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MECHANICAL AND TRIBOLOGICAL PERFORMANCE OF Al-x SiC COMPOSITES PRODUCED BY POWDER METALLURGY TECHNIQUE FOR THROTTLE VALVES APPLICATIONS

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ABSTRACT
The present work aims to study the effect of SiC particles addition on the microstructural, mechanical, and tribological properties of Al/SiC composites produced by hot compaction powder metallurgy technique. High-energy planetary ball milling was used for mixing the pure Al powder with different SiC particles content of 2.5, 5, 7.5, and 10 wt.% at a speed of 350 rpm for 12 h. A hot compaction technique was used to produce the present Al/SiC composites at a pressure and temperature of 900 MPa and 550 ºC, respectively. Theoretical, actual, and relative densities as well as porosity percentages were measured. Scanning electron microscopy (SEM) was used to study the microstructural observations of present composites. Mechanical properties tests, which include microhardness and compression tests, were conducted at room temperature to estimate the Vickers microhardness number and ultimate compression strength of the present Al/SiC composites. Moreover, wear rate and friction coefficient tests, as tribological properties, of Al/SiC composites were investigated under dry sliding conditions by a pin-on-disc test rig.

Based on the experimental results, all the mechanical and tribological properties showed significant improvement of pure Al with gradually increasing SiC content up to 10%. Relative density enhanced and reached the highest value of 98 % at 0.5 wt.% SiC content. Also, the microstructure examination showed that the dispersion of SiC particles within the Al matrix was good and uniform. Hence, Vickers microhardness number and ultimate compressive strength results of pure Al were enhanced by 66.5, and 50.53 %, respectively at SiC content of 5 wt.%. Moreover, the wear rate characteristics of Al/7.5 wt.% SiC composites were improved by 47.3, 47.6, and 40.9 % at applied loads of 5, 10, and 15 N, respectively compared to pure matrix Al. Finally, the friction coefficient of pure Al was improved and reached their optimum values at the SiC content of 5 wt.% under applied loads of 5, 10, and 15 N.

KEYWORDS
Al−SiC composite; powder metallurgy; microstructure; mechanical properties, tribological properties.

INTRODUCTION

Metal matrix composites (MMCs) are advanced materials that consist of a metal matrix reinforced with other materials, often in the form of particles, fibers, or whiskers, [1–3]. These materials are designed to combine the properties of metals with the enhanced mechanical, thermal, and electrical properties of the reinforcement materials, [4, 5]. The matrix in MMCs is typically a metal, such as aluminum, titanium, or magnesium, [6- 8]. The reinforcement materials can be ceramics, carbon fibers, silicon carbide (SiC), boron carbide B_4C, or other materials, [9-12]. These reinforcements are chosen based on the desired properties, such as increased strength, stiffness, wear resistance, and high-temperature performance, [13, 14]. The MMCs can be fabricated through various methods, including powder metallurgy, casting, and in-situ techniques, [15, 16]. Manufacturing technique depends on the specific composite design and desired properties, [17]. MMCs propose a range of advantageous properties, involving high strength-to-weight ratio, enhanced wear resistance, improved stiffness, and excellent thermal stability. They are applied in automotive, and electronic components, [18]. Also, MMCs are used in aircraft components to reduce weight while maintaining strength and durability such as engine parts, landing gear, and structural components, [19, 20]. MMCs can be found in high-performance car components like brake discs and engine parts. Moreover, MMCs can be used in heat sinks and electronic packaging to dissipate heat effectively, [21].

The main challenges in working with MMCs include production costs, limited designs for specific applications, and potential difficulties in achieving a good bond between the matrix and the reinforcement, [22]. MMCs continue to be an area of active research and development, with ongoing efforts to improve their properties, reduce production costs, and expand their applications in various areas such as throttle valve. Recently, the high demands for new technologies have toward the current production procedures requiring new equipment, either to decrease costs or optimize the products operation, [23]. There is an increase in demand and need for advanced materials to obtain desired properties. MMCs reinforced by ceramics are very promising materials for automobile, aerospace, and defiance applications due to excellent combination of properties, [24]. One of the well-known methods of MMNCs fabrications are the powder metallurgy technique which has an excellent distribution in the material than casting process, [25, 26]. MMCs with high stiffness and specific strength could be used in applications in which saving weight is an important factor.

Excellent wear resistance, along with raises specific strength also supports MMNCs use in brake parts, the automotive engine, and aircraft, excellent mechanical properties, low cost, ductility, and wide range of applications, [27, 28]. Aluminum is a

very important metal whose application and use are common industrially in engineering and product manufacturing. Aluminum is indeed a crucial metal with widespread industrial applications in engineering and product manufacturing due to its unique combination of properties. Some of the key characteristics that make aluminum a popular choice include its low density, high strength-to-weight ratio, corrosion resistance, electrical conductivity, and recyclability, [29]. Here are some of the common applications of aluminum in various industries, Aluminum is extensively used in the aerospace industry for manufacturing aircraft structures, including airframes, wings, and engine components. Its lightweight nature helps reduce fuel consumption and improve overall efficiency, [30]. Aluminum is employed in automotive manufacturing to reduce vehicle weight, thereby improving fuel efficiency, and reducing emissions. It is used in the production of engine blocks, transmission cases, wheels, and body panels, [30]. Aluminum is used in the construction industry for windows, doors, curtain walls, and structural components due to its corrosion resistance and ease of shaping. It's also commonly used in lightweight scaffolding and access systems, [31]. Aluminum is used in the construction of ships, trains, and bicycles due to its lightweight and corrosion-resistant properties. It's also employed in the marine industry for boat hulls and components, [32] . Aluminum's high electrical conductivity makes it ideal for electrical transmission lines and conductors. It's also used in heat sinks for electronic devices to dissipate heat efficiently, [33].

Some medical devices and equipment are made from aluminum due to its biocompatibility, corrosion resistance, and ease of sterilization, [34]. Aluminum can be alloyed with other elements to enhance its properties. Some common aluminum alloys include the 6061-T6 and 7075-T6 alloys, which are known for their high strength and durability, [35]. The versatility of aluminum and its wide range of applications make it one of the most important metals in modern industry. Its use continues to grow as industries seek lightweight, durable, and environmentally friendly materials for various applications, [36]. Aluminum Matrix Composites (AMCs) are a subset of Metal Matrix Composites (MMCs) in which aluminum serves as the matrix material, [37]. These composites are created by incorporating high-strength and high-stiffness reinforcement materials into an aluminum alloy matrix, [38]. The goal is to combine the lightweight and corrosion-resistant properties of aluminum with the enhanced mechanical properties offered by the reinforcement phase, [39].

