frontiers | Frontiers in Materials

TYPE Original Research
PUBLISHED 21 May 2024
DOI 10.3389/fmats.2024.1415907

OPEN ACCESS

EDITED BY
Vijay Raghunathan,
King Mongkut's University of Technology North Bangkok, Thailand

REVIEWED BY
Femiana Gapsari,
University of Brawijaya, Indonesia
L. Rajeshkumar,
KPR Institute of Engineering and Technology, Coimbatore, India

*CORRESPONDENCE
Ajay Kumar,
ajay.kumar30886@gmail.com

RECEIVED 11 April 2024
ACCEPTED 26 April 2024
PUBLISHED 21 May 2024

CITATION
Kumar Murmu S, Chattopadhayaya S, Cep R, Kumar A, Kumar A, Kumar Mahato S, Kumar A, Ranjan Sethy P and Logesh K (2024), Exploring tribological properties in the design and manufacturing of metal matrix composites: an investigation into the AL6061-SiC-fly ASH alloy fabricated via stir casting process. *Front. Mater.* 11:1415907.
doi: 10.3389/fmats.2024.1415907

COPYRIGHT
© 2024 Kumar Murmu, Chattopadhayaya, Cep, Kumar, Kumar, Kumar Mahato, Kumar, Ranjan Sethy and Logesh. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Exploring tribological properties in the design and manufacturing of metal matrix composites: an investigation into the AL6061-SiC-fly ASH alloy fabricated via stir casting process

Sagar Kumar Murmu[1], Somnath Chattopadhayaya[1], Robert Cep[2], Ajay Kumar[3]*, Ashwini Kumar[4], Shambhu Kumar Mahato[5], Amit Kumar[6], Priya Ranjan Sethy[7] and K. Logesh[8]

[1]Department of Mechanical Engineering, IIT (ISM) Dhanbad, India, [2]Department of Machining, Assembly and Engineering Metrology, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava, Ostrava, Czechia, [3]Department of Mechanical Engineering, School of Engineering and Technology, JECRC University, Jaipur, India, [4]Department of Mechanical Engineering, Manav Rachna International Institute of Research and Studies, Faridabad, Haryana, India, [5]Department of Mechanical Engineering, NIT Nagaland, Dimapur, Nagaland, India, [6]Centre for Augmented Intelligence and Design, Department of Mechanical Engineering, Sri Eshwar College of Engineering, Coimbatore, Tamil Nadu, India, [7]Departments of Mechanical Engineering, KIIT, Bhubaneswar, Odisha, India, [8]Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi, India

This study investigates a novel methodology to intricately craft a HAMMC and thoroughly examine its multifaceted mechanical and tribological characteristics. By combining silicon carbide (SiC) and fly ash as reinforcements, a unique identity is bestowed upon this hybrid composite, enhancing its structural integrity and functional attributes. Stir casting is the chosen methodology for fabricating this composite, favored for its economic viability and suitability for large-scale manufacturing. In this research, the emphasis is on developing a cost-effective composite that not only meets stringent economic considerations but also exhibits improved material properties. Within the realm of hybrid metal matrix composites, the well-regarded Al6061 takes on the role of the matrix material, while the synergistic inclusion of fly ash and SiC serves as reinforcing constituents. Three specimens with compostion 90% Al6061 + 5% SiC +5% Fly ash, 90% Al6061 + 10% SiC +6% Fly ash and 90% Al6061 + 15% SiC +7% Fly ash were fabricated. To unravel the intricacies of the fabricated Al6061 metal matrix composite, comprehensive tests are employed. These tests, including the Pin-on Disc test, Scratch test, Rockwell Hardness test, and Charpy Impact test, collectively work to unveil the nuanced tribological and mechanical behaviors encapsulated within this innovative alloy. The results indicated significant improvement in wear resistance in specimen comprising 78% Al6061 + 15% SiC +7% Fly Ash and volumetric loss found to have 0.96 g. Superior hardness characteristics and enhanced abrasion resistance found in

78% Al6061 + 15% SiC +7% Fly Ash than other two specimens. The highest impact strength exhibited in 90% Al 6,061 + 5% SiC +5% Fly ash specimen.

KEYWORDS

MMC, SiC, AMMC, HAMMC scratch test, rockwell hardness test, stir casting

1 Introduction

Creating design components that ensure excellent performance in various tribological applications requires careful consideration of wear resistance capacity. Hard reinforcing particles improve the wear performance of aluminium matrix composites (AMCs). With increasing reinforcing particles, the wear resistance of AMCs is increased (Pateriya and Pradhan, 2023). Metal matrix composites (MMCs), specifically those based on aluminum, play a pivotal role in achieving outstanding strength, improved wear performance, high hardness, and impact strength. This enhanced set of properties has significantly broadened the applicability of MMCs, particularly in industries such as automotive and aviation (Bhowmik et al., 2021).

When subjected to a focused load transfer, MMCs demonstrated the ability to withstand high tensile and compressive stresses, showcasing their superior mechanical resilience compared to unreinforced matrices (Sachinkumar, 2020). Overcoming the limitations of traditional aluminum alloys, also known as aluminum matrix composites (AMCs), is achievable by incorporating additional reinforcing components (Bandhu et al., 2018; Adesoji Adediran et al., 2020). The inclusion of these components is crucial to providing the necessary mechanical characteristics for diverse service situations. In sectors like aerospace, structural engineering, and automotive, Al-based MMCs have found widespread use. Their selection is driven by the robust mechanical, physical, and tribological characteristics that they possess and maintain during normal usage. (Moona et al., 2018; Sharma et al., 2018). The choice of aluminum as a matrix material is advantageous over steel due to its low density, excellent corrosion resistance, and superior mechanical qualities. Aluminum, being lightweight and cost-effective, is frequently utilized as a preferred transportation medium (Baskaran et al., 2014; Kaushik and Singhal, 2018). The mechanical strength of aluminum alloys experiences a significant improvement with the incorporation of hard particulate reinforcements such as SiC, TiB_2, B_4C, Al_2O_3, TiC, ZrB_2, and fly ash, among others (Dey et al., 2021; Hillary et al., 2022). Notably, fly ash, a byproduct of coal combustion in thermal power plants, stands out as a cost-effective reinforcement option. While traditional reinforcements like Al_2O_3, B_4C, TiC, and TiB_2 can be expensive, fly ash offers a more economical alternative. Its low density and affordability make fly ash a viable choice for enhancing tensile strength, hardness, and stiffness while simultaneously reducing the composite density and overall manufacturing costs for AMCs (Kasar et al., 2020; Satishkumar et al., 2021a; Hillary et al., 2022). The tribo mechanical behaviour of as-cast and heat treated A359/6 wt% Ti-based particulate reinforced homogeneous composites (TiB_2, TiO_2, and TiC) processed through modified stir casting technique. TiB_2 and TiO_2 exhibited superior interfacial bonding with Al-matrix, whereas TiC showed marginal wetting. Results revealed superior hardness, tensile strength and wear resistance for heat treated A359/TiB_2 composite than TiO_2 and TiC reinforced composites. A16061–TiB_2 composites with 3, six% and 9% by weight of reinforcements were fabricated and tempered in different media. Results of analysis of variance indicated that TiB_2 particles significantly influenced the tribological behaviour of Al6061–TiB_2 composites along with the variation in load, sliding velocity and sliding distance. (Radhika et al., 2020; Hanish Anand et al., 2024). A comparative study on the Erosion-Corrosion of aluminium silicon alloy (AA336) and its composites as AA336-7%SiC and AA336-7%TiB_2 in Basic, acidic, marine atmosphere. Composites show significantly improved wear resistance (less material loss) than alloy at all speeds and all concentrations except in basic medium (Yadav and Dixit, 2018).

