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Sustainable Improvements in Mechanical and Tribological Properties of AA2017-Aluminum Nitride Composites: A Comprehensive Investigation and Numerical Analysis

Senthil .R[1*], *M.* Vinayagam[2]

[1]Research Scholar, Department of Mechanical Engineering, Bharath Institute of Higher Education and Research, Chennai, India.
[2]Associate Professor, Centre for Materials Engineering and Regenerative Medicine, Bharath Institute of Higher Education and Research, Chennai, India.

Abstract. An AA2017-aluminum nitride composite was created through stir casting, and its tribological properties, like hardness and wear rate were examined by varying the aluminum nitride content from 5% to 15%. A numerical model was established to predict the wear rates of aluminum metal matrix composites (MMCs), and the accuracy of the model was confirmed through an analysis of variance (ANOVA). The findings demonstrated that the addition of aluminum nitride to AA2017 resulted in improved mechanical and wear characteristics for the composites. Furthermore, the utilization of sustainable materials and manufacturing techniques underscores the potential for environmentally responsible engineering solutions in material science and manufacturing processes. Aluminum nitride emerged as a critical component in enhancing the wear resistance of the metal matrix composites, contributing to their overall durability and sustainability.

Keywords: wear characteristics; Aluminium nitride; Response surface methodology; mechanical properties, Load, speed, sliding distance.

1 Introduction

Recently, a new type of material has emerged, with special prominence for the critical role it plays in cutting-edge material science and materials engineering: metal matrix composites[1]. The versatile properties of aluminium and its alloys include low density, great strength-to-weight ratio, dimensional stability, corrosion resistance, and high thermal conductivity. The tribological performance of common Al alloys is poor. Aluminum nitride or ceramic particles with a low zinc and magnesium percentage improve the material's characteristics when added to the mix[2–4].

[*] Corresponding author: mohanavel2k18@gmail.com

The reinforcing content, size, and type affect the friction and wear of AMCs. Particles of carbide, oxide, or nitride can be used as reinforcements [5]. Superior wear resistance and a low friction coefficient are achieved by reinforcing aluminium with aluminium oxide(Al_2O_3) particles. Al/Al_2O_3 nanocomposite, a new material in the field of AMMNC with enhanced tribological and mechanical properties [6, 7]. Potential improvements in energy savings, security, and reliability may result from using Al/Al_2O_3 nanocomposite materials [8].

Combining the solidification process with ultrasonic cavitation is a unique way for dispersing nanoparticles in molten metal, as demonstrated by authors [9, 10]. Authors synthesized A7075/Al_2O_3 nanocomposites utilizing Al_2O_3 powder of 0.4, 0.8, and 1.2wt % by the stir casting technique followed by extrusion. Nanocomposite outperforms matrix alloy A17075 in hardness, tensile strength, and compression strength. Researchers developed an RSM model to predict the wear rate of AA7075-SiC composite [11, 12].

The results of the hybrid composite's dry sliding wear were compared to those of an Al-SiC composite made by researchers by use of the liquid metallurgical method. A collection of carefully curated experimental data for optimization was created using the Taguchi method [13]. It was concluded that sliding distance was the major impact on wear of Al-SiC composites and AlSiC Gr hybrid composites. In order to investigate the input factors that influence the wear of Al-15 wt % SiC composite, authors created it through the powder metallurgy (PM) process and analyzed the data using analysis of variance (ANOVA). The grain size and hardness of the abrasive are two most important factors in determining the rate of abrasive wear, as shown in his study [14, 15]. Researchers produced a hybrid composite out of Al, SiC, and Gr using a stir casting technique, and studied its tribological behavior. Using a method called "design of experiments," the impact of various variables was studied. Considerations included mass, slide length, slide velocity, and reinforcement percentage. Authors found that by increasing the load and the sliding distance, wear on the hybrid composite could be decreased. Optimization of AMCs and their wear behavior has been the subject of many reports [16, 17].

The mechanical characteristics of MMCs are governed by the composition of aluminium matrix and percentage of volume , particle size distribution, and shape of aluminium nitride and magnesium MMCs are created using a wide range of production techniques, including powder metallurgy, stir casting, mechanical alloying, etc [18, 19]. Properties of Al-Si-aluminum nitride composites by stir casting methods. Stir casting was easier and more suited to mass production. Therefore, in this study, MMCs with various reinforcing-material compositions were fabricated utilizing the stir casting process. B y incorporating these sustainable practices into the fabrication process of Al-Si-aluminum nitride composites, you can reduce the environmental footprint associated with their production while promoting resource efficiency and responsible manufacturing

2 Materials and methods

2.1 Preparation of MMC

Table 1 details the chemical composition of the matrix metal and the properties of principal reinforcing material (aluminium). Following the preheating of 500 gm of aluminum nitride at 750ºC for a duration of 3 hours, the measurement of loss due to ignition yielded a result of 2.23 %, after which the material was subsequently cooled to room temperature.

