Morphological characterization, statistical modelling and tribological behaviour of aluminum hybrid nanocomposites reinforced with micro-nano-silicon carbide

Sajjad Arif, Tanwir Alam, Akhter H. Ansari and Mohd Bilal Naim Shaikh

Powder Metallurgy Laboratory, Department of Mechanical Engineering, Zakir Husain College of Engineering and Technology, AMU, Aligarh, India

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1. Introduction

Demand for high-performance composite materials to resist harsh engineering environments has been exponentially rising. Extensive research has therefore been directed toward development of aluminum matrix composites (AMCs) due to their high specific strength, stiffness, good wear resistance, superior thermal conductivity and lower thermal expansion [1,2]. These exceptional properties of AMCs have provided a major focus for the production of various parts in the aerospace, defense and automotive industries [3,4]. Apart from these superior properties, the enhancement in wear behavior of AMCs has attracted great attention in the field of tribology. Material loss due to wear in many engineering applications is the most commonly encountered phenomenon creating a need for replacement of parts and assemblies in working plants. Operating economies are also severely impacted by wear for the following reasons: (a) loss of materials, (b) high fuel usage, and (c) frequent replacement of engineering components. Thus, an appropriate assessment of the tribological behavior of AMCs is essential.

In this context, both the tribological and mechanical behavior of aluminum matrix composites have been improved by reinforcing various hard ceramic particles such as SiC [5], B4C [6], Al2O3 [7] and TiC [8] etc. Amongst these, SiC ceramic particles are the most widely used due to the density of SiC, which is comparable to that of aluminum. SiC offers various outstanding features, moreover including high hardness, high wear resistance and fair thermal stability. In addition, SiC does not react with aluminum at low temperatures, thus preventing unwanted brittle reactions at the interfaces [9,10].

In tribological applications, micro- and nanoparticle-reinforced aluminum matrix composites have been explored increasingly for the following reasons: (a) their soft aluminum matrix skeleton is supported by microparticles [11,12]; (b) nanoparticle addition controls the loss of fracture toughness and ductility, thus preventing catastrophic failure during service [13]; (c) the overall performance of the composites can be enhanced by uniform distribution of nanoparticles due to the Orowan strengthening mechanism; (d) when the reinforcement size is reduced from micro to nano, enhanced microstructure and mechanical behavior can be obtained [14]; and (e) nanoparticles also enhance mechanical properties by encouraging development of fine grain structures and obstructing dislocation movement. The composite lose their ductility at relatively high nanoparticle concentrations however, cracks occur under load bearing. Enhancement of the tribological behavior can therefore be accomplished through the combined effects of reinforcing both the micro- and nanoceramic particles in the soft aluminum matrix.
Amongst the numerous synthesis techniques for aluminum matrix composites, powder metallurgy is the preferential option because it’s low processing temperature which restricts the propagation of interface reactions [9,10]. Furthermore, uniform distribution of reinforcements in the matrix and development of almost net-shaped products are added advantages of the powder metallurgy technique. Assessment of the tribological behavior of composites is a complex process, however, because it depends upon various factors such as reinforcement [15] (volume fraction, size, shape and characteristics), sliding distance [16], sliding speed [17] and applied load [18]. Therefore, scientific assessment of the tribological behavior of AMCs using a statistical technique is very important for reducing time and cost.

An exhaustive review of literature reveals, moreover that use of a statistical approach is severely limited in analyzing the tribology behavior of aluminum matrix nanocomposites. Therefore, the present work has the following objectives: (a) to investigate the effect of nano-silicon carbide addition, sliding distance and the applied load using a full factorial experimental design; (b) to analyze the wear phenomena using both SEM and EDS techniques; (c) to develop models to estimate the tribological behavior of aluminum matrix composites fabricated using the powder metallurgy technique; and (d) to determine the best model for prediction of wear loss using statistical analysis.

