A comprehensive analysis to assess the impact of nano MoS$_2$ on the wear characteristic of Al-TiB$_2$-Gr composite

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Abstract
The present study evaluates the influence of nano MoS$_2$ particles on the wear properties of newly developed TiB$_2$ and Graphite reinforced Aluminium composite. Micro particles of MoS$_2$ are downsized into nano levels using a planetary ball mill. Three different compositions of specimens are fabricated through stir casting, with a constant 10% of weight of TiB$_2$, graphite, and nano MoS$_2$ is kept at varying amounts of 10, 15, and 20%. The dry sliding wear tests are executed by following Taguchi’s design of experiment. The wear rate and coefficient of friction are considered as responses, whereas the normal load, sliding distance and the composition of MoS$_2$ are considered as the chief parameters with three levels. The hybridized Taguchi-Grey Relational -Principal Component Analysis mathematical model is implemented to study the effect of wear parameters and inclusion of MoS$_2$ on the wear behavior. Mathematical and experimental results explore the increasing nano MoS$_2$ content reduces the wear rate and coefficient of friction of composites. Analysis of variance results also acknowledge that nano MoS$_2$ content in the composite is a remarkable parameter to impact the tribological property. The hybrid statistical model results explore that the optimum parameter to yield better tribological property are 30 N normal load, 2 km sliding distance and 20% of MoS$_2$. Worn surfaces are analyzed using scanning electron microscopy to picturize the wear mechanism concerning the varying content of reinforcement.

1. Introduction
Increasing demands of materials with multiple properties are inevitable in modern industrials sectors. Particle reinforced metal matrix composites are the best choice to fulfil these requirements. Metal matrix composites are capable of easy manufacturing with tailor-made properties. Machining these metal matrix composites is also very comfortable; hence, most conventional materials have been replaced by these advanced composites. The abundant availability of aluminium and its compatibility to blend with either soft or hard particles make it the right candidate for various applications [1–3]. Aluminium metal matrix composites (AMMC) reinforced with ceramic or hard particles exhibit high specific strength with low specific weight [4]. The nature of imparting good mechanical properties with low specific weight attracted the aeronautical, automobile, and structural
industries to use these AMMCs hugely [5]. More recent research literatures have proved the development of tailor-made wear resistance property of AMMCs. Linear relations between the wear rate of AMMCs and reinforcing materials and the wear test parameters have been validated through various reports [6–9]. Significant influence of the percentage of composition of reinforcement particle on the wear rate and coefficient of friction is also realized [10]. Similarly, the wear rate could be influenced by optimizing the wear test parameters [11]. The improvement of wear resistance could also be achieved with the balanced inclusion of hard particles and solid lubricants [12–16]. Further, the wear resistance capability can also be affected by the size of the reinforced particles [17].

Sajjad Arif et al [18] conducted a morphological and wear study on aluminium matrix reinforced micro graphite and nano zirconia particles with varying volume fractions. The authors concluded that the inclusion of graphite particles enhances the wear resistance. N.G.Siddesh Kumar et al [19] explored the findings that the hybrid reinforcement of 2% nano B4C and 2% micro MoS2 minimizes the wear loss at high temperatures. Jaroslav Kovacik et al [20] concluded that the inclusion of 16 μm graphite powder minimizes the coefficient of friction of Copper- graphite composites, whereas 25–40 μm graphite particles maximize the coefficient of friction. Rajkumar et al [21] have investigated the impact of nano and micro graphite particles over the improvement of wear properties, and they concluded that the reinforcement of nano graphite imparts good tribological properties than microparticles. Ajith Arul denial et al [22] carried out an experimental examination of tribological behavior of Al-SiC-MoS2 composite and revealed that the inclusion of SiC and MoS2 minimizes the wear loss and friction coefficient. Subsequently, they extended their report that the lesser particle size of SiC further improves the tribological property. P. Narayasamy et al [23] investigated dry sliding wear on an aluminum matrix reinforced with TiC and MoS2. The authors revealed that the inclusion of MoS2 reduces the hardness, and a significant improvement in wear loss was recorded for the higher composition of TiC and MoS2. P.Senthilkumar et al [24] developed a Copper– Tin alloy containing various percentages of molybdenum disulfide. The wear test results revealed that the wear rate and friction coefficient were decreased with the increment in weight percentage of MoS2. K.Kanthavel et al [25] observed the effects of significant improvement in wear loss for the developed aluminium composite reinforced with 5% Al2O3 and 5% MoS2.

