 was accepted in Metal Science and Heat treatment journal and waiting for publication.

As a result, 2.5 weight percent of Al_2O_3 reinforced Al composite can be suggested for usage in a variety of aerospace applications, including engine connecting rods and bearing housings, among others. In the current study, we examined how the applied load, the sliding duration, and the sliding speed affected the specific wear rate of an Al composite that was manufactured, with a Taguchi-based L9 orthogonal array chosen to optimize the process parameters.

2. Experimental Details

2.1 Materials Selection

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

Table 1
Composition of aluminum

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

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. An external air blower was used to provide enough air to maintain a constant temperature while burning gas. 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 05 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 Fig. 1, and sample specimens were made in accordance with ASTM standard G99 G95a. The fabricated Al composite was used to create cylindrical pins with dimensions of 05 mm in diameter and 12 mm in height. The fabricated Al composite had a Brinell hardness of 139.32 and a Vickers mirco hardness of 35.72 respectively. All of the pins were thoroughly cleaned and dried before the wear tests. 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)

One of the most palatable statistical methods for examining the effects of numerous process factors simultaneously is DOE [13]. 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, S/N ratio is utilized to identify the process parameters that would produce the best results. 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 [14]. Prakas et al. (2014) investigated the sliding wear behavior of Al_2O_3-reinforced metal matrix composites with applied loads ranging from 15 to 45 N and sliding speeds ranging from 390 to 780 RPM [15]. 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 [16]. In the current investigation, the L9 orthogonal arrays of Taguchi's approach were used to create the experimental plan, and the ANOVA method was used to analyze the process parameters.

3.1 Taguchi’s Technique

In the current study, the experimental design was developed using Taguchi's approach's L9 orthogonal arrays, and the process parameters were examined using the ANOVA method.

Table 2
Process parameters and their levels

Level	Applied Load (L)	Sliding Speed (N)	Sliding Duration (t)
Units	N	RPM	Minutes
01	20	100	05
02	35	150	10
03	50	200	15

The purpose of the current work was to determine the minimum specific wear rate as much as possible. Sliding distance and specific wear rate were determined respectively using Eq. 1 and Eq. 2.

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Here, D is the diameter of sliding arm, N is sliding speed and t is the sliding time/duration. In this experiment, diameter of sliding arm kept fixed as 49 mm.

Specific wear rate= $\frac{\Delta \varvec{V}}{\varvec{S}\varvec{D}\times\varvec{L}}$ (2)

Here, SD is sliding distance, ΔV is loss of wear volume and L is applied load.

ANOVA was used to analyze the results of all the systematized responses. Depending on the sort of data being evaluated, the S/N ratio generates a lot of data points. Smaller is better, nominal is best, and larger is better are the three variations of the S/N ratio. ‘Smaller the better” was considered for the specific wear rate by Taguchi as per Table 3.

TABLE 3: Experimental outcomes of specific wear rate, signal to noise ratio and mean

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

(a) (b)

FIGURE 2: Residual Plots for (a) Signal to Noise Ratios; (b) Means

3.2 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. The ANOVA results for Means and Signal to Noise ratios are presented in Tables 4 and Table 5. 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 6 and Table 7.

Table 4
ANOVA for signal to noise ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Load	2	136.460	136.460	68.2298	285.19	0.003
Speed	2	1.197	1.197	0.5983	2.50	0.286
Duration	2	2.297	2.297	1.1484	4.80	0.172
Residual Error	2	0.478	0.478	0.2392		
Total	8	140.431				

Table 5
ANOVA for means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Load	2	11.0037	11.0037	5.50184	3521.53	0.000
Speed	2	0.0297	0.0297	0.01487	9.51	0.095
Duration	2	0.1520	0.1520	0.07599	48.64	0.020
Residual Error	2	0.0031	0.0031	0.00156		
Total	8	11.1885				

Table 6
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 7
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

- Tables 6 and 7 show that the applied load is the process variable that has the greatest impact on the particular wear rate of $_{Al2O3}$ reinforced Al composite. In their experimental study on the tribological properties of nitride-reinforced aluminum metal matrix composites, Bhuvanesh and Radhika (2017) found that the dominating factor was applied load, which contributed 25.58% to the wear rate [17]. Consequently, our research supports Bhuvanesh and Radhika's findings (2017).

3.3 Regression Analysis

3.3.1 Analysis of Specific Wear Rate

A regression model that illustrates the link between the independent variable and the response variable was produced by the statistical program "MINITAB 18". This equation illustrates the interaction between applied stress, sliding speed, and distance on specific wear rate through ANOVA analysis. As per the regression analysis, with R^2 and adj R^2 values for this model of 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% and pred R^2 99.56%. The higher the R^2 values, the better the polynomial is for describing the behavior of the system. The model is valid only within this range of parameters (applied load, sliding speed, and duration).