Al MMCs normally fabricated by powder metallurgy, spray co-deposition, diffusion bonding, spark plasma sintering, or liquid casting techniques, which fabricate a reinforced Al form with improved mechanical properties compared to the pure Al alloy, [40- 45]. Although particulates are homogenously distributed over liquid metal at the liquid casting technique, this method is cost effective, [46]. Moreover, powder metallurgy route is preferred to fabricate Al MMCs, whereas the ball milling is used to blend the Al with reinforcement materials. Then, powders were heated and compacted in a die to fabricate Al MMCs, [47]. Al MMCs could be enhanced with various fillers, such as boron carbide (B_4C), alumina (Al_2O_3), titanium carbide (TiC),

tungsten carbide (WC), carbon nano tubes (CNTs), silicon nitride (Si_3N_4), graphite (Gr), titanium dioxide (TiO_2) silica (SiO_2), aluminum nitride (AlN), and silicon carbide (SiC), [49- 57]. The use of alumina and silicon carbide (SiC) as ceramic reinforcements in aluminum matrix composites (Al MMCs) is quite common due to their advantageous properties, [58]. When silicon carbide or alumina particles are incorporated into aluminum alloys, they enhance the strength and specific stiffness of the resulting composite, [59]. This makes the material stronger and more rigid than the base alloy.

SiC is known for its excellent wear resistance, [60]. This property is beneficial in applications where the composite is exposed to abrasive wear. This makes it an attractive choice for reinforcing materials, [61]. The addition of SiC can lead to improvements in various mechanical properties of the composite, including Young's modulus (a measure of stiffness), tensile strength, ductility, and fracture toughness. These improvements are highly valuable in engineering applications, [62]. Ceramic reinforcements are typically used at the micro-level. This means that the SiC or alumina particles are very fine, and they are dispersed within the aluminum matrix to achieve the desired material properties, [63]. Some ceramic reinforcements, including SiC, can enhance the machinability of the composite. This is important for manufacturing and shaping components from the material, [64].

Accordingly, some challenges subjected to throttle valves as wear and low mechanical properties. So, to improve tribological and mechanical properties of throttle valves, we are scattering and dispersing different weight fraction contents of x wt.% SiC inside aluminum. The incorporation of silicon carbide as ceramic reinforcements in aluminum matrix composites offers a wide range of advantages especially via Powder Metallurgy (PM) method, including enhanced strength, wear resistance, and improved mechanical properties. These composites are used in various applications such as throttle valve where these properties are highly valuable.

MATERIALS AND EXPERIMINTS

Materials

In this work, the present MMCs composed of pure matrix Al reinforced with various SiC particles contents. The matrix material composed of pure Al powder with an average size of 50 µm, which obtained from El-gomhouria Chemicals Company, Egypt. The reinforcement material was SiC particles with an average size of 20 µm. It was supplied by Marjan Chemicals Company, Egypt.

Specimens Preparation

Al/SiC MMCs preparation involves material collection to obtain specimens with different weight fractions (wt. %) of SiC. The main purpose of SiC addition to Al metal was to enhance the strength of the produced material, [65]. To remove any powder clusters and get more homogeneity, amounts of pure Al with 2.5, 5, 7.5, and 10 wt.% of SiC particles were mixed by PQ-N2 planetary ball milling machine at 350 rpm for 12 h with ball to powder weight ratio of 15:1. Then, the composites were

compacted at 550 ºC in a uniaxial press at 900 MPa. Figure 1 shows the composites preparation steps, and Table 1 shows the prepared samples compositio

Table 1 Composition of the prepared samples.

Samples No.	Materials content	
	Al, wt.%	SiC, wt.%
1	100	0
2	97.5	2.5
3	95	5
4	92.5	7.5
5	90	10

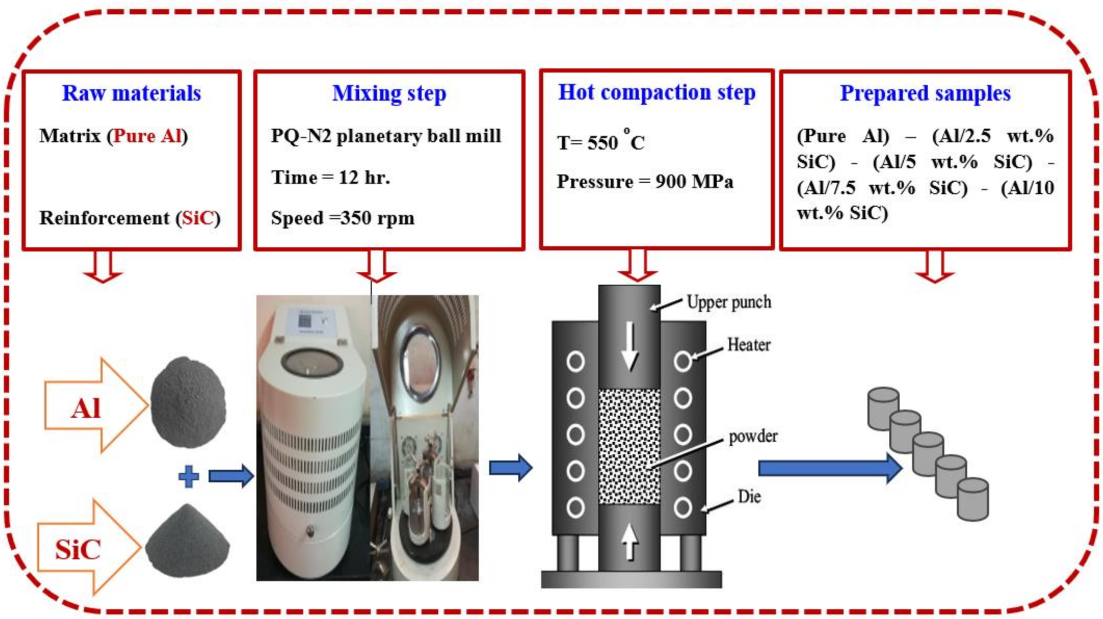

Fig. 1 Composites preparation steps.

Characterizations of Al-SiC Composites.

Density of Al-SiC Composite.

The actual density of the present composites was measured according to Archimedes' principle, as following:

$$\text{Actual Density} = \frac{W_a}{W_a - W_w} \quad \text{gm/cm}^3 \qquad (1)$$

Where, W_w and W_a are the sample weight in water and air, respectively.

The rule of mixture was also used to calculate the theoretical density (D_{th}) of the present composites, as following:

$$\frac{1}{D_{th}} = \frac{wt.\%\,M}{D_M} + \frac{wt.\%\,R}{D_R} \qquad \text{gm/cm}^3 \qquad (2)$$

Where, wt. % M and wt. % R is weight fraction of matrix and reinforcement, respectively; DM and DR are the density of matrix and reinforcement, respectively. Relative density was determined by dividing the actual density by theoretical density.

Microstructure Examination of Al-SiC

SEM instrument with energy dispersive spectroscopy (EDS) was used to study the characteristics of morphology of grains on metallographic polished samples. Moreover, to examine if there are any other formed phases during the hot compaction, the microstructure characterization studies of Al–SiC composite specimens were evaluated by X-ray diffraction (XRD).

Mechanical Properties

Surface Microhardness

Vickers microhardness test was performed for the present composites using a load of 500 gf for 15 seconds as the dwell time of the indenter on the sample surface according to ASTM E384-99. An average of six readings along the cross-section polished surface of the samples were reported. VHN was estimated as follows:

$$VHN = 1.854\left(\frac{P}{d^2}\right) \qquad (3)$$

Where, P is the applied load, gf, and d is the indentation mean diagonal length, µm.

