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Optimizing Tribological Performance of AA5128/SiC/AlN Hybrid Metal Matrix Nanocomposites by Taguchi Technique

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Abstract

Hybrid AlN (Aluminum 5128 alloy/silicon carbide/aluminum nitride) metal matrix nanocomposites (MMNCs) with titratable Silicon carbide (SC) and AlN and a fixed AA5128 content may be fabricated via ultrasonic-assisted stir casting (in increments of 0.6 from 0 to 3%). Tribological characteristics of produced composites are evaluated at room temperature using a pin-on-disc (POD) device. The tribological behaviour of nanocomposites is investigated using Taguchi approach to determine how process factors affect the outcome. Taguchi method experiments were designed using the L18 orthogonal array (OA), and Analysis of variance (ANOVA) was employed to determine the best variables to control the process. According to the results of the experiments, A-composition (81.57%) has the greatest impact on wear rate (WR), subsequent by B-applying load (16.29%), C-sliding velocity (1.72%), and D-sliding distance (0.42%). The composition of the material has the greatest impact on the coefficient of friction (COF) (58.27%), subsequent by the sliding velocity (30.38%), the sliding distance (6.71%), and the applied load (3.85%).

Keywords

Optimization, Tribological properties, AA5128, Silicon carbide, Aluminum nitride, Taguchi

Introduction

The unique properties of MMNCs have led to their rising popularity in recent years. High strength and low density, high fatigue strength without significant loss of ductility, and capability maintenance even at high temperatures are all examples of these features [1]. AMMNCs are distinguished among MMNCs by their low density, high strength, resistance to corrosion, and good electrical and thermal conductivity. The defense, military, aerospace, and automotive industries are just some of the many places where its superior strength-to-weight ratio is put to good use [2]. Differences in temperature between the nanoparticles and the basic matrix improved the AMMNCs' characteristics. However, ensuring that the nanoparticles are distributed uniformly throughout the aluminum matrix is crucial for enhancing the AMMNCs' mechanical qualities. Homogeneous dispersion in AMMNCs is difficult because nanoparticles have a high surface-to-volume ratio, poor wettability, and high viscosity [3, 4]. The agglomeration of particles is also influenced by the manufacturing process variables.

Due to its high cost and lengthy production time, powder metallurgy is only useful for making flat or cylindrical components [5]. The use of ultrasonic-assisted stir casting to create AMMNCs allows for the elimination of these challenges. The capacity of the ultrasonic-assisted stir casting method to wet and distribute nanoparticles uniformly in the base alloy is another advantage [6]. It lessens voids, uniformly disperses particles, and improves the composite tribological grain structure. Using an ultrasonic-assisted stir casting method, the authors created a hybrid nanocomposite composed of SiC (35%) and graphene (13%) [7]. They found nanoparticles of graphene and SiC distributed uniformly throughout the A357 matrix. The composites made using this technology have a finer microstructure and better mechanical properties than those made using conventional methods. Researchers [8] studied the mechanical characteristics of Al/AlN nanocomposites that had been ball-milled and hot-extruded, and that included 1, 2, and 4% aluminium nitride particles. Tensile strength was raised from 212 MPa to 333 MPa and hardness was increased from 55% to 90% when AlN particle percentage was increased in nanocomposites of hot extruded samples [9, 10].

The composite's tribological qualities are crucial to its usefulness. Aluminum matrices are being reinforced with a wide variety of hard ceramic particles to improve their wear properties [11]. Wear resistance and COF can be enhanced by incorporating hard and soft particles into an aluminum matrix [12]. Some examples are TiC, Al_2O_3, SiC, MoS_2, WC, AlN, and TiB_2. The authors of this work described the tribological and mechanical characteristics of Al/B_4C nanocomposites that had SiC nanoparticles added to them by mechanical alloying and heat processing. Increases in wear resistance and compressive strength were seen after increasing the amount of SiC nanoparticles incorporated into the aluminum matrix [13]. The dry sliding wear and friction properties of stir-cast AI/SiC/red mud hybrid composites were examined [14, 15]. Using the Taguchi approach, only a few control variables, such as the percentage of red mud's weight, processing factors, as well as their interactions, are analyzed. On the COF of the hybridized composites, it was discovered that sliding distance (19.74%) and applied load (3.86%) considerably affected wear loss. With increasing volumes of red mud added, the WR of the hybridized composites declined, but increased with applied force and sliding distance [16, 17]. Researchers [17, 18] analyzed the impact of Titanium carbide particles on the tribological properties of Al7075-titanium carbide composites using the reactive stir casting technique.

