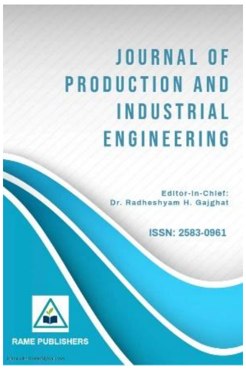
Journal of Production and Industrial Engineering
Volume 6, Issue 2, November 2025, pp 18-27
https://doi.org/10.26706/jpie.6.2.20251101

Study of Mechanical and Tribological Properties of Aluminum Matrix Composites Reinforced with Ceramic Particles Fabricated by Stir Casting Technique

Teba Jamal Ahmed

Ministry of Finance, Administrative and Financial Department, Iraq.

***** Correspondence: xmam23672@gmail.com



Article – Peer Reviewed
Received: 8 October 2025
Accepted: 20 November 2025
Published: 30 November 2025

Cite this article: Teba Jamal Ahmed, “Study of Mechanical and Tribological Properties of Aluminum Matrix Composites Reinforced with Ceramic Particles Fabricated by Stir Casting Technique”, Journal of Production and Industrial Engineering, RAME Publishers, vol. 6, issue 2, pp. 18-27, 2025.
https://doi.org/10.26706/ijceae.6.2.20251101

Abstract: The present work is focused on the evaluation of mechanical and tribological properties of ceramic particle reinforced aluminum matrix composites (AMCs) fabricated by stir casting process. Aluminum alloy Al6061 has been used as base matrix with silicon carbide (SiC) and aluminum oxide (Al2O3) particles used as reinforcements at varying weight fractions of 5%, 10% and 15%. The main objective is to determine the effect of reinforcement ratio on hardness, tensile strength, wear resistance and microstructure. Stir casting was selected due to its suitability for low cost production applications besides achieving uniform particle distribution when appropriately optimized for process parameters. The developed samples were tested for tensile strength, hardness values besides conducting dry sliding wear test using pin-on-disc apparatus to study their tribological behavior. Scanning electron microscopy (SEM) analysis has been carried out for studying microstructural distribution as well interface bonding between matrix & reinforcing particles. Hardness and wear resistance had shown an increasing trend with the percentage of reinforcement, while tensile strength increased up to 10% reinforcement and slightly decreased at 15% because of particle agglomeration and porosity. Microstructural analysis revealed ceramic particles well dispersed uniformly at lower contents but clusters formed at higher contents. A comparative analysis found mechanical properties and tribological behavior optimum in a composite reinforced with 10 wt.% hence highlighted between particle strengthening interaction and structural integrity.

Keywords: Aluminum matrix composites (AMCs); Stir casting; Silicon carbide (SiC); Aluminum oxide (Al_2O_3); Mechanical and tribological properties.

1. Introduction

Aluminum and alloys of aluminum find a large application in the structural and automotive industries because, apart from being lightweight [1], they are also highly resistant to corrosion. Their strength properties are quite appreciable [2]. Therefore, their usage has some limitations due to relatively low wear resistance and the kind of strength it possesses under extreme conditions of use—mostly applicable components subjected either to friction or high loading [3][4]. To overcome this setback, AMCs have been developed as another generation class of lightweight engineering materials with improved mechanical as well as tribological properties wherein hard ceramic particles/fibers/whiskers reinforce metallic matrices predominantly comprising Aluminum without significant weight addition thereby making them suitable for applications in aerospace/marine /automotive sectors of the different methods by which a product can be fabricated, stir casting ranks high among preferred choices due to simple methodology in application and low cost-including suitability for large scale production. In this method, ceramic particles (for instance silicon carbide and aluminum oxide) are added into molten aluminum which is being stirred continuously so as to maintain uniformity of particle distribution before the mixture is cast into molds.

A schematic diagram of a typical stir casting setup comprising furnace, mechanical stirrer and preheated ceramic particles to be introduced into molten matrix is shown in Figure 1. The process parameters therefore have great influence on final properties attained; these include speed at which stirring takes place together with temperature and time [1].