There is extensive research reports available to improve the wear resistance property of metal matrix composite reinforced only with ceramic or hard particles. However, few research reports are dealt with the reinforcement of solid lubricants like graphite and Molybdenum disulphide in the micron range. But, no significant research work has been reported so far by reinforcing the nano size of MoS2. This research work is designed to evaluate the effect of percentage of weight fraction of nano MoS2 in addition to the common dry sliding wear test parameters like normal load and sliding distance through mathematical modelling. Nanoparticles of MoS2 with varying wt.% of 10, 15, and 20 have been reinforced with graphite and Titanium diboride (TiB2).

2. Materials and methods

2.1. Materials

Aluminium 6061 alloy was considered to be a matrix material whose compositions are furnished in table 1. Graphite, TiB2, and nano MoS2 were employed to reinforce and develop the hybrid composite. The mechanical properties of Graphite, TiB2, and nano MoS2 are also shown in table 2.

2.2. Synthesis of nano MoS2

The high-energy planetary ball mill (Fritsch, Germany - Mono Mill classic line Pulverisette–6) was utilized to pulverize the micro MoS2 into nano MoS2, as shown in figure 1. Initially, the powder (50 mg) was dried in a vacuum to expel the moisture present in the particles. Then the powder was kept in a tempered steel grinding bowl of a capacity of 125 g. A 30 number of tungsten carbide balls with 10 mm diameter were pressed into the service of pulverization. The particles could be milled as fine particles with manipulation of ball diameter, rotational speed, and time [26]. The rotational speed was set to 400 rpm for 12 h to reach the fineness of the particle nearly 80 nm. The ball to powder ratio was made to 20:1.

| Table 1. Composition of matrix material. |
|----------------------------------------|
| Aluminium  | Silicon  | Magnesium | Chromium | Copper |
| 97.9%      | 0.6%     | 1%        | 0.6%     | 0.28%  |
2.3. Fabrication of the hybrid composite

First of all, aluminium 6061 was melted at 850°C in a muffle furnace (SWAM EQUIP, Chennai). The motorized stirrer is used to stir the melt continuously, encountering oxidation due to the open environment. But the oxidation of the melt results in poor wettability with the reinforcing particles. An inert atmosphere was created to increase the wettability by adding a small amount of Mg with the melt [27]. The premeasured and preheated graphite, TiB₂, and nano MoS₂ reinforcing particles were mixed into the melt. The stirring speed, stirrer blade angle, and time of stirring are the chief parameters to influence the distribution homogeneity of the reinforcement particles [28]. The blade angle was set to 30°, and the stirring speed was followed at 600 rpm for 30 min to reach the maximum homogeneity. The stirred melt was transferred into the steel mould (100 × 60 × 15 mm) and was allowed to solidify in an open-air. Nine specimens were cast with constant wt% of 10% graphite and TiB₂ but varying wt% of nano MoS₂ in 10, 15, and 20%. The existence of reinforced particles is validated with the XRD data shown in figure 2.

2.4. Wear test

The dry sliding test was performed by using the Pin and disc apparatus (DUCOM). The required numbers of specimens were prepared by following the ASTM standard dimensions of 10 mm in diameter and 30 mm in length. An EN-31 grade steel disc with a surface roughness of 0.11 μm and a hardness value of 72 HRC was employed to rotate against the specimen. The track diameter and rotational speed of the disc were set as 100 mm and 575 rpm, respectively, to achieve a maximum velocity of 3 m s⁻¹. Each specimen was tested with three levels of varying sliding distance and varying normal load as per the experiment design shown in table 3. The computer-controlled pneumatic loading arrangement was used to vary the normal load on the pin. Before each trial, the disc was polished through an emery sheet of 120 grade and rinsed using acetone to maintain the surface roughness. The height loss of the pin and frictional force was observed through a computerized data acquisition system built with the apparatus. The following relation was used to ascertain the wear rate in terms of volume loss by considering the cross-sectional area of the pin.