Compression Test

A compression test was performed to obtain the ultimate compressive strength of the present composites. The compression test was conducted using a universal testing machine at room temperature according to ASTM D-695 standard. The dimensions of the test sample were 10.4 mm in diameter and 10 mm in length, and the crosshead speed was kept at 1.5 mm/min.

Tribological Properties

Wear Rate and Friction Coefficient Tests

Dry sliding wear rate and friction coefficient tests were conducted using a pin-on-disk test rig according to G99 standard. Samples were polished and cleaned with ethanol before and after the testing to eliminate any impurities. The sample was used as a pin and the AISI 52100 steel (with the hardness of 63 HRC) was used as a sliding disk. Wear and friction tests were conducted under applied loads of 5, 10, and 15 N at sliding speed of 1.2 m/s. The wear rate was determined by weighting the resulting debris after sliding distance of 360 m. The friction force was measured during the wear test by a load cell of 40 Kg, and it was recorded by a calibrated data logger every one millisecond. Then, the friction coefficient was calculated by dividing the friction force by the applied normal load. Each sample was tested at least three times in the tribological tests, and the readings were averaged to obtain accurate results.

RESULTS AND DISCUSSION

Microstructure Estimations

SEM images of consolidated specimens containing different SiC particles contents of 2.5, 5, 7.5, and 10 wt.% were displayed in Fig. 2 a, b, c, and d, respectively. SEM characterization was conducted for the specimen containing 10 wt.% SiC. These images show the microstructure of the consolidated specimens. Microstructure refers to the arrangement of grains, phases, and distribution of SiC particles within the aluminum matrix, which is a crucial factor that affects the properties of the material, such as mechanical strength and wear resistance. The microstructure shown in Fig. 2 reveals a grainy structure in the consolidated specimens. This grainy structure represents the arrangement of aluminum and SiC particles within the composite material.

As the SiC particles content increases up to 5 wt.%, it is noted that the grain size of the Al-SiC composite becomes finer, as shown in Fig. 5 b. This suggests that the addition of SiC particles refines the grain structure of the aluminum matrix. SiC has a positive effect on the mechanical properties of the composite. Therefore, smaller grains result in more grain boundaries. The increase in the number of grain boundaries is often associated with improvements in the mechanical properties, such as increased strength, hardness, and toughness. The microstructure analysis also indicates the presence of porosity in the consolidated specimens. This porosity is likely a result of the hot compaction process used during the fabrication of the composite material.

Reducing porosity is important for achieving the desired mechanical properties, as excessive porosity can weaken the material. Micro-voids are detected in all the consolidated specimens even in the one that is free of reinforcement, as indicated in Fig. 2 a. Reinforcement of the Al metal matrix with ceramic SiC particles often lead to the formation of voids and pores. This phenomenon is related to the significant difference in surface energy between metals and ceramics. The presence of these voids can affect the mechanical properties of the composite material. The arbitrary shape of the ceramic phase affects the number of voids in the composite during the compaction process. Irregularly shaped ceramic particles create spaces or voids within the material, affecting its overall density and properties. Also, Fig. 2 indicates that the increase in content of SiC particles can facilitate the tendency to form macro-sized voids. This means that as the concentration of SiC particles increases, the likelihood of larger voids or pores forming within the composite material also increases, as shown in Fig. 2 d.

In summary, increasing the weight percentage of SiC in the Al-SiC composite results in a finer grain structure, which in turn, leads to more grain boundaries and enhanced mechanical properties. However, the presence of porosity needs to be addressed to optimize the material's quality and performance. Proper manufacturing and processing techniques can help minimize porosity and maximize the benefits of SiC reinforcement in the composite.

EDAX analysis, as indicated in Fig. 2 e, shows the grainy structure of Al- 10 wt. % SiC composites. EDAX is used to study the grainy structure of the Al-SiC composites, to reveal the exact percentage of silicon, aluminum, and any other elements present in the composite. It can reveal information about the distribution of elements within the grains and at grain boundaries. This information is critical for understanding the microstructure and mechanical properties of the composite material. If the SiC content is expected to be 10 wt.% in a particular sample, EDAX can confirm whether this target percentage has been achieved. Also, as indicated in Fig. 2 e, during the hot compaction process, there is no new element developed. The XRD patterns of the Al-SiC composite were analyzed in Fig. 3. The XRD patterns reveal the presence of SiC phases in the composite. This means that the SiC particles have been successfully incorporated into the Al matrix.

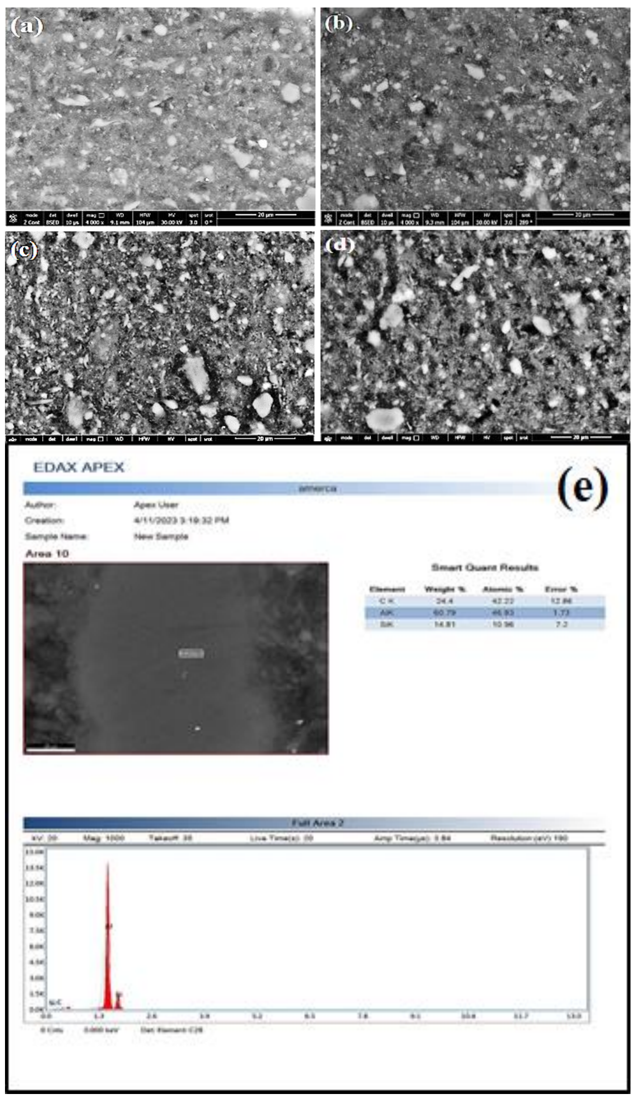

Fig. 2 SEM micrograph of Al/SiC composites: (a) 2.5, (b) 5, (c) 7.5, (d) 10 wt.% SiC particles, and (e) EDAX analysis of Al/10 wt.% SiC particles.

