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Optimization of Wear Parameters of Al7075 Metal Matrix Composite Reinforced with TiO_2 Nanoparticles Using Taguchi Method

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Abstract

The goal of this study was to describe the results of a Taguchi analysis of the tribological behaviour of a matrix of Al7075 alloy reinforced with 0%, 1%, 2%, and 3% by weight nanoscale titanium dioxide (TiO_2) particles. Wear patterns were studied using a three-dimensional optical microscope. Abrasive and adhesive wear may be seen in images obtained from the optical microscope, and both of these types of wear contributed to the surface's degeneration. Sliding velocities, distances, loads, and percentages of mass were determined using the Taguchi model. The proportion of nano TiO_2 in the material had the greatest impact on the coefficient of friction (38.54%), whereas the normal load had the greatest impact on the wear rate (35.61%).

Keywords

Aluminum 7075 alloy, Wear, Nanocomposites, Taguchi

Introduction

The exceptional qualities of metal matrix composites (MMCs) have led to their replacement of the materialstraditionally used in a variety of structural applications, including the aerospace, defense, sports, and transportation industries. Because of their low weight, increased strength and stiffness, and improved wear resistance capacity, metal matrix composites based on aluminum alloy are given priority. Matrix and reinforcement selection is an important factor to consider while developing specific applications for a variety of domains. A variety of different sorts of particles may be used to strengthen an aluminum alloy, including SiC, TiB_2, Al_2O_3, B_4C, fly ash, and so on [1-5]. The manufacturing technique known as stir casting is usedbecause it is less expensive, more flexible, and simpler to work with. During the stir casting process, the matrix material and the reinforcing particle mixture is combined at a predetermined temperature while the stirring speed is kept constant. It has been shown that the highest possible stirring speed results in the development of oxide and reduces the porosity of the composite [6-9]. Tribological interactions between the exposed surface of a solid surface and the materials with which it interfaces, and the surroundings may result in material being removed from the surface. Wear may be described as the contact between surfaces that ultimately results in the loss of material. Investigations in tribology may be beneficial in a variety of important domains, including the design of bearings and braking systems, for example [10, 11]. The study of tribology and wear is an extremely important component of the production and design processes. Materials with strong tribological characteristics are required for the majority of applications in the automotive and aerospace industries. As a result, there has been an increase in the usage of metal matrixcomposites for these kinds of applications.

The current work focuses on creating nanocomposite by adding 1%, 2%, and

3% TiO_2 by weight to Aluminum 7075 alloy. The composite is then utilized for Taguchi-based wear and frictional investigations.

Materials and Methods

In the present study base alloy matrix Al7075 and nano TiO_2 as reinforcing material has been selected. The average size of reinforcing material is 30 - 50 nm in the form of powders. Chemical compositionof the alloy matrix is shown in table 1.

The principal method used to create the composite is stir casting. In this procedure, the reinforcements arecontinuously stirred into the molten base metal before being sent to the mould to solidify. The ingot was first warmed for three to four hours at around 550 °C. Simultaneously, the preheating furnace warmed thepowder of TiO_2 to 800 - 850 °C. The metal matrix was kept at the same temperature in the furnaceto allow for thorough mixing of the titanium dioxide into the molten aluminum. The stirring mechanism waslowered into the crucible (within the furnace) to the proper depth to enable for 10 minutes of strong automated stirring at 650 rpm, which helped to ensure homogeneous dispersion of the powders throughout the aluminum alloy matrix. The argon gas flow was maintained continuously to prevent oxidation. Once the melt had been successfully incorporated with the particles, it was cast into a cylindrical mould chamber having dimensions of 25 mm x 150 mm. Figure1 shows the stir casting setup used during fabrication of the nanocomposite.

Morphological analysis

The 3D optical microscope was used to analyze the wear behaviour of nanocomposite, in order to identifythe type of wear during tribo-test at different conditions.