In accordance with documented research, elevating the weight percentage of silicon carbide (SiC) within an aluminum (Al) matrix imparts strength to it, concurrently enhancing the compressive strength and stiffness of the Metal Matrix Composite (MMC) while diminishing its durability. Notably, heavy metals exhibit a strength-to-weight ratio three times higher. The microstructural analysis reveals a uniform distribution of Nano- SiC in the metal matrix, showcasing a robust bond between the component and matrix at their interface. Aluminium composites were synthesized through an ultrasonically assisted stir casting method by reinforcing 0.5 wt% SiC, 1.0 wt% SiC, 1.5 wt% SiC and 2.0 wt% SiC nanoparticles. The mechanical properties of the synthesized composites were significantly enhanced with the incorporation of SiC reinforcements and the maximum hardness and ultimate tensile strength (U.T.S) was attained for 1.5 wt% SiC reinforced composite [(Satishkumar et al., 2021b), 39]. V. Bhuvaneswari et al. analyzed aluminium alloy matrix Composites fabricated using conventional casting with 1, two% and 3% by weight of seashell powder. Wear and frictional resistance of the composites increased with the content of seashell powders and it was the most influential factor according to optimization results. (Bhuvaneswari et al., 2021). As a readily available byproduct in large quantities, fly ash proves to be a practical and cost-efficient solution for expanding the use of these advanced materials in various applications. Researchers have discerned that incorporating a small quantity of silicon into the Al matrix prevents SiC dissolution and curbs the formation of aluminum carbide (Al_4C_3), an undesirable needle-like structure. An intriguing facet is the presence of SiO_2 as the primary component in fly ash, rendering it a plausible source of SiC. Within the literature, several studies explore Aluminum Matrix Composites (AMCs) reinforced with fly ash particles (Dey et al., 2021; Ganeshkumar et al., 2023). R. Venkatesh et al. (Venkatesh R. et al., 2023), investigated on fabricating the lightweight aluminium alloy composite reinforced with fy ash, and its mechanical and thermal properties were improved by the introduction of diferent weight percentages (1 wt%, 3 wt% and

5 wt%) of bioceramic silicon nanoparticles (SiNPs) through the gravity stir cast technique 15 wt% fy ash/5 wt% bioceramic SiNPs sample showed the maximum tensile strength and hardness of 198 ± 1.03 Hv and 77 ± 1.22 Hv, respectively Muthy et al. (Murthy et al., 2024), Investigated on thermal properties of LM13- QUARTZ-FLYASH hybrid composite The specific heat capacity was found to be lower for the fly ash-reinforced composites and higher for the quartz-reinforced composites in comparison to the LM13 base matrix alloy. However, the highest value of thermal diffusivity and thermal conductivity were reported for the hybrid composites with a 10 wt% inclusion of both fly ash and quartz particulate reinforcements. Murthy et al. (Zuliantoni et al., 2022) adopted an ultrasonic cavitation method to fabricate nano AMCs consisting of AA2024 alloy and fly ash, placing a spotlight on the intricate exploration of their mechanical characteristics. The stir casting process, characterized by the addition of reinforcing particles to molten aluminum matrix followed by mechanical stirring, stands out as a widely embraced liquid-state processing technique for AMC creation (Ganeshkumar et al., 2023). Its popularity stems from its accessibility, versatility, and straightforwardness, making it a favored production technology. This technique proves especially efficient in melting aluminum, copper, and other alloys, accelerating the amalgamation of matrix and reinforcement materials, thus forming a composite (Kumar RR. et al., 2022; Singh et al., 2023; Vijaya et al., 2023; Kumar et al., 2024). Remarkably reliable, stir casting serves as a fabrication method for composites featuring up to 30 weight percent of reinforcement particles. This not only diminishes porosity but also ensures a uniform distribution of reinforcement throughout the composite (Kumar et al., 2019; Kumar RR. et al., 2023).

Within the scope of this research, the emphasis is placed on the development of aluminum composites utilizing silicon carbide (SiC) and fly ash particles, aimed at creating an economically viable composite with heightened properties. The chosen matrix material is AA6061, while fly ash and SiC serve as the reinforcing particles, culminating in the formation of hybrid metal matrix composites. Rigorous experimentation was conducted to unravel the tribological and mechanical behavior of the resultant AA6061 metal matrix composite. This comprehensive assessment included the Charpy impact test, scratch test, pin-on-disc test, and Rockwell hardness test (Manimaran et al., 2018; Kumar et al., 2019; Singh et al., 2022; Kumar RR. et al., 2023). In the casting result of Al-Si compound used formulation of moulding sand with bentonite binding material and Portland cement, The impact toughness test result presented that the use of non-swelling bentonite produced better toughness value while the mickroVickers hardness test result showed that Al-Si compound result using non-swelling bentonite produced 111.04 HV hardness (Andoko et al., 2018; Kumar Amit et al., 2022; Suprapto et al., 2022; Zuliantoni et al., 2022; Bhardwaj et al., 2023; Hanish Anand et al., 2024). The development of Al-Zn-based AMC alloy is limited by its low hardness and low corrosion resistance, which limits its use in many applications. This corrosion process can cause fitting corrosion and can damage the passive oxide layer that protects the metal from corrosion. To increase the corrosion resistance of AMC Al-Zn was added with hydroxyapatite ceramic reinforcement from snail shells in a corrosive medium of 3.5% NaCl solution. The addition of HAP snail waste at a concentration of 20% by weight with matrix composition Al_{90}-Zn_{10} showed optimal corrosion resistance. The corrosion resistance of Al-Cu, Al-Zn and Al-Cu-Zn alloys based on the analytical balance of the elements according to weight, thermodynamic, metallurgical rules on metal alloys, kinetic and other properties were analyzed. It was found that the Al-Zn-Cu alloy has the best corrosion resistance. Next is the Al-Cu alloy, while Al-Zn alloy has the lowest corrosion resistance (Radhika et al., 2020; Kumar Ajay et al., 2023; Venkatesh V. S. S. et al., 2023; Kumar et al., 2023c; Kumar et al., 2023d). However, most of the work concentrated on using aluminium composite with single ceramic reinforcement material such as SiC, TiB_2, B_4C. The performance of the Al6061 reinforced with SiC and Flyash has received less attention. Since no liable theory is available to guide the metal matrix composite material hence an attempt is made to study the wear characteristics of such a composite. This research contributes significantly to the advancement of MMCs by introducing a novel alloy composition and optimizing the stir casting process. The comprehensive evaluation of tribological properties and mechanical behavior provides valuable insights that can guide further research and development in this area. Additionally, the emphasis on environmental sustainability through the utilization of fly ash adds an extra dimension to the study, highlighting the potential of eco-friendly materials in modern manufacturing practices. This present study is aimed to analyze the tribological properties of stir casted aluminium hybrid composite materials. Al6061 is reinforced with Fly ash and silicon carbide particles to improve its strength and to produce a lightweight composite. Different tests like Pin on Disc Test, Micro-Hardness test and Scratch test were conducted to investigate the tribological behavior of the Al6061 metal matrix composite. The study's conclusions are intended to provide important new information for the creation of inexpensive, highly effective composites made of aluminum with a variety of industrial uses. Al6061-SiC- Fly ash metal matrix composites suitable for a range of demanding applications across various industries such as automotive components like brake discs, pistons, and engine components, lightweight armor plates for military vehicles and marine applications such as boat hulls and offshore structures.