Table 2. Properties of Matrix and reinforcement material.

| Material                  | Density (gm/cm³) | Melting point (°C) | Yield strength (MPa) |
|---------------------------|------------------|--------------------|----------------------|
| Aluminium 6061           | 2.7              | 600                | 270                  |
| Graphite                 | 0.65             | 3527               | 85                   |
| Molybdenum disulfide     | 4500             | 2375               | 270                  |
| Titanium diboride        | 5.06             | 3230               | 400                  |

Figure 1. High energy planetary ball mill.
Where, \( v_s \) and \( v_e \) are the volume of the pin before start and end, respectively. The notations \( s_d \) and \( s_e \) denote the sliding distance before start and end, respectively. Then, wear rate and coefficient of friction were calculated using the following equation.

\[
W_r = \frac{v_s - v_e}{s_d - s_e}
\]  

(1)

\[
W_r = \frac{W_r}{F}
\]  

(2)

\[
\mu = \frac{F_r}{F_i}
\]  

(3)

### 3. Statistical evaluation

#### 3.1. Taguchi-GRA coupled principal component analysis

**3.1.1. Taguchi’s design of experiment**

It is an important technique to address the minimum number of combinations of experiments by considering the number of dependent and independent variables at their levels \([27, 29]\). The L9 orthogonal array was recommended for the existing work with the three-parameter and two objectives. Table 4 depicts the observed values of the two objectives, namely wear rate and coefficient of friction (CoF) for each combination of wear tests.

**3.1.2. Grey Relational Analysis (GRA)**

Though the number of available data is limited, the intricate problems can be solved with the help of GRA suggested by Prof. Deng (1989) \([30]\). Normalizing strategy is the core concept of GRA theory. Another exceptional dimension of GRA is its ability to solve multi-objective cases by converting them into a single objective \([31–34]\). The variability in the wear process can be controlled by minimizing the effect of uncontrolled variables (noise factors), which can be addressed mathematically by using signal-to-noise ratio (S/N).

Performance expectation of the responses like larger or smaller is a key factor to arrive S/N ratio \([35–37]\). The current study involves the tribological behavior, which requires both the responses wear and CoF to be as minimum as possible. The following equation was used to calculate the S/N ratio for each experimental run.

![](image)

**Figure 2.** XRD image of the composite specimen.

| Table 3. Levels of dry sliding wear parameters used in the study. |
|------------------|---|---|---|
| Parameters        | Level 1 | Level 2 | Level 3 |
| Normal load, (N)  | 15 | 30 | 45 |
| Sliding distance, \(D\) (km) | 1 | 2 | 3 |
| Wt\% of MoS2      | 10 | 15 | 20 |
The normalization of the data from 0 to 1 was done by using the following relation,

\[ Z_{ij} = \frac{\max(Y_{ij}, i = 1, 2, \ldots, n) - Y_{ij}}{\max(Y_{ij}, i = 1, 2, \ldots, n) - \min(Y_{ij}, i = 1, 2, \ldots, n)} \]  

The grey relational coefficients are determined with the following relation by incorporating the appropriate quality loss \( (\Delta_{\min}, \Delta_{\max}) \). Table 5 shows the computed grey coefficient value, S/N ratio, and normalized S/N ratio.

\[ GC_{ij} = \frac{\Delta_{\min} + \lambda\Delta_{\max}}{\Delta_{ij} + \lambda\Delta_{\max}} \]  

### Table 4. Experimental matrix and recorded response value.

| S.No. | Normal load (N) | Sliding distance (km) | MoS₂ content (Wt. %) | wear rate (m³/m) | CoF |
|-------|----------------|-----------------------|----------------------|------------------|-----|
| 1     | 15             | 1                     | 10                   | 4.84             | 0.24 |
| 2     | 15             | 3                     | 15                   | 1.92             | 0.201 |
| 3     | 15             | 5                     | 20                   | 1.26             | 0.161 |
| 4     | 30             | 1                     | 15                   | 2.94             | 0.25 |
| 5     | 30             | 3                     | 20                   | 1.56             | 0.185 |
| 6     | 30             | 5                     | 10                   | 6.10             | 0.347 |
| 7     | 45             | 1                     | 20                   | 2.10             | 0.227 |
| 8     | 45             | 3                     | 10                   | 4.34             | 0.32 |
| 9     | 45             | 5                     | 15                   | 5.34             | 0.28 |