Wear analysis

Pin-on-Disc, an instrument was used to examine the friction and wear behaviour of nanocomposites in dry environments, as illustrated in figure 2. The samples were produced in accordance with the ASTMG99 standard. EN31 steel was used to make the counter disc. For the purpose of calculating the wear rate, thespecimen weight was recorded both initially and after each tribo-test. Following each experiment, the counter disc surface was cleaned with acetone to eliminate debris.

The input process parameters used for both nanocomposites were the same. At-room-temperature tribological investigations were conducted. The wear behaviour of nanocomposites was examined using a 3D optical microscope at different loads, speeds, and sliding distances as shown in table 3.

Design of experiment

Using the Taguchi method, experimental data are gathered, and after collection, these data are often transformed into S/N ratios. The process parameters were analyzed using the Minitab 19 software, and an ANOVA test was run in order to evaluate the percentage impact of the control factors. Both of these steps were carried out in order to identify the optimal values for the process parameters. The parameters and the levels associated with them are presented in table 2, and the response of the signal-to-noise ratio is presented in table 3.

The 'Lower is Better' strategy for determining the S/N ratio was used since the primary objective was to produce the lowest possible wear loss and friction coefficient. The S/N ratio may be determined using the following formula:

$$\left(\frac{S}{N}\right) = -10\log\left(\frac{1}{n}\right) * (y_1^2 + y_2^2 + \ldots y_n^2)$$

Where, "n" is total number of observations and $y_1, y_2, y_3 \ldots y_n$ are the response values.

Table 2: Showing the levels at various parameters.

Sl. No.	Factors	Stage 1	Stage 2	Stage 3	Stage 4
1	Speed (m/s)	1	2	3	4
2	Distance (m)	500	1000	1500	2000
3	Normal load (N)	10	20	30	40
4	Wt.% of nano TiO_2	0	1	2	3

Figure 1: Stir casting arrangement.

Table1: Aluminum7075: Its constituent chemicals.

Constituents	Zn	Mg	Cu	Fe	Si	Mn	Cr	Ti	Al
Wt.%	5.8	2.2	1.5	0.42	0.39	0.30	0.26	0.20	Balanced

Figure 2: Pin-on-disc arrangement.

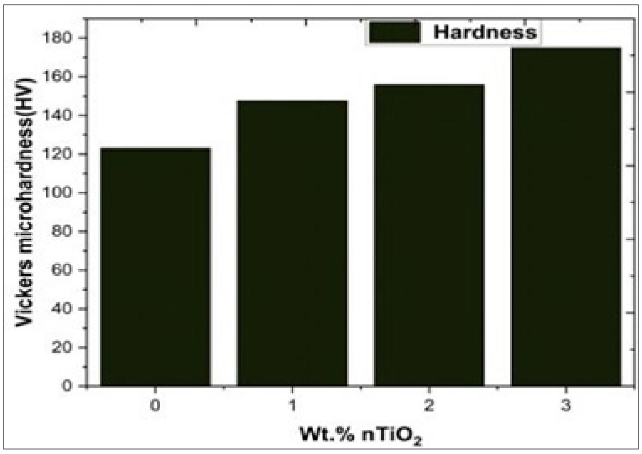

Figure 3: Hardness value of nanocomposite.

Table 4 shows the mean values of the chosen variables, and table 5 shows the component-level S/N ratios. The signal-to-noise ratio (S/N ratio) summarizes numerous iterations and noise levels in a single data point. S/N ratio analysis of variance identifies statistically significant features. ANOVA analysis established the testing parameters' involvement, and Minitab-19 developed mean-response graphs.

Table 4: The lower the signal-to-noise ratio, the better for COF.

Level	Speed	Distance	Load	Wt.%
1	8.798	8.267	8.730	8.041
2	8.454	8.669	8.519	8.585
3	8.316	8.718	8.524	8.473
4	8.356	8.269	8.150	8.825
Delta	0.482	0.582	0.494	0.784
Rank	4	2	3	1

Table 5: The lower the signal-to-noise ratio, the better for wear rate.