2 Materials and methods

2.1 Materials

In this work, a composite material based on Al6061 that is reinforced with fly ash and silicon carbide (SiC) particles is made and characterized. Al6061 alloy, which is a commonly used aluminum alloy in the automotive and aerospace industries, led to its selection as the matrix material. SiC and fly ash, two reinforcing elements, were selected for the composite because of their availability and capacity to enhance its mechanical qualities. SiC particles measuring 100 µm in size and fly ash particles with a 40 µm particle size were mixed with the Al6061 matrix to create an inexpensive composite with improved properties. Tables 2,3 provide specific information about the chemical compositions of fly ash and SiC, respectively. Using X-ray fluorescence (XRF) spectroscopy, the chemical composition of the Al6061 alloy was ascertained in order to guarantee the uniformity and quality of the produced composite. The results are shown in Table 1. Additionally,

TABLE 1 Chemical composition of Al6061.

Elements	Si	Mn	Mg	Cu	Cr	Fe	Others	Al
Amount(wt%)	0.623	0.414	0.895	0.297	0.214	0.279	0.110	Balance

TABLE 2 Chemical composition of SiC.

Elements	SiC	SiO_2+SiC	C	Fe_2O	H_2O	Al_2O_3
Amount(wt%)	0.623	0.414	0.895	0.297	0.214	0.279

TABLE 3 Chemical composition of fly ash.

Elements	Si	Mn	Mg	Cu	Cr	Fe	Others	Al
Amount(wt%)	0.623	0.414	0.895	0.297	0.214	0.279	0.110	Balance

an optical emission spectrometer was used to examine the alloy's constituent composition following casting. Gaining a thorough understanding of the mechanical and tribological behavior of the Al6061-SiC-fly ash composite is the primary goal of this research. Three different weight percentages of fly ash and SiC were used in these tests to examine how they affected the performance of the composite. An overview of the Al6061-SiC-fly ash composite's production method, material characterization, tribological behavior and mechanical performance assessment are given in this article. The fabricated Al6061 metal matrix composite underwent a number of investigations to ascertain it's tribological and mechanical behavior including the Charpy impact test for general usage, the pin-on-disc test, the scratch test, the Rockwell hardness test, and the Rockwell hardness test.

2.2 Fabrication process

The utilization of the stir casting technique was imperative in the fabrication of aluminum (Al) metal matrix composites. This sophisticated process involves inducing a vortex within the molten metal, thereby facilitating a meticulous and uniform dispersion of reinforcement throughout the matrix material. In this particular study, silicon carbide (SiC) ceramic particles were chosen as the reinforcement, while aluminum alloy 6,061 was selected as the matrix material. To initiate effective mixing of the particles, the vortex generation becomes a crucial step. Commencing the process, aluminum plates were initially precision-cut into dimensions of (5 ∗ 2) cm using an abrasive cutting grinder. Subsequently, 1 kg of the Al6061 was meticulously placed in a graphite crucible within a high-temperature electric furnace, undergoing an hour-long heating process spanning temperatures from 830°C to 900°C.

Simultaneously, SiC reinforcement particles underwent preheating in a specialized furnace, attaining a temperature range of 373°C–415°C. Employing a mechanical mild steel stirrer, the stirring procedure commenced. The preheated SiC particles were methodically introduced into the molten alloy at a consistent rate of 1.2–1.4 g/s during the vortex formation phase. In a nuanced approach, a minimal amount of magnesium (0.5–0.6 weight percent) was judiciously incorporated into the mixture. This strategic addition served the dual purpose of enhancing moisture absorption and eliminating oxygen from fly ash particles. The amalgamated melt was meticulously blended before being poured into a designated mold to form the specimen. Executing the next phase, the molten metal amalgamation underwent swirling at a rate of 400 rpm for duration of 5 minutes. Following this, the amalgamated material was transferred into a die, allowing it to cool and solidify. Post a 10-min cooling period, the composite materials were extracted from the die and allowed to reach room temperature. Similar methodologies were applied to produce a variety of composite specimens with varying fractions of reinforcement. In the case of the hybrid composite, the identical processes were employed, with the differentiating factor being the inclusion of both SiC and fly ash in the reinforcing chamber. The casting was removed once the die had cooled, and Figure 1 exemplifies the bottom-pouring type stir casting method employed in this intricate procedure.

2.3 Wear testing

To assess the extent of wear on a pin-on-disc tribometer, specifically the Ducom Instruments Pvt Ltd Model No TR-201V, illustrated in Figure 2, cylindrical pins were fabricated from a cast composite material. These pins, boasting a diameter of 10 mm and a length of 50 mm, were utilized in conjunction with a disc adhering to ASTM G99-04 standards. The disc, featuring a diameter of 140 mm, a hardness rating of 58 HRC, and a surface roughness of 1.6 m, served as the counterpart in the wear evaluation. Conforming to the methodology established in previous research endeavors, a wear test was conducted under controlled conditions. The parameters included a load of 10 N, a circular track with a diameter of 80 mm, a sliding speed of 0.5 m/s, and a total sliding distance of 150 m, meticulously documented in Tables 4 (a, b) for reference. It is noteworthy that these specific test settings align with those