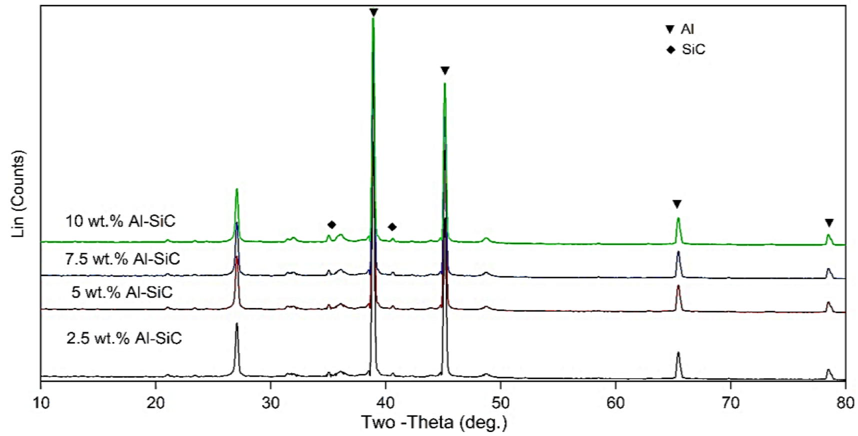

Fig. 3 XRD patterns of the Al- SiC composites with different weight fraction (wt.%) contents.

As the SiC particles content was increased up to 10 wt. %, the intensity of the SiC peaks in the XRD pattern gradually increases. This indicates that the concentration of SiC particles in the composite is higher as the SiC content increases. The description also mentions that the Al peak becomes less broad with increasing SiC particles content. This may be due to the aluminum phase in the composite becoming more defined and crystalline as more SiC is added. The broadening of peaks often indicates smaller or less defined crystalline structures, so the narrowing of the Al peak suggests improved crystal structure with increased SiC content. The XRD analysis indicates that by raising SiC particles as weight fraction of in the composite, the SiC peaks become more intense, and the aluminum peak becomes narrower and more defined. This suggests a better incorporation of SiC into the composite and a more crystalline structure for the aluminum phase.

Densification Estimation

Fig. 4 illustrates the effect of SiC content on the relative density of Al matrix. As the SiC content in the composite material increases, the relative density of the Al matrix decreases. This may be due to the increased porosity at the SiC grain boundaries within the Al matrix. Additionally, as SiC content increases, some agglomerations or clumping of SiC particles may occur within the composite. These agglomerations can lead to the formation of internal voids or gaps in the material. These voids further reduce the overall density of the composite, as they represent areas where the material is less dense. In general, the decrease in relative density is due to the combination of the lower density of Al compared to SiC, and the presence of internal voids or gaps caused by SiC agglomerations. This information is valuable in understanding how the composition of a composite material affects its overall density and, by extension, its properties and performance.

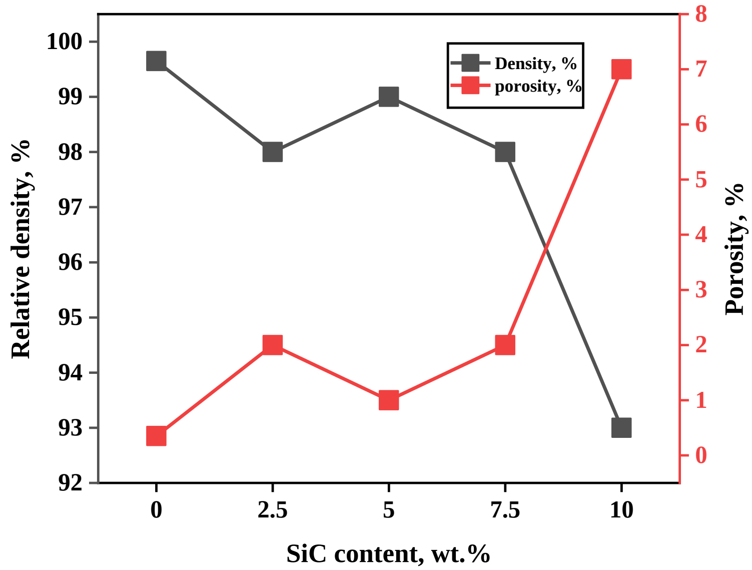

Fig. 4 Relative density and porosity percentages of Al-SiC composites.

Microhardness and Compression Tests Results

Microhardness measurements are a useful technique for assessing the hardness of materials on a small scale, typically at the micro or nano level. When it comes to Al-SiC composites, micro hardness testing can provide valuable information about the material's mechanical properties. Actual results for microhardness of Al–SiC composites were exposed in Fig. 5. The microhardness number of the composites increases as the content of SiC increases up to 5 wt.%. The addition of SiC helps in refining the grain structure of the composite. Smaller grains typically result in increasing hardness. SiC particles possess significantly higher hardness properties compared to pure Al.

Therefore, the presence of SiC in the composite also contributes to the overall increase in hardness. On the other hand, as the SiC content in the composites increases beyond 5 wt.%, the hardness of the aluminum matrix decreases. This is likely due to several factors, including agglomeration of SiC particles observed in these composites, as shown in Fig. 2 c. Agglomeration leads to non-uniform distribution and may result in areas of reduced hardness. The increase in crystalline size is mentioned as a contributing factor to the lower strength of these composites. Larger crystalline may reduce the overall hardness of the material. The mechanical properties of Al/SiC composites were influenced by the SiC content. An optimal balance of these constituents, particularly up to 5 wt.% SiC, results in improved hardness due to grain refinement and the intrinsic hardness of SiC. Beyond this point, the agglomeration of SiC and increased crystalline size in the matrix can lead to a reduction in hardness and strength.

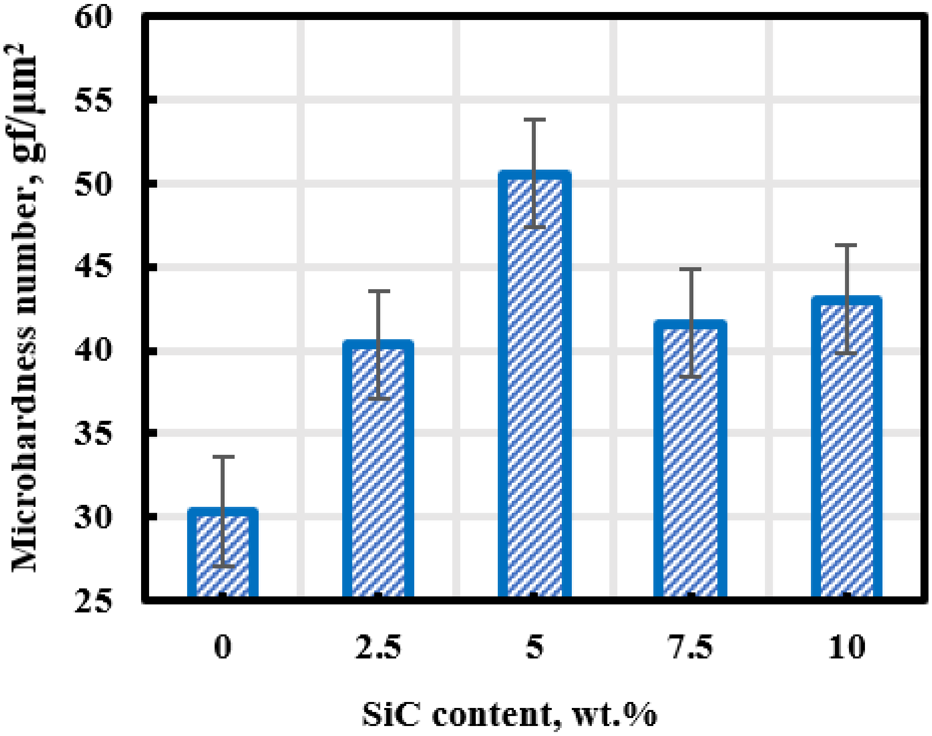

Fig. 5 Microhardness values as a function of SiC content.

