Kovove Mater. 62 2024 101–109
DOI: 10.31577/km.2024.2.101

Evaluating the mechanical and tribological characteristics of aluminium hybrid composites incorporating ZrO_2 and graphite micro-particles

Kannapiran Karuppasamy*, Baskaran Ranganathan, Satheesh Rajendran

Department of Industrial Engineering, College of Engineering Guindy, Anna University, Chennai 600025, India

Received 15 February 2024, received in revised form 18 March 2024, accepted 23 April 2024

Abstract

This study uses the stir casting method to evaluate how reinforcements enhance wear resistance in aluminium-based hybrid metal matrix composites. Zirconia (ZrO_2) and graphite were used to reinforce AA6082. Archimedes' method assessed density and porosity, Vickers hardness tested hardness, and a universal test machine measured tensile strength. Results showed improvements in micro-Vickers hardness, porosity, and tensile strength from 84 VHN, 2.44 %, 132 MPa (AHC5) to 128 VHN, 3.23 %, and 180 MPa (AHC15). Wear properties were tested under varied loads and sliding speeds, revealing that the wear rate decreases with higher speeds but increases with load. ZrO_2 demonstrated superior wear resistance in AHCs, while graphite proved highly effective as a solid lubricant. These findings underscore the effectiveness of specific reinforcements in enhancing wear properties in metal matrix composites.

Key words: AA6082 alloy, graphite, ZrO_2 particulates, microstructure, hardness, tensile strength, wear behaviour

1. Introduction

The purpose of trituration in engineering is to search for new materials with desirable mechanical properties. Metal matrix composites (MMCs) offer great opportunities to develop lightweight components [1]. Researchers are studying aluminium alloy-based metal matrix composites (MMCs) for advanced technical applications in aviation, automotive, and naval industries. MMCs are increasingly replacing traditional metallic alloys [2–4]. It has been observed that unreinforced aluminium and its alloys are subordinate to the hard particles reinforced aluminium-based composites [5].

Aluminium and aluminium composites are versatile materials used in many industries. Their light weight, corrosion resistance, and excellent strength-to-weight ratio make them popular. Their application in aerospace fuselage panels and wings improves fuel efficiency and payload. Automotive manufacturers use aluminium and its composites to reduce weight, improve fuel efficiency, and improve crashworthiness. Due to their corrosion resistance, aluminium alloys are utilised in shipbuilding, offshore structures, and marine components [6]. Aluminium composites are efficient heat sinks in the electronics and electrical industry, extending gadget lifespans. Aluminium and its composites are used for facades, roofs, windows, and structural components because of its corrosion resistance, strength, and aesthetics. The broad use of aluminium and aluminium composites shows their importance in technical innovation and sustainable growth across industries [7].

Hybrid metal matrix composites (HMMCs) have emerged as promising materials offering superior mechanical properties and tailored performance compared to conventional monolithic metals and single-reinforcement MMCs. Combining reinforcement materials, such as ceramic particles, fibres, and nanomaterials, hybrid MMCs can achieve synergistic effects, enhancing strength, stiffness, and other desirable properties while mitigating inherent limitations [8]. Recent research in hybrid metal matrix composites (MMCs) focuses on optimising combinations of reinforcements