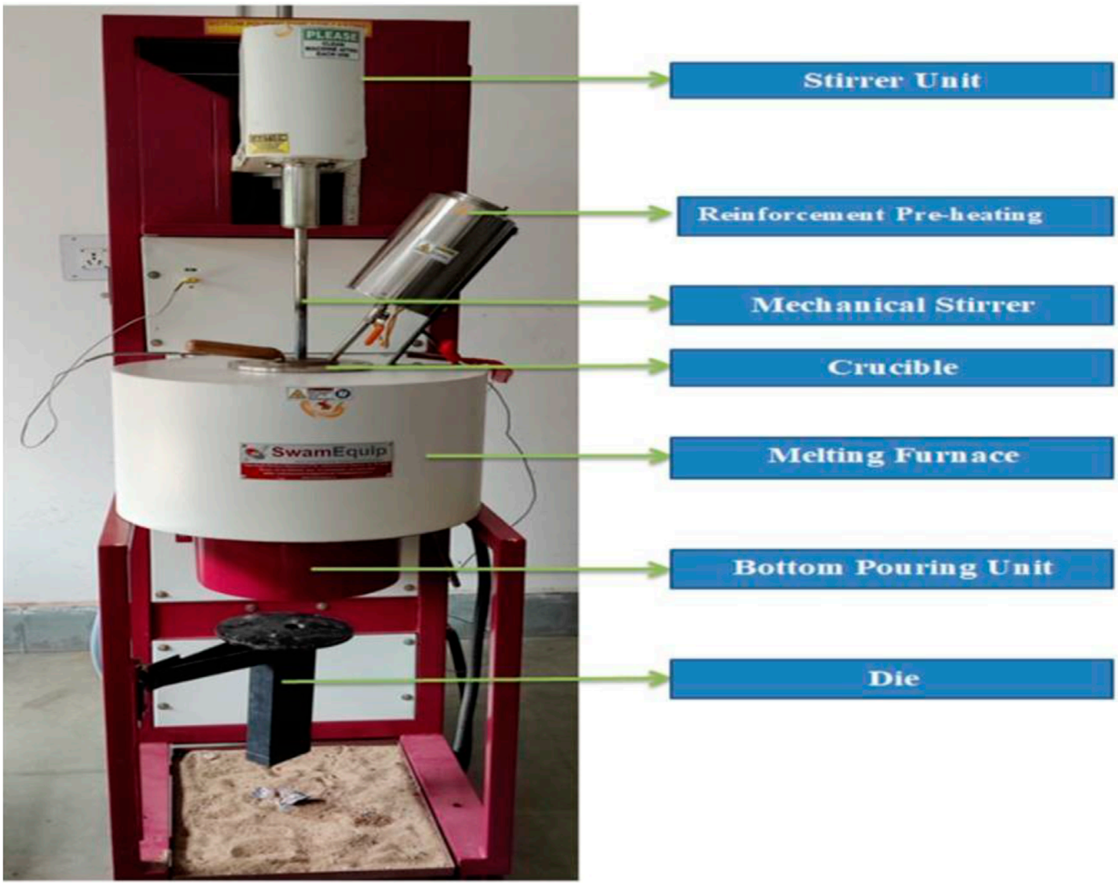


FIGURE 1
Bottom pouring types stir casting setup.

employed in the researchers' antecedent experiments. Following the wear test, the specimens were examined, and the outcomes are visually depicted in Figure 3. This meticulous experimental approach not only adheres to standardized practices but also ensures a comprehensive evaluation of the tribological behavior under the specified conditions.

2.4 Rockwell hardness test

The assessment of hardness through the Rockwell Hardness Test involves gauging the depth of indentation resulting from the application of a specific weight. In the context of this investigation, the Rockwell hardness scale H test serves as the primary method for evaluating the hardness levels. The experimentation entails the utilization of three specimens composed of Al6061. These specimens undergo a rigorous hardness assessment employing the specialized hardness tester machine, specifically the model RASN (T) (E) SR NO 2020-21/169 S.S. S INSTRUMENTS. The applied load for this assessment is precisely 60 Kgf, and the indenting tool is a steel ball with a diameter of 1/8."Figure 4 and Figure 5 accompanying this discourse visually present the specimens subsequent to their completion of the hardness testing procedure, as well as showcasing the intricacies of the hardness tester equipment used in this investigative process.

2.5 Scratch testing

The scratch tester, specifically the Ducom model, serves the purpose of determining the critical load at the point of failure in coatings, alongside assessing the scratch hardness of solid materials' surfaces. The fundamental operational concept involves the utilization of an indenter to initiate a scratch on the surface of the sample. This is achieved by applying a specified normal load, which facilitates the penetration of the indenter into the sample's surface. Subsequently, the sample is retracted from the indenter at a predetermined speed. The detailed test conditions for conducting scratch tests are meticulously outlined in Table 5, providing a comprehensive reference for ensuring precision and consistency in the experimental procedures.

2.6 Charpy impact test

The assessment of the energy absorption capacity during fracture of Al6061-SiC-Flyash composites was conducted through

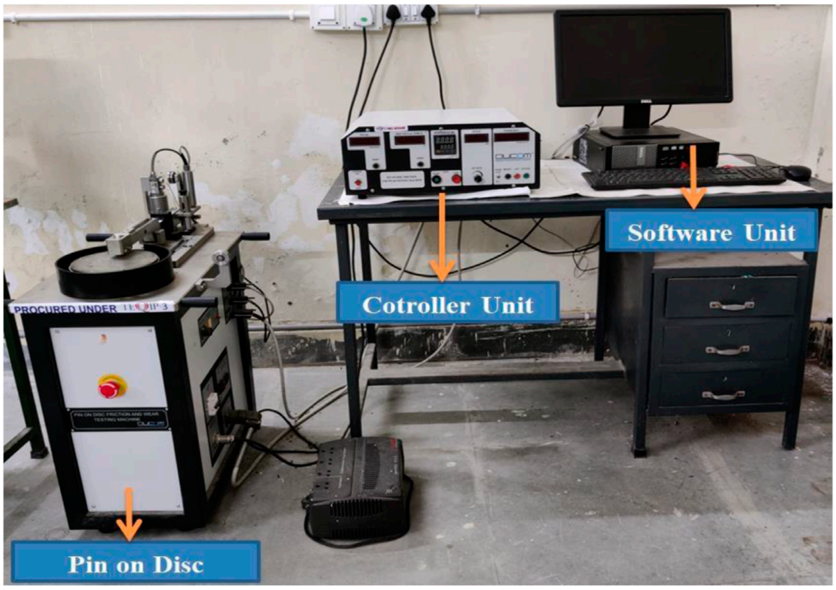


FIGURE 2
Pin on disc machine setup.

TABLE 4a Specimen composition of Al 6,061 metal matrix.

Specimens	Weightof Al (6,061)		Weightof SiC		WeightofFly ash	
	Weight %	Weight (gm)	Weight %	Weight (gm)	Weight %	Weight (gm)
Specimen1	90	990	5	55	5	55
Specimen 2	84	924	10	110	6	66
Specimen 3	78	858	15	165	7	77

TABLE 4b Wear test conditions.

Sl. No.	Test conditions	Values
1	Load	10 N
2	Pin diameter	10 mm
3	Track diameter	80 mm
4	Sliding distance	150 m
5	Rpm	185 rpm
6	Disc roughness	1.6 µm
7	Disc hardness	58 HRC

rigorous testing utilizing the Charpy impact method on specimens denoted as 1, 2, and 3. Each individual specimen, measuring 10 × 10 × 55 mm, was meticulously fabricated, featuring a centrally located 2 mm-deep v-notch. The experimental setup involved positioning a Charpy V-notched specimen within the impact testing apparatus, arranged as a straightforward supported beam between parallel jaws. In the experimental protocol, the hammer was elevated to its maximum height, establishing the initial conditions for the impact test. Subsequently, the hammer was released from this elevated position, directed towards the specimen. The entire process emulates a controlled impact scenario. Throughout the experiment, careful observations were made, documenting both the behavior of the specimen and the energy absorbed during the fracture event. This systematic approach ensured a comprehensive analysis of the fracture characteristics and energy absorption capabilities of the Al6061-SiC-Flyash composites, shedding light on their structural performance under impact conditions.