Level	Speed	Distance	Load	Wt.%
1	-13.73	-12.41	-11.63	-13.10
2	-13.93	-13.20	-12.23	-14.54
3	-12.64	-12.52	-11.71	-10.92
4	-10.49	-12.65	-15.21	-12.22
Delta	3.44	0.79	3.58	3.62
Rank	2	4	3	1

Results and Discussion

Microhardness

Microhardness as affected by the presence of TiO_2 nanoparticles is seen in figure 3. It has been shown that the addition of hard ceramic nanoparticles (TiO_2) to the base alloy matrix of Al7075 results in an increase in the material's hardness when compared to the base alloy matrix. After reaching a maximum of 3 weight percent (174.95 VHN) in enhanced hardness. This kind of finding may also be connected to improved interactions between the Al7075 matrix and the reinforced TiO_2 nanoparticles, as well as to the Hall-Petch (grain refinement) and Orowan strengthening mechanisms (homogeneous dispersion of ceramic nanoparticles), which limited the distortion during the indentation.

Table 3: Responses on the output side of input parameters according to the L16 orthogonal array.

Sl. No.	Sliding Speed (m/s)	Sliding Distance (m)	Load (N)	Wt. % of nano TiO_2	COF	COF S/N ratio	Wear rate $(mm^3/m) * 10^{-3}$	Wear rate S/N ratio
1	1	500	10	0	0.3814	8.372386226	4.712	-3.46410564
2	1	1000	20	1	0.3458	9.223500221	5.644	-15.0317401
3	1	1500	30	2	0.3522	9.064212967	3.364	-10.53711974
4	1	2000	40	3	0.3745	8.530963559	6.215	-15.86882266
5	2	500	20	2	0.389	8.201007973	3.78	-11.549836
6	2	1000	10	3	0.3456	9.228525324	4.278	-12.6248156
7	2	1500	40	0	0.3974	8.015442745	6.389	-16.10865776
8	2	2000	30	1	0.3815	8.370109154	5.9085	-15.4295448
9	3	500	30	3	0.3722	8.584472624	3.281	-10.32012461
10	3	1000	40	2	0.3915	8.145364672	5.347	-14.56220368
11	3	1500	10	1	0.3615	8.837833967	4.673	-13.39191562
12	3	2000	20	0	0.4123	7.695733304	4.108	-12.2726087
13	4	500	40	1	0.4023	7.908999349	5.189	-14.30167341
14	4	1000	30	0	0.3945	8.079059849	3.378	-10.5731929
15	4	1500	20	3	0.3566	8.956373223	3.18	-10.0485424
16	4	2000	10	2	0.3767	8.480087596	2.25	-7.043650362

Wear analysis

The investigations employed an orthogonal array. This array links load (L), sliding speed (S), sliding distance (D), and weight percent TiO_2 (W). These variables influence composite formation and tribology.

ANOVA investigation

Analysis of variance was the method that was utilized in order to investigate the findings of the experiment (ANOVA). It is possible to make an accurate estimate on the ways in which the various elements affect wear rate and coefficient of friction (COF) independently by examining the data. This may be done in a straightforward manner.

The findings of the ANOVA performed on the coefficient of friction and wear loss for each of the factors that were looked into, as well as the interactions between those factors, are presented in table 6 and table 7, respectively. The observed data were converted into a signal-to-noise ratio so that it could be used as a metric for determining how successfully the process parameters are being implemented. In order to calculate the S/N ratio, it was necessary to conduct an investigation into the influence that the process control parameters had on the frictional coefficient and the rate of wear. According to the signal- to-noise ratio, the friction rate coefficient and the wear rate coefficient are rated differently in table 4 and table 5, respectively, depending on the level of the process parameters. Following sliding speed, sliding distance, and load as the most important factors in determining the friction coefficient and wear rate, the results presented in these tables indicate that the weight percent of nano TiO_2 particles is the most important component in determining these properties. It is obvious from looking at table 6 that the integration of nano TiO_2 has the highest effect on COF (38.54%); hence, this property has to acquire greater focus and study. The sliding distance (21.76%), the usual load (20.82%), and the sliding speed (17.16%) are three more elements that have the potential to influence the COF. According to the findings of an investigation into the impact that various factors have on the rate of wear and tear (Table 7), the typical load is the one that has the greatest impact (35.61%). When compared to the standard load, the sliding speed has a considerable influence that accounts for 30.66% of the total. Sliding distance and typical load affect wear loss the least. The primary effects plot in figure 4a and 4b shows how many test factors affect friction and wear rate. Process parameters have little effect if their lines are very close to the horizontal. A parameter has a greater influence if its line is slanted at an angle greater than ninety degrees to the horizontal. Nano TiO_2 has the greatest influence on COF (Figure 4a), whereas the other components have a smaller effect. Load and sliding speed raise the friction coefficient, however sliding distance and nano TiO_2 weight percent lower it.