The traditional approach of constructing experiments is difficult, time-consuming, costly, wasteful, and unable to determine a connection between process factors and the outcomes being evaluated. Therefore, most scientists use Design of Experiments (DoE), a systematic approach to include statistical testing into experimental design. It's a method for analyzing product and processing data to find the optimal settings. The Taguchi method, which entails carrying out trials in accordance with OA, is a straightforward and reliable technique. Experiment results may be analyzed in a few ways once they have been collected. ANOVA is one of the most often used techniques for data analysis.

The Taguchi method is used to analyze the tribological performance of the manufactured AA5128/SiC/AlN hybrid MMNCs. Six different nanocomposites were tested. Here, four process parameters: A, B, C, and D were evaluated. By examining the relationship between these four process factors and output metrics like WR and COF, we may find the optimum number of control variables. The relative weights given to the various control variables and their ability to affect the outcomes of interest were also calculated using the ANOVA test.

Materials and Methodology

Materials

The AA5128 is employed as the primary material here. As reinforcing particles, we employ SiC and AlN nanoparticles purchased from Go green products in India. Table 1 displays information on SiC and AlN. Table 2 shows the elements that make up AA5128 alloy.

Experimental methodology

Figure 1 is a flowchart depicting the experimental approach taken in the present investigation. Ultrasonic-assisted stir casting techniques are used to create the composites from their individual parts. Standard wear test specimens may be made using the composites, and the WR and COF can be determined with the WR and friction monitor. Parametric analysis employs the ANOVA method.

Table 1: Characteristics of SiC and AIN.

Characteristics	SiC	AlN
Density (g/cm^3)	3.21	2.29
Thermal conductivity (W/mK)	125	35
Elastic modulus (GPa)	500	678
Colour	Dark grey to black	White
Melting point (°C)	2730	2975

Table 2: Chemical properties of AA5128.

Materials	Fe	Zn	Ni	Cu	Mg	Zr	Mn	Ti	Si	Cr	Al
Wt.%	0.15	3.5	0.03	0.2	0.6	0.1	0.05	0.05	0.1	0.03	Bal

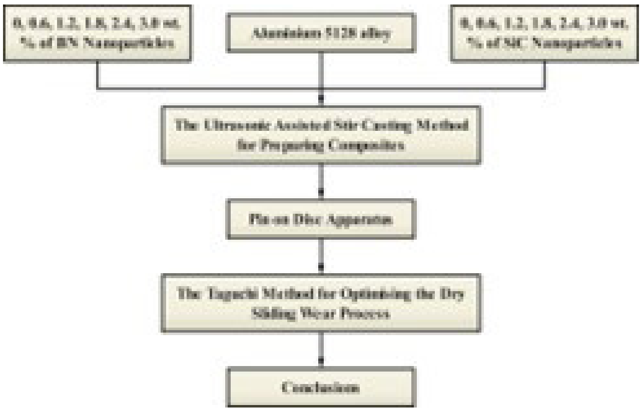

Figure 1: An outline of the experimental process.

Fabrication

The AHMMNCs depicted in figure 2 were manufactured using ultrasonically-assisted stir casting in combination with a liquid metallurgical technique. The electric resistance heating furnace, inert gas protection system, and ultrasonic generator make up this set of tools. Before using the furnace, a graphite crucible that can contain up to 1.5 kg of metal is placed within. 1 kg of AA 5128 alloy is heated to 750 °C in a graphite crucible in an argon gas environment for each melt. Nanoparticles' wettability is improved by preheating them in a muffle furnace to 450 ºC (SiC and AlN) [19, 20]. The mixture is then agitated with a mechanical stirrer at 500 rpm for 25 min after the appropriate quantity of warmed particles have been introduced. After 25 minutes of vibrating a titanium ultrasonic probe at 30 mm depth, the AlN and SiC nanoparticles are retrieved from the melt [21, 22]. The molten metal is poured into a mild steel mould that has been preheated to a temperature of around 600 °C when the furnace stopper is removed. Once the composite has cooled, it is released from the mould and subsequently subdivided into test samples. Using the Archimedean principle and the law of mixing, we can determine the composite's theoretical density.