### 2. Materials and methods

Aluminum with an average particle size of 10 μm was purchased from Otto Chemicals Ltd, Mumbai, India. The size of the SiC particles was 37 μm and 50 nm, respectively. SEM images of the as received powders are shown in Figure 1(a–c). For the investigation, five combinations of powders (Al+10% SiC₃µm, Al+10% SiC₃µm+1% SiC₅nm, Al+10% SiC₃µm+3% SiC₅nm, Al+10% SiC₃µm+5% SiC₅nm, Al+10% SiC₃µm+7% SiC₅nm) were thoroughly mixed in a centrifugal ball mill (FRITSCH, Germany) at a rotation speed and ball-to-powder ratio of 125 rpm and 10:1, respectively, to prepare a homogeneous mixture. The mixed powders were compressed in a uniaxial hydraulic machine to prepare green samples. Green pellets with dimensions of 8 mm and height 13 mm were fabricated at 585 MPa compaction pressure. The die and plungers were cleaned and lubricated with acetone and zinc stearate, respectively, to prevent jamming and allow easy removal of the pellets. The samples were then sintered at 450°C in an electric tubular furnace for 1 hour. The sintering was performed under a constant flow of argon gas (flow rate = 1 litre/min.) to safeguard the composites from oxidation [19]. A dry sliding wear test of the specimens was performed with pin-on-disc equipment (Ducom, Model No: TR-201 CL, Bangalore, India) built according to the full factorial design shown in Table 1. Prior to each experiment, the specimens were polished and cleaned thoroughly with acetone to remove adhering wear debris. The weight of the specimens was noted before and after the test using an electronic balance with an accuracy of 0.1 mg. For every set of experimental condition, the test was performed three times and the average value was considered to be the wear loss.

### 2.1. Experimental plan

The experiments in the investigation, were conducted according to a full factorial design [20]. Three factors were chosen, of which one had five levels, while the other two have three and two levels respectively. The
Table 1. Full factorial design (5 × 3 × 2) of the experiments and their respective results.

| Control factors | Unit | Level I | Level II | Level III | Level IV | Level V |
|-----------------|------|---------|----------|-----------|----------|---------|
| Sliding distance (B) | m | 300 | 600 | 900 | – | – |
| Applied load (C) | N | 20 | 40 | – | – | – |
| SIC reinforcements (A) | wt. % | 0 | 1 | 3 | 5 | 7 |

Table 2. Multilevel factorial design of experiments.

| S. No. | SIC concentration (wt. %) | Sliding distance (m) | Applied load (N) | Wear loss (mg) |
|--------|--------------------------|----------------------|------------------|----------------|
| 1      | 0                        | 300                  | 20               | 3.0            |
| 2      | 0                        | 300                  | 40               | 4.7            |
| 3      | 0                        | 600                  | 20               | 4.1            |
| 4      | 0                        | 600                  | 40               | 5.3            |
| 5      | 0                        | 900                  | 20               | 5.6            |
| 6      | 0                        | 900                  | 40               | 5.9            |
| 7      | 1                        | 300                  | 20               | 2.7            |
| 8      | 1                        | 300                  | 40               | 3.5            |
| 9      | 1                        | 600                  | 20               | 2.7            |
| 10     | 1                        | 600                  | 40               | 4.2            |
| 11     | 1                        | 900                  | 20               | 4.2            |
| 12     | 1                        | 900                  | 40               | 5.1            |
| 13     | 3                        | 300                  | 20               | 1.8            |
| 14     | 3                        | 300                  | 40               | 3.1            |
| 15     | 3                        | 600                  | 20               | 2.3            |
| 16     | 3                        | 600                  | 40               | 3.6            |
| 17     | 3                        | 900                  | 20               | 4.3            |
| 18     | 3                        | 900                  | 40               | 4.5            |
| 19     | 5                        | 300                  | 20               | 1.1            |
| 20     | 5                        | 300                  | 40               | 1.7            |
| 21     | 5                        | 600                  | 20               | 1.6            |
| 22     | 5                        | 600                  | 40               | 2.5            |
| 23     | 5                        | 900                  | 20               | 3.5            |
| 24     | 5                        | 900                  | 40               | 3.9            |
| 25     | 7                        | 300                  | 20               | 1.3            |
| 26     | 7                        | 300                  | 40               | 2.1            |
| 27     | 7                        | 600                  | 20               | 1.7            |
| 28     | 7                        | 600                  | 40               | 3.1            |
| 29     | 7                        | 900                  | 20               | 3.7            |
| 30     | 7                        | 900                  | 40               | 4.1            |

concentration of nano-silicon carbide, sliding distance and applied load were the three independent factors. Table 1 shows the magnitude and different levels of each independent variable. Full factorial design founds an immense range of application in the early stages of experimental work, particularly when the number of independent variables is less than or equal to 4. The present full factorial design consists of 30 rows and 3 columns, as shown in Table 2.