Table 1. Materials properties and chemical composition used in this analysis.

AA2017 (Elements)	Wt%
Cu	4.5
Fe	0.7
Mn	0.4
Mg	0.8
Si	0.8
Zn	0.25
Ti	0.15
Cr	0.1
Aluminium	Balance
Aluminium Nitride	**Range**
Melting Point	2200°C
Boiling Point	2517°C
Density	3.3g/cm^3
Specific heat	780 J/kg.k
Thermal conductivity	200 W/mk

2.2 Wear behavior on AA2017 – aluminium nitride composite

The scientists observed that as they increased the volume fractions of Si and aluminum nitride in the Al/AlN material, the wear rate exhibited a linear decrease. In reference [20], the authors demonstrated that both the operational performance and wear resistance of Al/Sic and Al-based MMC containing hard particles were significantly improved, resulting in an extended service life. Literature reviews [21] found that by increasing the amount of aluminium nitride in the composites, wear resistance was much improved. The authors [22] improved upon the performance of commercially available original brake pads by formulating brakes using test samples that included aluminium nitride and Al. According to the authors [23], a significant improvement in abrasion resistance was seen after reinforcing SiC with Al.

2.3. Sample preparation

The stir casting technique was used to synthesise Al MMC in this study. In tests, the reinforcing materials were used as particles, and the aluminium was in the form of round rods. The aluminium rods were melted at a constant temperature of 725 °C in the furnace at first. Progressive melting was used to heat the metal to 800°C, where it remained for 30 minutes while 0.5 % Magnesium was added to enhance the wetness of the aluminium nitride particles and 0.1 % Zinc powder was mixed in to generate a vortex. Aluminum nitride, zinc, and magnesium were added consistently while the stirring was maintained. To ensure that the aluminium nitride was well mixed and distributed throughout the molten metal, the mixture was agitated at 250 rpm under a blanket of argon for 20 minutes. Aluminum nitride mass fractions in the resulting castings were varied by allowing the moult to cool and solidify. After cutting and testing several polished and etched samples, conclusions were drawn.

2.3.1 Analysis on Mechanical properties

The investigations involved sectioning both with reinforcement and without reinforcement composites. After cutting, the samples were mechanically ground and polished with 1m aluminium powder. The samples were coarsely processed with SiC impregnated 200-300 grit emery paper before being finely ground with 600-700 grit paper.

2.3.1.1 Testing on Hardness

Using a Rockwell hardness testing equipment, the hardness of both Al and AlN composites were compared. Each test specimen was subjected to a 100 kg weight while being struck with 1.6 mm steel ball intender. The difficulty test required a 20 second detention time [24].

2.3.3 Analysis on Wear properties

Wear properties of Al MMCs were investigated utilising an automated DUCOM pin-on-disc sliding wear testing system [25]. Al MMCs' wear behaviour in dry sliding was analysed as a function of applied load, sliding velocity, and distance. Each specimen's volume loss from wear was measured and calculated as it was put through its paces in the testing procedure. For each experiment, the volume reduction due to wear was measured twice and averaged.

2.4. Advance of numerical model for wear rate

Table 2. Sliding wear parameters

Parameters	Notations	Unit	levels		
			-1	**0**	**1**
Sliding distance	D	m	1500	2000	2500
Speed	S	rpm	600	1200	1800
Load	L	N	30	60	90
Reinforcement of Aluminium nitride	R	%	5	10	15

The study of a factorial experiment's results is greatly aided by the use of response surface technique. Table 2 displays the values for the sliding wear parameters. Sliding speed (S), load (L), aluminium nitride mass fraction (R), and Sliding distance (D) all affect the response wear rate (W),

$$W = f(D, S, L, R) \quad (1)$$

A central composite rotatable design was developed by Box and Hunter to accommodate a second order reaction surface. The experiments, conducted with the use of the central composite design (CCD), made use of the 31 coded conditions listed in Table 3. The above experiment was planned utilising a half-replicated 25-factorial architecture with 7 centre points and 8 "star" points that were held constant in location. These lines represent rows 1-6, 17-26, and the first 16 rows of the displayed design matrix.