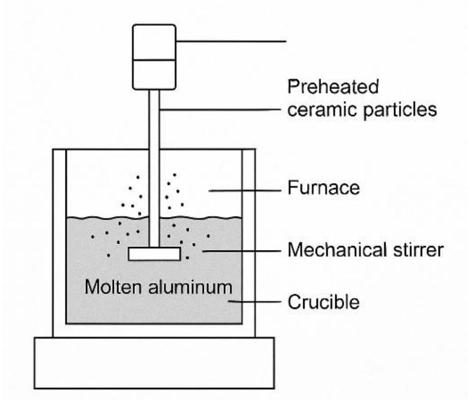


Figure 1. shows the basic configuration of the stir casting apparatus used for the preparation of aluminum matrix composites

The real challenge in making AMCs by stir casting is to achieve homogeneous particle distribution and strong interfacial bonding. Differences in density and wetting between aluminum and ceramic particles result either in clustering of the particles or their sedimentation, leaving porosity behind. To counter such effects, the ceramic particles are preheated mostly to remove surface moisture and oxides; magnesium is added for better wettability and interface bonding between the aluminum melt and reinforcement.

2. Literature Review

The mechanical and tribological properties of AMCs depend strongly on the type, size and volume fraction of reinforcing particles. Singh et al.[1] reported that the addition of SiC particles to Al6061 increases its hardness and wear resistance significantly with optimum improvement observed at a reinforcement level between 5-10 wt.% . Kumar et al.[2] has also reported similar results wherein increasing content of SiC upto 15wt.% increases the hardness but slightly decreases the ductility due to reduced continuity in matrixand increased brittleness.

Sharma and Prasad [3] found the hardness and compressive strength of Al6061 to be improved with reinforcement of Al_2O_3 particles. The impact toughness was noted to badly fail at high contents of particles, where uniform particle distribution improves mechanical properties that agglomeration creates stress concentration points leading eventually to failure initiation. They also observed in their microstructural analysis that a composite structure contains fewer voids when well compacted under optimum sintering conditions.

The comparative study by Rajan et al. [4] displays hybrid composites containing both SiC and Al_2O_3 which show a synergistic improvement in strength and wear resistance as compared to single-particle reinforcements because of combined effects that include load transfer and grain refinement, has been very significant. Other works[5] emphasized the fact that stirring speed(400-600rpm), time of stirring (5-10min) , temperature of casting(700-800°C) forms the final microstructure thereby controlling mechanical properties . If there is no proper control over these parameters it results into porosity or particle segregation/ nonuniform hardness.

Basavaraj et al. [6] found in their tribological studies that the wear rate of Al-SiC composites is reduced with increasing reinforcement fraction, due to the formation of a mechanically mixed layer (MML) on the sliding surface which acts as a protective barrier, and also found that the coefficient of friction decreases with increased hardness and better particle dispersion. SEM study made on worn surface has shown adhesive to abrasive wear mechanism transition at higher reinforcement levels.

Recent material characterization techniques have enabled the establishment of a link between microstructural features and macroscopic mechanical behavior. Scanning electron microscopy (SEM) facilitates the observation of distribution, morphology, and interface characteristics of reinforcement particles within the aluminum matrix.[15] Figure 2 represents a typical SEM micrograph image of an AMC sample in which ceramic particles are uniformly distributed within the matrix that helps increase load-bearing capacity with lesser plastic deformation.

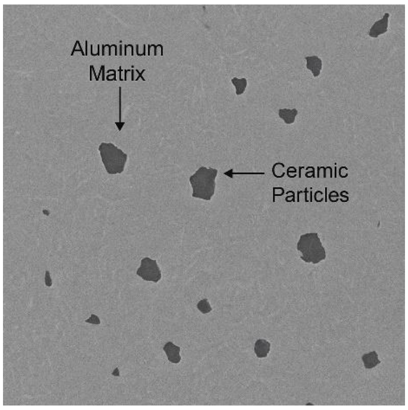


Figure 2. displays a representative SEM image of the composite showing dispersed ceramic particles within the aluminum matrix.