3. Results and discussion

3.1. Microstructural characterization

Figure 2 depicts the microstructures of developed Al-based nanocomposites. It can be observed that from Figure 2(a–d) that SiCu and SiCn particles were fairly and uniformly distributed across the micrograph. This concludes the authentication of the powder-processing route for the preparation of composites. Further addition of SiCu particles causes formation of porosity due to differences in the geometrical, mechanical and thermal behavior of the SiC and Al particles. Incorporation of nano-SiC particles fills the empty spaces and reduce porosity at the lower level, while a higher level of nano-SiC particle incorporation increases the porosity due to clustering and agglomeration of particles, as shown in Figure 2(d).

An X-ray diffractometer was used to identify the reinforced particles and phases present in the sintered composites. XRD patterns of fabricated composites with varying amounts of nano-silicon carbide are shown in Figure 3. From the XRD plot the presence of aluminum and SiC are confirmed by their respective peaks. Aluminum shows the highest peak, followed by SiC. The peak intensities of SiC are distinctly visible, moreover, they increase with increases in the SiC content. These findings are in line with previous research results [9,10]. No new peak appeared in any XRD pattern, indicating that no new phase formation occurred during the sintering process. It can therefore be recognized that the fabricated samples are reinforced with SiC. DIFFRAC® plus software, (Bruker AXS inc.) was used for the calculations.

The energy dispersive spectroscopy (EDS) analysis and microstructure of Al+10%SiC+5%SiCn nanocomposites are shown in Figure 4. The peaks of Al, Si, C and O elements are evident from the EDS study and are shown in Figure 4. Similar results have been reported by a previous researcher [13]. Furthermore, Table 3 displays the elements present in Al+10%SiC+5%SiCn nanocomposites with their weight and atomic percentages. Hence, evidence of zirconia and graphite particles is again confirmed for the synthesized nanocomposites.

Figure 5 displays the elemental mapping of Al+10% SiC+5%SiCn-reinforced nanocomposites. The elemental mapping confirms the presence of silicon carbide along with its even distribution in the aluminum matrix.

3.2. Porosity and hardness measurements

Figure 6 displays the percentage porosity and hardness of all the fabricated composites with respect to nano-SiC addition. It was found that as micro-SiC particles are added to the aluminum matrix, the porosity of a composite increases. The sharp escalation in porosity seen here is attributed to the following: (a) hard SiC particles do not flatten in the compaction process, which leads to the development of porosity, and (b) densification is also hindered by the SiC particles as it causes immense friction with the die wall. This finding is in line with the previously reported results [21]. The addition of nano-SiC particles reduces the porosity up to 3 wt. %, however, because the available micro-porosities are filled by nanoparticles [22]. Incremental increase in nanoparticles drastically expand the porosity for the following reasons: (a) the nanoparticles cluster and agglomerate at
high concentrations, and (b) the dense, random distribution and high melting point of silicon carbide particles hinder effective sintering operation [14].

The variations in the hardness of all fabricated composites are plotted in Figure 6. The hardness of pure aluminum is 28.86, which reaches 47 when reinforced with 10 wt. % of SiC microparticles. The rapid escalation in hardness is because of the hard nature of SiC particles. Furthermore, the addition of nano-SiC particles to aluminum increases the hardness of the
composites by up to 3 wt. %. The uniform distribution, reduced porosity and enhanced dislocation caused by the hard ceramic particles and good interfacial bonding between the reinforcing particles and aluminum are the underlying reasons for the remarkable enhancement in hardness. These results are in accordance with the findings of previous research [13,14]. However, further addition of nanoparticles causes the hardness decline due to increased porosity and the clustering of nanoparticles [23].