*Corresponding author: e-mail address: srikanna.piran@gmail.com

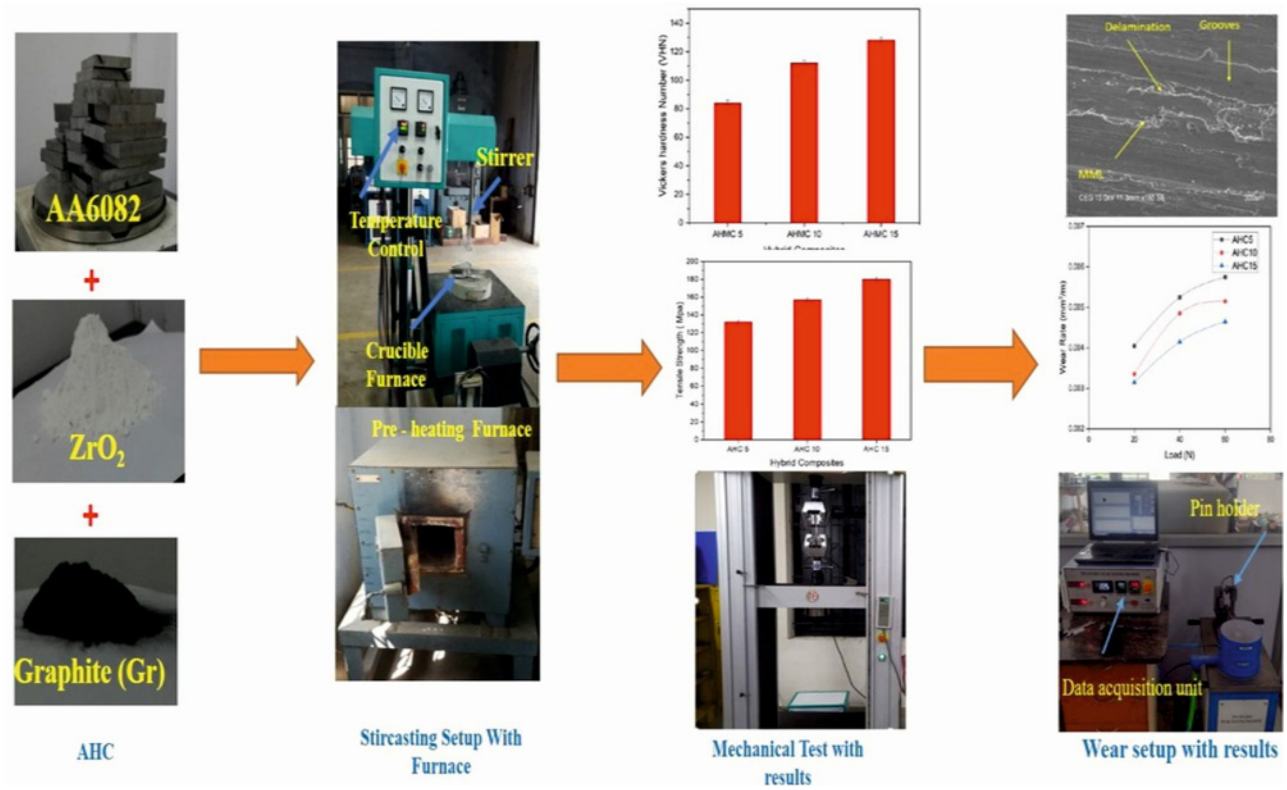

Fig. 1. Graphical abstract.

like ceramic particles, fibres, and nanomaterials within a metal matrix. Researchers aim to achieve synergistic effects through techniques such as powder metallurgy and stir casting, enhancing mechanical performance and thermal stability. Characterisation methods, including microscopy and mechanical testing, contribute to understanding structure-property relationships. These advancements pave the way for hybrid MMCs to find applications in aerospace, automotive, and other industries requiring high-performance materials [9].

Aluminium hybrid metal matrix composites (AHC) have superior characteristics compared to traditional composites, such as fracture propagation resistance, superior durability, and enhanced plasticity under extreme loads [10]. The mechanical and tribological properties of composites are affected by various factors, including the size of the reinforcement particles, the amount of reinforcement present, the phase of the reinforcement inside the base material, and the manufacturing procedure employed [11]. Researchers added several ceramic reinforcing particles to the aluminium matrix, such as nitrides, oxides, carbides, sulfides, and borides, to improve the wear resistance of AMCs [12].

Zirconia (ZrO_2) is a highly effective and readily accessible material in various reinforcements. It exhibits commendable mechanical properties and boasts excellent wear resistance even at elevated temperatures. Zirconia finds application in diverse fields, such as medical devices, electronic components, valves, oxygen sensors, pump seals, cutting tools, thread guides, driveshafts, and metrology components [13]. The addition of graphite into aluminium matrix composites results in an alloy with low density, low friction, and self-lubricating properties, making it suitable for structural and functional functions. Aluminium and its alloys are fortified by including reinforcements to improve their mechanical characteristics, such as tensile durability and resistance to wear [14]. Besides a single reinforcement, multiple particles are employed to enhance the properties of Metal Matrix Composites (MMCs). When sliding, the hard-reinforcing particles have the potential to abrade the counter surface material and dislodge fragmented pieces. Abrasion action significantly affects the tribological properties of the composites. Hexagonal boron nitride (h-BN), carbon nanotubes (CNT), and graphite (Gr) are regarded as highly promising solid lubricants [15]. Among these, graphite increases wear resistance and anti-frictional properties, reducing material loss from AHMCs. Different fabrication techniques have benefits and drawbacks; the best technique can be chosen according to the situation. Multiple methods exist for producing AHCs, but the two predominant approaches are liquid-state and solid-state production processes. The liquid-state method for AHCs is comparatively uncomplicated and more cost-effective than solid-state manufacture [16]. However, research studies have been

Table 1. The constituent parts of the composites

S. No.	AA6082 (vol.%)	ZrO_2 (vol.%)	Gr (vol.%)	Code
1	90	5	5	AHC5
2	85	10	5	AHC10
3	80	15	5	AHC15

scarce on using ZrO_2 and graphite to reinforce AHCs, mostly due to the elevated costs of the raw materials and the inadequate wetting properties. This study aims to comprehensively investigate the mechanical properties and durability of a novel aluminium hybrid composite material. The composite comprises an aluminium matrix (AA6082) reinforced with ZrO_2 and graphite. The composite is manufactured using the stir casting technique, well-known for its versatility and cost-effectiveness. This study aimed to analyse the influence of ZrO_2 and graphite on the mechanical properties of aluminium hybrid composites. Specifically, the investigation focused on density, porosity, hardness, and tensile strength. Additionally, the dry sliding wear behaviour of the composites was examined by varying the volume percentage of ZrO_2 and graphite particles.

2. Materials and methods

2.1. Fabrication of composites

The experimental approach intends to develop aluminium-based hybrid metal matrix composites. Zirconia and graphite particles, reinforced at various concentrations, were used to achieve the desired results. A technique known as stir casting was used to make the AHCs. This was done to establish a standard and low-cost way of producing aluminium hybrid metal matrix composites and obtain uniform ceramic material dispersion. The materials used include zirconia with grit sizes ranging from 100–150 μm, aluminium alloy (AA6082), and graphite (5 μm). An experiment was carried out in which the concentration of graphite was held constant while the weight fractions of ZrO_2 varied between 5, 10, and 15 vol.%.