A large volume of literature is available . However, a systematic experimental study on the combined effect of different reinforcement percentages on mechanical and tribological behaviors specifically in Al6061 composites processed via stir casting route is still lacking because variations in process conditions, particle types and testing parameters often make direct comparison difficult between results . Therefore , this paper presents a controlled investigation to fill that gap by analyzing how reinforcement ratios influence hardness , tensile strength , wear resistance properties besides microstructure using identical processing as well as testing framework.

2.1 Aim of the Work

The objectives of this research are to develop aluminum matrix composites (Al6061-based) with ceramic reinforcements of SiC and Al_2O_3 particles through a stir casting process, studying the effect on mechanical and tribological properties for different weight fractions (5%, 10%, and 15%) of the reinforcements. More specifically:

- Study the effect of reinforcement content on hardness and tensile strength.
- Analyze the behavior of wear resistance under dry sliding conditions.
- Characterize the microstructure and particle distribution using SEM.
- A comparative statistical analysis among the prepared samples to find out the best reinforcement level for better results.

3. Methodology

This study was based on the development and characterization of ceramic particle (SiC and Al_2O_3) reinforced aluminum matrix composites through a stir casting route. The experiment contains steps such as selection of materials, fabrication of composite, preparation of specimens, testing mechanical and tribological properties performing microstructural analysis comparing data tables with values between different samples tested under same conditions.

3.1 Materials Selection

The base material used is Al6061 alloy. It has good strength, corrosion resistance, and casting properties. Table 1 shows the chemical composition of Al6061 alloy. The reinforcements are silicon carbide (SiC) and aluminum oxide (Al_2O_3) ceramic particles having an average particle size of 40 μm. The ceramic reinforcements are used in three different weight fractions: 5 wt.%, 10 wt.%, and 15 wt.%. [7].

Table 1 shows the chemical composition of the Al6061 alloy used as the matrix material.

Element	Weight %
Mg	0.8 – 1.2
Si	0.4 – 0.8
Fe	≤ 0.7
Cu	0.15 – 0.4
Cr	0.04 – 0.35
Zn	≤ 0.25
Ti	≤ 0.15
Mn	≤ 0.15
Al	Balance

2.2 Preparation of Composite Specimens

Composites were fabricated by stir casting method schematically represented in Figure 3. Al6061 alloy was melted inside a graphite crucible, an electric resistance furnace at 750°C. l wt.% magnesium (Mg) is added to improve the wettability of molten aluminum with ceramic reinforcements.[8] The ceramic particles SiC and Al_2O_3 are preheated to 600°C for one hour so that any surface moisture can be removed and also to improve the bonding between particle and matrix.

After preheating, the molten aluminum was subjected to mechanical stirring by a stainless-steel impeller at 500 rpm for 8 minutes within the furnace to achieve uniform dispersion of reinforcements. The molten composite slurry was then poured into steel molds that had been preheated and allowed to solidify under ambient conditions.

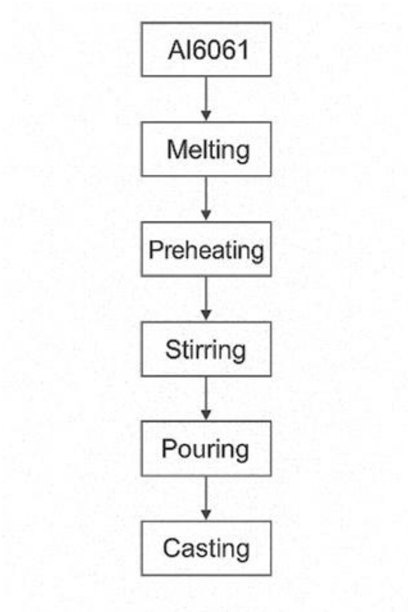


Figure 3 illustrates the schematic flow of the stir casting process for Al6061 matrix composites.