### 3.3. Analysis of variance (ANOVA)

The experiments were performed according to the full factorial experimental design and their corresponding wear values are recorded in Table 2.

\[
R - S_0 = 99.26\% R - S_0(\text{adj}) = 97.32\% 
\]

Analysis of variance is a statistical tool which is used to find out the influence of independent variables (SiC

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**Table 3.** Elements present in Al+10% SiC+5% SiC nanocomposites.

| Elements | Weight% | Atomic% |
|----------|---------|---------|
| C        | 25.22   | 15.81   |
| O        | 1.04    | 0.62    |
| Al       | 57.82   | 61.13   |
| Si       | 15.93   | 22.44   |
| Total    | 100     | 100     |

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**Figure 4.** EDS of Al+10%SiC$_{\mu m}$+5%SiC$_{nm}$ nanocomposites.

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**Figure 5.** Elemental mapping of Al+10%SiC$_{\mu m}$+5%SiC$_{nm}$ nanocomposites.
reinforcement, sliding distance and applied load) and their percentage contributions to the experimental results (wear loss). ANOVA calculations were performed using MINITAB-17 software. This analysis was undertaken for a level of significance of 5%. Analysis of variance finds the F-ratio, which gives the level of significance of independent variables by considering the variance of all the terms included in the error terms at the desired significance level. Table 3 provides the ANOVA results for the wear loss of all the composites. The percentage contribution of each independent factor is also incorporated in the last column of Table 4. Table 4 clearly shows that the concentration of nano-silicon carbide (42.4%) and the sliding distance (42.3%) make the largest contribution to the wear loss, while the applied load contributes only 11.3% to the wear loss, which is considerably less. The contribution of interactions among these parameters shows even less significance. The main influences on the interaction are the sliding distance and applied load, however which is 2.3%, whereas the other interactions respectively sliding distance and concentrations as well as load and concentrations contribute only 0.5 and 0.1% respectively, which are insignificant as suggested by the p-value. Thus, the investigation revealed that the selected independent variables (silicon carbide reinforcement, sliding distance and applied load) and their respective interactions have statistical and physical significance for the wear behavior of fabricated hybrid composites [24, 25].

3.4. Effects of different process parameters on wear loss

The effect of each independent variable on wear behavior can be analyzed with the help of the main effect plot and interaction plot. Figure 7 shows the main effect plot; it depicts the effect of different process parameters on wear loss. If the line of any process parameter in the main effect plot has a low variation with respect to the mean value, it is interpreted that the given process parameter has no significant effect [26]. On the other hand, if the plot of any process parameter has a higher slope with respect to the mean value, it is recognized as proving significant effect. Thus, it is evident from the main effect plot that the SiC concentration is the most influential parameter, followed by the sliding distance and applied load.

The SiC concentration is clearly the most significant parameter for the wear behavior of nanocomposites. The wear resistance of developed composites increases for the following reasons: (a) nanoparticles impart greater hardness to composites leading to a reduction in abrasion phenomena [9]; (b) the plastic flow is also hindered

![Figure 6. Variations in porosity and hardness with respect to silicon carbide addition.](image)

| Source                     | DF | Seq SS | Adj SS | Adj MS | F       | P    | Pr   |
|----------------------------|----|--------|--------|--------|---------|------|------|
| SiC concentration (wt. %)  | 4  | 21.77  | 21.77  | 5.4    | 114.79  | 0.000| 42.4 |
| Sliding distance (m)       | 2  | 21.68  | 21.68  | 10.85  | 228.8   | 0.000| 42.3 |
| Applied load (N)           | 1  | 5.8    | 5.8    | 5.80   | 122.49  | 0.000| 11.3 |
| SiC concentration (wt. %)* | 8  | 0.34   | 0.34   | 0.043  | 0.92    | 0.546| 0.5  |
| Sliding distance (m)*      | 4  | 0.148  | 0.148  | 0.0372 | 0.78    | 0.566| 0.1  |
| Applied load (N)*         | 2  | 1.154  | 1.154  | 0.5770 | 12.17   | 0.004| 2.3  |
| Error                      | 8  | 0.379  | 0.379  | 0.0474 | 0.7     |      |      |
| Total                      | 29 | 51.30  |        |        |         |      |      |
by hard nanoparticles in a sliding environment [13]; and (c) nanoparticles support a greater sliding load due to an increase in the ratio of hard and soft contact areas of exposure resulting from the raised concentration of nanoparticles. Several reported results have suggested that the addition of nanoparticles improves the wear behavior of composites for the reasons discussed above. In the present study, however, increases in SiC content up to 5 wt. % resulted in a sharp deterioration of wear resistance, which is in line with previously reported results [13]. This observed trend can be attributed to the following reasons: (a) increased in porosity due to a clustering and agglomeration of nanoparticles at high concentrations [23], and (b) proliferation of numbers of nanoparticles restricting proper sintering operation [5].

