Advanced Engineering Letters Vol.4, No.4, 187-197 (2025) e-ISSN: 2812-9709

TRIBOLOGICAL ANALYSIS OF INNOVATIVE HYBRID Al-SiC-ZrO_2 METAL MATRIX COMPOSITES FABRICATED USING POWDER METALLURGY ROUTE FOR AUTOMOTIVE APPLICATIONS

UDC:620.16:629.017
Original scientific paper https://doi.org/10.46793/adeletters.2025.4.4.2

Pallab Sarmah[1], **Kapil Gupta**[1*]

[1]Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Doornfontein Campus, Johannesburg 2028, South Africa

Abstract:
Extensive research in materials science is needed to address the global paucity of natural (or monolithic) materials. Aluminum (Al) based hybrid metal matrix composites (HMMCs) are ideal for automotive engineering and medical applications due to their lightweight, high stiffness, hardness, and wear resistance. Wear characteristics of such composites are evaluated by a tribology study. In the present work, Al-based hybrid MMCs with silicon carbide (SiC) and zirconium oxide (ZrO_2) reinforcing particles have been developed via powder metallurgy. A total of 25 different types of MMCs were fabricated using the Taguchi robust technique. Tribology investigation with evaluation of the coefficient of friction (COF) using a pin-on-disc tribometer at a load of 10 N and a sliding time of 50 minutes has been carried out. The fabricated hybrid Al MMCs containing 7 wt.% SiC and 14 wt.% ZrO_2 particles exhibited the lowest COF during the wear test. The greatest and lowest microhardness and COF values obtained among all fabricated hybrid MMCs are (86.6 HVN and 30.6 HVN) and (0.8403 and 0.4518), respectively. The scanning electron microscopic investigation confirmed the improved wear characteristic of the developed MMCs, suitable for engine block pistons, piston insert rings, and brake rotors of automobiles.

ARTICLE HISTORY
Received: 16 September 2025
Revised: 12 October 2025
Accepted: 3 November 2025
Published: 15 December 2025

KEYWORDS
Al-SiC-ZrO_2, Powder Metallurgy, Tribology, Coefficient of friction, Wear

1. INTRODUCTION

Hybrid composites belong to a novel class of materials for application in various areas where tribological properties are of importance. Aluminium-based composites have superior mechanical and tribological capabilities, making mono ceramics an effective reinforcement material. Various reinforcement combinations are utilized to enhance hybrid composites' performance in tribological applications [1]. Aluminum matrix composites (AMCs) are exclusively utilized in the automotive industry for manufacturing brake rotors, block pistons, piston insert rings, and engine brake pads [2]. The majority of these vehicle engine parts are vulnerable to dry sliding wear (adhesive wear) [3]. Reinforcements such as Al_2O_3, ZrO_2, Al_2O_3 and TiB_2 improve the tribological characteristics of aluminum and its alloys [4]. Aluminium, due to its low density and high strength properties, as an MMC matrix, is superior to other metals such as Cu, Ti, Mg, and Fe. Composite materials can be developed by mixing a lightweight aluminum alloy with reinforcements, resulting in components with high strength and low weight [4,5]. AMCs have great potential for applications where wear and friction are important characteristics. Improved tribological performance, notably sliding wear resistance, of particle or whisker-embedded AMCs depends on reinforcement, fabrication method, counterface material, and surface exposure. The strength of the interfacial bond, as well as the

*CONTACT: Kapil Gupta, e-mail: kgupta@uj.ac.za

mechanical characteristics of the matrix and reinforcements, significantly impact the tribological performance of composites [6]. Powder metallurgy (PM), an adaptable and cost-effective manufacturing technique, has proven highly effective in producing aluminum-based hybrid MMCs with consistent quality and controlled microstructures [7]. The manufacturing parameters of MMCs utilizing PM processes are critical for maximizing mechanical characteristics and performance [8]. Significant constraints like compaction pressure, sintering temperature, and reinforcement type all have a significant influence on the microstructure and consequently on composite qualities [9]. The sintering temperature influences particle diffusion and bonding, hence affecting hardness and wear resistance. The selection of reinforcements (e.g., SiC, CNTs) and their uniform distribution are crucial for improving mechanical characteristics and preventing performance-related issues. Achieving uniformity in powder dispersion is critical to ensuring consistent composite characteristics. Poor bonding between the matrix and reinforcements might result in lower mechanical performance, necessitating surface modifications or enhanced processing parameters [10].