Table 3. Design of experiments

No.of.Runs	Sliding wear parameters				Wear rate (10^{-5} mm^3m^{-1})
	D	**S**	L	R	
1	2000	1200	60	10	573
2	1500	1800	90	5	608
3	2500	1800	30	15	600
4	2000	1200	60	20	656
5	2000	1200	60	10	598
6	1500	1800	30	5	652
7	1500	600	90	5	623
8	1500	600	30	5	691
9	2000	0	60	10	393
0	2000	1200	60	0	418
11	2000	1200	60	10	428
12	1000	1200	60	10	446
13	2500	1800	90	5	414
14	2000	1200	60	10	438
15	2000	1200	120	10	450
16	3000	1200	60	10	491
17	2500	600	30	5	459
18	2000	1200	60	10	583
19	2000	2400	60	10	458
20	2000	1200	60	10	568
21	2000	1200	60	10	466
22	2500	600	30	15	577
23	2000	1200	0	10	773
24	1500	1800	90	15	358
25	2500	1800	30	5	509
26	1500	1800	30	15	520
27	1500	600	30	15	514
28	1500	600	90	15	495
29	2500	600	90	15	516
30	2500	1800	90	15	515
31	2500	600	90	5	511

$$X_i = \frac{2[2X-(X_{\max}+X_{\min})]}{[X_{\max}-X_{\min}]}. \quad (2)$$

For k factors, the response surface 'Y' represented by the second order polynomial regression equation [26]

$$Y = b_0 + \sum_{i=1}^{k} b_i X_t + \sum_{i=1}^{k} b_i X_i^2 + \sum_{i=1}^{k} b_i X_i X_j \quad (3)$$

In this context, 'b0' represents the average or mean value, while 'bi,' 'bii,' and 'bij' are coefficients that vary based on the main and interaction effects of the parameters [8]. These coefficients were determined through calculations performed using MINITAB 20, a statistical software program. The resulting polynomial for the four variables looks like this:

$$W = b_0 + b_j D + b_2 S + b_3 L + b_4 R + b_{13} D^2 + b_{22} S^2 + b_{33} L^2 + b_{44} R^2 + b_{12} DS + b_{13} DL + b_{14} DR + b_{23} SR + b_{24} SR + b_{34} LR \quad (4)$$

Following the methodology [2], the important coefficients were determined and their significance was evaluated at the 95% confidence level before the mathematical model was built. Parameters for dry sliding wear are encoded in the final mathematical model as follows:

$$W = 452.763 + 23.708D + 21.292S + 19.042L - 98.042R + 13.014R^2. \quad (5)$$

2.4.1 Adequacy model Confirmation

The results of the numerical model's validity tests are presented in Table 4. The derived model accounts for 61.82 %of the experimental data (R^2 = 0.6182). The model's standard error of approximation is 80.7234, and these results verify the importance of the various parameters.

Table 4. Appropriateness of the ANOVA outcomes for the created model.

Dependent variable	Wear rate
Squared multiple R	0.6182
Adjusted squared multiple R	0.2841
Standard error of estimate	80.7234

Figure 1 demonstrates that the mathematical model's anticipated values are spread out on both sides of the 45 degree line, confirming the model's accuracy.

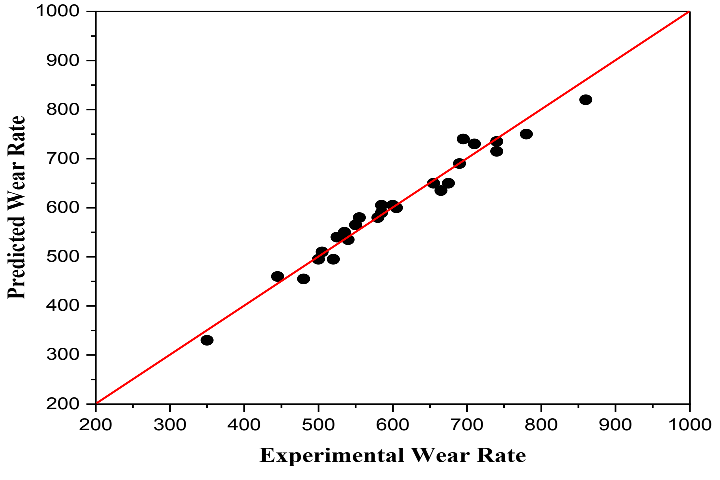


Fig. 1. Results of predicted and experimented wear rate.