The sliding distance is the second most significant factor affecting the wear behavior of nanocomposites. Wear loss increases with increases in the sliding distance for all the fabricated composites. These results are in accordance with previously reported findings [13]. Thermal softening phenomena and an unstable protective oxide layer in the high sliding distance range are the major reasons for the gross material loss from the mating surface [16,17]. Further, the trend observed with lengthening of the sliding distance satisfies the pattern suggested by the Archard wear equation. The applied load makes only an 11.3% contribution, as suggested by ANOVA analysis, on the wear behavior of nanocomposites. The loss in wear resistance due to increases in the applied load are as follows: (a) delamination is greater at high loads, and (b) interfacial bonds weaken at high loads due to frictional heat generated.

The influence of silicon carbide reinforcement, the sliding distance, the applied load and their respective interactions can be interpreted from the interaction plot shown in Figure 8. The ANOVA results suggest that the interaction of the sliding distance and applied load is also significant. Other interactions (SiC concentration × sliding distance and SiC concentration × applied load) are not statistically significant, however, because the lines do not intersect with each other or else tend to intersect only when extended further. Hence, appropriate discussion of every factor comprising the main effect plot is difficult without considering the interaction plot. The interaction plot indicates that the material loss due to wear is minimal when the composites are subjected to a 20 N load for a sliding distance of 300m. Similarly, inferences can be drawn for composites subjected to a given sliding wear environment: 600m sliding distance and 40N applied load. However, there is very little variation in the wear loss of composites when they are tested at a 900m sliding distance for both applied loads. This is evident from the interaction plot, because the above-tested condition line has the lowest slope.

3.5. Investigation of wear mechanisms by SEM
To analyze the wear mechanisms, SEM was performed on all the synthesized nanocomposites and aluminum, as displayed in Figure 9(a–f). The worn surface morph graphs of composites reinforced with nanoparticles exhibit dissimilar wear profiles when matched to the unreinforced aluminum matrix. This verifies the variations in wear mechanisms. A large number of craters, pits and grooves were observed on pure aluminum surfaces as shown in Figure 9(a). Severe plastic deformation also occurred on the aluminum surfaces due to the generation of frictional heat, escalating wear loss in comparison to other micro and nanocomposites [27]. The existence of severe delamination on the worn surfaces of pure aluminum was confirmed by the SEM micrographs.

Figure 9(b) shows the presence of micro pits and permanent grooves on the worn surface of an Al-10%
SiC composite. Addition of silicon carbide particles diminishes the wear loss on composites due to increased hardness. The decline in wear loss also results from reduced adhesion of the matrix material to the counter disc due to the presence of silicon carbide particles [28]. Figure 9(c–f) exhibit the worn morphologies of composites reinforced with nanoparticles. At 1 wt. % SiC nanoparticle addition, the morph graph in Figure 9(c) displays obvious signs of grooves and shallower scratches that confirm material loss due to abrasion [29]. The rise in frictional heat, cyclic stress and nano silicon carbide is responsible for the development of aluminum and iron oxides along with fragmented silicon carbide particles on the mating surfaces. The existence of aluminum and iron oxides and fragmented silicon carbide particles together is known as a mechanically mixed layer (MML) as shown in Figure 9(d). Further, the EDS spectrum in Figure 9(e) validates the existence of MML in the area surrounding Figure 9(d). MML’s hard nature, acts as a solid lubricant, inhibiting direct metallic interactions and resulting in a reduction of wear loss [13]. A worn surface of composite containing 5 wt. % SiC nanoparticles is displayed in Figure 9(f). The surface appears to be even and the grooves to be largely controlled, as suggested by the SEM micrographs. A homogeneous distribution of micro- and nanoparticles, enhanced hardness and the presence of MML on the mating surfaces are the major reasons for the enhanced wear resistance [8].