### Table 5. S/N ratio, normalized S/N ratio, and Grey coefficients.

| S/N Ratio | Normalized S/N ratio | Deviation sequence | Grey Relational Coefficient (GRC) |
|-----------|----------------------|--------------------|-----------------------------------|
| (W.R.)    | (COF)                | (W.R.)             | (COF)                            |
| 15        | 12.40                | 0.85               | 0.38                             | 0.15               | 0.62               | 0.3333             | 0.31               |
| 5.67      | 13.94                | 0.27               | 0.21                             | 0.73               | 0.79               | 0.4055             | 0.27               |
| -2.01     | 15.86                | 0.00               | 0.00                             | 1.00               | 1.00               | 0.9995             | 0.26               |
| -9.37     | 12.04                | 0.54               | 0.42                             | 0.46               | 0.58               | 0.5192             | 0.33               |
| -3.86     | 14.66                | 0.14               | 0.13                             | 0.86               | 0.87               | 0.7729             | 0.24               |
| -15.71    | 9.19                 | 1.00               | 0.73                             | 0.00               | 0.27               | 0.3664             | 0.46               |
| -6.44     | 12.88                | 0.32               | 0.32                             | 0.68               | 0.68               | 0.4251             | 0.30               |
| -12.75    | 9.82                 | 0.78               | 0.66                             | 0.22               | 0.34               | 0.6983             | 0.42               |
| -14.55    | 11.18                | 0.92               | 0.51                             | 0.08               | 0.49               | 0.8553             | 0.36               |

\[
S/N \text{ ratio} = -10 \log \frac{1}{n} \sum_{i=1}^{n} Y_{i}^{2}
\]  

The normalization of the data from 0 to 1 was done by using the following relation,

\[
Z_{ij} = \frac{\max(Y_{ij}, i = 1, 2, \ldots, n) - Y_{ij}}{\max(Y_{ij}, i = 1, 2, \ldots, n) - \min(Y_{ij}, i = 1, 2, \ldots, n)}
\]  

The grey relational coefficients are determined with the following relation by incorporating the appropriate quality loss \( (\Delta_{\min}, \Delta_{\max}) \). Table 5 shows the computed grey coefficient value, S/N ratio, and normalized S/N ratio.

\[
GC_{ij} = \frac{\Delta_{\min} + \lambda\Delta_{\max}}{\Delta_{ij} + \lambda\Delta_{\max}}
\]

3.1.3. Principal component analysis (PCA)

The concept of maintaining the variations in the data pool to reduce the dimensionality of the data is employed in PCA [38–40]. The new data group transformed from the recorded responses through mathematical way is called principal component. The normalized data of recorded responses are utilized to compute the value of GRC. The GRC is used to construct the covariance matrix as per the PCA model. The Eigenvectors of the transformed matrix are manipulated, and the corresponding Eigenvalues are also computed with the help of the relation (7) shown below [41].

\[
\begin{bmatrix}
    x_1(1) & x_1(2) & \cdots & x_1(n) \\
    x_2(1) & x_2(2) & \cdots & x_2(n) \\
    \vdots & \vdots & \ddots & \vdots \\
    x_m(1) & x_m(2) & \cdots & x_m(n)
\end{bmatrix}
\]

Where, \( x_i(j) \) illustrates the value in the matrix, \( i = 1, 2, 3, \ldots m \) and \( j = 1, 2, 3, \ldots n \)

\( X \) is the value of grey relational coefficients of each response, ‘m’ is the number of experiments, and ‘n’ is the number of responses.
The coefficient of the correlation array can be calculated as,

\[ R_{ij} = \frac{\text{Cov}(x_i(j), x_i(l))}{\sigma x_i(j) \times \sigma x_i(l)} \]  

Where, \( \text{Cov}(x_i(j), x_i(l)) \) is covariance sequence of \( x_i(j) \) and \( x_i(l) \) and \( \sigma x_i(j) \), \( \sigma x_i(l) \) are the standard deviations of the sequence \( x_i(j) \) and \( x_i(l) \).

Then, the Eigenvectors and Eigenvalues are resolved by using coefficient correlation array with the help of the relation shown below,

\[ (R - \lambda_k I_n) V_k = 0 \]  

In above equation \( \lambda_k \) expresses the eigenvalues; \( \sum_{k=1}^{n} \lambda_k = n \); \( k = 1,2,3 \ldots n \), the entity \( V_k \) is the eigenvector, \( V_k = [a_{k1}, a_{k2}, \ldots \ldots, a_{kn}]^T \) for the corresponding eigenvalues of \( \lambda_k \).