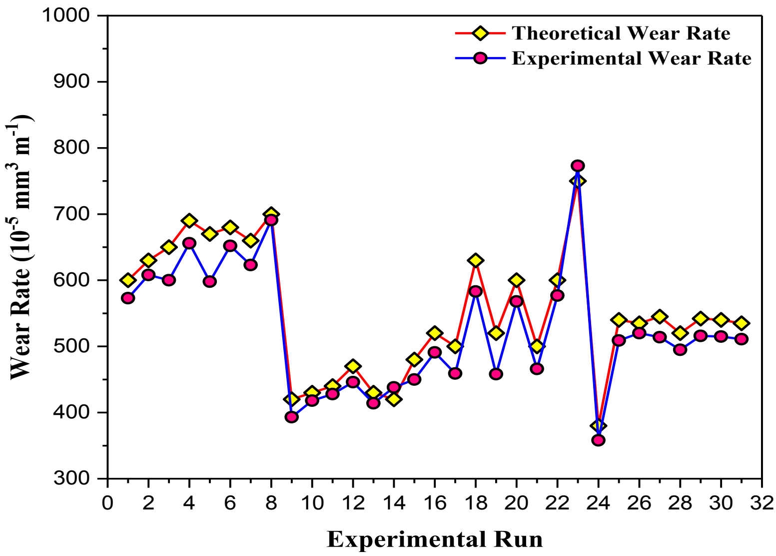


Fig. 2. Evaluation of Theoretical and experimented values.

The wear rate can be predicted using equation (5), and when plotted against the total number of trail runs, the experimental and predicted values are quite close to one another, with just a little discrepancy noticeable.

2.4.2 Confirmation of the experiment

Confirmation wear tests using non-analytical parameter levels were performed to ensure the accuracy of the regression model.

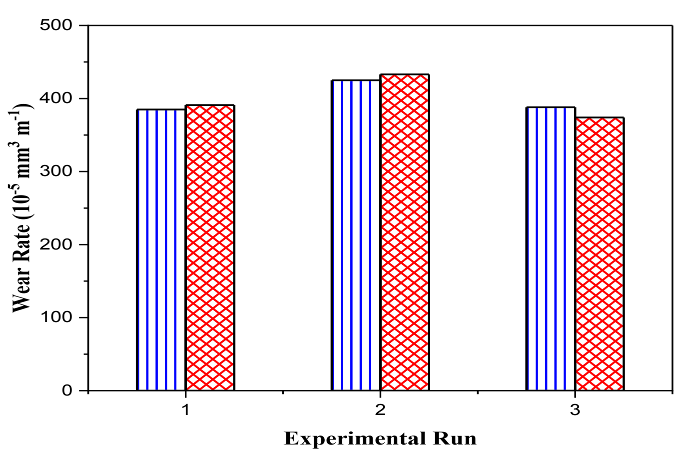
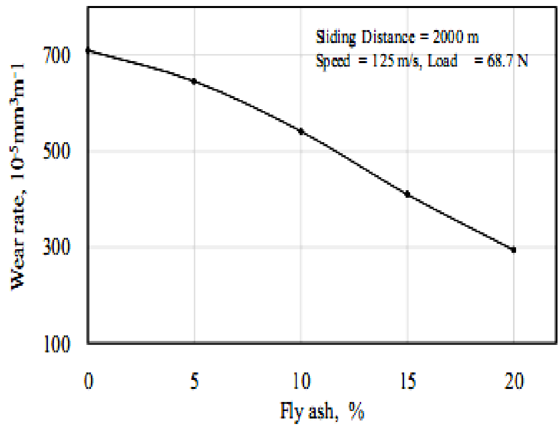


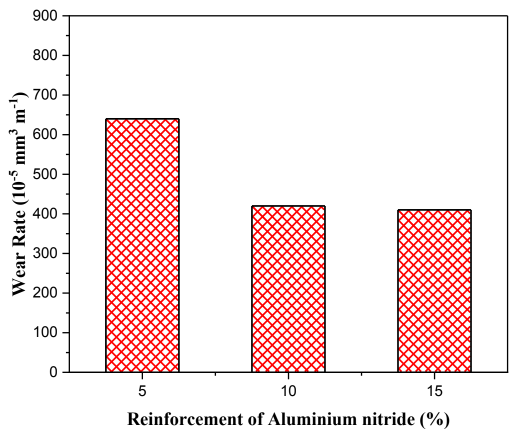
Fig. 3. Confirmation test results.