Analysis of wear test

To investigate the composite's tribological behaviour, DUCOM (TR-20LE) POD equipment at ASTM standard G99-05 is used (Figure 3). From the finished composite, an 8 mm diameter by 35 mm long wear test specimen was cut. Each series of testing is followed by a thorough cleaning with acetone and polishing with emery paper of increasingly finer grits (400, 600, 800, and 1,200) to ensure reproducibility. The material is weighed on a computerized scale that can distinguish weight changes of just 0.001 mg before and after the analysis [23]. A standard weight of 25, 35, and 45 N, 0.6, 1.2, and 1.8 m/s, and 600, 1200, and 1800 m were used in the sliding trials, which were conducted at room temperature. The diameter of the track has been maintained at 110 mm throughout all our wear tests.

Taguchi method

The present study employs the Taguchi methodology, one of the DoE method, in the planning and execution of its tests. The steps of the Taguchi approach for optimizing process parameters are as follows: parameter selection, experimental design, experimentation, data collection and analysis, result evaluation, and finally, verification. When compared to the other DoE techniques, this decreases the number of experimented runs. Taguchi OA design provides a simple and efficient method for cutting down on production time and expenses without sacrificing quality. Taguchi method has the following benefits and drawbacks:

Taguchi is a method for estimating response parameters using both the signal-to-noise ratio and OA [24]. Control variables with varied levels are chosen, tests are planned and carried out in line with an OA, and response parameters are determined in an OA. Depending on the context, a greater or lower S/N ratio may be preferable. It is possible to determine the "bigger is better" and "lower is better" S/N ratios by solving equations 1 and 2, respectively [25].

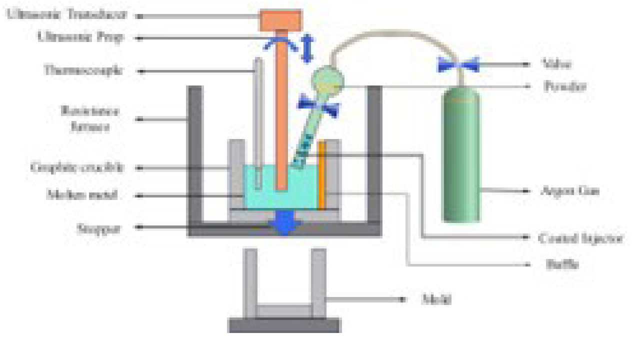

Figure 2: Experimental arrangement of ultrasonically assisted stir casting.

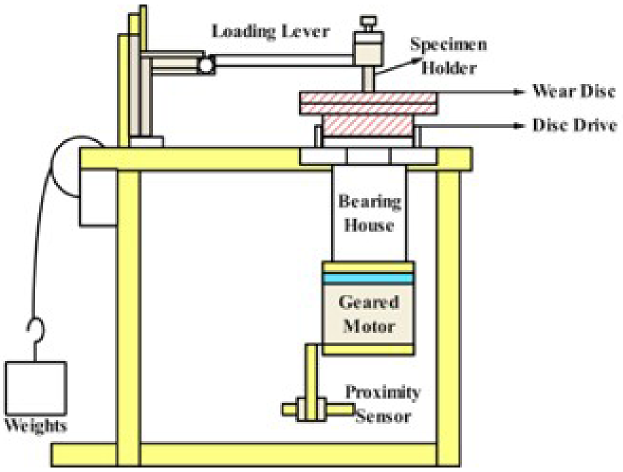

Figure 3: Experimental arrangement of POD test.

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum \square_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{1}$$

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{2}$$

Where

H = S/N ratio of experimental values;

yi = Experimental values from the ith experiment; and

n = Total number of trials.

Minitab17.0 is utilized to compute these properties. Table 3 lists the amounts of the independent variables utilized in this experiment. Table 4 displays the mean and standard deviation of WR and COF for the aluminum hybrid MMNCs over the L18 orthogonal array. Utilizing analysis of variance (ANOVA) statistics, we may verify the weight assigned to each control parameter.

Results and Discussion

Results on WR

The WR and S/N ratios are shown in table 4. Table 5 displays the typical S/N ratios for the AHMMNC WR. The significance of delta was computed by calculating the range of extreme values for each variable. The greatest impact on the performance response is made by the variable with the largest delta. The composition that placed first had a higher delta value (4.46). In addition, the following variables' rankings de-

Table 3: Processing factors and its levels.

Factors	Levels					
	1	2	3	4	5	6
A (%)	0	0.6	1.2	1.8	2.4	3
B (N)	25	35	45	-	-	-
C (m/s)	0.6	1.2	1.8	-	-	-
D (m)	600	1200	1800	-	-	-

Table 5: Response table for WR.