2.2. Studies on mechanical properties and wear behaviour

2.2.1. Hardness test

The specimens were manufactured in compliance with the requirements specified by ASTM E92-16. They were refined using emery sheets of different mesh sizes. Subsequently, they should be subjected to a velvet disc polishing machine to get an exceedingly polished surface. The hardness of the fabricated material was assessed via a Vickers hardness tester. The specimen was exposed to an applied force of 20 kgf that caused indentation for 10 s.

2.2.2. Density and porosity measurement

Applying the law of mixtures, the theoretical density of the AHC was calculated. Archimedes' principle was utilised to ascertain the actual density of the AHC. Following the initial measurement of the cylindrical sample's weight in air (m), the sample was submerged in distilled water and re-measured (m_1) after the immersion.

The actual density was determined using the formula stated in Eq. (1) [17]:

$$\rho_{\mathrm{ahc}} = \frac{m}{m - m_1}\rho_{\mathrm{w}}, \tag{1}$$

where ρ_{ahc} is the actual density and ρ_{w} is the density of water. The sample was measured using a weighing scale with a precision of 0.1 mg. ρ_{ahc} of each substance can be determined using Eq. (1). ρ_{th} (theoretical density) of the material is calculated by dividing the mass by the volume. P(porosity) of each material can be determined using the Eq. (2) [17]:

$$P = \frac{\rho_{\mathrm{th}} - \rho_{\mathrm{ahc}}}{\rho_{\mathrm{th}}}. \tag{2}$$

Equation (2) expresses the correlation between P, ρ_{ahc}, and ρ_{th}.

Table 2 presents the quantitative measurements of the samples' density, porosity, ultimate tensile strength, and hardness.

Table 2. Mechanical properties of AHC5, AHC10, and AHC15

Composition (wt.%)	Density ($g\,cm^{-3}$)	Porosity (%)	Ultimate tensile strength (MPa)	Hardness, VHN
AHC5	2.827	2.44	132	84
AHC10	2.976	3.20	157	112
AHC15	3.125	3.23	180	128

Fig. 2. Pin-on-disc wear testing setup.

2.2.3. Tensile test

The tensile strength of the AHC was measured using universal testing equipment according to the ASTM A370 standard. The hardness of the composite increased with an increase in the percentage of reinforcement. The matrix was reinforced by adding ZrO_2 and graphite, enhancing the composite's tensile strength. Moreover, a strong interfacial binding was established as the volume percentage of the reinforcing particles increased, resulting in an enhancement of the tensile strength. Table 2 displays the tensile strength and hardness of the prepared samples, which vary in the amount of reinforcement present.

2.2.4. Wear test

The wear rate of the composite is determined using the pin-on-disc tester (NOVUS TRIBO SOLUTIONS) shown in Fig. 2. The experiment was conducted following the ASTM standard G99-05. The EN31 hardened steel disc had been utilised with a hardness grade of 60 HRC. The studies were conducted under typical environmental conditions. After each experiment, the disc was meticulously cleaned and polished with acetone to ensure consistency. Prior to and following each test, the pin was subjected to a thorough cleaning using acetone. Subsequently, the pin's weight was measured using a very sensitive electronic scale capable of detecting mass fluctuations as minute as 0.001 g.

3. Results and discussion

3.1. Hardness test

The graph demonstrates that augmenting the quantity of reinforcement in the composite material leads to a corresponding increase in its hardness. The inclusion of ZrO_2 particles in the matrix increased its strength.

3.2. Tensile test

Incorporating ZrO_2 and graphite increased the composite's tensile strength. Furthermore, a strong bond between the interfaces formed as the proportion of the reinforcing particles increased, which significantly improved tensile strength, as depicted in Fig. 1.

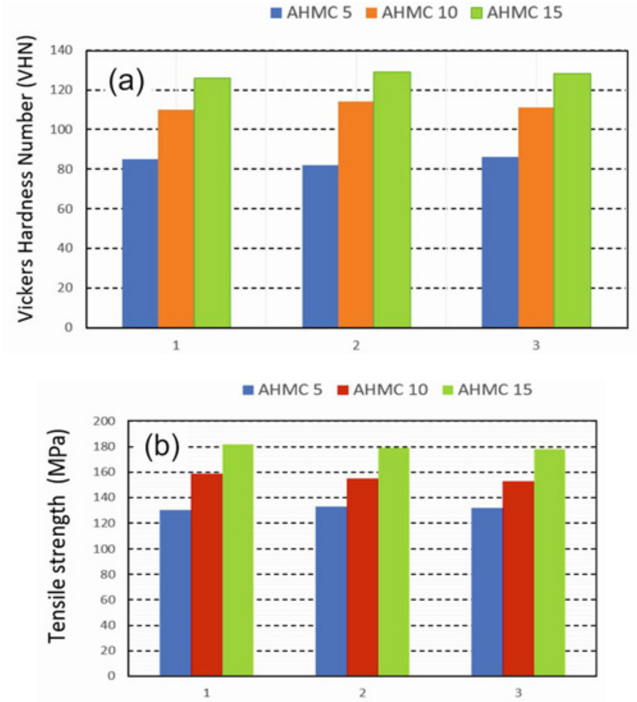

Fig. 3. Vicker's hardness (a) and tensile strength (b) graphical illustration.

3.3. Wear behaviour on AHMC

This study investigates the impact of the AL (applied load) and SS (sliding speed) on the dry sliding wear characteristics of several composites of AA6082, ZrO_2, and graphite. The main objective is to ascertain the precise percentage influence of the wear rate.