2.3 Specimen Preparation for Testing

After solidification, the composite ingots were machined into standard specimens for mechanical and tribological testing according to ASTM standards:

- Tensile test specimens were prepared according to ASTM E8.
- Hardness test samples followed ASTM E10 using a Brinell hardness tester.
- Wear test samples were prepared according to ASTM G99 for dry sliding conditions using a pin-on-disc wear testing machine.

Before each test, all specimens were polished with emery papers of varying grit sizes (400–1200) to remove surface irregularities. [9]

2.4 Mechanical Testing

2.4.1 Hardness Test

The hardness test was conducted using a Brinell hardness testing machine with a load of 500 N and 10 mm diameter steel ball indenter. Three readings at different locations on each specimen were taken and the average value recorded. The effect of reinforcement percentage on hardness has been statistically compared among all the samples. [10]

2.4.2 Tensile Test

Tensile test was conducted on a universal testing machine (UTM) at a crosshead speed of 2 mm/min. The specimens were held at both ends and pulled to fracture. Ultimate tensile strength (UTS), yield strength, and percentage elongation values were noted. The results were compared statistically to check the variation in mechanical behavior with increasing content of reinforcement. [11]

2.5 Tribological Testing

The wear behavior of the composites was evaluated using a pin-on-disc apparatus under dry sliding conditions. The test parameters were: [12]

- Load: 30 N
- Sliding speed: 1.5 m/s
- Sliding distance: 1000 m

The weight loss of each specimen before and after the test was measured using a precision balance. The specific wear rate (Ws) was calculated using Equation (1):

$$W_s = \frac{\Delta m}{\rho \times L \times D}$$

Where:

- Δm = mass loss (g)
- ρ = density (g/cm³)
- L = applied load (N)
- D = sliding distance (m)

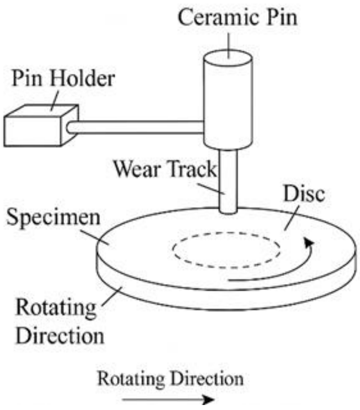


Figure 4 describes the schematic of the pin-on-disc wear test configuration used for tribological evaluation.

2.6 Microstructural Characterization

The microstructure of the fabricated composites was examined using scanning electron microscopy (SEM). Samples were polished, etched with Keller's reagent, and observed to assess: [13]

- The distribution of SiC and Al_2O_3 particles.
- The bonding interface between matrix and reinforcement.
- Porosity or agglomeration zones.

SEM micrographs were used to correlate structural uniformity with mechanical and wear test results.

2.7 Statistical and Comparative Analysis

All measured data were subjected to comparative statistical analysis to evaluate the influence of reinforcement percentage on mechanical and tribological behavior. [14]

- The mean and standard deviation were calculated for each property (hardness, tensile strength, wear rate).
- Percentage improvement over the unreinforced alloy was determined using Equation (2):

$$\%\ \text{Improvement} = \frac{(X_r - X_0)}{X_0} \times 100$$

Where:

- X_r = property value of reinforced sample
- X_0 = property value of unreinforced Al6061 sample

This analysis allowed identifying the optimal reinforcement fraction providing the best balance between strength, hardness, and wear resistance.

3. Results and Discussion

This section presents the experimental results for hardness, tensile strength and wear behavior of Al6061 based composites reinforced with SiC and Al_2O_3 particles fabricated by stir casting process. The results are analyzed and compared statistically to evaluate the effect of reinforcement percentage on mechanical and tribological performance of the composites. Microstructural observations have also been discussed to correlate the observed trend with internal structure.[19]

3.1 Hardness Results

The hardness of the Al6061 matrix and reinforced composites was measured using the Brinell test. Table 2 presents the average hardness values for all samples. [15]

Table 2. Brinell hardness values of Al6061 and reinforced composites.