The principal component of each response value can be determined as follows,

\[ Y_{mk} = \sum_{i=1}^{n} X_m(i) V_k \]  

The principal component value of each response for an individual experimental run arrived is shown in table 6, and the Eigenvalue of each principal component is shown in table 7.

### Table 6. Principal component values.

| S.No. | Wear Rate | Coefficient of Friction | Wear Rate | Coefficient of Friction |
|-------|-----------|--------------------------|-----------|--------------------------|
| 1     | 0.3333    | 0.31                     | 0.24      | 0.31                     |
| 2     | 0.4055    | 0.27                     | 0.29      | 0.27                     |
| 3     | 0.9995    | 0.26                     | 0.71      | 0.24                     |
| 4     | 0.5192    | 0.33                     | 0.37      | 0.33                     |
| 5     | 0.7729    | 0.24                     | 0.55      | 0.26                     |
| 6     | 0.3664    | 0.46                     | 0.26      | 0.46                     |
| 7     | 0.4251    | 0.30                     | 0.30      | 0.30                     |
| 8     | 0.6983    | 0.42                     | 0.49      | 0.42                     |
| 9     | 0.8553    | 0.36                     | 0.60      | 0.36                     |

### Table 7. Eigenvalues of principal components.

| Principal Component | Eigen Value | Percentage of contribution | Cumulative |
|---------------------|-------------|-----------------------------|------------|
| PC1                 | 1.1824      | 94.10                       | 94.10      |
| PC2                 | 0.1176      | 5.90                        | 100        |

### Table 8. Eigen vectors value of the responses.

| Responses          | PC1     | PC2     |
|--------------------|---------|---------|
| Specific Wear Rate | 0.707   | -0.707  |
| Coefficient of Friction | 0.707 | 0.707   |

3.1.4. Determination of grey relational grades (GRG)

After arriving at the weightage value of the principal component of each response as shown in table 8, the grey relational grade can be determined for each response using the following equation [42],

\[ \gamma_i = \frac{1}{n} \sum_{j=1}^{n} \beta_j (GC_{ij}) \]  

Where, \( \gamma_i \) is a grey relational grade of an \( i^{th} \) experiment; \( n \) is the number of responses; \( \beta_j \) is weightage of principal component and \( GC_{ij} \) is grey relational coefficient of \( j^{th} \) response in an \( i^{th} \) experiment. The computed GRGs and their ranking are plotted in table 8.
Figure 3. Main effect plot for GRG.

Figure 4. Predicted and experimental results comparison of (a) Wear rate (b) CoF.

Table 9. Grey Relational Grade and their rankings.

| S. No. | GRG<sub>SWR</sub> | GRG<sub>COF</sub> | CGRG   | Rank |
|--------|-------------------|-------------------|--------|------|
| 1      | 0.24              | 0.31              | 0.275  | 9    |
| 2      | 0.29              | 0.27              | 0.280  | 8    |
| 3      | 0.71              | 0.24              | 0.475  | 1    |
| 4      | 0.37              | 0.33              | 0.350  | 6    |
| 5      | 0.55              | 0.26              | 0.405  | 4    |
| 6      | 0.26              | 0.46              | 0.360  | 5    |
| 7      | 0.60              | 0.30              | 0.450  | 3    |
| 8      | 0.49              | 0.42              | 0.455  | 2    |
| 9      | 0.30              | 0.36              | 0.330  | 7    |
3.1.5. Optimal combination of input parameters and their levels

The optimal combination of wear test parameters and the percentage composition of nano MoS$_2$ to yield a low wear loss and friction coefficient can be estimated through GRG analysis. The grey relational grade acts as an index that has arrived through grey relational coefficient and principal component weightage, which is used to imply the degree of quality characteristics. The ranking has been assigned to each experimental run based on the values of GRG. Table 9 shows that experimental number 3 has got the highest GRG ranking, which expresses the better quality characteristic. The combinations level of experiment 3 are 15 N normal loads, 5 km sliding distance, and 20 wt% of nano MoS$_2$. The main effect plot plotted for the data means, and GRG is shown in figure 3. The main effect plot acknowledges the optimal input parameters.