3.3.1. Effect of sliding speed and reinforcement on wear rate

This study investigates the impact of the AL and SS on the dry sliding wear characteristics of several composites consisting of AA6082, ZrO_2, and graphite. The main objective is to ascertain the precise percentage effect of the wear rate. Figures 3–6 depict the correlation between the sliding velocity and the wear rate of a composite material containing a specific quantity of reinforcements. Based on various literature, the weights employed were 20, 40, and 60 N, respectively, while maintaining a constant sliding distance of 1250 m. The graph demonstrates that the composite alloy exhibits a diminishing wear rate as the sliding speed increases, reaching a maximum of $2\ m\ s^{-1}$. The phenomenon arises because of the oxidation process of

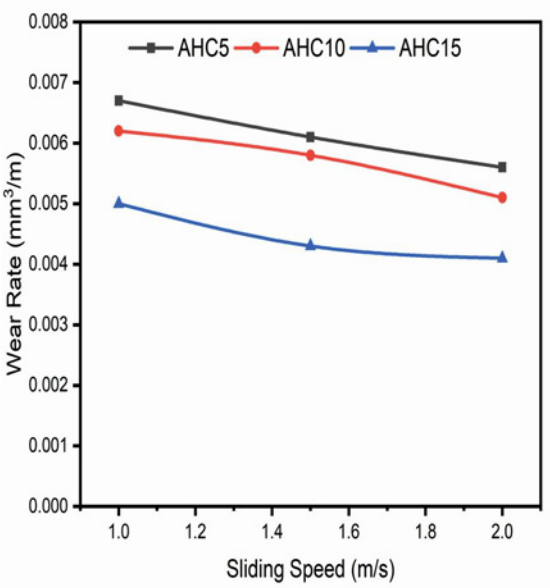

Fig. 4. Fluctuation of wear rate with the SS at a load of 20 N.

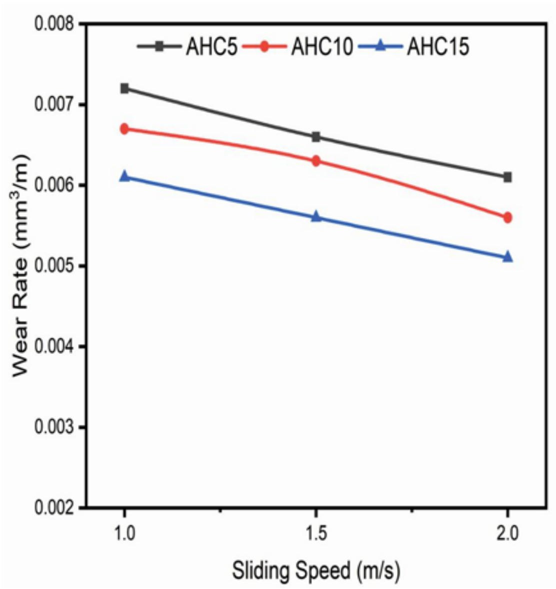

Fig. 5. Fluctuation of wear rate with the SS at a load of 40 N.

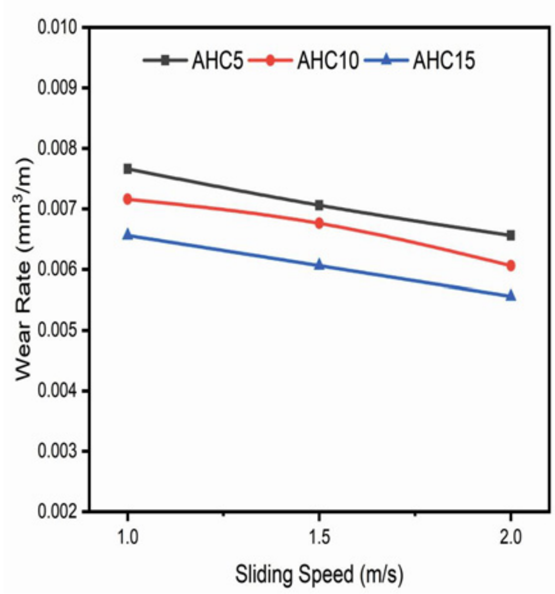

Fig. 6. Fluctuation of wear rate with the SS at a load of 60 N.

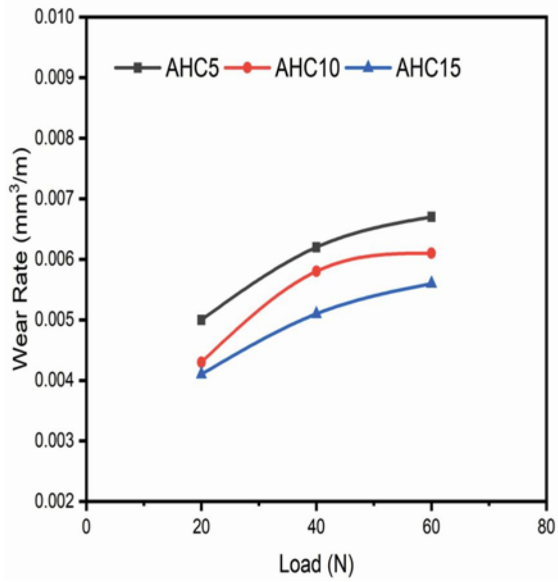

Fig. 7. Fluctuation of wear rate with AL at an SS of 1 m s^{-1}.

the aluminium hybrid composites, creating an oxide layer when the interfacial temperatures are elevated. This layer acts as a barrier, reducing the pace of degradation by restricting the movement between the surfaces. As the velocity at which the AA6082 alloy slides and the proportion of ZrO_2 in the alloy increases, the rate of wear reduces [17].