Level	A (%)	B (N)	C (m/s)	D (m)
1	-17.10	-13.59	-14.33	-14.44
2	-15.93	-14.69	-14.56	-14.57
3	-14.29	-15.33	-14.71	-14.59
4	-14.17	-	-	-
5	-13.09	-	-	-
6	-12.64	-	-	-
Delta	4.46	1.74	0.38	0.15
Rank	1	2	3	4

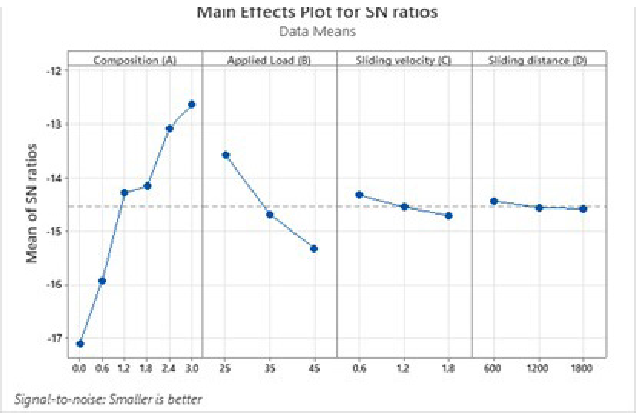

Figure 4: Main effects plot for WR (S/N ratio).

scribe the WR behaviour of the AHMMNCs: One (A), two (B), three (C), and four (D) composition, applied load, and sliding velocity and distance.

The S/N ratio main effect plot is depicted in figure 4. The hardness of AHMMNCs may be improved without sacrificing WR by increasing the SiC and AlN content of the aluminum matrix. Interfacial binding between the base alloy and reinforcements appears to be governed by the relative abundances of SiC and AlN in the aluminum alloy [26]. Increasing the load has been shown to considerably increase AHMMNCs' WR. When the pressure between the counter bodies increases due to the pin's weight, there will be more friction and a higher composite rate. As the strain on the pin grows, so does the area of contact between them. The AHMMNCs' WR increases with both sliding distance and speed [27]. The WR increases as the POD sliding distance increases. When moving at high speeds, the pin and disc create heat through friction, which softens the materials and quickens the rate of wear. Sliding distance had the least impact on WR of the parameters considered. Next, we look at the frictional force, material composition, and sliding speed. The literature also reports similar findings [28].

The impact of WR's control variables on performance factors is measured using ANOVA. It also determines the extent to which wear performance is affected by control process factors.

The results of the ANOVA are shown in table 6, where it is determined that composition is the most important element (A contributing 81.57% to the performance measure), followed by B (16.29%), D (1.72%), and C (0.42%). A value of 'P' less than 0.05 is considered significant when doing an ANOVA with a 95% confidence interval. Sliding speed and distance have little effects on WR, but composition and applied load are crucial.

Results on COF

Table 4 lists several S/N ratios and COFs. Table 7 displays the results of a delta-statistics analysis of the mean S/N ratios for COF of aluminum hybrid MMNCs across all levels.

Table 4: DoE.

S No.	A (%)	B (N)	C (m/s)	D (m)	WR (mm³/m)	COF	S/N ratio of WR	S/N ratio of COF
1	0.0	25	0.6	600	6.322	0.535	-16.0171	5.43292
2	0.0	35	1.2	1200	7.31	0.555	-17.2783	5.11414
3	0.0	45	1.8	1800	7.938	0.581	-17.9942	4.71648
4	0.6	25	0.6	1200	5.513	0.54	-14.8278	5.35212
5	0.6	35	1.2	1800	6.48	0.551	-16.2315	5.17697
6	0.6	45	1.8	600	6.857	0.559	-16.7227	5.05176
7	1.2	25	1.2	600	4.548	0.533	-13.1564	5.46546
8	1.2	35	1.8	1200	5.47	0.562	-14.7597	5.00527
9	1.2	45	0.6	1800	5.602	0.546	-14.9669	5.25615
10	1.8	25	1.8	1800	4.783	0.556	-13.5940	5.09850
11	1.8	35	0.6	600	4.925	0.528	-13.8481	5.54732
12	1.8	45	1.2	1200	5.662	0.544	-15.0594	5.28802
13	2.4	25	1.2	1800	4.047	0.534	-12.1427	5.44917
14	2.4	35	1.8	600	4.685	0.549	-13.4142	5.20855
15	2.4	45	0.6	1200	4.848	0.53	-13.7113	5.51448
16	3.0	25	1.8	1200	3.887	0.522	-11.7923	5.64659
17	3.0	35	0.6	1800	4.28	0.512	-12.6289	5.81460
18	3.0	45	1.2	600	4.733	0.509	-13.5027	5.86564