The compression test of the present Al/SiC particles composites were conducted at room temperature using universal testing machine. The stress-strain curves resulted from compression test were plotted to estimate the ultimate compressive strength of the composites, as indicated in Fig. 6.

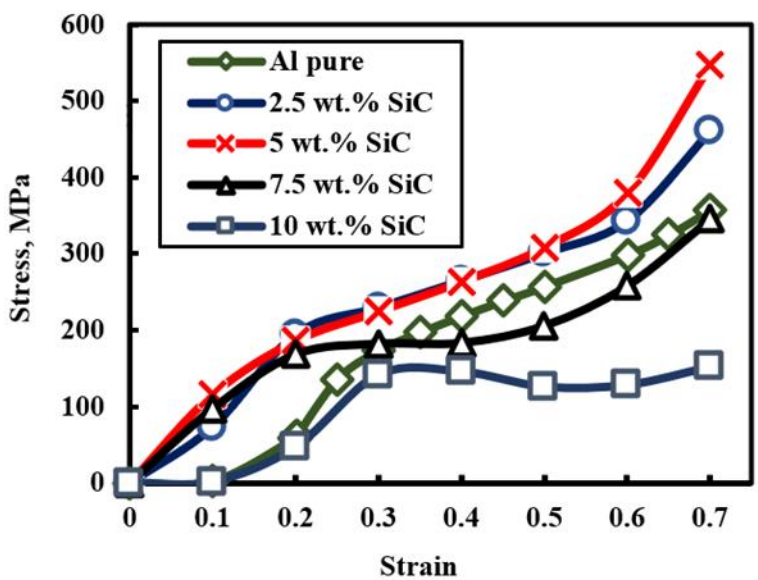

Fig. 6 Compression stress-strain curves of the present Al/SiC composites.

Fig. 7 shows the ultimate compressive strength results of the present Al/SiC composites versus SiC particles content. The ultimate compressive strength at 5 wt. % SiC has the highest compressive strength value compared to other composites, as displayed in Fig. 7. This may be due to the lower porosity of this specimen than the other ones. The ultimate compressive strength rises via decreasing the porosity and increasing both the density and Al-content. The porosity of Al-SiC composite increases by increasing SiC content that is considered as an appropriate site for growth and crack nucleation where the stress concentrate, [66].

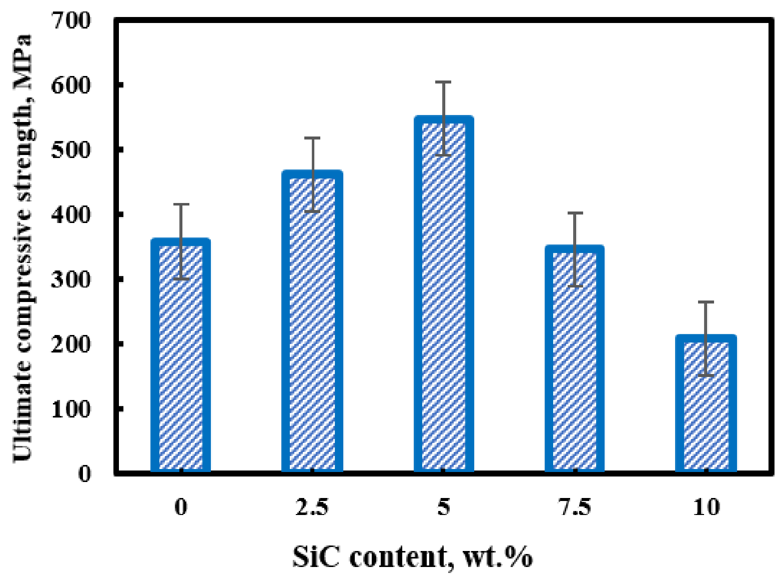

Fig. 7 Ultimate compressive strength of the present the present Al/SiC composites.

The tribological properties that were studied on the present composites were wear rate and coefficient of friction. Wear rate and friction coefficient of pure Al and its composites were performed under dry sliding conditions using pin-on-disk test rig. Wear rate results as a function of applied loads were introduced in Fig. 8. As shown in Fig. 8, the wear rate gradually increases significantly with increasing applied loads up to 15 N. This may be due to the increased penetration of the hard disk asperities into the tested specimen during increased loading. Moreover, the rate of pure Al decreases with increasing SiC particles content up to 7.5 wt.% under applied loads of 5, 10, 15 N. This may be attributed to the increased surface resistance to abrasion because SiC particles are an abrasive ceramic material with high abrasion resistance. It is worth noting that there is an inverse relationship between the hardness number and the wear rate, [67]. Therefore, composites with a high hardness number have lower wear rates compared to composites with a lower hardness number.

The friction force of the present composites was measured by a load cell of 40 kg and recorded every 1 millisecond by a calibrated data logger. The friction coefficient was then calculated by dividing the friction force by the applied load. Therefore, the results of the friction coefficient of pure Al and its composites as a function of the applied loads were then presented in Fig. 9.

The friction coefficient of pure Al enhanced with increasing SiC content up to 10 wt.%. The best improvement in friction coefficient was achieved at 5 wt.% SiC particles content. Moreover, the significant improvement in the friction coefficient results can be attributed to the self-lubrication generated by the carbon present in the SiC particles.

Also, it is worth noting that the surface mechanical properties have an important effect on improving the friction coefficient of the present composites. Therefore, the lowest value of the coefficient of friction was obtained at a SiC content of 5 wt.%. Because the highest value of hardness number and ultimate compressive strength is achieved at 5 wt. % SiC content.

In addition, the transfer film formed between the tested sample and the sliding disk has a prominent role in reducing the friction coefficient because it contains self-lubricating carbonaceous materials. After increasing the SiC particles content up to 10 wt.%, it was observed that the friction coefficient gradually increased. This may be because SiC particles agglomerate inside the composites, leading to poor wettability between Al and SiC particles, thus increasing the coefficient of friction.