3.3.2. Effect of load and reinforcement on wear rate

The weight of the applied load during wear testing significantly impacts the wear resistance. Figures 7–9 show the variability in the wear rate of the AHC when subjected to varying loads. The results demonstrate that the composite composition of AHC5 displayed the highest rate of wear. Incorporating ZrO_2 and graphite into AHCs reduces the wear rate in the

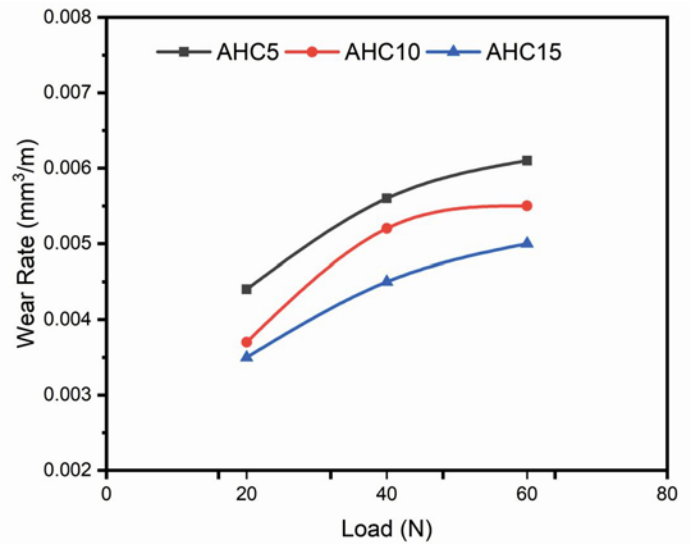

Fig. 8. Fluctuation of wear rate with AL at an SS of 1.5 m s^{-1}.

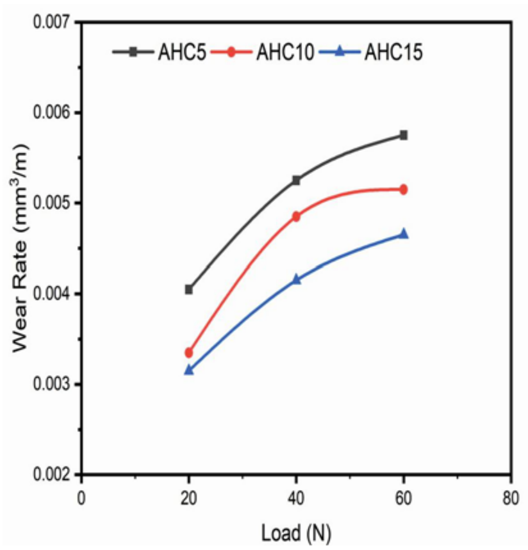

Fig. 9. Fluctuation of wear rate with AL at an SS of 2 m s^{-1}.

composites. It was noted that the degradation rate escalates linearly with the magnitude of applied force. The AHC15 composite demonstrated superior wear properties compared to the other compositions. Figures 7–9 demonstrate the impact of different loads on the degradation rate of a composite material having a particular amount of reinforcements.

3.4. SEM investigation of wear behaviour on AHMC

Scanning electron microscopy was used to study the worn surfaces and better understand the wear

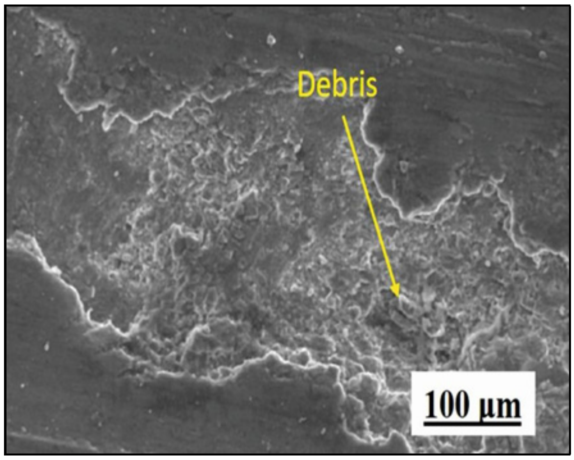

Fig. 10. SEM image showing the deteriorated surface of an AHC5 at a load of 60 N; $V = 2$ m s^{-1}.

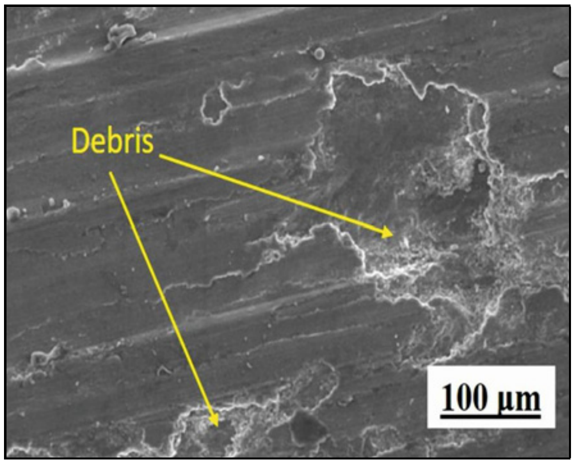

Fig. 11. SEM image showing the deteriorated surface of an AHC5 at a load of 60 N, $V = 2$ m s^{-1}.

mechanism of AHCs. During the sliding motion, the pin comes into contact with the entire surface of the steel disc, enabling the inspection of machine markings. Micrographs show the worn surface of AHCs under a load of 60 N, sliding at a speed of 2 m s^{-1}, and covering a distance of 1250 m. The micrograph of the AHC exhibits a more pronounced level of material deterioration on the pin's surface due to wear.