3 Results and discussions

3.1 Wear rate (WR)



(a)



(b)

Fig. 4.(a)&(b) Impact of aluminium nitride reinforcement on wear rate.

Wear on the composites as shown vs aluminium nitride concentration (volume percent) under a standard load of 60 N in Fig. 4. As the aluminium nitride concentration improved, so did the wear resistance. The presence of tough silica particles in the aluminium nitride is mostly to responsible for this.

3.2.1 Impact of applied load

The sliding tests involved testing five samples, and the outcomes indicated that the applied load played a crucial role in determining the wear rates of the composites. As depicted in Figure 5, it is evident that an escalation in the applied load corresponds to improve in the wear rate. The dominant mechanism behind this trend is adhesive wear. As the applied load rises, there is a concurrent increase in the coefficient of friction, which in turn results in accelerated wear. Micro-ploughing, delamination, and other unfavorable outcomes are inevitable [27].

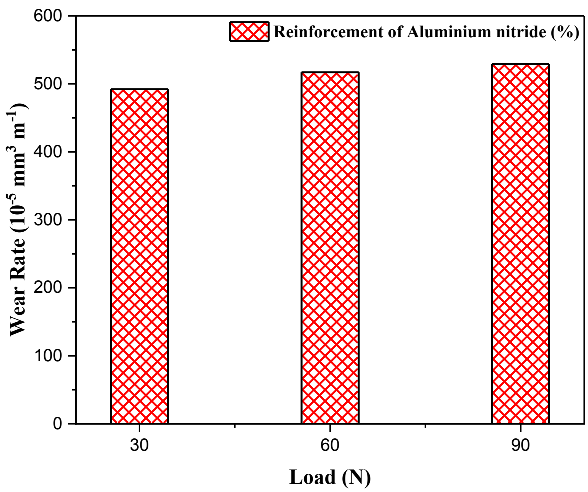


Fig. 5. Impact of applying load on WR.

3.2.2 Impact of sliding velocity on WR

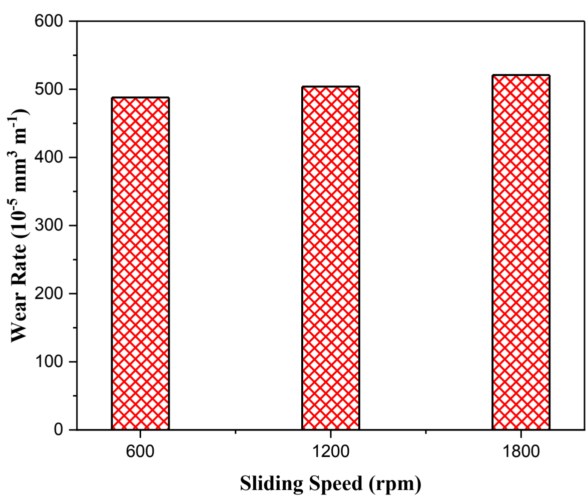


Fig. 6. Impact of sliding velocity on WR.

Increasing the sliding velocity results in a wear rate, as seen in Fig. 6. The sub surfaces and worn surfaces undergo plastic deformation as the velocity increases. The resulting rate of wear is quite high. When two asperities come into touch with one another at high speeds, frictional heating of the surfaces causes a thin melted layer to develop.

3.2.3 Impact of sliding distance on WR

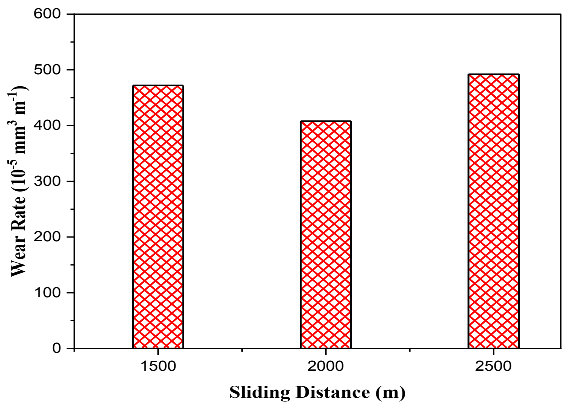


Fig. 7. Impact of sliding distance on wear rate.

The link between wear rate and sliding distance is depicted graphically in Fig. 7. As the distance between two points increases, a greater percentage of each is subjected to the wear process, and a greater percentage of each is lost as wear debris. During the mild wear regime, it was observed that both the volume lost due to wear and the sliding distance exhibited a consistent and gradual increase as time passed. This pattern suggests that wear was advancing under stable and steady-state conditions.