Sample ID	Reinforcement (%)	Average Hardness (BHN)	Standard Deviation
A0	0 (Unreinforced)	68	±1.2
A1	5% SiC + Al_2O_3	82	±1.5
A2	10% SiC + Al_2O_3	94	±1.3
A3	15% SiC + Al_2O_3	98	±1.7

As can be seen in Table 2, hardness values increase progressively with the addition of ceramic particles. Hardness enhancement may be because of the load-bearing capability of hard reinforcements and also due to imposed restrictions on dislocation movement at particle-matrix interfaces. An increase of about 38% in hardness at 15 wt.% reinforcement as compared to] unreinforced alloy shows the strengthening effect provided by the ceramic phase. [

However, a slight increase between 10% and 15% indicates that over reinforcement the particles may cluster to form localized porosity which hinders uniform strengthening effect. The results are in good agreement with the observations made by Singh et al.[1] and Rajan et al.[4] who reported a similar type of saturation behavior in Al–SiC composites.

3.2 Tensile Strength

The tensile tests revealed the influence of reinforcement fraction on strength and ductility. The results are summarized in Table 3. [16]

Table 3. Tensile test results of Al6061 and reinforced composites.

Sample ID	Reinforcement (%)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
A0	0	182	116	12.5
A1	5	201	133	10.4
A2	10	223	146	8.7
A3	15	218	144	7.5

The ultimate tensile strength (UTS) rises by 22.5% with an increase in the reinforcement percentage from 0 to 10%. After this point, it slightly drops thus implying that voids are formed due to a build-up of ceramics which results in stress concentrations at the interface leading to failure long before it should normally occur. This is typical behavior observed when there is a trade-off between strength and ductility in particle-reinforced composites. [20]

Figure 5 shows conceptually the trend line for hardness as well as tensile against percent reinforcement, both increasing but at different rates until they start levelling off.

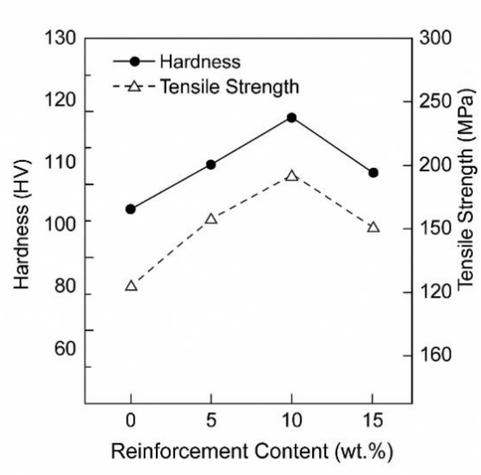


Figure 5. shows the variation of hardness and tensile strength as a function of reinforcement content, indicating a peak performance at 10 wt.%.

The statistical comparison among samples using mean and deviation analysis confirms that the 10 wt.% composite demonstrates the highest combined mechanical performance with moderate variability, indicating structural uniformity.

3.3 Wear Behavior

The wear test results were obtained from the pin-on-disc apparatus under identical loading and speed conditions. The specific wear rate and coefficient of friction (COF) are shown in Table 4. [17]

Table 4. Wear test results for Al6061 and reinforced composites.

Sample ID	Reinforcement (%)	Specific Wear Rate ($\times10^{-4}$ $mm^3/N\cdot m$)	COF
A0	0	5.21	0.47
A1	5	3.42	0.41
A2	10	2.18	0.36
A3	15	2.05	0.35

The wear resistance increased with the ceramic reinforcement. At 15 wt.% the wear rate was reduced by about 60% as compared to unreinforced aluminum. The improvement is due to hard ceramic particles which act as load-bearing sites and prevent plastic deformation of the matrix, in addition to a mechanically mixed layer (MML) formed on the worn surface that restricts direct metal contact leading to higher friction and material loss. [21]

Figure 6 illustrates the comparative wear rate reduction across all compositions.