3.1.6. ANOVA analysis to study the effect of parameters over the response

Analysis of variance is carried out with the first principal component, which has got the most prominent weightage. The principal component with the largest Eigenvalues always retains the highest variance \[43, 44\].

Tables 10 & 11 show the ANOVA analysis for wear rate and coefficient of friction, respectively.

The ANOVA analysis explores the ranking importance of each parameter on the effect of performance characteristics. $R^2$ and $R^2(\text{adj})$ values arrived for the analysis are nearly 90%, which acknowledges that the proposed mathematical model is realistic \[45\]. The research emphasizes the importance of including the nano MoS$_2$ particles to impart excellent wear-resistant characteristics. ANOVA analysis reveals that the increased composition of nano MoS$_2$ particles in the developed hybrid composite plays a pivotal role in improving the tribological property than any other parameters. Both the wear responses wear rate and coefficient of friction have been influenced by the percentage of composition of nano MoS$_2$ to a remarkable extent. As far as the impact of the rest of the other parameters is considered, normal load scores second ranking by leaving the sliding distance as insignificant. Figures 5(a) & (b) depicts normal probability plots where the points are linearly arranged, indicating the adequacy of the proposed model with a 95% confidence interval. Figure 5(c) indicates the effectiveness of the model to showcase the performance characteristic of the responses.

The developed mathematical employed the following regression equation to predict the relation between wear test parameters and responses. The equation acknowledges the optimized level of parameter of each response with the positive sign convention. Furthermore, figure 4 shows the predicted result and experimental
results at optimized level of parameters which acknowledges the good agreement between predicted and experimental.

\[
\text{Wearrate} = 0.5363 + 0.0426 x_1 - 0.0065 x_2 + 0.00491 x_3 - 0.00265 y_1 + 0.00318 y_2 - 0.0053 y_3 - 0.3505 z_1 - 0.1631 z_2 + 0.1874 z_3 \tag{12}
\]

\[
\text{Coefficient of friction} = 0.5515 + 0.1176 x_1 - 0.0191 x_2 + 0.1366 x_3 - 0.0496 y_1 + 0.0476 y_2 - 0.0020 y_3 - 0.2065 z_1 - 0.0464 z_2 + 0.1601 z_3 \tag{13}
\]

Where \(x_1, x_2, \) and \(x_3\) are normal load at levels 1, 2, and 3, respectively
Where \(y_1, y_2, \) and \(y_3\) are the sliding distances at levels 1, 2, and 3, respectively
Where \(z_1, z_2, \) and \(z_3\) are the wt\% of nano MoS\(_2\) at levels 1, 2, and 3, respectively.

4. Results and discussions

4.1. Wear rate

The wear rates for the three varied amounts of nano MoS\(_2\) particles in the hybrid composites under various loading conditions and sliding distances are shown in figure 6. It is noticed that the increment in loading accelerates the wear rate in the least significant way and the improved wt\% of nano MoS\(_2\) decelerates the wear rate in the most significant way. This pronounces the remarkable impact wt\% of nanoMoS\(_2\) on the wear rate. Similar findings have been earned through statistical analysis also. ANOVA results acknowledge the significant contribution of nano MoS\(_2\) on the wear rate by securing the higher F-value of 105.70.

Further, the results assure the impact of normal load on the wear rate with a meager F-value of 2.45. The enhancement of wear resistance with the inclusion more amount of nano MoS\(_2\) particles is attributed to the ability of MoS\(_2\) to form a tribo-layer between the interfaces. Usually, the graphite also forms such tribo-layer, but more amount of MoS\(_2\) is responsible for the distributed tribo-layer. Moreover, the MoS\(_2\) particles are lamellar structures with bound layers interfaced by weak Vander wall forces, allowing the easy sliding of layers, which forms the tribo-layers [46].

4.2. Coefficient of friction

The coefficient of friction values obtained for three distinct fractions of nano MoS\(_2\) particles in the hybrid composites under various loading conditions and sliding distances are shown in figure 7.