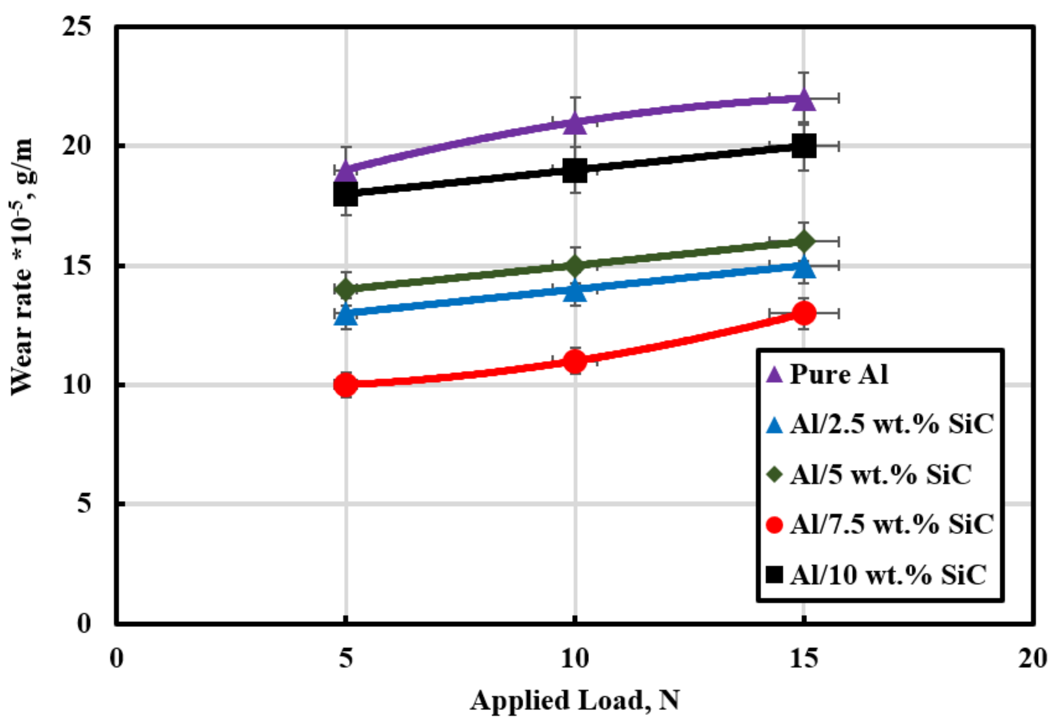

Fig. 8 Wear rate of Al-SiC composites.

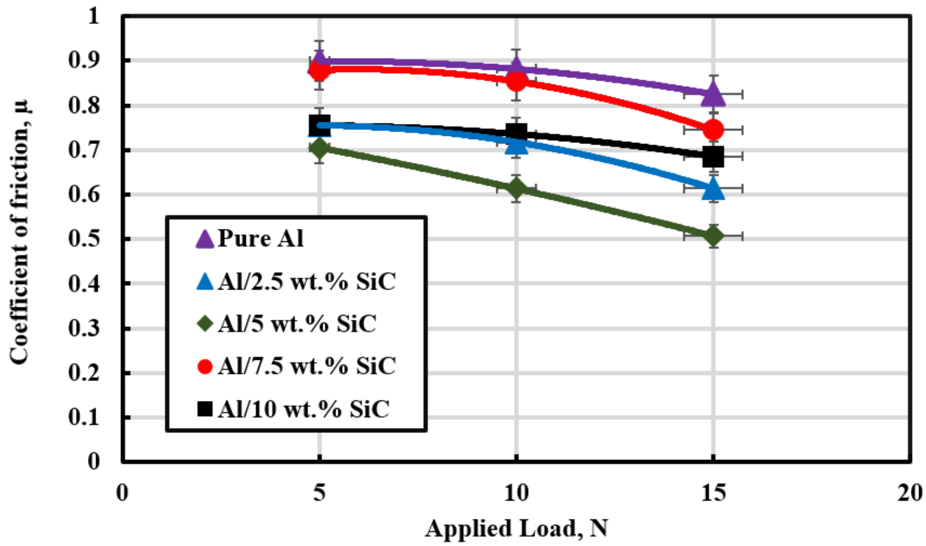

Fig. 9 Friction coefficient of the present Al/SiC composites.

CONCLUSIONS

The present work is summarized in studying the mechanical and tribological characteristics of Al/SiC nanocomposites prepared by a hot-compaction powder metallurgy technique. SiC particles were added in different concentrations of 0, 2.5, 5, 7.5 and 10 wt.%. Al and SiC particles were mixed by PQ-N2 planetary ball milling machine at 350 rpm for 12 h to obtain the homogenous composites. All composites were produced at pressure of 900 MPa and temperature of 550 °C. Hence, the relative density, microstructure, and mechanical and tribological properties of the present composites were examined. After that, the present work could be concluded in the following below:

1. **With increasing SiC contents, the relative density of the present composites decreased compared to the unreinforced specimens.**
2. **With increasing SiC contents up to 5 wt.%, the grain size of the Al-SiC composite is more fine compared to the other SiC contents.**
3. **At a compaction pressure 900 MPa and temperature 550 ºC, the relative density enhanced up to 98%.**
4. **The relative density decreased with increasing SiC composite at 5 wt.%.**
5. **The fabricated sample at 5 wt.% SiC has a homogeneous microstructure with any imperfections.**
6. **The microhardness value was increased with increasing SiC content at 5 wt.%.**
7. **Ultimate compressive strength of the composite containing 5 wt.% SiC was the highest, compared to the other composites.**
8. **The wear rate decreased with increasing the SiC content up to 7.5 wt.% at applied loads of 5, 10, and 15 N compared to the other SiC contents.**
9. **Wear rate characteristics of Al/7.5 wt.% SiC composites were improved by 47.3, 47.6, and 40.9 % at applied loads of 5, 10, and 15 N, respectively compared to pure matrix Al.**

10. The friction coefficient of the pure matrix Al was reduced by 24.56, 30.42, and 38.53% under applied loads of 5, 10, and 15 N, respectively after increasing the SiC content up to 5 wt.%.

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REFERENCES

1. **S.A. Sajjadi, H.R. Ezatpour, H. Beygi, "Microstructure and mechanical properties of Al-Al_2O_3 micro and nano composites fabricated by stir casting", *Materials Science and Engineering: A.* 528, (2011).**
2. **P. Roy, S. Singh, K. Pal, "Enhancement of mechanical and tribological properties of SiC- and CB-reinforced aluminium 7075 hybrid composites through friction stir processing", *Advanced Composite Materials*. 28, 1–18, (2019).**
3. **I.B. Singh, D.P. Mandal, M. Singh, S. Das, "Influence of SiC particles addition on the corrosion behavior of 2014 Al-Cu alloy in 3.5% NaCl solution*", Corros Sci.* 51, 234–241, (2009).**
4. **A. Prasad Reddy, P. Vamsi Krishna, R. Narasimha Rao, N. V. Murthy, "Silicon Carbide Reinforced Aluminium Metal Matrix Nano Composites-A Review", in: *Mater Today Proc*, Elsevier Ltd, pp. 3959–3971, (2017).**
5. **A. Kumar Rajamanickam, U. V C, B. Narayanan, A. Professor, "Investigation of Mechanical and Tribological Properties of Aluminium Metal Matrix Composites-A Review", n.d*, Mater Today Proc*, (2014).**
6. **A.K. Sharma, R. Bhandari, C. Pinca-Bretotean, A systematic overview on fabrication aspects and methods of aluminum metal matrix composites, *Mater Today Proc.* 45, 4133–4138, (2021).**
7. **M. Krasnowski, S. Gierlotka, T. Kulik, "TiC–Al composites with nanocrystalline matrix produced by consolidation of milled powders, *Advanced Powder Technology*", 26, 1269–1272, (2015).**
8. **J. Cho, M.S. Joshi, C.T. Sun, "Effect of inclusion size on mechanical properties of polymeric composites with micro and nano particles", *Compos Sci Technol*. 66 1941–1952, (2006).**
9. **A.W. Urquhart, "Novel reinforced ceramics and metals: a review of Lanxide's composite technologies", *Materials Science and Engineering*: A. 144,75–82, (1991).**
10. **F. Lamouroux, S. Bertrand, R. Pailler, R. Naslain, M. Cataldi, "Oxidation-resistant carbon-fiber-reinforced ceramic-matrix composites", *Compos Sci Technol*. 59 1073–1085, (1999).**
11. **M.H. Rahman, H.M.M. Al Rashed, "Characterization of silicon carbide reinforced aluminum matrix Composites", in: *Procedia Eng,* Elsevier Ltd, pp. 103–109, (2014).**
12. **A. Alizadeh, A. Abdollahi, H. Biukani, Creep behavior and wear resistance of Al 5083 based hybrid composites reinforced with carbon nanotubes (CNTs) and boron carbide (B_4C), *J Alloys Compd*. 650, 783–793, (2015).**
13. **A. Ranjan, A. Shanmugasundaram, Experimental Investigation of Mechanical and Tribological Properties of Al 7075—MoS_2/ZrO_2/Ni Hybrid Composite, in: Lecture Notes in Mechanical Engineering, *Pleiades journals*, pp. 299–309, (2019).**