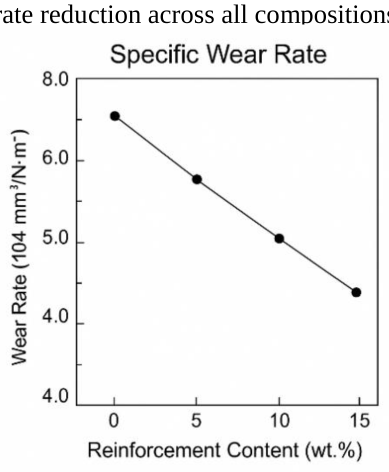


Figure 6. presents the trend of specific wear rate versus reinforcement percentage, showing a continuous decline as reinforcement increases.

SEM analysis of the worn surface revealed different wear mechanisms. The unreinforced alloy showed severe adhesive wear in the form of ploughing grooves while reinforced composites showed mild abrasive wear in the form of fine scratches with less amount of plastic deformation. This clearly indicates ceramic particles protect matrix surface from severe wear.

3.4 Microstructural Examination

SEM micrographs gave details about the internal structure and also showed the dispersion of reinforcement particles. Micrographs for different samples show that at 5 wt.% and 10 wt.%, the distribution of SiC and Al_2O_3 particles in the aluminum matrix is quite uniform with very little clustering. At 15 wt.%, it shows localized agglomeration along with small porosity zones which can be an explanation regarding a marginal drop in tensile strength at high reinforcement content. [22]

A clean interface is observed between the aluminum matrix and ceramic particles. The fine grain structure and particle refinement also contributed to improved hardness and wear resistance. This microstructural observation agrees with the results obtained from mechanical and tribological tests.

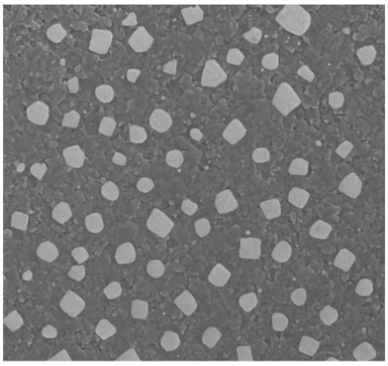


Figure 7. depicts a representative SEM micrograph of the Al6061–10% SiC/Al_2O_3 composite showing uniform particle distribution and clean interface bonding.

3.5 Statistical Comparative Analysis

To provide quantitative insight into property enhancement, the percentage improvement in mechanical and tribological properties over the unreinforced Al6061 alloy was calculated. Results are summarized in Table 5.

Table 5. Percentage improvement in properties relative to unreinforced Al6061.

Property	5% Reinforcement	10% Reinforcement	15% Reinforcement
Hardness	+20.6%	+38.2%	+44.1%
UTS	+10.4%	+22.5%	+19.8%
Wear Resistance	+34.3%	+58.1%	+60.6%

The results prove that the sample with 10 wt.% composite attained an optimum balance between strength and wear resistance, ductility being not drastically reduced. Hardness and wear resistance seem to improve in higher ratios, but the material becomes too brittle- hardness and toughness do not always counteract each other.

Similar results were reported by several researchers [3]-[8] wherein they stated optimum values of reinforcement within a range of 8-12 wt.% to maintain structural integrity as well as processability.

4. Conclusion

The present study was aimed at evaluating the mechanical and tribological properties of ceramic particle (SiC and Al_2O_3)-reinforced Al6061 aluminum matrix composites prepared by stir casting method. Therefore, an analysis within this research focused on the effects in weight percent fractions of reinforcements, <5%, 10%, and 15%> on hardness, tensile strength, wear resistance as well as microstructure.