The wear rate of hybrid composites with different volume percentages of ZrO_2 and a constant 5-volume percentage of graphite under varied loading conditions is shown in Figs. 10–15. The following factors may be associated with the elevated rate of wear due to AL. Raising the temperature facilitates the process of plastic deformation, resulting in a notable acceleration of wear and ultimately leading to adhesion wear. The abrasion wear process takes precedence when the loads are low. As the load increases, grooves deepen and pro-

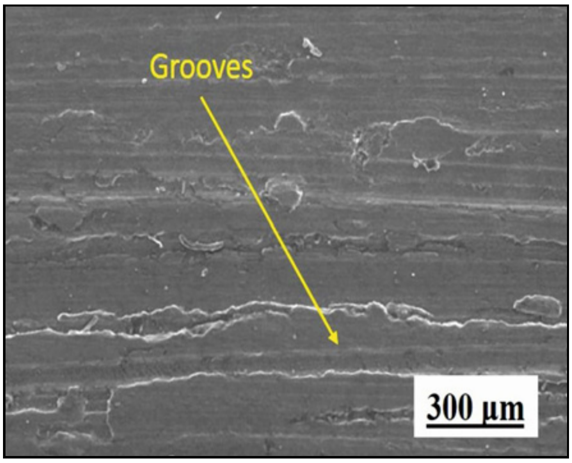

Fig. 12. SEM image showing the deteriorated surface of an AHC15 at a load of 20 N, $V = 2\,\mathrm{m\,s^{-1}}$.

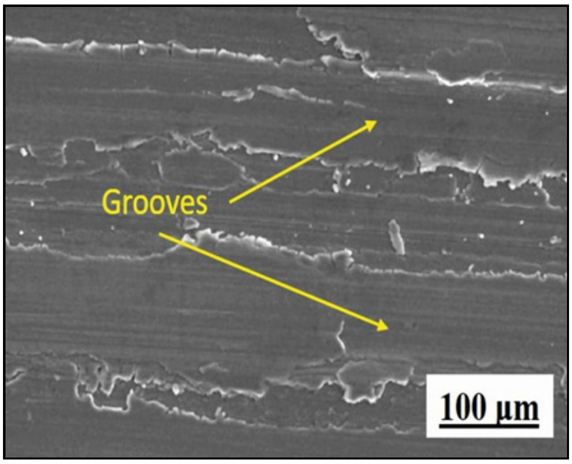

Fig. 13. SEM image showing the deteriorated surface of an AHC15 at a load of 60 N, $V = 1\,\mathrm{m\,s^{-1}}$.

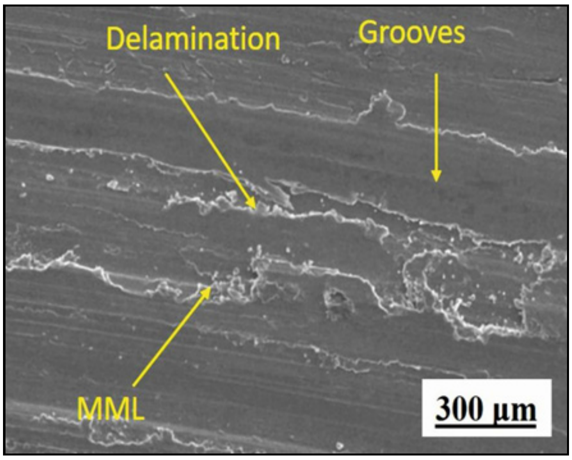

Fig. 14. SEM image showing the deteriorated surface of an AHC5 at a load of 60 N, $V = 1\,\mathrm{m\,s^{-1}}$.

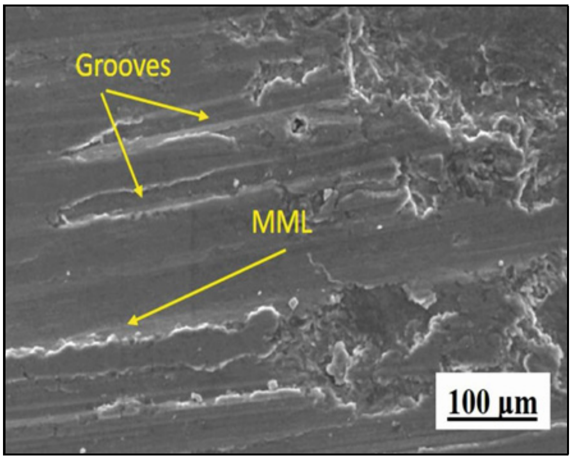

Fig. 15. SEM image showing the deteriorated surface of an AHC5 at a load of 60 N, $V = 2\,\mathrm{m\,s^{-1}}$.

duce stresses that exceed particle fracture strength, causing a fracture. The broken zirconia particles rubbing on the steel disc also transmit material from pin to disc. These increase the wear. As the sliding speed increases, the number of grooves also increases, and the reinforcements extend out from the surface of the pin because of the ploughing action between the counter face and the pin. Additional material is removed from the surface of the pin, due to which MML is created. As a result of strengthening the reinforcements, this mechanically mixed layer will be more stable. Higher weight percentages of ZrO_2 concentration reduced the wear rate while keeping the AL constant. Archard's rule, which establishes a direct correlation between the hardness of composites and the amount of reinforcing content, can explain the decrease in the wear rate of the composites. Consequently, it was shown that the degradation rate on composites decreased in proportion to the hardness of the composites. The wear rates of AHCs sliding over counter disc materials (EN31 Steel) were affected by the generation of wear debris.