14. X. Wang, X. Gao, Z. Zhang, L. Cheng, H. Ma, W. Yang, Advances in modifications and high-temperature applications of silicon carbide ceramic matrix composites in aerospace: A focused review, *J Eur Ceram Soc*. 41, 4671–4688, (2021).

15. S. Li, Y. Su, Q. Ouyang, D. Zhang, In-situ carbon nanotube-covered silicon carbide particle reinforced aluminum matrix composites fabricated by powder metallurgy, *Mater Lett*. 167, 118–121, (2016).

16. V. Balaji, N. Sateesh, M.M. Hussain, Manufacture of Aluminium Metal Matrix Composite (Al7075-SiC) by Stir Casting Technique, *Mater Today Proc*. 2 3403–3408, (2015).

17. M. V. Gandhi, B.S. Thompson, F. Fischer, Manufacturing-process-driven design methodologies for components fabricated in composite materials, *Mater Des*. 11 235–242, (1990).

18. D.K. Koli, G. Agnihotri, R. Purohit, Advanced Aluminium Matrix Composites: The Critical Need of Automotive and Aerospace Engineering Fields, *Mater Today Proc*. 2, 3032–3041, (2015).

19. A.K. Sharma, R. Bhandari, A. Aherwar, R. Rimašauskiene, Matrix materials used in composites: A comprehensive study, *Mater Today Proc*. 21, 1559–1562, (2020).

20. R. Soni, R. Verma, R. Kumar Garg, V. Sharma, A critical review of recent advances in the aerospace materials, *Mater Today Proc*. (2023).

21. H. Singh, G. Singh Brar, H. Kumar, V. Aggarwal, A review on metal matrix composite for automobile applications, *Mater Today Proc.* 43, 320–325, (2021).

22. A. Ramanathan, P.K. Krishnan, R. Muraliraja, A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities, *J Manuf Process*. 42, 213–245, (2019).

23. A. Mohamed, M.M. Mohammed, A.F. Ibrahim, O.A. El-Kady, Effect of nano Al2O3 coated Ag reinforced Cu matrix nanocomposites on mechanical and tribological behavior synthesis by P/M technique, *J Compos Mater*. 54, 4921–4928, (2020).

24. A. Prasad Reddy, P. Vamsi Krishna, R. Narasimha Rao, N. V. Murthy, Silicon Carbide Reinforced Aluminium Metal Matrix Nano Composites-A Review, *Mater Today Proc*. 4, 3959–3971, (2017).

25. A.M., Sadoun, B. A, M.M., C, Mohammed, E.M., D, Elsayed, A.F., Meselhy, B, Omyma, E, A., El-Kady, Effect of nano Al2O3 coated Ag addition on the corrosion resistance and electrochemical behavior of Cu-Al2O3 nanocompositespdf, *Journal of Materials Research and Technology*. 9(3), 4485–4493, (2020).

26. O.A.E.-K. A.M. Sadouna, b, M.M. Mohammedc, A. Fathyb, Effect of nano Al2O3 coated Ag.pdf, *Journal of Materials Research and Technology*. 9(3), 5024–5033, (2020).

27. P.A.N. Purant, R.R. Joshi, S.B. Mhetre, A.A. Patil, P.R.R. Joshi, P.S.B. Mhetre, P.A.A. Patil, Applications of Metal Matrix Composites in Modern Engineering, *International Research Journal of Engineering and Technology*, 4555–4558, (2020).

28. A. Prasad Reddy, P. Vamsi Krishna, R. Narasimha Rao, N. V. Murthy, Silicon Carbide Reinforced Aluminium Metal Matrix Nano Composites-A Review, *Mater Today Proc.* 4, 3959–3971, (2017).

29. R. Manikandan, T. V. Arjunan, A.R. Akhil, Studies on micro structural characteristics, mechanical and tribological behaviours of boron carbide and cow

dung ash reinforced aluminium (Al 7075) hybrid metal matrix composite, *Compos B Eng.* 183 (2020).

30. E.A. Starke, J.T. Staley, Application of modern aluminum alloys to aircraft, *Progress in Aerospace Sciences*. 32, 131–172, (1996).

31. B. Sjögren, A. Iregren, J. Montelius, R.A. Yokel, Aluminum*, Handbook on the Toxicology of Metals:* Fourth Edition. 1, 549–564, (2015).

32. D. Ashkenazi, How aluminum changed the world: A metallurgical revolution through technological and cultural perspectives, *Technol Forecast Soc Change*. 143 101–113, (2019).

33. A.M. Bayomy, M.Z. Saghir, T. Yousefi, Electronic cooling using water flow in aluminum metal foam heat sink: Experimental and numerical approach, International Journal of Thermal Sciences. 109, 182–200, (2016).

34. K. Sakurai, M. Hiratsuka, H. Nakamori, K. Namiki, K. Hirakuri, Evaluation of sliding properties and durability of DLC coating for medical devices, *Diam Relat Mater*. 96, 97–103, (2019).

35. B.T. Ogunsemi, T.E. Abioye, T.I. Ogedengbe, H. Zuhailawati, A review of various improvement strategies for joint quality of AA 6061-T6 friction stir weldments, *Journal of Materials Research and Technology*. 11, 1061–1089, (2021).

36. J. Hirsch, Recent development in aluminium for automotive applications, *Transactions of Nonferrous Metals Society of China*. 24, 1995–2002, (2014).

37. J. Singh, A. Chauhan, Characterization of hybrid aluminum matrix composites for advanced applications – A review, *Journal of Materials Research and Technology*. 5, 159–169, (2016).

38. S. Rangrej, S. Pandya, J. Menghani, Effects of reinforcement additions on properties of aluminium matrix composites – A review, *Mater Today Proc*. 44, 637–641, (2021).