The worn surface of an Al+10% SiC_{μ}m+7%SiC_{nm} nanocomposite is shown in Figure 9(g). The morph graphs reveal that reinforced particles are debonded/ pulled out from the aluminum matrix, thus reducing wear resistance. A proper sintering operation is hindered by the clustering and agglomeration of nanoparticles at high concentrations [21]. The escalated porosity, reduced hardness and the poor interfacial bonds between aluminum and silicon carbide particles are principally responsible, moreover, for the sudden drop in wear resistance.

### 3.6. Wear debris analysis

The mechanisms of wear were also studied by conducting SEM on the debris. The fragmented particles micrographs obtained from wear tests on all the fabricated composites and nanocomposites are presented in Figure 10(a–f). Figure 10(a) displays the wear debris of aluminum, which occurs in the form of thin sheets/elongated debris. These sheets/elongated debris are a clear indication of severe plastic deformation. Thus, loss from the pure aluminum matrix in a sliding environment is due to delamination mode of wear. These findings are in line with previously reported studies [20,24]. The wear debris of Al-10%SiC composites is shown in Figure 10(b), which contains adhering particles and thin fragments. The wear debris micrographs exhibit the presence of delamination and a mild abrasive wear mechanism. This evidence of the wear mechanism is demonstrated by the presence of a combination of thin sheets and fine particles in the collected debris. With the increase in nano-SiC shown in Figure 10(c), moreover, the mode of wear changes from abrasion to adhesion. This is confirmed by the presence of large wear debris with
irregular shapes and sizes. Similar observations were made in previous studies [30]. The wear debris of Al +10% SiC$_{\mu m}$+3%SiC$_{\text{nano}}$ nanocomposites is shown in Figure 10(d). SEM micrographs show that as the quantity of SiC nanoparticles is raised from 1 to 3 wt. %, the size of the wear debris collected declines. Furthermore, clusters of particles are evident due to the effect of micromachining while in the sliding environment. Indications of loose fragments of oxide debris reveal that fretting wear is also operative along
with abrasion. This is due to cyclic stress developed during sliding of the mating surfaces. Figure 10(e) shows the wear debris of nanocomposites containing 5 wt. % SiC nanoparticles. Addition of SiC nanoparticles imparts extreme hardness to the composites and enhances in wear resistance. The micrographs indicate that the debris consists of fine particles of uniform size. Furthermore, the decrease in the debris size may due to the following factors: (a) enhanced hardness imparted by nanoparticles, (b) a reduction in porosity, and (c) development of a mechanically mixed protective layer. The presence of shallow scratches and rows of furrows on the worn surface, moreover, indicates the existence of adhesive wear loss by the composite containing 5 wt. % silicon carbide nanoparticles. These findings are in line with previously reported results [30]. Figure 10(f) shows the wear debris of the nanocomposites containing the highest amount of silicon carbide nanoparticles. The wear debris consists of a combination of a large number of coarse particles (large strip debris) with irregular shapes, confirming the occurrence of severe delamination. Hence, it can be concluded that the concentration of silicon carbide nanoparticles dictates the size and morphology of the wear debris. The modes of wear identified through the SEM micrographs of wear debris of corresponding composites are summarized in Table 5 which sums up the wear mechanisms identified for the corresponding material.

The EDS of Al+10%SiC_{μm}+5%SiC_{nm} and Al+10% SiC_{μm}+7%SiC_{nm} nanocomposite wear debris are shown in Figure 11(a–b). The high intensity of Si and low intensity of Al validates the smearing of silicon carbide particles from the sample while in a sliding environment. Peaks of Fe are also evident in both the EDS spectrum, moreover, because hard SiC particles abrade the counter disc material. In both the EDS results, the peak of oxygen is also observed because
of the development of aluminum and iron oxides due to the combined effects of frictional heat and environmental reactions [20].