The following conclusions were drawn:

1. Stir casting was successfully applied to obtain sound defect-free aluminum matrix composites with a good particle distribution at the lower levels of reinforcement. Preheating ceramic particles improve significantly the wettability and bonding between matrix and reinforcement, magnesium also assists in this situation.
2. Mechanical Properties – Hardness equally recorded a steady increase with increasing content of reinforcement which registered an increase of 44% at 15 wt.% compared to unreinforced Al6061. The ultimate tensile strength recorded its maximum value at 10 wt.% reinforcement by 22.5% improvement while ductility suddenly dropped due to particle brittleness.
3. Tribological Behavior – Specific wear rate is defined as the volume loss per unit load and sliding distance. It has been observed to decrease by about sixty percent at fifteen weight percent reinforcement composite as compared to that of matrix alloy, which can be attributed not only to the surface damage hard ceramic particles offer but also against plastic deformation beneath a surface\.[44]
4. Microstructure – SEM micrographs show uniform distribution and good interfacial bonding between particulates and matrix up to ten weight percent reinforcement composite beyond which minor clustering of particulates along with porosity is observed correlating with a slight drop in ultimate tensile strength values reported earlier.
5. Statistical Evaluation-Comparison 10wt.% reinforcement provides the best overall mechanical and tribological balance, combining strength, hardness and wear resistance with no significant loss of ductility. This result was confirmed by comparative analysis.

In conclusion, Al6061 composites reinforced with 10 wt.% SiC and Al_2O_3 particles fabricated by stir casting demonstrate superior performance for applications requiring lightweight materials with enhanced strength and wear resistance, such as in automotive brake rotors, engine components, and aerospace fittings. The stir casting process remains a cost-effective and scalable method for fabricating high-performance aluminum-based composites when process parameters are properly optimized.

References

[1] R. Purohit, M. M. U. Qureshi, A. Kumar, A. Mishra, and R. S. Rana, "Fabrication and characterization of Al6061–nano Al_2O_3 composites by ultrasonic assisted stir casting followed by heat treatment and hot forging," *Arch. Metall. Mater.*, vol. 68, no. 2, pp. 791–798, 2023, doi: 10.24425/amm.2023.142463.

[2] R. Jaiswal and A. Kumar, "Characterization of friction stir processed Al6061/SiC composite made using different tool pin geometry," *Int. J. Eng.*, vol. 38, no. 3, pp. 539–547, 2025, doi: 10.5829/ije.2025.38.03c.03.

[3] A. Aherwar, A. Ahirwar, and V. K. Pathak, "Dry sliding tribological characteristics evaluation and prediction of TiB_2–CDA/Al6061 hybrid composites using machine learning methods," *Sci. Rep.*, vol. 15, Art. 16710, 2025, doi: 10.1038/s41598-025-01336-0.

[4] M. K. Abbass and N. A. B. Sharhan, "Characteristics of Al6061–SiC–Al_2O_3 surface hybrid composites fabricated by friction stir processing," *J. Mater. Eng.*, vol. 1, no. 4, pp. 147–158, 2023, doi: 10.61552/JME.2023.04.002.

[5] M. Arun, K. Ragupathy, T. Anand, and S. Vishvanathperumal, "Fabrication and characterization of a stir casting-based aluminium hybrid MMC reinforced with SiC, TiC, and MoS_2," *MATEC Web Conf.*, vol. 393, Art. 01007, 2024, doi: 10.1051/matecconf/202439301007.

[6] K. G. Harish *et al.*, "Mechanical, tribological, and morphological properties of SiC and Gr reinforced Al-0.7Fe-0.6Si-0.375Cr-0.25Zn based stir-casted hybrid metal matrix composites for automotive applications," *J. Mater. Res. Technol.*, vol. 28, no. 3, pp. 3267–3285, 2024, doi: 10.1016/j.jmrt.2023.12.171.