SiC is an important ceramic and is considered for high-performance applications [11,12]. Zirconium oxide (ZrO_2) is an extraordinarily strong, malleable, and ductile substance. ZrO_2 shares many physical and chemical properties with titanium, demonstrating its hardness and wear resistance. ZrO_2 is a sophisticated ceramic substance that is widely used in the production of various hard ceramics. Due to its hardness, chemical inertness, and other biocompatible qualities, this material is extensively used in the production of various dental implants [13]. Properly distributing reinforcement elements in an aluminum matrix improves mechanical and tribological properties [14]. SiC was combined with fly ash and red mud to enhance compressive strength and wear resistance. Abbasipour et al. [15] investigated AMCs with carbon nanotube (CNT) reinforcement using several production methods, including melt agitation, rheo casting, stir casting, and compo casting procedures. Adding CNT and switching from liquid to semisolid methods led to decreased wear characteristics due to adhesion and delamination. Sharma et al. [16] developed Al 6061 composites utilizing the stir casting process. SiC and CNTs were introduced in the appropriate amounts during casting. The microhardness and wear properties improved by 36% as related to the Al6061 alloy. Homogeneous spreading of reinforcing elements in the aluminum matrix is primarily responsible for the observed findings. Suresh et al. [17] investigated a hybrid composite of Al7075, Al_2O_3, SiC, and Mg using stir casting. The study found that adding Al_2O_3/SiC advances wear resistance and mechanical characteristics of hybrid Al7075 composites. During a study on Al7075/Gr/TiO_2 MMCs, adding 8 wt.% TiO_2 nanoparticles reduced the wear rate significantly [18]. An investigation on the fabrication of Al7075/Al_2O_3/5wt.%Gr using liquid metallurgy revealed that adding more Al_2O_3 to the Al7075 lowers wear loss [19]. Carbide particles are often used in AMCs to increase mechanical performance. The Al7075 matrix containing 6% SiC exhibited greater tensile strength and hardness. However, growing the wt.% of SiC particles dramatically decreased the mechanical characteristics. Furthermore, with 8 wt.% SiC reinforcement with Al7075 matrix, the wear rate was significantly reduced. Another work successfully manufactured Al-SiC-ZrO_2 nanocomposites with fixed SiC (5 wt.%) and varied ZrO_2 concentrations (3, 6, and 9 wt.%) using powder metallurgy and microwave sintering, where Al-5wt.%SiC-9wt.%ZrO_2 increased yield strength by 119% and 56%, respectively [20]. Sridhar et al. [21] explored how Gr and SiC influence wear features of a hybrid composite. They observed that Gr has a constant and robust wear reaction. In another work, 4 wt.% SiC particles were found to be effective in improving the wear characteristics of Al 7075/SiC nano-composites [22]. The introduction of B_4C and MoS_2 in the Al 7075-based composites was also found effective in improving wear resistance and tribology performance [23].

The literature indicates that Al-SiC-ZrO_2 composites have been explored limited. To fill that gap, the present research attempts to investigate a broad range of ball milling and sintering process parameters and their effects on the performance of composites. Specifically, the study reported in this article evaluates the effect of manufacturing conditions in terms of process parameter combinations on the tribological performance of Al-SiC-ZrO_2 hybrid MMCs, intending to find their suitability for automotive applications. As investigated in this research that appropriately fixed process parameters have a synergistic effect on the tribological performance of Al-SiC-ZrO_2 MMCs, which has not been extensively reported in earlier research. The findings of this research can be highly useful for the automobile and other sectors where wear characteristics of mechanical components are of paramount importance.

2. MATERIALS AND METHODS

In the present work, for the development of Al hybrid MMCs, Al-based matrix and SiC and ZrO_2 reinforcements have been used. Zimco Aluminum Company, South Africa, supplies pure Al powder (purity > 99%, particle size 75 µm) and SiC and ZrO_2 reinforcement elements of 16 and 5 microns, respectively, provided through Merck Life Science (Pty) Ltd, South Africa were used in this present work. The powder metallurgy route has been followed to develop Al hybrid MMCs. The sequence of operations followed in the present research is shown in Fig. 1. A hydraulic pellet press (Make: Specac Ltd, UK; Model: GS15011) was used for green compaction with ten tons of pressure applied after the powdered ingredients were mixed in a high-energy ball mill. The fixed ball milling parameters are presented in Table 1. Each green compact sample of cylindrical shape (diameter = 13 mm and thickness = 8 mm) was subjected to a conventional sintering process utilizing a muffle furnace (Make: Lenton Laboratory and Scientific Equipment, Randburg, South Africa) following the cold compression procedure. The most cost-effective method of sintering is the conventional method, which is superior to the microwave and plasma arc methods. The process parameters for MMC manufacture were the wt.% of SiC and ZrO_2 reinforcement particles, milling time, sintering temperature and time as indicated in Table 1, where all are at five levels. The values and levels were selected based on literature, trial experiments, machine constraints, and availability of the resources. The Taguchi L25 robust technique was utilized to design experiments for the fabrication of MMCs because of its uniqueness to scientifically design experiments much lesser in number than full factorial and hence to save cost, time, and efforts significantly. A total of 25 distinct MMC samples were fabricated at various fabrication conditions. The results of SEM analysis for all the procured base Al matrix, ZrO_2, SiC particles, and fabricated hybrid MMCs (Al+7wt.%SiC+14wt.%ZrO_2) are illustrated in Figs. 2 and 3, respectively.