3.2.4 Impact of sliding time on WR

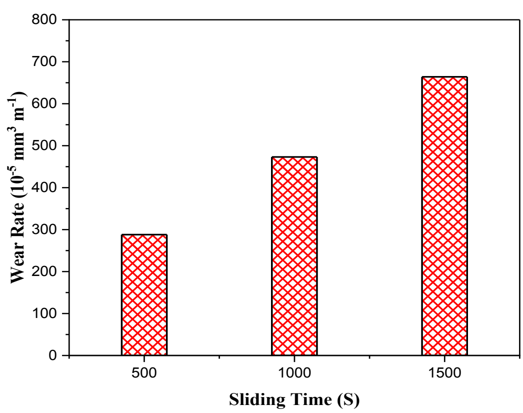


Fig. 8. Impact of sliding time on WR.

Figure 8 indicates how the amount of duration spent sliding has a direct impact on the amount of wear experienced. The graph clearly demonstrates that wear increases linearly with increasing sliding time. When there is both a maximum WR and a lot of wear debris, surfaces experience extreme wear and tear.

3.3 Hardness

Hardness of aluminium reinforcement composites is shown in Fig. 9 as a function of the concentration of aluminium nitride in the pure AA2017 condition. Al had a hardness of 30 HRc, while Al MMC with 15% reinforcing material had a hardness of 45 HRc. Since aluminium nitride contains hard minerals like silica and alumina, increasing its proportion in a composite makes it more resistant to abrasion. Additionally, it was discovered that the hardness of Al somewhat varies with 10 and 15 wt % of aluminium nitride, and that adding more aluminium nitride particles has no influence on hardness.

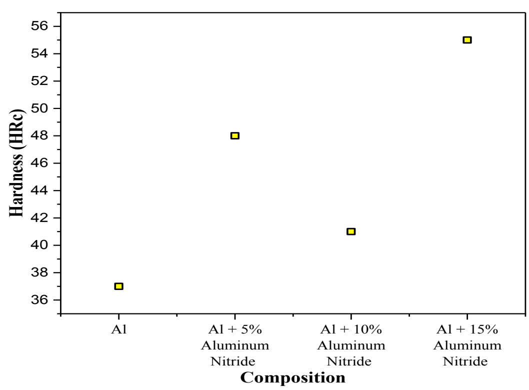


Fig. 9. Impact of aluminium nitride reinforcement on hardness

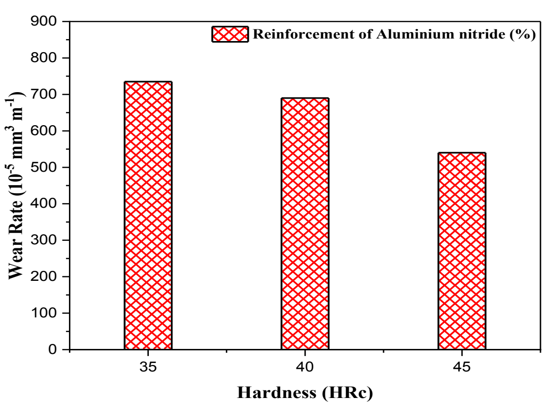


Fig. 10. Impact of hardness

The relationship between wear rate and hardness is illustrated in Figure 10. It is evident that as hardness increases, the wear rate decreases significantly, primarily due to the enhanced properties of the reinforcing material. Particles of aluminium nitride, which increase the composite material's bulk hardness, are responsible for its decreased wear rate.

4. Response surface Methodology

4.1 Impact of Interaction on applying load and aluminium nitride on the WR

The quantity of aluminum nitride particles within the reinforcement material plays a vital role in reducing wear as the applied load increases. This effect is highlighted by the interactive influence of load and the volume fraction of the reinforcement, as shown in Fig 11. At a maximum stress of 107.91 N and a minimum aluminium nitride concentration, an 800 x 10^5 mm^3/m wear rate was recorded. Similar comparisons may be made for various load conditions and aluminium nitride concentrations. Aluminum nitride's strengthening ensures a low rate of wear. The trend seen in Fig. 12 is confirmed by the surface plot.