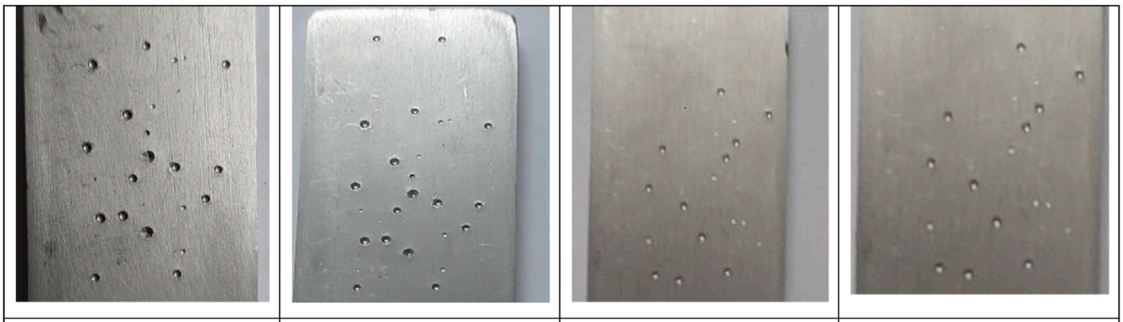
3 Result and discussion

A diverse array of examinations was conducted on the fabricated aluminum metal matrix composite specimens to meticulously scrutinize their tribological and mechanical attributes, along with an exploration of various other features. The assessment of tribological characteristics was accomplished through pin-on-disc testing,

Specimen 1 after wear test | Specimen 2 after wear test | Specimen 3 after wear test

FIGURE 3
Specimen after pin on disc wear test.

FIGURE 4
Rockwell hardness tester.



Al 6061 specimen | specimen-1 | specimen 2 | specimen 3

FIGURE 5
Hardness test samples of Al 6,061, specimen-1, specimen two and specimen three.

TABLE 5 Test condition of scratch testing.

Parameter	SPECIMEN1	SPECIMEN2	SPECIMEN3
Load type	Constant	Constant	Constant
Start Load(N)	50,60,70,80,90	50,60,70,80,90	50,60,70,80,90
Stroke (mm)	15	15	15
Scratch Speed (mm/s)	1.0	1.0	1.0
Scratch Offset (mm)	2.0	2.0	2.0

TABLE 6 Tabulation of Specimen-1 for pin on disc.

Sl. No.	Initial wt.(gm)	Final wt.(gm)	Time(min)	WearRate(μm)	Frictionalforce(N)	Coefficient of friction	Volumetricloss(mm^3)
1	6.950	6.850	5	431	13.4	0.67	0.023
2	6.850	6.720	5	509	3.4	0.17	0.030
3	6.720	6.630	5	659	16	0.8	0.021
4	6.630	6.440	5	749	16.4	0.82	0.044
5	6.440	6.380	5	332	17.2	0.86	0.141
6	6.380	5.850	5	2,315	16.5	0.826	0.124
7	5.850	5.690	5	891	18.8	0.94	0.037
8	5.690	5.530	5	844	18.8	0.94	0.037
9	5.530	5.370	5	815	17.7	0.885	0.037
10	5.370	5.220	5	726	18	0.9	0.035

complemented by an in-depth investigation of hardness using a Rockwell hardness tester. Additionally, the specimens underwent rigorous scrutiny through scratch tests conducted on a specialized scratch tester, and the impact resilience was evaluated via testing on a Charpy testing machine. This comprehensive battery of tests sought to unveil a holistic understanding of the specimens' performance across a spectrum of critical parameters.

3.1 Wear analysis

Table 6, Table 7, and Table 8 meticulously illustrate the fluctuations in wear rates across diverse compositions of metal matrix composites. The wear rate within the meticulously prepared composites escalates proportionally with the augmentation of applied load, attributing this phenomenon to the heightened contacting pressure experienced by the pin. Notably, aluminum alloys infused with robust ceramic reinforcing particles exhibit composites characterized by augmented hardness and heightened resistance to wear (Bhuvaneswari et al., 2021). Examining the detailed data presented in the tables, it becomes evident that Specimen two manifests a significantly lower wear rate when compared to its counterparts. Conversely, Specimen one emerges as the one with the maximum wear rate among the compositions. This discernible trend underscores the intricate relationship between composition, applied load, and wear characteristics in these metal matrix composites.

Examining the depicted graph in Figure 6 unveils the wear loss exhibited by the scrutinized samples. Notably, Sample 3, fortified with 7% Fly ash and 15% SiC, emerges as the frontrunner, displaying the most minimal wear loss among its counterparts. Conversely, Sample 1 records a higher magnitude of wear loss in grams when compared with Samples two and 3. The pivotal factor contributing to the wear resistance of Specimen three lies in the well-dispersed SiC particles shouldering the predominant load, thereby facilitating negligible metal-to-metal contact. Consequently, Specimen three showcases an exceptionally trifling wear loss.

It is imperative to underscore that the heightened hardness observed in the fabricated samples is intricately linked to an augmented wear resistance. This correlation further accentuates

TABLE 7 Tabulation of Specimen-2 for pin on disc.

S.No	Initial wt.(gm)	Final wt.(gm)	Time(min)	WearRate(μm)	Frictional force(N)	Coefficient of friction	Volumetric loss(mm^3)
1	9.280	9.170	5	710	16.5	0.83	0.040
2	9.170	9.070	5	630	15.5	0.8	0.037
3	9.070	8.960	5	710	15	0.75	0.040
4	8.960	8.860	5	340	14	0.68	0.037
5	8.860	8.740	5	620	8.1	0.69	0.044
6	8.740	8.650	5	540	13.9	0.69	0.033
7	8.650	8.550	5	600	14.9	0.75	0.037
8	8.550	8.470	5	590	13.9	0.69	0.029
9	8.470	8.320	5	360	10	0.5	0.055
10	8.380	8.290	5	560	14.9	0.75	0.033

TABLE 8 Tabulation of Specimen-2 for pin on disc.

Sl. N0.o	Initial wt.(gm)	Final wt.(gm)	Time(min)	WearRate(μm)	Frictional force(N)	Coefficient of friction	Volumetric loss(mm^3)
1	10.06	9.97	5	750	17.6	0.8	0.0331
2	9.97	9.85	5	590	14	0.7	0.0441
3	9.85	9.76	5	550	15	0.75	0.0331
4	9.76	9.67	5	720	16	0.8	0.0331
5	9.67	9.56	5	700	16	0.82	0.0404
6	9.56	9.44	5	700	17.5	0.85	0.0441
7	9.44	9.33	5	650	16	0.81	0.0404
8	9.33	9.25	5	540	13	0.65	0.0294
9	9.25	9.15	5	750	15.2	0.78	0.0367
10	9.15	9.10	5	740	16.9	0.85	0.0404

the significance of hardness as a determining factor in mitigating wear and tear.

3.2 Rockwell hardness (HRH)

In Figure 7, the discernible impact of incorporating reinforcement on the hardness of the composite material is vividly portrayed. Notably, Specimen-3, and Metal Matrix Composite (MMC) comprising 15% Silicon Carbide (SiC) and 7% Fly Ash, emerged as the most formidable contender with a measured hardness of 60.49 HRH. This heightened hardness is attributed to the remarkable capacity of ceramic SiC to impede dislocation movement within the material. The augmentation of fly ash particles and the fortification provided by SiC have collectively contributed to elevating the hardness of Specimen-3 beyond that of its precursors. In direct comparison with other manufactured composite specimens, it is evident that Al6061 exhibits the lowest