3.7. Mathematical modeling and statistical analysis of models

Linear regression models were developed using MINITAB 17 statistical software for predicting wear loss. The regression models described the relationship between the independent variables and output values by fitting linear and quadratic equations [20, 25]. The statistical analysis revealed that wear loss is dependent on the three independent variables SiC reinforcement, sliding distance and applied load. The standard Archard wear equation [31] suggests that the wear loss is directly proportional to the sliding distance and external load. However, it does not include the reinforced particle factors in any metal matrix composites. The interaction of these factors is also difficult to calculate. To engage this complex tribological phenomenon, a number of efforts have been directed to empirically modeling wear behavior in terms of independent factors and their interactions [20, 25]. In line with this, different empirical correlations have been developed in the current approach to highlight the significance of the input variables and their interactions on the wear behavior of aluminum nanocomposites within the range under consideration. In addition, only those factors and interactions are considered which are significant on the basis of ANOVA analysis (as depicted in Table 4), namely, the SiC concentration, sliding distance, applied load and their interactions. The analysis comprises the development of five different predictive models, of which one was linear and four were quadratic in nature.

The models for the prediction of wear loss is given below:

**Model 1**

\[
W_{\text{loss}} = 0.113902 - 0.30122 \times A + 3.38333 \times 10^{-3} B + 0.088 \times C
\]

Model 2

\[
W_{\text{loss}} = -1.6361 - 0.30 \times A + 0.0063 \times B + 0.158 \times C - 1.16667 \times 10^{-4} BC
\]

**Model 3**

\[
W_{\text{loss}} = 0.46 - 0.750 \times A + 3.3 \times 10^{-3} B + 0.088 \times C + 0.064 \times A^2
\]

**Model 4**

\[
W_{\text{loss}} = 1.46 - 0.30 \times A - 0.002 \times B + 0.088 \times C + 4.5 \times 10^{-6} \times B^2
\]

**Model 5**

\[
W_{\text{loss}} = 0.062 - 0.75 \times A + 0.0009 \times B + 0.158 \times C + 0.065 \times A^2 + 4.5 \times 10^{-6} B^3 - 1.16667 \times 10^{-4} BC
\]

By applying Equations (1–5), the wear loss of all the fabricated composites was estimated for all 30 sets of experiments. The experimental wear loss and the predicted values for the all models are plotted in Figure 12. The predicted wear loss for the models and the experimental data are very close to each other. A further validation of the predicted and experimental values is shown in Figure 13 by scatter diagram.

3.8. Statistical analysis of regression models

The five most commonly used statistical indicators were adopted to perform statistical analysis of developed regression models. The mathematical equations of these indicators are given below:

![Figure 11. EDS charts of wear debris: (a) 5 wt. % SiC\text{nano} and (b) 7 wt. % SiC\text{nano} reinforced Al composites.](image-url)
The results for all the statistical indicators [Equations (6–10)] of developed regression models are shown in Table 6. The significant value of each statistical indicator shown in bold in Table 6. The value of MBE lies in the range of $-9.20E-10$ to $-4.00E-09$, which is displayed with a minus sign, indicating the underestimation of the data. However, the overall value of MBE for all the models is significantly small and close to zero. Finally, model 3 exhibits a significant value for MBE (the closest to zero). The RMSE values for all the models are found to be small with the least value of 0.000272 for Model 5. The range of MAPE values is shown to be 7.9045% to 14.8269%, with Model 5 demonstrating the least value. The correlation coefficient ($R$) for all the models lies in the range of 0.9289–0.9932 which validates a good data fitting. The highest value of $R$ is observed for Model 2. The values of MAE are seen in the range from 0.00022535 to 0.00040356, with the lowest observed for Model 5.