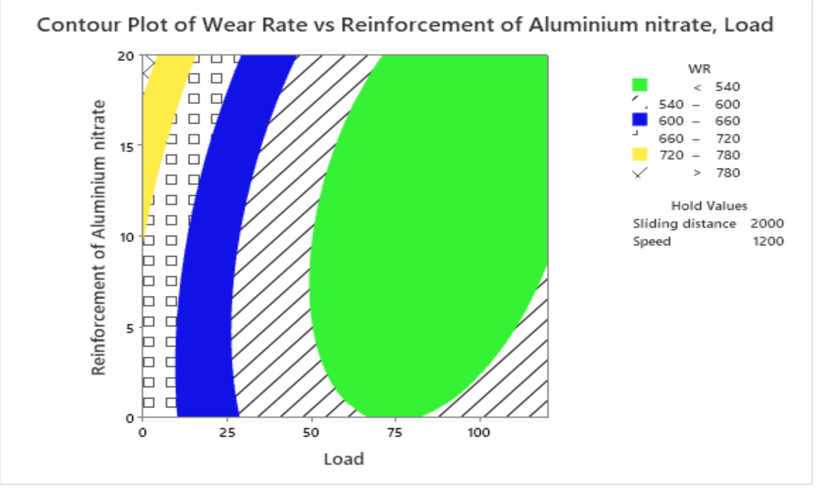


Fig. 11. 3D plot of WR vs load and aluminium nitride

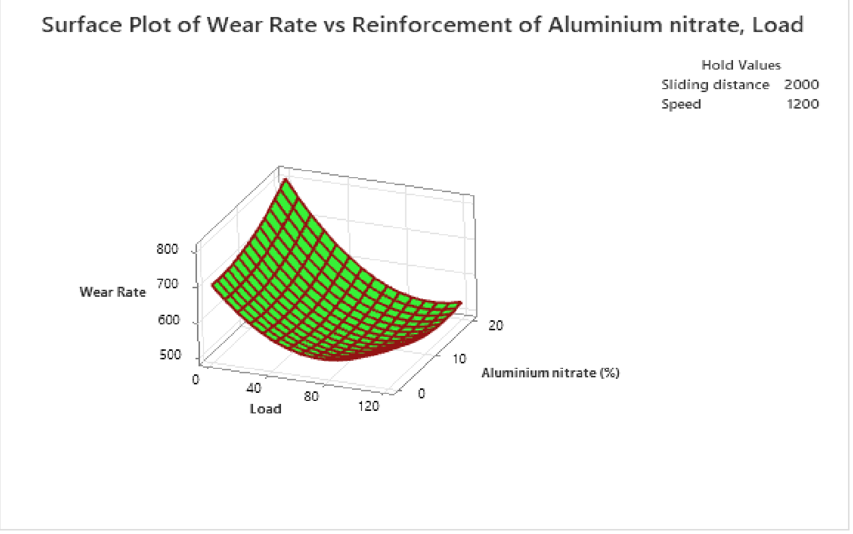
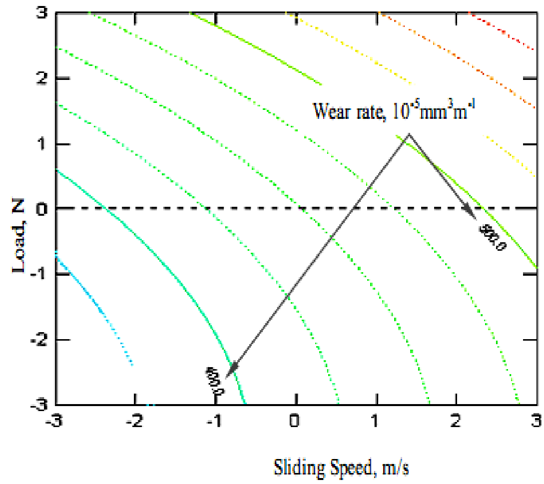
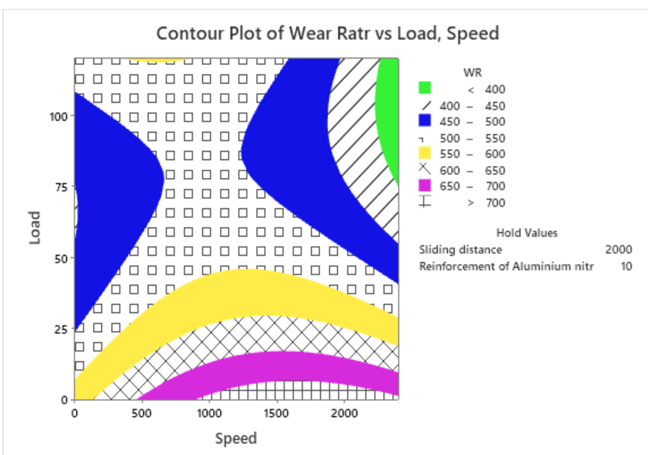


Fig. 12. 2D plot of WR vs load and aluminium nitride %.