Table 6: Results on ANOVA for WR.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
A (%)	5	18.1866	81.57%	18.1866	3.63732	527997.58	0.000
B (N)	2	3.6319	16.29%	3.6319	1.81595	263605.65	0.000
C (m/s)	2	0.3837	1.72%	0.3837	0.19185	27849.19	0.000
D (m)	2	0.0945	0.42%	0.0945	0.04727	6861.29	0.000
Error	6	0.0000	0.00%	0.0000	0.00001	-	-
Total	17	22.2968	100.00%	-	-	-	-

Table 7: COF response table.

Level	A (%)	B (N)	C (m/s)	D (m)
1	5.088	5.407	5.486	5.429
2	5.194	5.311	5.393	5.320
3	5.242	5.282	5.121	5.252
4	5.311	-	-	-
5	5.391	-	-	-
6	5.776	-	-	-
Delta	0.688	0.125	0.365	0.177
Rank	1	4	2	3

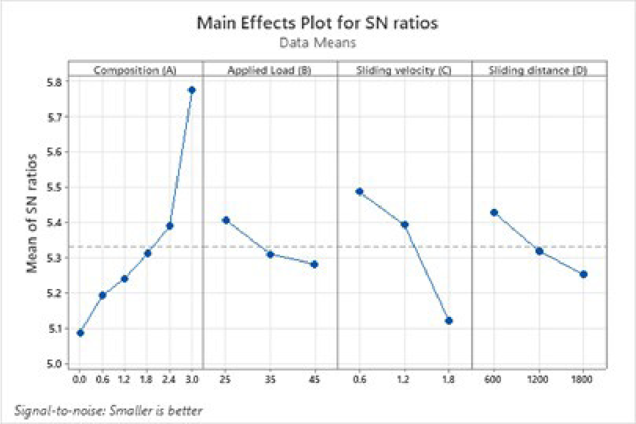

Figure 5: COF main effects plot (S/N ratio).

Table 8: ANOVA results for COF.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
A (%)	5	0.003290	58.27%	0.003290	0.000658	89.06	0.000
B (N)	2	0.000217	3.85%	0.000217	0.000109	14.71	0.005
C (m/s)	2	0.001715	30.38%	0.001715	0.000858	116.08	0.000
D (m)	2	0.000379	6.71%	0.000379	0.000189	25.63	0.001
Error	6	0.000044	0.79%	0.000044	0.000007	-	-
Total	17	0.005646	100.00%	-	-	-	-

Evidence suggests that the composition has a maximal value of 0.688 and a minimal value of 0.125 for the applied load. A, D, C and B have been ranked as the top four parameters for COF, in that order.

The S/N plot of the COF shows the primary influence. Because the area of contact is diminished by the presence of projecting SiC and AlN nanoparticles on the surface of AHMMNCs, the COF is decreased. The harder AHMMNCs may be the reason why increasing the weight % of SiC and AlN reduces COF. In this case, COF is mostly affected by composition. With an increase in load, the COF decreases somewhat (Figure 5).

ANOVA is performed to see how significantly different groups of controls affect COF. The impact of the regulating factors on the COF is displayed in table 8. According to the statistics, composition (contributing 58.27% to performance measure) and sliding speed (30.38% of total) are the two most influencing factors, whereas sliding distance (3.85% of total) and applied load (6.71% of total) are the two least significant variables. At the 95% confidence level, a significant one-way ANOVA has a p value of less than 0.05.

Conclusions

Ultrasonic-assisted stir casting was used to create AA5128/SiC/AlN hybrid MMNCs, and the Taguchi method was used to discover the elements most important to the nanocomposites' desired tribological behaviour. Here are the results of the output.

- Taguchi L18 OA provides $A_1B_3C_3D_3$ as the optimal control parameter condition for least WR.
- The optimal process parameters lead to a minimal COF of $A_1B_3C_3D_3$.
- The composition of the material is the most significant factor in evaluating the WR (81.57%), followed by the applied load (16.29%), the sliding distance (1.72%), and the sliding speed (0.51%). (0.42 %).
- Composition (58.27), sliding speed (30.38), sliding distance (3.85), and applied load (3.90) are the primary determinants of COF (6.71).

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None.

Conflict of Interest

None.

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