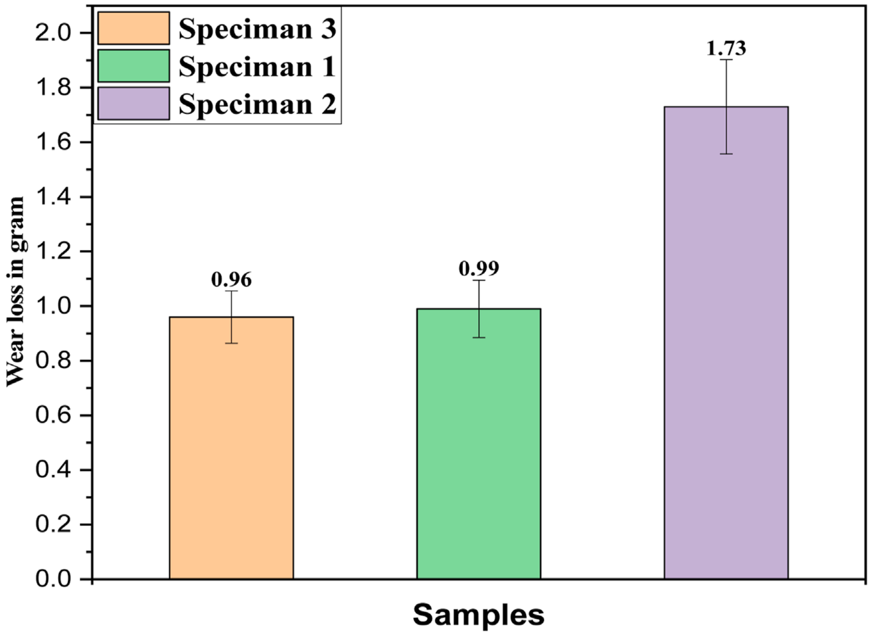


FIGURE 6
Wear Loss in grams.

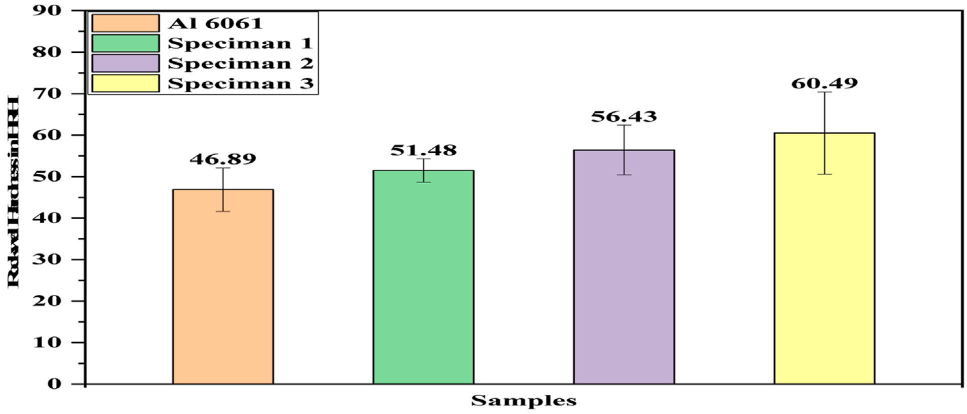


FIGURE 7
Hardness value (HRH) of specimens.

level of hardness among the tested materials. A comprehensive overview of the Rockwell hardness values for all specimens is conveniently presented in Table 9, encapsulating the nuanced variations in material hardness ensuing from distinct compositions and reinforcement strategies.

3.3 Scratch test

Commencing with an initial load of 50 N for every sample, progressively elevating to 90 N at a scratch velocity of 1 mm/s, and the work piece undergoes a meticulous scratching process. This procedure employs a diamond indenter characterized by a tip radius measuring 200 μm. Upon thorough examination, it is discerned that sample three showcases a notably heightened level of abrasion resistance compared to specimen 1. This discernment is made particularly evident when evaluating the output in terms of resistance to abrasion, a parameter that exhibits reduced susceptibility to the influence of surface fluctuations.

3.4 Impact test

Figure 8 provides a visual representation of the impact of varying weight contents of fly ash (six to seven wt%) and silicon carbide (5–15 wt%) on the Charpy impact energy. The data clearly

TABLE 9 Rockwell hardness value (HRH) of the specimens.

Samples	Al6061	Specimen -1	Specimen -2	Specimen -3
Hardness (HRH)	52	51.3	51.0	50.3
	48.6	49.4	66.1	45.4
	38.4	45.6	52.7	50.6
	40.3	43.7	50.8	60.8
	58.1	60.1	56.3	77.8
	46.5	48.9	52.1	49.4
	42.3	51.6	65.7	72.9
	32.4	43.5	53.9	59.3
	31.4	47.5	62.4	50.3
	33.3	54.7	53.3	52.6
Average hardness(HRH)	46.89	51.48	56.43	60.49

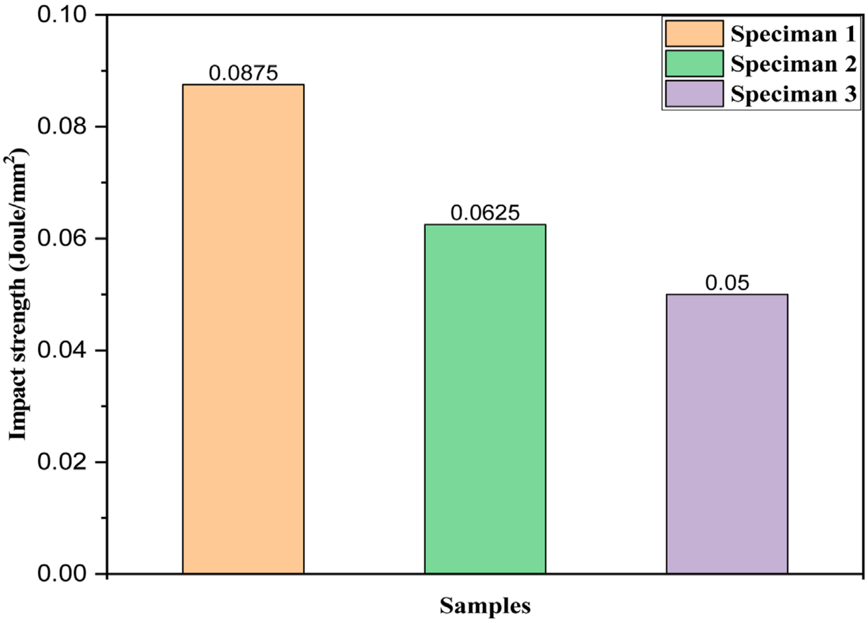


FIGURE 8
Strength of specimens Impact.

demonstrates that as the proportions of fly ash and SiC increase, there is a noticeable decrease in the energy required to induce fracture in the composite samples. The augmented presence of fly ash and SiC in the composite material leads to a significant reduction in the energy absorption capacity during fracture events. The observed decline in energy absorption is attributed to the heightened quantities of particle pores generated with the addition of SiC and fly ash percentages surpassing the wt% fly ash threshold. This phenomenon arises due to the inherent brittleness of the reinforced fly ash particles and silicon carbide, which in turn diminishes the capacity of the metal composites to undergo deformation and compromises their ductility. In essence, the greater the concentrations of SiC and fly ash, the more pronounced the adverse effect on the composite material's mechanical properties, specifically in terms of its ability to withstand and absorb impact energy during fractures. The diminution in impact strength of aluminum-silicon carbide (Al-SiC) and fly ash composites is directly attributable to the escalation in particle concentration and the presence of structural flaws. Notably, the augmenting presence of fly ash within these composites functions as a formidable impediment, strategically positioned to impede the plastic deformation of the Al6061 matrix during dislocating movements.