Wear rate as affected by various factors is seen in figure 4b. The figure demonstrates that the normal loadhas the steepest slope of all the components, and hence has the greatest impact on the wear rate. It has been shown that increasing the amount of nano-TiO_2 has a slowing impact on wear, whereas increasing the usual load has the opposite effect.

The statistical tools in MINITAB 19 were used to assist in the development of a model for multivariate linearregression. The generated model illustrates how previously unidentified quantities and components are linearly connected to one another in some way.

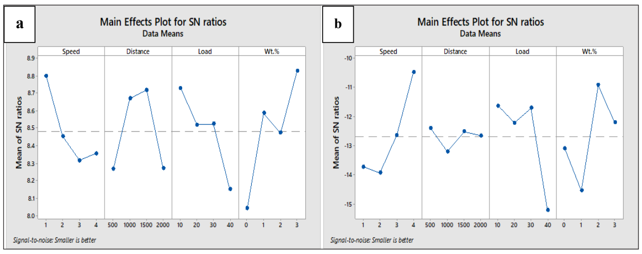

Figure 4: A plot depicting the primary effects of Al7075/nano TiO_2 composites: **(a)** The friction coefficient and **(b)** the amount of wear.

Table 6: ANOVA for the S/N ratio with regard to the COF.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Contribution
Speed	3	0.57579	0.57579	0.19193	10.16	0.044	17.16
Distance	3	0.73017	0.73017	0.24339	12.88	0.032	21.76
Load	3	0.69854	0.69854	0.23285	12.32	0.034	20.82
Wt.%	3	1.29282	1.29282	0.43094	22.80	0.014	38.54
Residual Error	3	0.05670	0.05670	0.01890			1.69
Total	15	3.35402					

Table 7: ANOVA for the S/N ratio with regard to the wear rate.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Contribution
Speed	3	29.761	29.761	9.9204	8.47	0.056	30.66
Distance	3	1.466	1.466	0.4888	0.42	0.754	1.51
Load	3	34.558	34.558	11.5192	9.83	0.046	35.61
Wt.%	3	27.745	27.745	9.2483	7.90	0.062	28.59
Residual Error	3	3.514	3.514	1.1713			3.621
Total	15	97.044					

It was found that the friction coefficient has a linear relationship with the sliding speed (S), the sliding distance (D), the normal load, and the addition of nano TiO_2 (W). The following is the usual linear equation that is used to calculate the frictional coefficient.

$$COF = 0.3580 + 0.00631 * Speed - 0.000012 * Distance + 0.000745 * Load - 0.00979 * Wt.\% \quad (1)$$

$$Wear\ Rate = 4.69 - 0.519 * Speed + 0.000176 * Distance + 0.0523 * Load - 0.289 * Wt.\% \quad (2)$$

From equations 1 and 2, each portion greatly impacts friction coefficient and wear rate. The COF and wear rate reduce with nano sized TiO_2 but increase with normal load. The equations 1 and 2 are the models used to estimate the nanocomposites' COF and wear loss, and the locations in figure 5 and figure 6 are acceptable answers since they are close to the expected line and have low deviation from it.