Using Archimedes' principle, the porosity of the sintered samples was measured; the samples were submerged in water to ascertain their bulk density, and the maximum porosity was found to be approximately 4.7%. During the PM process, appropriate measures were taken to minimize porosity. These included using the ideal compaction pressure to minimize inter-particle voids, properly homogenizing the powder during mixing, and controlling the sintering parameters to encourage diffusion bonding without oxidation or pore entrapment. Following successful fabrication, all 25 MMC samples were subjected to micro-hardness examination. Vickers' hardness testing equipment (Make: Indentec Hardness Testing Machines Ltd, UK; Model: Zhu-M) was used to measure the MMCs' micro-hardness in accordance with ASTM standards. Table 1 demonstrates the Vickers hardness values with standard deviations corresponding to all experiments. According to Table 1, the microhardness value of 86.6 obtained under fabrication circumstances 10 is the highest, while 30.6 is the lowest under fabrication conditions 14. Microhardness values of the fabricated MMCs were previously reported in [24]. The best-performing hybrid composite samples in terms of hardness are 7 wt.% SiC and 14 wt.% ZrO_2, milled for 60 minutes, sintered at 500°C, and held for 90 minutes under fabrication condition 10. The addition of reinforcing particles like SiC and ZrO_2 greatly increased the micro-hardness of Al-based hybrid MMCs. Because these ceramic particles can better spread stress within the matrix and enhance the microstructure, their presence results in improved mechanical characteristics.

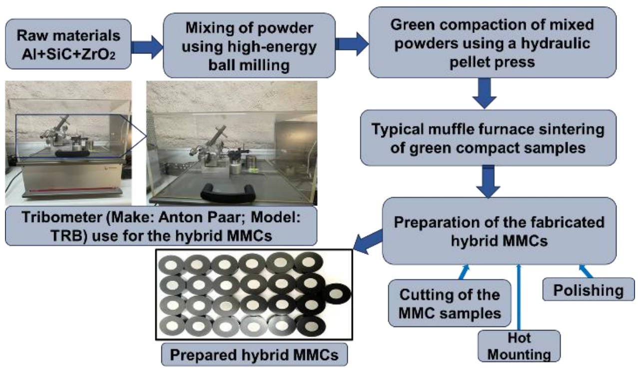
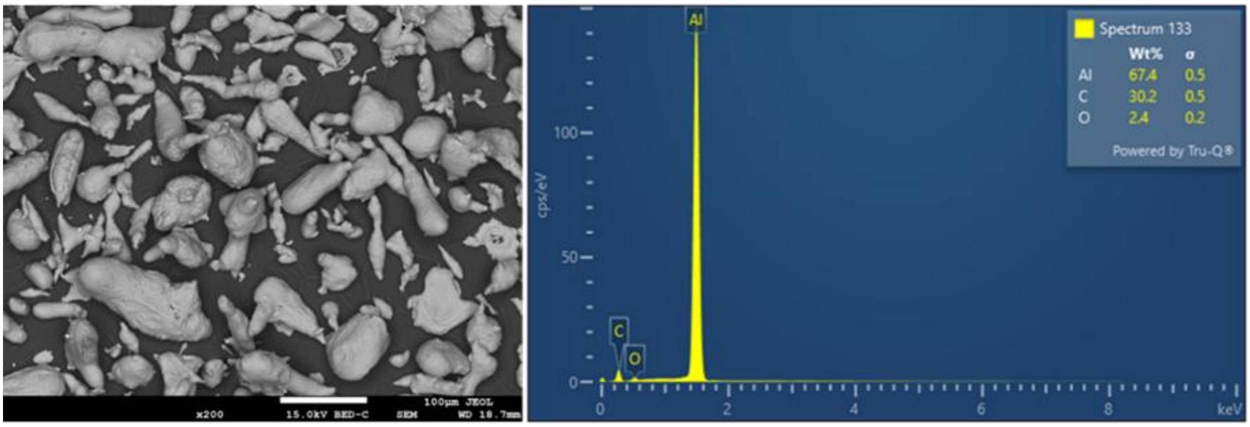


Fig. 1. Sequence of operations followed in the present work for the fabrication and analysis of hybrid MMCs