4.2 Impact of applying load and sliding speed



(a)



(b)

Fig. 13.(a)&(b) Contour plot of WR vs load and sliding speed.

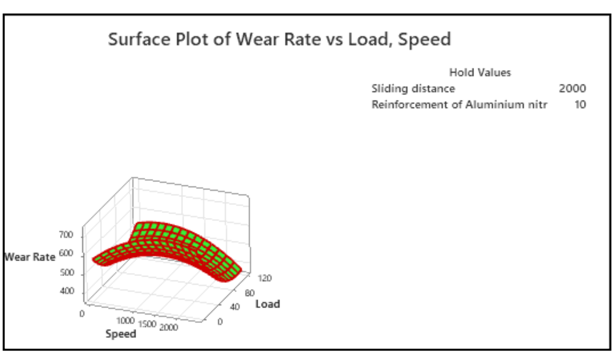


Fig. 14. Surface plot of WR vs load and sliding speed.

The relationship between velocity and load on the rate of wear is seen in Figs. 13 and 14. The rate of wear rises from a light to a heavy load and from a slow to a fast speed. The elevated dry sliding wear could be accountable for this phenomenon, as it induces material's plastic deformation at surface and sub-surface.

4.3 Interaction plot on ANOVA

Figure 15 displays the tolerance range for the sliding distance, velocity, load, and percentage of aluminium nitride used in the design. The least square values from the analysis of variance are used to generate the resulting graphic. The figures demonstrate that the design is reliable because the estimated errors are small.

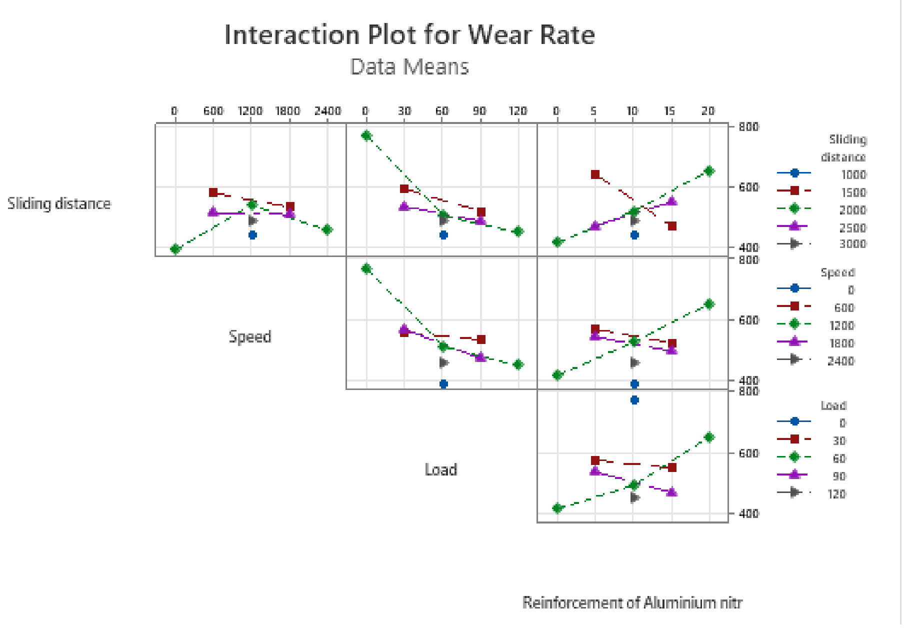


Fig. 15. ANOVA interaction graphs.

5 Conclusions

Based on the results of this investigation on the wear characteristics of AA2017-MMC specimens manufactured using the stir cast technique, it was found that:

- In this work, a CCD second-order RSM was used to show a numerical model built to predict the wear rate (WR) of AA2017 MMC (Aluminum Alloy 2017 Metal Matrix Composite) depending on the composition of sustainable material like aluminum nitride, the applied normal stress, and the sliding speed..
- The mathematical model made it evident that under typical load, the wear loss would grow. But when aluminium nitride concentrations increased, wear rates reduced.
- A cheaper and easier stir casting process was used to create a defect-free aluminium matrix aluminium nitride reinforced composite.
- The Al MMCs' hardness improved with increasing amounts of aluminium nitride.

- The addition of silicon into aluminum nitride significantly enhanced the wear resistance of the Aluminum Metal Matrix Composite (Al MMC), and these findings align well with previous research investigations.

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