The experimental results explore that the coefficient of friction increases with increment in applied load; on the other hand, it decreases in trend with the increment in nano MoS\(_2\) particles. The observed behavior is validated with mathematical modeling results. The ANOVA results shown in table 10 confirm the contribution
of nano MoS2 in the reduction of coefficient of friction to a significant extent by securing the highest F-value of 14.07. Further results from ANOVA analysis highlight the impact of normal load with an F-value of 6.56. Descending index of coefficient of friction with the increased content of nano MoS2 is attributed to the film formation. The formation of lubricant film minimizes the effect of interlocking of asperities, reducing the frictional forces. The linear relation between the coefficient of friction and normal load is attributed to the brittle failure of the lubricant layer. The increased applied load induces more contact pressure which damages the developed tribo-layer, thereby promoting the chances of metal to metal contact to magnify the frictional forces. However, the mathematical modeling results reveal that the third parameter sliding distance is least significant in influencing both responses.

4.3. Analysis of worn-out surfaces
The experimental and mathematical analysis invariably upholds the influence of both wt% of nano MoS2 and normal load on the wear behavior of the hybrid composite. The actual physical behavior of the wear mechanism is highlighted to support the findings through microscopic analysis of worn-out surfaces. The formation of the lubricant layer realizes the improved wear resistance due to the increased inclusion of nano MoS2. The SEM micrograph is shown in figure 8(a) acknowledges the presence of tribo-layer of both the lubricants in a considerable way. As the load increases from 15N to 30 N, the change in the wear mechanism is observed. The effect of wear is intensified due to the increased contact pressure, which initiates the catastrophic failure of the lubricant layer in a brittle manner. This phenomenon is captured in figure 8(b). The failure of the tribo-layer further promotes the metal-to-metal contact, as shown in figure 8(c). Hence more pronounced wear at the extreme load of 45 N was recorded.
Two different versions of wear behavior with the protected and unprotected region are seen in figure 8(d). Noticeable groove formation in the direction of sliding through plastic deformation of asperities due to higher load is exposed in part of the surface. However, the remaining part of the surface is subjected to negligible plastic deformation. This attributes to the lubricant layer formation [47–49], which protects the peaks and valleys of the asperities.

The worn-out analysis annunciates that evident change in wear mechanism for each step of load incremental with respect to the varying reinforcement content. At higher load, proactive, and controversial wear behavior were recorded. The magnitude of frictional force is comparatively more at higher load, which imparts more heat at the interface of sliding surfaces. The formation of fragmented metal oxide layers due to the frictional heat is observed and acknowledged through the EDX result shown in figure 9. The formation of these oxide layers also protects the surfaces from wear, which seems to be proactive. However, at higher load, worn-out edges of the groove are subject to brittle fracture due to low fracture toughness. The fractured debris acts as a third particle which changes the wear scenario from two-body abrasion to three-body abrasion. Then more pronounced wear behavior is recorded.

4.4. Property map
The available data extracted from important research literature are presented in the form of a property map. The property map can act as guidelines for the researchers and industrial experts to select the appropriate material to fulfil their needs. The property map illustrated in figure 10 is drawn between CoF and normal load. The importance of the present work has been highlighted in comparison with most of the Aluminium matrix material reinforced with graphite and MoS2. The present work is compared with Silver, Magnesium, and
Aluminium matrix materials reinforced with varying proportions of graphite, MoS₂. The newly synthesized hybrid composite can be treated as the best wear resistance material due to its very low CoF for all loading levels compared with the materials used in previous studies.

5. Conclusions

In the present study, the dry sliding wear behavior of nano MoS₂ reinforced Al-TiB₂-Gr hybrid composite has been investigated, with varying wear test parameters and wt% of nano MoS₂ through the experimental and mathematical approach. As a result, the following conclusions have arrived.
The remarkable improvement in wear rate and coefficient of friction has been observed with the increased inclusion of nano MoS2 with the hybrid composite.

20% of MoS2 reinforcement reduces the wear rate by 40% and CoF by 54% compared to 10% of MoS2. This improvement in tribological property is believed due to the formation of lubricant-layer by the two solid lubricants.

The hybrid mathematical modeling Taguchi-GRA-PCA analysis results confirm the highest impact of the addition of nano MoS2 on the wear rate and CoF followed by the normal load.

The main effects plot plotted for grey relational grade corroborates the optimum level of wear parameters, and wt.% of nano MoS2 inclusion to improve the wear characteristics are 15N normal load, 2 km sliding distance, and 20% nano MoS2.

The notable indicators like R2 value, adj R2 value, and normal probability plots are affirmed that the proposed mathematical model is adequate.

The micrographic results proclaim the existence of tribo-layer and phases in the wear mechanism.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Additional information

The authors declare that there are no competing interests.
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