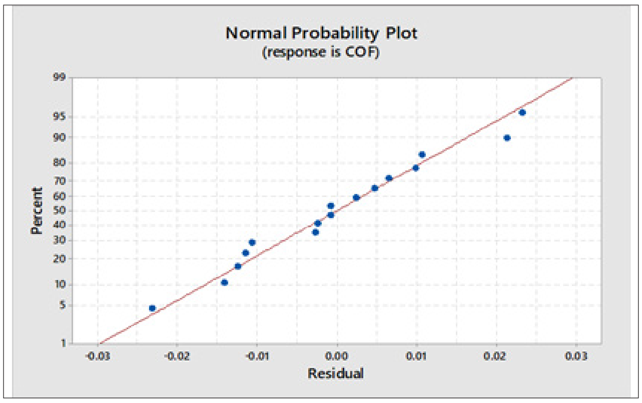

Figure 5: Plots of residuals based on the normal probability, showing the friction coefficient of nanocomposite.

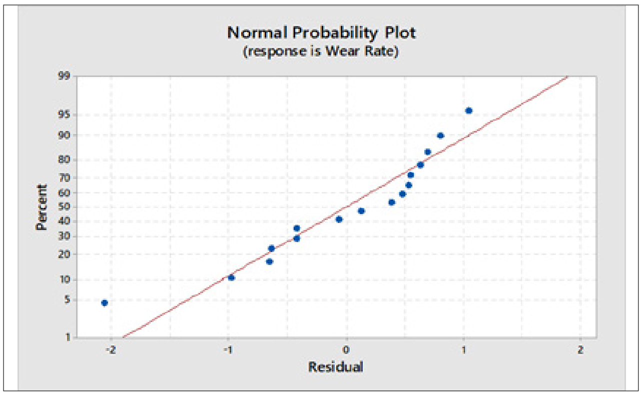

Figure 6: Plots of residuals based on the normal probability, showing the wear rate of nanocomposite.

Wear morphology

Optical microscope images of the nanocomposite's worn surface at optimum sliding speeds, distances, and loads for each weight percent of nano TiO_2 particles are presented in figure 7a - 7d. There are two main types of wear that may be readily identified: abrasive wear (which includes micro-cutting and micro- ploughing) and adhesive wear. Figure 7a shows a micro-cutting specimen that was not strengthened. Because of this, the surface became increasingly scratched and damaged. The increased quantity of micro-cutting is caused by the lack of