39. A. Chinnamahammad Bhasha, K. Balamurugan, Studies on mechanical properties of Al6061/RHC/TiC hybrid composite, *International Journal of Lightweight Materials and Manufacture*. 4, 405–415, (2021).

40. A.K. Bodukuri, K. Eswaraiah, K. Rajendar, V. Sampath, Fabrication of Al–SiC–B4C metal matrix composite by powder metallurgy technique and evaluating mechanical properties, *Perspect Sci (Neth)*. 8, 428–431, (2016).

41. T. Peat, A. Galloway, A. Toumpis, P. McNutt, N. Iqbal, The erosion performance of particle reinforced metal matrix composite coatings produced by co-deposition cold gas dynamic spraying, *Appl Surf Sci*. 396, 1623–1634, (2017).

42. X.P. Zhang, L. Ye, Y.W. Mai, G.F. Quan, W. Wei, Investigation on diffusion bonding characteristics of SiC particulate reinforced aluminium metal matrix composites (Al/SiCp-MMC), *Compos Part A Appl Sci Manuf*. 30,1415–1421, (1999).

43. E. Ghasali, M. Alizadeh, M. Niazmand, T. Ebadzadeh, Fabrication of magnesium-boron carbide metal matrix composite by powder metallurgy route: Comparison between microwave and spark plasma sintering, J Alloys Compd. 697, 200–207, (2017).

44. N. Panwar, A. Chauhan, Fabrication methods of particulate reinforced Aluminium metal matrix composite-A review, Mater Today Proc. 5, 5933–5939, (2018).

45. V. Chak, H. Chattopadhyay, T.L. Dora, A review on fabrication methods, reinforcements and mechanical properties of aluminum matrix composites, *J Manuf Process*. 56, 1059–1074, (2020).
46. J. Hashim, L. Looney, M.S.J. Hashmi, Particle distribution in cast metal matrix composites—Part I, *J Mater Process Technol*. 123, 251–257, (2002).
47. K.K. Sadhu, N. Mandal, R.R. Sahoo, SiC/graphene reinforced aluminum metal matrix composites prepared by powder metallurgy: A review, *J Manuf Process.* 91, 10–43, (2023).
48. K.K. Alaneme, K.O. Sanusi, Microstructural characteristics, mechanical and wear behaviour of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite, *Engineering Science and Technology, an International Journal.* 18, 416–422, (2015).
49. M. Krasnowski, S. Gierlotka, T. Kulik, TiC–Al composites with nanocrystalline matrix produced by consolidation of milled powders, *Advanced Powder Technology*. 26, 1269–1272, (2015).
50. A. Lekatou, A.E. Karantzalis, A. Evangelou, V. Gousia, G. Kaptay, Z. Gácsi, P. Baumli, A. Simon, Aluminium reinforced by WC and TiC nanoparticles (ex-situ) and aluminide particles (in-situ): Microstructure, wear and corrosion behaviour, *Materials & Design* (1980-2015). 65, 1121–1135, (2015).
51. F. Housaer, F. Beclin, M. Touzin, D. Tingaud, A. Legris, A. Addad, Interfacial characterization in carbon nanotube reinforced aluminum matrix composites, *Mater Charact*. 110, 94–101, (2015).
52. P. Sharma, S. Sharma, D. Khanduja, Production and some properties of Si3N4 reinforced aluminium alloy composites, *Journal of Asian Ceramic Societies*. 3, 352–359, (2015).
53. A. Baradeswaran, S.C. Vettivel, A. Elaya Perumal, N. Selvakumar, R. Franklin Issac, Experimental investigation on mechanical behaviour, modelling and optimization of wear parameters of B4C and graphite reinforced aluminium hybrid composites, *Mater Des.* 63, 620–632, (2014).
54. J.H. Shin, H.J. Choi, D.H. Bae, The structure and properties of 2024 aluminum composites reinforced with TiO2 nanoparticles, *Materials Science and Engineering: A*. 607, 605–610, (2014).
55. A. Dixit, K. Kumar, Optimization of Mechanical Properties of Silica Gel Reinforced Aluminium MMC by using Taguchi Method, *Mater Today Proc. 2* 2359–2366, (2015).
56. L. Jia, K. Kondoh, H. Imai, M. Onishi, B. Chen, S.F. Li, Nano-scale AlN powders and AlN/Al composites by full and partial direct nitridation of aluminum in solid-state, *J Alloys Compd*. 629, 184–187, (2015).
57. M.H. Rahman, H.M.M. Al Rashed, Characterization of Silicon Carbide Reinforced Aluminum Matrix Composites, *Procedia Eng*. 90, 103–109, (2014).
58. J. Chandradass, T. Thirugnanasambandham, P. Jawahar, T.T.M. Kannan, Effect of silicon carbide and silicon carbide/alumina reinforced aluminum alloy (AA6061) metal matrix composite, *Mater Today Proc.* 45, 7147–7150, (2021).
59. V.S. Aigbodion, S.B. Hassan, Effects of silicon carbide reinforcement on microstructure and properties of cast Al–Si–Fe/SiC particulate composites, *Materials Science and Engineering: A.* 447, 355–360, (2007).

60. S. Suresha, B.K. Sridhara, Effect of silicon carbide particulates on wear resistance of graphitic aluminium matrix composites, *Mater Des.* 31, 4470–4477, (2010).
61. J.H. Eom, Y.W. Kim, S. Raju, Processing and properties of macroporous silicon carbide ceramics: A review, *Journal of Asian Ceramic Societies*. 1, 220–242, (2013).
62. Y. Morisada, Y. Miyamoto, Y. Takaura, K. Hirota, N. Tamari, Mechanical properties of SiC composites incorporating SiC-coated multi-walled carbon nanotubes, *Int J Refract Metals Hard Mater*. 25, 322–327, (2007).
63. A. Prasad Reddy, P. Vamsi Krishna, R. Narasimha Rao, N. V. Murthy, Silicon Carbide Reinforced Aluminium Metal Matrix Nano Composites-A Review, *Mater Today Proc.* 4, 3959–3971, (2017).
64. Q. AN, J. CHEN, W. MING, M. CHEN, Machining of SiC ceramic matrix composites: A review, *Chinese Journal of Aeronautics*. 34, 540–567, (2021).
65. M.M. Mohammed, 1, N.H. Alrasheedi, 2, O.A. El-Kady, 3, 2, J. Djuansjah, 4, F.A. Essa, and A.H. Elsheikh, 5, *, Impact of Using Tungsten, Cobalt, and Aluminum Additives on the Tribological and Mechanical Properties of Iron Composites, *Crystals (Basel)*, 13, 1–14, (2023).
66. R.S. Rana, R. Purohit, V.K. Soni, S. Das, Characterization of Mechanical Properties and Microstructure of Aluminium Alloy-SiC Composites, Mater Today Proc. 2, 1149–1156, (2015).
67. A. E. S. M. Hassan, A. I. Ei, M. El-Sheikh, and W. Y. Ali, "Effect of Graphene Nanoplatelets and Paraffin Oil Addition on the Mechanical and Tribological Properties of Low-Density Polyethylene Nanocomposites," *Arab. J. Sci. Eng.*, vol. 43, no. 3, pp. 1435–1443, (2018).