Upon the introduction of fly ash, a discernible attenuation in the plasticity of the Al6061 composite becomes manifest. Consequently, an inescapable reduction in toughness ensues when fly ash reinforcements are incorporated into the ductile Al6061 alloy matrices. This decline in toughness is intricately linked to the altered plasticity of the composite material due to the introduction of fly ash.

Moreover, it is imperative to underscore the critical role played by interfacial adhesion in determining the capacity of particle composites to withstand impacts. The effectiveness of the interfacial bond between the reinforcement (in this case, fly ash) and the matrix (Al6061) emerges as a pivotal factor influencing the composite material's overall resilience against impact forces. The intricacies of this interfacial adhesion profoundly shape the composite's ability to resist the deleterious effects of external forces, thereby underscoring its significance in the realm of composite material science.

4 Conclusion

In the context of bottom pouring type stir casting of Al6061-SiC-Fly ash hybrid MMC and subsequent testing for tribological and mechanical properties of the casted composite, the following conclusions have been drawn.

- The hybrid MMC (specimen-3) comprising 78% Al6061 + 15% SiC + 7% Fly Ash exhibited the lowest volumetric loss, specifically 0.96 g. In comparison, specimens two and one displayed higher wear and volumetric losses. Specimen-1 (90% Al6061 + 5% SiC + 5% Fly ash) recorded the highest wear and volumetric losses among all tested compositions.
- The hybrid MMC with a composition of 78% Al6061 + 15% SiC + 7% Fly Ash by weight % (specimen-3) demonstrated superior hardness characteristics with 60.49 HRH compared to the other specimens.
- Notably, Al6061 showed lowest hardness value of 46.89 HRH followed by specimen-1 (90% Al 6,061 + 5% SiC + 5% Fly ash) with hardness value 51.48 HRH.
- From scratch test, hybrid MMC specimen 3 exhibited significantly enhanced abrasion resistance when compared to the other specimens.
- In terms of impact strength, specimen 3 outperformed specimens 2 and 1, with a minimum value of 0.05 J/mm^2. The highest impact strength among the specimens was recorded for Specimen 1 at 0.0875 J/mm^2.

Al6061-SiC-Fly ash MMCs offer promising properties, there are challenges such as uniform dispersion and oxide layer formation that need to be addressed to fully exploit their potential. Continued research and development efforts can pave the way for overcoming these limitations and expanding the application range of these composites in various industries.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AjK: Conceptualization, Methodology, Supervision, Writing–review and editing. SK: Conceptualization, Writing–original draft. SC: Methodology, Software, Writing–original draft. RC: Formal Analysis, Validation, Writing–review and editing. AK: Investigation, Methodology, Visualization, Writing–review and editing. AmK: Investigation, Methodology, Visualization, Writing–review and editing. SKM: Methodology, Software, Visualization, Writing–review and editing. PR: Conceptualization, Investigation, Writing–review and editing. KL Methodology, Software, Visualization, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

Authors heartily thanks to Head and staffs of CSIR-MPML group for their support, where this work is carried out.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Adesoji Adediran, A., Kanayo Alaneme, K., TitilayoAkinlabi, I. O. O. &E., and Akinlabi, E. T. (2020). Wear characteristics of aluminium matrix composites reinforced with Si-based refractory compounds derived from rice husks. *Cogent Eng.* 7 (1), 1826634. doi:10.1080/23311916.2020.1826634

Andoko, F., Puspitasari, P., Gapsari, F., et al. (2018). The analysis of strength and fracture morphology of Al-Si compound made from moulding sand formulation with bentonite binding material and Portland cement. *J. Achiev. Mater. Manuf. Eng.* 89 (1), 5–12. doi:10.5604/01.3001.0012.6664

Bandhu, D., Thakur, A., Purohit, R., Verma, R. K., and Abhishek, K. (2018). Characterization and evaluation of Al7075 MMCs reinforced with ceramic particulates and influence of age hardening on their tensile behavior. *J. MechSciTechnol* 32 (7), 3123–3128. doi:10.1007/s12206-018-0615-9

Baskaran, S., Anandakrishnan, V., and Duraiselvam, M. (2014). Investigations on dry sliding wear behavior of *in situ* casted aa7075–tic metal matrix composites by using taguchi technique. *Mater Des.* 60, 184–192. doi:10.1016/j.matdes.2014.03.074

Bhardwaj, A., Bhatnagar, A., and Kumar, A. (2023). "Current trends of application of additive manufacturing in oral healthcare system, in a book: advances in Additive Manufacturing Artificial Intelligence," in *Nature-inspired, and biomanufacturing* (Amsterdam, Netherlands: Elsevier), 479–491.

Bhowmik, A., and Biswas, A. A. (2021). Wear resistivity of Al7075/6Wt.%Sic composite by using grey-fuzzy optimization technique. *Silicon* 14, 3843–3856. doi:10.1007/S12633-021-01160-X

Bhuvaneswari, V., Rajeshkumar, L., and Nimel SwornaRoss, K. (2021). Influence of bioceramic reinforcement on tribological behaviour of aluminium alloy metal matrix composites: experimental study and analysis. *J. Mater. Res. Technol.* 15, 2802–2819. doi:10.1016/j.jmrt.2021.09.090

Dey, D., Bhowmik, A., and Biswas, A. (2021). Characterization of physical and mechanical properties of aluminium based composites reinforced with titanium diboride particulates. *J. Compos. Mater.* 55 (14), 1979–1991. doi:10.1177/0021998320980800

Ganeshkumar, S., Kumar, A., Maniraj, J., Babu, Y. S., Ansu, A. K., Goyal, A., et al. (2023). Exploring the potential of nano Technology: a assessment of nano-scale multi-layered-composite coatings for cutting tool performance. *Arabian J. Of Chem.* 16 (10), 105173. doi:10.1016/j.arabjc.2023.105173

Hanish Anand, S., Venkateswaran, N., Sathishkumar, B., and Rajeshkumar, L. (2024). Microstructural, mechanical and tribological analysis of TiB2 ceramic-reinforced Al6061 aluminium alloy composites. *Arab. J. SciEng* 49, 1827–1842. doi:10.1007/s13369-023-07978-4

Hillary, J. J. M., Sundaramoorthy, R., Ramamoorthi, R., and Chelladurai, S. J. S. (2022). Investigation on microstructural characterization and mechanical behaviour of aluminium 6061 – CSFA/sicp hybrid metal matrix composites. *Silicon* 14, 11561–11576. doi:10.1007/s12633-022-01881-7

Kasar, A. K., Gupta, N., Rohatgi, P. K., and Menezes, P. L. (2020). A brief review of fly ash as reinforcement for composites with improved mechanical and tribological properties. *JOM* 72, 2340–2351. doi:10.1007/S11837-020-04170-Z

Kaushik, N., and Singhal, S. (2018). Hybrid combination of taguchi- GRA-PCA for optimization of wear behavior in aa6063/sicp matrix composite. *Prod. &Manufacturing Res.* 6 (1), 171–189. doi:10.1080/21693277.2018.1479666

Kumar, A., Gulati, V., Kumar, P., Singh, V., Kumar, B., and Singh, H. (2019). Parametric effects on formability of AA2024-O aluminum alloy sheets in single point incremental forming. *J. Of Mater. Res. And Tech.* 8, 1461–1469. doi:10.1016/j.jmrt.2018.11.001

Kumar, A., Kumar, P., Mittal, R. K., and Singh, H. (2023c). "Preprocessing and postprocessing in additive manufacturing, in a book: advances in additive manufacturing artificial intelligence," in *Nature-inspired, and bio manufacturing* (Amsterdam, Netherlands: Elsevier), 141–165.