3.3.2 Study of Variance

The regression analysis for specific wear rate was carried out for a 95% confidence level and a 5% significance level. The significance of several aspects, including the regression model, terms, and lack of fit, is investigated using this analysis. Figure 3 shows the residual plot for specific wear rate. As per the analysis, regression equations (3) was obtained for specific wear rate as follows:

The regression equation of specific wear rate = -1.863 + 0.18182 Applied Load + 0.002886 Sliding Speed + 0.05724 Sliding Duration (3)

4. Confirmation Test

In this current work, the confirmation test was carried out by choosing the process parameters as given in Table 8. The tests were carried out and the outcomes were compared with the predicted value given by the regression Eq. (3). The comparison between the experimental and predicted value is exhibited in Table 10.

Table 8
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%

As per Table 8, 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 4.2% difference between initial parameter and optimal parameters settings [18].

5. Microstructure Observation

The SEM pictures of lowest and highest specific wear rate are exhibited respectively in Fig. 4(a) and Fig. 4(b) to observe the wear status of pins. The process parameters of pin having lowest specific wear rate are 20 N as applied load, 100 RPM as sliding speed and 5 minutes as sliding duration. Figure 4(a) exhibits the worn out surface with minor grooves developed for adhesive wear. The wear marks was due to the selected process parameters. We identified a minor crack of 51.73 μm^2 and few grooves lines measured through SEM image processing denoted as L1 to L4 in Fig. 4(a).

The process parameters of pin having highest specific wear rate are applied load 50 N as applied load, 200 RPM as sliding speed and 10 minutes as sliding duration. Figure 4(b) shows that delamination was maximum at this process parameter condition. 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 Fig. 4 (b), we identified 02 cracks at the worn surface of pin, one having missing distance of 2.70 μm and another one having 104.57 μm^2.We also observed few chips of surface which area measured as 477.40 μm^2 (A1) and 459.437μm^2 (A2). One of the deep groove measured with 6951.55μm^2.

1. (b)

FIGURE 4: SEM images of the pin worn surfaces at (a) applied load: 20 N, sliding speed: 100 RPM and sliding duration: 5 mins; (b) (a) applied load: 50 N, sliding speed: 200 RPM and sliding duration: 10 mins

Rajesh et al. (2013) performed a tribological study on red mud-reinforced aluminum metal matrix composites. At the applied load of 20N load, they identified a formation of an oxide layer which reduces the specific wear rate of the composite [18]. As per our investigation, we also observed a similar few oxide layers as per Fig. 4(a) for which the specific wear rate is minimum at the applied load of 20 N. Natrayan and Kumar (2019) investigated the wear behaviour on AA6061/Al_2O_3/SiC metal matrix composite. As per their investigation, they observed cavities and a few dimples formed for the applied of 30N [19]. As per Fig. 4(b), we also observe similar wear condition at the applied load of 50 N. Therefore, we understand that our fabricated Al MMC reinforced with Al_2O_3 having less abrasive wear.

6. Result And Discussion

6.1 Effect of applied load on Specific Wear Rate

We observe the escalation of specific wear rate with the increase of load from 20 N to 50 N nearly in linear proportion as shown in Fig. 5 (a) and Fig. 5(b). 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 pin and disc. Also acute wear is developed for adhesion when the applied load escalates from 35 N to 50 N and similar pattern is observed by Radhika et al. (2014) [20].

6.2 Effect of Sliding Speed on Specific Wear Rate

We also observe the escalation of the specific wear rate with increase of speed from 100 RPM to 200 RPM as shown in Fig. 5 (a) and Fig. 5(b), As the sliding speed of the disc escalates up to 150 RPM, the reinforcement particles of nano Al_2O_3 crushes and develops a thin layer on the surface which can be defined as a mechanically mixed layer. Also, the developed layer withstands high stress and which reduces the sliding wear as the sliding speed escalates to 200 RPM. 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 [16]. Our findings goes in line with the wear behavior of Poovalingam Muthu (2020).

6.3 Effect of sliding duration on Specific Wear Rate

We observe an escalation of specific wear rate with an increase of duration. Both Fig. 5 (a) and Fig. 5(b) exhibit 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 [21]. As per Fig. 4(b), 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 influence of process parameters on wear properties of nano Al_2O_3 reinforced Al composite indicated the following conclusions:

1. As per Taguchi's DOEs and ANOVA, we identified the most effective parameters (in rank order) as an applied load which remarkably affects the specific wear rate. We also identified sliding duration as 2nd most effective and sliding speed as the least effective parameter for specific wear rate.
2. A model has been developed as a regression equation to predict specific wear of nano Al2O3 reinforced Al composite. As per the developed model, R^2 and adj R^2 are respectively 99.85% and 99.76%.

3. Two confirmation experiments were done and the outcomes of those experimental data were compared with the predicted value provided by regression Eq. (3). The comparison between the experimental and predicted values from two confirmation tests are showing an error of 2.1% and 6.6% respectively.
4. SEM image of a pin having lowest specific wear rate shows narrow grooves and a minor crack on the surfaces for 20 N as applied load, 100 RPM as sliding speed 5 minutes as sliding duration. SEM image of the pin having highest specific wear rate also identified with deep grooves and several cracks on the surfaces for 50 N as applied load, 200 RPM as sliding speed and 10 minutes as sliding duration.
5. The optimized condition achieved in the current study can be utilized to improve the wear properties of the components and these components can be used in the aerospace industry for wear resistance applications.

Declarations

Declarations

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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