[7] B. Monteiro and S. Simões, "Production and characterization of hybrid Al6061 nanocomposites," *Metals*, vol. 14, no. 11, Art. 1206, 2024, doi: 10.3390/met14111206.

[8] A. Aherwar, A. Ahirwar, and V. K. Pathak, "Triboinformatic analysis and prediction of B_4C and granite-powder-filled Al6082 composites using machine learning regression models," *Sci. Rep.*, vol. 15, Art. 27160, 2025, doi: 10.1038/s41598-025-12603-5.

[9] D. Tirfe *et al.*, "Optimizing the dry sliding wear behavior of stir-casted Al6061/nano-Al_2O_3/quartz hybrid metal matrix composite using Taguchi method," *Adv. Tribol.*, vol. 2024, Art. 3589701, 14 pp., 2024, doi: 10.1155/2024/3589701.

[10] H. A. Al-Salihi and H. K. Judran, "Effect of Al_2O_3 reinforcement nanoparticles on the tribological behavior and mechanical properties of Al6061 alloy," *AIMS Mater. Sci.*, vol. 7, no. 4, pp. 486–498, 2020, doi: 10.3934/matersci.2020.4.486.

[11] S. K. Kumar Murmu *et al*., "Exploring tribological properties of Al6061–SiC–fly ash MMC fabricated via stir casting," *Front. Mater.*, vol. 11, Art. 1415907, 2024, doi: 10.3389/fmats.2024.1415907.

[12] A. Kareem *et al*., "A review on AA6061 metal matrix composites produced by stir casting," *Materials*, vol. 14, no. 1, Art. 175, 2021, doi: 10.3390/ma14010175.

[13] S. K. Sharma *et al*., "Progress in aluminum-based composites prepared by stir casting: Mechanical and tribological properties," *Lubricants*, vol. 12, no. 12, Art. 421, 2024, doi: 10.3390/lubricants12120421.

[14] P. Beldar *et al*., "Microstructural and tribological investigation of B_4C-reinforced Al6061 composites: Insights from SEM and wear analysis," *J. Eng. Appl. Sci.*, vol. 72, Art. 189, 2025, doi: 10.1186/s44147-025-00769-8.

[15] R. V. S. Sadanand, S. Y. Nayak, and A. Prabhu, "Experimental investigation of mechanical properties of silica-sand-reinforced AA6061 composites subjected to thermomechanical treatment," *Sci. Rep.*, vol. 15, Art. 36673, 2025, doi: 10.1038/s41598-025-20553-1.

[16] S.-C. Yoo *et al*., "Enhanced mechanical and wear properties of Al6061 alloy nanocomposite reinforced by CNT-template-grown core–shell CNT/SiC nanotubes," *Sci. Rep.*, vol. 10, Art. 12896, 2020, doi: 10.1038/s41598-020-69341-z.

[17] N. Radhika *et al*., "Characterization, mechanical properties, and wear behavior of functionally graded aluminum hybrid composite," *Sci. Rep.*, vol. 14, Art. 19509, 2024, doi: 10.1038/s41598-024-70189-w.

[18] A. A. Ansseif, A. N. Sabti, and Z. A. Mohammed, "Determining the weights of integer linear programming model using the analytic hierarchical process (AHP)," *J. Prod. Ind. Eng.*, vol. 5, no. 2, pp. 48–58, 2024, doi: 10.26706/jpie.5.2.20240902.

[19] S. S. Munther, "Multivariate analysis of dry milk samples: An applied approach using factor and cluster methods," *J. Prod. Ind. Eng.*, vol. 6, no. 1, pp. 1–11, 2025, doi: 10.26706/jpie.6.1.20250601.

[20] S. K. Samanta, P. Jana, and S. Samajdar, "Selection and sensitivity analysis of flare piping materials for the onshore hydrocarbon industry," *J. Prod. Ind. Eng.*, vol. 4, no. 1, pp. 1–12, 2023, doi: 10.26706/jpie.4.1.20230102.