Figure 16 displays the results of the EDS analysis conducted on the worn surface of the AHC15 sample, which was subjected to a normal load of 60 N. The EDS studies indicated the presence of a significant quantity of oxygen and iron on the worn surface adjacent to the aluminium element shown in Fig. 17. The presence of Fe indicates that Fe is transferred from the disc to the worn surface, whereas the oxygen element indicates the occurrence of the oxidation reaction. The results suggest that there has been a transfer and mechanical mixing of materials between the two surfaces that are sliding against one other. This has resulted in the formation of a mechanically mixed layer (MML) on the surfaces that have been worn. Prior studies have documented the emergence of this layer, as evidenced by the work of multiple re-

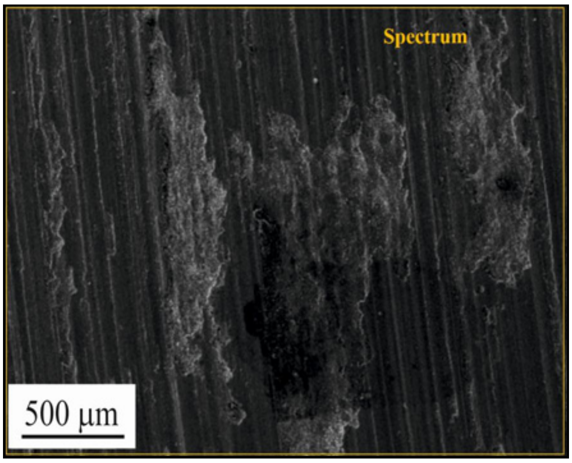

Fig. 16. SEM micrograph of worn surface AHC15.

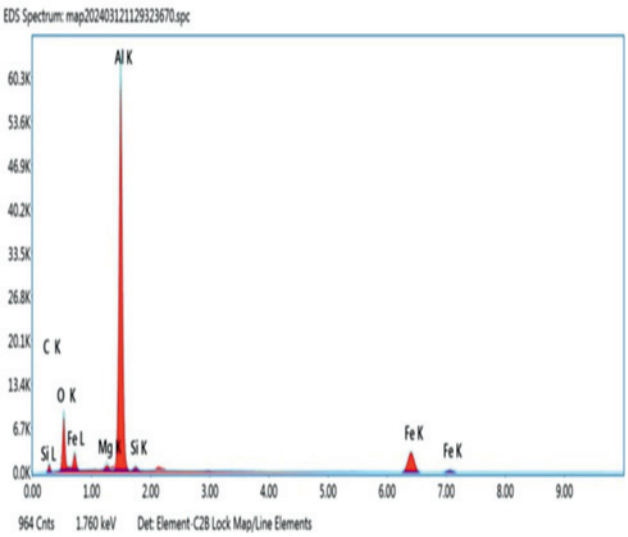

Fig. 17. EDS Analysis of AHC15.

searchers [18–21]. Consequently, it appears that a mechanical mixing layer process was the dominant wear mechanism in the current investigation.

4. Conclusions

Investigations on AHC5, AHC10, and AHC15 focused on their wear and mechanical properties. The main results that were found are listed below:

The mechanical property results showed that when the amount of reinforcing material increased, the AHC material's density, porosity (%), hardness, and tensile strength significantly increased. The AHC material that contained 15 % ZrO_2 and 5 % Gr attained the highest values for density, porosity percentage, hardness, and tensile strength.

Increasing the SS and the AL reduces the wear rate and coefficient of friction of all the manufactured samples. The wear rate can be reduced by adding various quantities of ZrO_2 and the solid lubricant graphite to the composites.

The wear test results indicated that a 2 m s^{-1} velocity resulted in the lowest wear rate. The findings demonstrate that the optimal combination of minimal wear rate was attained when the sliding speed was 2 m s$^{-1,}$ and the load was 20 N. In the future, optimisation techniques such as response surface methodology (RSM), particle swarm optimisation (PSO), genetic algorithms (GA), and Taguchi methods are likely to be utilised for optimising input parameters in the machining of AHC materials.

References

[1] N. Radhika, R. Subramanian, S. V. Prasat, B. Anandavel, Dry sliding wear behaviour of aluminium/alumina/graphite hybrid metal matrix composites, Ind. Lubr. Tribol. 64 (2012) 359–366. https://doi.org/10.1108/00368791211262499

[2] A. Baradeswaran, A. Elaya Perumal, Study on mechanical and wear properties of Al 7075/Al_2O_3/graphite hybrid composites, Compos. Part B Eng. 56 (2014) 464–471. https://doi.org/10.1016/j.compositesb.2013.08.013

[3] G. Karthikeyan, G. R. Jinu, Experimental investigation on mechanical and wear behaviour of aluminium LM6/ZrO_2 composites fabricated by stir casting method, J. Balk. Tribol. Assoc. 21 (2015) 539–356.