Among all the models developed, the MBE value of Model 1 is lowest. The coefficient of determination of Model 2 is lowest, while the RMSE, MAPE and MAE of Model 5 are the lowest among all the regression analyzes developed. This indicates satisfactory performance by all the models as compared to the experimental data. However, the best model among all of them is still not determined because not all the statistical errors favor any one specific regression model. For this reason, further analysis of the models developed is presented in the following section.

3.9. Ranking of models by the global performance indicator (GPI)

It is interesting to see that all the statistical indicators show different patterns and hence fail to identify the best predictive model. This difficulty can be overcome further improvement of the results of statistical analysis using the Global Performance Indicator (GPI).

The Global Performance Indicator is a useful technique developed by Despotovic et al. [32] that accumulates the effects of all the individual statistical indicators. With this technique, all the statistical indicators are scaled down in such a way that all the
values fall between zero and one [33]. The scaled-down values are then deducted from their corresponding medians, respectively. Finally, all the calculated values with the appropriate weight factors are added together. The mathematical equation of GPI for i model can be defined as follows:

$$GPI_i = \sum_{k=1}^{5} \alpha_k (\bar{y}_k - \tilde{y}_{ik})$$

where, $\alpha_k$ equals $-1$ for the indicator R only, while remaining indicator, its recommended value is 1. $\bar{y}_k$ represents the median of scaled values of indicator k, $\tilde{y}_{ik}$ is the scaled value of indicator k for model i. The model achieving the highest GPI value is the most accurate model.

The scaled values (from 0 to 1) of all the statistical indicators along with their corresponding GPI and the resultant rankings for all the models developed are tabulated in Table 7. The GPI values lie between $-1.2120$ and $2.3204$. The maximum GPI is found to be $2.3204$ for...
Model 5, which consists of all the independent terms viz. the silicon carbide concentrations, sliding distance, applied load and their interactions between sliding distance and applied load, as was previously suggested by the ANOVA analysis (depicted in Table 4). Among all the models, the top performer is Model 5. Therefore, this model can be used to estimate the wear loss for aluminum matrix nanocomposites with a high level of accuracy within the range selected for the investigations.

4. Conclusions

In this investigation, a full factorial design has been successfully implemented and described to comprehend the tribological behavior of aluminum hybrid nanocomposites. The major conclusions are described below:

(i) Addition of SiC nanoparticles reduced porosity and enhanced hardness. Nanocomposites reinforced with 5 wt. % SiC nanoparticles showed superior hardness to all the other fabricated nanocomposites.

(ii) Increases in the sliding distance and applied load lead to increases in the wear loss of the composites. The addition of SiC nanoparticles reduces wear loss which reaches the minimum at 5 wt. %. Further addition of SiC increases wear loss due to a sudden rise in porosity.

(iii) The most significant factors influencing wear behavior were deduced based on ANOVA to be the silicon carbide concentration (42.4%), sliding distance (42.3%) and applied load (11.3%), together with the interaction effect of the sliding distance and applied load (2.3%), within the selected span of interest.

(iv) SEM images of worn surfaces show that delamination and abrasion are the dominant wear mechanisms. EDS analysis confirmed the formation of mechanically mixed layer (MML) at the mating surfaces, which were responsible for enhanced wear resistance.

(v) Five different regression models were developed using MINITAB 17 software to estimate the wear loss as a function of silicon carbide concentration, sliding distance and applied load.

(vi) For the models under consideration, the GPI was found to be in the range from $-1.2120$ to $2.3204$. The GPI of model 5 was highest indicating this as estimating the wear loss.

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Nomenclature

Abbreviations

ANOVA Analysis of variance
GPI Global Performance Indicator
MML Mechanically mixed layer
MAE Mean absolute error
MAPE Mean absolute percentage error
MBE Mean bias error
RMSE Root mean square error

Latin Symbols

$R$ Correlation coefficient
$W_{\text{loss}}(i, \text{exp})$ Experimental wear loss (g)
$W_{\text{loss}}(i, \text{model})$ Predicted wear loss (g)
$W_{\text{loss}}(i, \text{avg.})$ Average wear loss (g)

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Sajjad Arif http://orcid.org/0000-0002-3177-5883
Tanwir Alam http://orcid.org/0000-0002-5311-6379

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