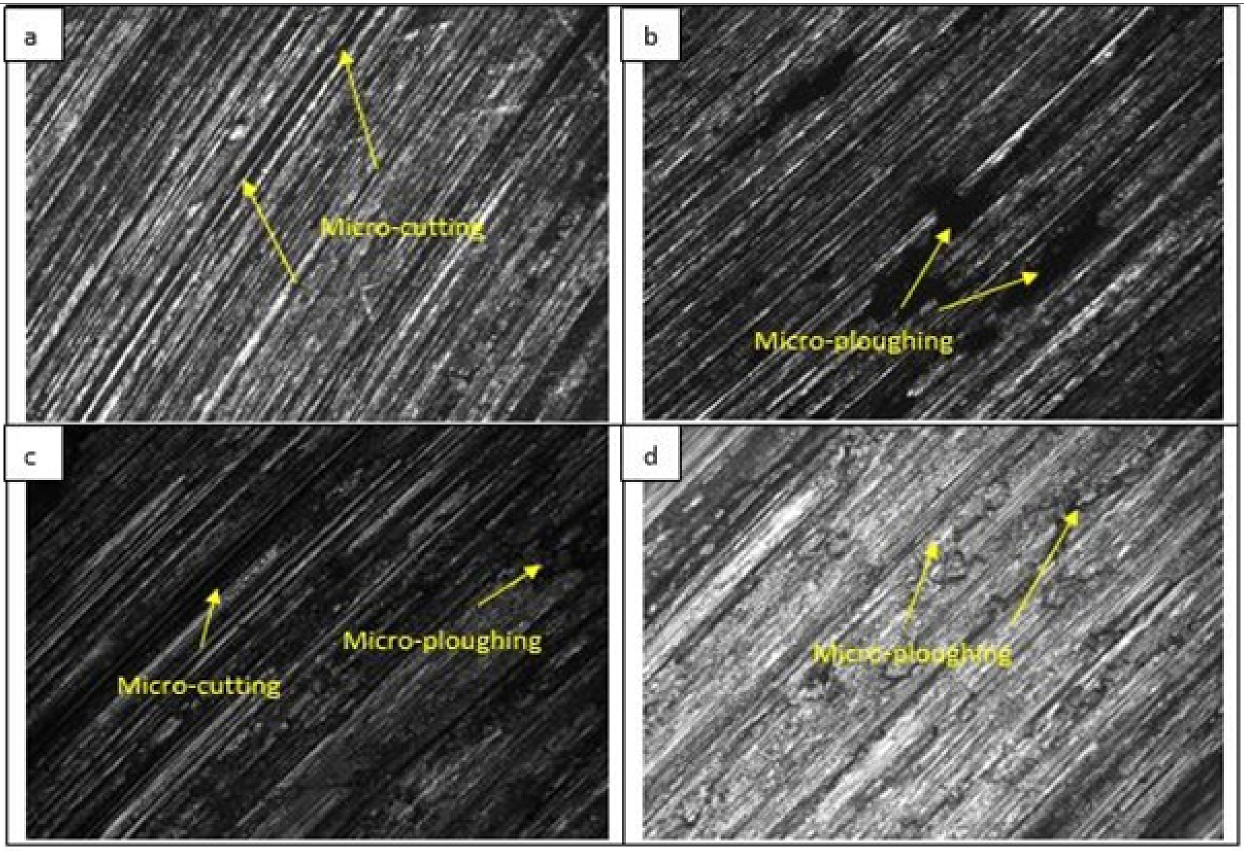

Figure 7: Optical microscope image of worn surface of **(a)** Matrix Al7075, **(b)** 1%/Al7075, **(c)** 2%/Al7075, and **(d)** 3%/Al7075.

any resistive feature or reinforcement that may act as a barrier. Adhesive wear processes can create uneven pits and grooves in the underlying material. On the other hand, as shown in figure 7b, 7c, and 7d, the specimen shows very little wear due to the fact that it has an increasing number of micro-edges and a decreasing number of instances of micro-cutting as the weight percent of nano TiO_2 particles rises. This is due to the fact that the specimen has more micro-edges. The strength of the interaction between nano TiO_2 and Al7075 is what determines the wear resistance of metal matrix composites. TiO_2 is used as a barrier because of its ability to endure large weights, speeds, and sliding distances. Ceramic does not deform plastically as matrix does because of the strong ionic and atomic connections that hold it together.

Conclusions

The investigation of the wear behaviour of stir-cast aluminum metal matrix composites and Al-SiC led to the following conclusions:

- Stir casting was used to successfully create Al7075-SiC nanocomposites with varying amounts of SiC particles as reinforcement.
- Weight percent of nanoparticle and normal load has the most significant impact on the COF and wear rate.
- The ideal conditions for the COF were achieved at a sliding speed of 2 m per sec, a distance of 1000 m, a normal load of 10 newtons, and 3 weight percent of TiO_2. However, the ideal conditions for wear rate were reached at a sliding speed of 4 m per second, a distance of 2000 m,a typical load of 10 newtons, and a concentration of 2 weight percent TiO_2.
- Optical microscope study revealed that the main reason of wear was micro-cutting and micro- ploughing.

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None.

Conflict of Interest

There is no conflict of interest.

Credit Author Statement

Nikhil Bharat: Conception, Design, Study; Rajat Jain and B. Rangilal: Manuscript - original draft preparation, Writing - review and editing; P.S.C. Bose: Analysis, Interpretation. All the authors read and approved the manuscript.

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