Kumar, A., Kumar, P., Mittal, R. K., and Singh, H. (2023d). "Printing file formats for additive manufacturing technologies, in a book: advances in additive manufacturing artificial intelligence," in *Nature-inspired, and bio manufacturing* (Amsterdam, Netherlands: Elsevier), 87–102.

Kumar, A., Kumar, V., and VikasModgil, A. K. (2022b). Stochastic Petri nets modelling for performance assessment of a manufacturing unit. *Mater. Today Proc.* 56, 215–219. doi:10.1016/j.matpr.2022.01.073

Kumar, A., Mittal, R. K., and Haleem, A. (2023b). "Advances in additive manufacturing: artificial intelligence," in *Nature-inspired, and biomanufacturing* (Amsterdam, Netherlands: Elsevier). ISBN- 978-0-323-91834-3.

Kumar, M., Sivaiah, P., Vijaya, G., Kumar, A., Kumar, D., Pandey, S., et al. (2024). Simulation of metal ceramic single layer coatings for solar energy applications. *Mater. Sci. For Energy Technol.* 7, 85–90. doi:10.1016/j.mset.2023.06.003

Kumar, R. R., Kumar, A., Kumar, A., Ansu, A. K., Goyal, A., Saxena, K. K., et al. (2023a). Thermal simulation on friction stir welding of AA6061 aluminum alloy by computational fluid dynamics. *Int. J. Interact. Des. And Manuf. (Ijidem)* 3, 1. doi:10.1007/s12008-023-01311-x

Kumar, R. R., Singh, A., Kumar, A., Ansu, A. K., Kumar, A., Kumar, S., et al. (2022a). Enhancement of friction stir welding characteristics of alloy AA6061 By design of experiment methodology. *Int. J. Interact. Des. And Manuf. (Ijidem)* 17, 2659–2671. doi:10.1007/s12008-022-01106-6

Manimaran, R., Jayakumar, I., Mohammad Giyahudeen, R., and Narayanan, L. (2018). Mechanical properties of fly ash composites—a review. *Energy Sources, Part A* 40 (8), 887–893. doi:10.1080/15567036.2018.1463319

Moona, G., Walia, R. S., Rastogi, V., and Sharma, R. (2018). Aluminium metal matrix composites: a retrospective investigation. *Indian J. Pure ApplPhys (IJPAP)* 56 (2), 164–175.

Murthy, B. R. N., Ambekar, A. M., and Hiremath, A. (2024). An investigation of the thermal properties of LM13- quartz- fly-ash hybrid composites. *J. Compos. Sci.* 8 (3), 90. doi:10.3390/jcs8030090

Pateriya, A., and Pradhan, M. K. (2023). Dry sliding wear response of aluminium matrix composites (AMCs): a critical review. *Mater. Res. Express* 10 (2), 022001. doi:10.1088/2053-1591/acb63c

Radhika, N., Sasikumar, J., and &Arulmozhivarman, J. (2020). Tribo-mechanical behaviour of Ti-based particulate reinforced as-cast and heat treated A359 composites. *Silicon* 12, 2769–2782. doi:10.1007/s12633-019-00370-8

Sachinkumar, S. (2020). Studies on microstructure and mechanical characteristics of as cast AA6061/SiC/fly ash hybrid AMCs produced by stir casting. *Mater. Today Proc.* 20, A1–A5. doi:10.1016/j.matpr.2020.01.266

Satishkumar, P., Infant Jegan Rakesh, A. J., Meenakshi, R., and Saravana Murthi, C. (2021a). Characterization, mechanical and wear properties of Al6061/Sicp/fly ashp composites by stir casting technique. *Mater. Today Proc.* 37 (Part 2), 2687–2694. doi:10.1016/j.matpr.2020.08.530

Satishkumar, P., Infant JeganRakesh, A. J., Meenakshi, R., and SaravanaMurthi, C. (2021b). Characterization, mechanical and wear properties of Al6061/Sicp/fly ashp composites by stir casting technique. *Mater. Today Proc.* 37, 2687–2694. doi:10.1016/j.matpr.2020.08.530

Sharma, P., Paliwal, K., Dabra, V., Sharma, S., Sharma, N., and Singh, G. (2018). Influence of silicon carbide/graphite addition on properties of AA6082 reinforced composites. *Aust. J. Mech. Eng.* 18, S176–S184. doi:10.1080/14484846.2018.1505995

Singh, B. K., Chauhan, N., Mishra, A. K., Yadhuvanshi, A. A., Kumar, A., Ansu, A. K., et al. (2023). Experimental investigation of welding parameters to enhance the impact strength using gas tungsten arc welding. *Int. J. Interact. Des. And Manuf. (Ijidem)* 15, 1–8. doi:10.1007/s12008-023-01264-1

Singh, V., Kumar, A., Alam, M., Kumar, A., Kumar, P., and Goyat, V. (2022). A study of morphology, UV measurements and zeta potential of zinc ferrite and Al2O3 nanofluids. *Mater. Today Proc.* 59, 1034–1039. doi:10.1016/j.matpr.2022.02.371

Suprapto, W., Zuliantoni, Z., Setyarini, P. H., Gapsari, F., Sudjito, S., and Irawan, Y. S. (2022). Corrosion resistance analysis of Al-Cu, Al-Zn and Al-Cu-Zn alloys. *Key Eng. Mater.* 935, 33–40. doi:10.4028/p-04p5jx

Venkatesh, R., Sakthivel, P., Selvakumar, G., Krishnan, A. M., Purushothaman, P., and Priya, C. B. (2023a). Mechanical and thermal properties of a waste fly ash-bonded Al-10 Mg alloy composite improved by bioceramic silicon nanoparticles. *Biomass Conv. bioref.*, doi:10.1007/s13399-023-04588-w

Venkatesh, V. S. S., Rao, G. P., Patnaik, L., Gupta, N., Kumar, S., Saxena, K. K., et al. (2023b). Processing and evaluation of nanoSiC reinforced aluminium composite synthesized through ultrasonically assisted stir casting process. *J. Mater. Res. Technol.* 24, 7394–7408. doi:10.1016/j.jmrt.2023.05.030

Vijaya, G., Singh, M. M., Kumar, M., Kumar, A., Kumar, M. A., Kumar, D., et al. (2023). Nano indentation studies on ceramic thinfilms coatings deposited using sputtering process for energy applications. *Mater. Sci. For Energy Technol.*,

Yadav, P. K., and Dixit, G. (2018). Erosive-corrosive wear of aluminium-silicon matrix (AA336) and sicp/tib2p ceramic composites. *Silicon* 11, 1649–1660. doi:10.1007/s12633-018-9981-2

Zuliantoni, Z., Suprapto, W., Setyarini, P. H., and &Gapsari, F. (2022). Hydroxyapatite effect on the corrosion rate of AMC Al-Zn by powder metallurgy. *Key Eng. Mater.* 935, 41–48. doi:10.4028/p-613s0t