[4] M. C. Senel, M. Ustun, Dry sliding wear and friction behavior of graphene/ZrO_2 binary nanoparticles reinforced aluminum hybrid composites, Arab. J. Sci. Eng. 47 (2022) 9253–9269. https://doi.org/10.1007/s13369-022-06661-4

[5] M. John Iruthaya Raj, K. Manisekar, M. Gupta, Mechanical and wear properties of Mg/Mo nanocomposites, Kovove Mater. 57 (2019) 237–246. https://doi.org/10.4149/km_2019_4_237

[6] B. Stojanovic, M. Bukvic, I. Epler, Application of aluminum and aluminum alloys in engineering, Appl. Eng. Lett. 3 (2018) 52–62. https://doi.org/10.18485/aeletters.2018.3.2.2

[7] B. Stojanovic, L. Ivanovic, Application of aluminium hybrid composites in automotive industry, Teh. Vjesn. 22 (2015) 247–51. (in Croatian) https://doi.org/10.17559/TV-20130905094303

[8] B. Stojanovic, S. Gajevic, N. Miloradovic, R. Nikolic, S. Miladinovic, P. Svoboda, Comparative analysis of hybrid composites based on A356 and ZA-27 alloys regarding their tribological behaviour, Commun. – Sci. Lett. Univ. Zilina 25 (2023) B215–B227. https://doi.org/10.26552/com.C.2023.056

[9] V. Rana, H. Kumar, A. Kumar, Fabrication of hybrid metal matrix composites (HMMCs) – A review of comprehensive research studies, Mater. Today Proc. 56 (2022) 3102–3107. https://doi.org/10.1016/j.matpr.2021.12.241

[10] S. Pichumani, R. Srinivasan, V. Ramamoorthi, Investigation on mechanical behavior and material characteristics of various weight composition of SiCp reinforced aluminium metal matrix composite, IOP Conf. Ser. Mater. Sci. Eng. 310 (2018) 125–138. https://doi.org/10.1088/1757-899X/310/1/012082

[11] J. Umar Mohamed, P. L. K. Palaniappan, P. Maran, R. Pandiyarajan, Influences of ZrO_2 and B_4C reinforcement on metallurgical, mechanical, and tribological properties of AA6082 hybrid composite materials, J. Ceram. Process Res. 22 (2021) 306–316. https://doi.org/10.36410/jcpr.2021.22.3.306

[12] R. Xia, D. Lou, H. Younes, J. Haiston, H. Chen, H. Hong, Synergistic effect of hexagonal boron nitride and carbon nanofibers on tribological behavior of nanolubricant, Tribol. Int. 177 (2023) 57–65. https://doi.org/10.1016/j.triboint.2022.107957

[13] P. Samal, B. Surekha, P. R. Vundavilli, Experimental investigations on microstructure, mechanical behavior and tribological analysis of AA5154/SiC composites by stir casting, Silicon 14 (2022) 3317–3328. https://doi.org/10.1007/s12633-021-01115-2

[14] G. B. Veeresh Kumar, P. S. Shivakumar Gouda, R. Pramod, N. D. Prasanna, H. S. Balasubramanya, S. M. Aradhya, Fabrication, mechanical and wear properties of aluminum (Al6061)-silicon carbide-graphite hybrid metal matrix composites, Frattura ed Integrita Strutturale 16 (2022) 134–49. https://doi.org/10.3221/IGF-ESIS.62.10

[15] K. Karuppasamy, B. Ranganathan, Investigation of the surface quality of AA6082-ZrO_2-Gr MMCs using abrasive waterjet machining, Mater. Technol. 57 (2023) 19–26. https://doi.org/10.17222/mit.2022.602

[16] M. P. Reddy, H. P. Raju, N. R. Banapurmath, V. K. V. Meti, Influence of ZrO_2 nano particles on the behavior of mechanical and tribological properties of the AA7075 composite, Proc. Inst. Mech. Eng., Part N, J. Nanomater. Nanoeng. Nanosyst. 236 (2022) 55–62. https://doi.org/10.1177/2397791420981525

[17] I. Aatthisugan, A. Razal Rose, D. Selwyn Jebadurai, Mechanical and wear behaviour of AZ91D magnesium matrix hybrid composite reinforced with boron carbide and graphite, J. Magnes. Alloy 5 (2017) 20–25. https://doi.org/10.1016/j.jma.2016.12.004

[18] S. Miladinovic, S. Gajevic, S. Savic, I. Miletic, B. Stojanovic, A. Vencl, Tribological behaviour of hypereutectic Al-Si composites: A multi-response optimisation approach with ANN and Taguchi grey method, Lubricants 12 (2024) 61. https://doi.org/10.3390/lubricants12020061

[19] I. Manivannan, S. Ranganathan, S. Gopalakannan, S. Suresh, K. Nagakarthigan, R. Jubendradass, Tribological and surface behavior of silicon carbide reinforced aluminum matrix nanocomposite, Surfaces and Interfaces 8 (2017) 127–136. https://doi.org/10.1016/j.surfin.2017.05.007

[20] M. H. Adib, R. Abedinzadeh, Study of mechanical properties and wear behavior of hybrid Al/(Al_2O_3+SiC) nanocomposites fabricated by powder technology, Mater. Chem. Phys. 5 (2023) 127922. https://doi.org/10.1016/j.matchemphys.2023.127922

[21] S. Sirin, S. Akincioglu, M. K. Gupta, T. Kivak, N. Khanna, A tribological performance of vegetable-based oil combined with GNPs and hBN nanoparticles on the friction-wear tests of titanium grade 2, Tribol. Int. 4 (2023) 108314. https://doi.org/10.1016/j.triboint.2023.108314