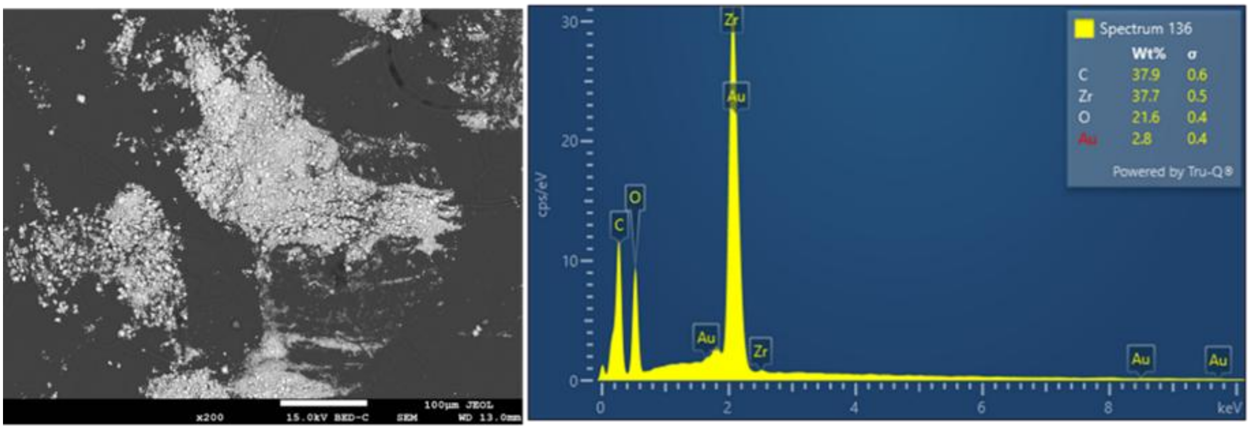
Table 1. Standard operating parameters for the ball milling method

Fixed Parameters	Values
Material for the ball	Stainless steel
Powder to ball ratio	1:10
PCA	Stearic Acid
Milling speed	200 rpm

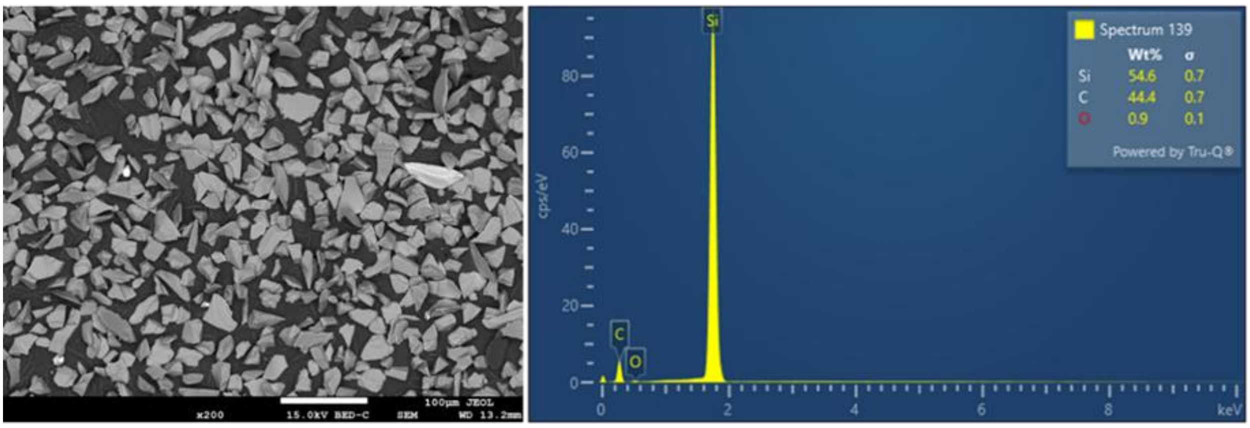
SiC elements provided Al-based composites with more hardness and tensile strength. Because SiC and ZrO_2 are evenly dispersed throughout the Al matrix, agglomeration is avoided, resulting in finer grain structures and improved mechanical performance. On the other hand, even though adding these reinforcements usually increases hardness, problems like uniform dispersion and particle aggregation still pose serious issues to the overall performance of MMCs. Increasing the hardness of HMMCs reduces wear and porosity. Following these, each of the 25 MMC specimens conducted a dry wear tribo test using a pin-on-disc tribometer (Make: Anton Paar Southern Africa (Pty.) Ltd., South Africa; Model: TRB). The pin-on-disc wear test was conducted in accordance with the ASTM G99-17 standard. It was performed at an applied load of 10 N, sliding speed 0.5m/sec, while maintaining the room temperature at 25°C and 50% humidity.



(a)



(b)



(c)

Fig. 2. Before the fabrication of hybrid MMCs, SEM and EDS examination of procured materials (a) Al powder, (b) ZrO_2, and (c) SiC [24]

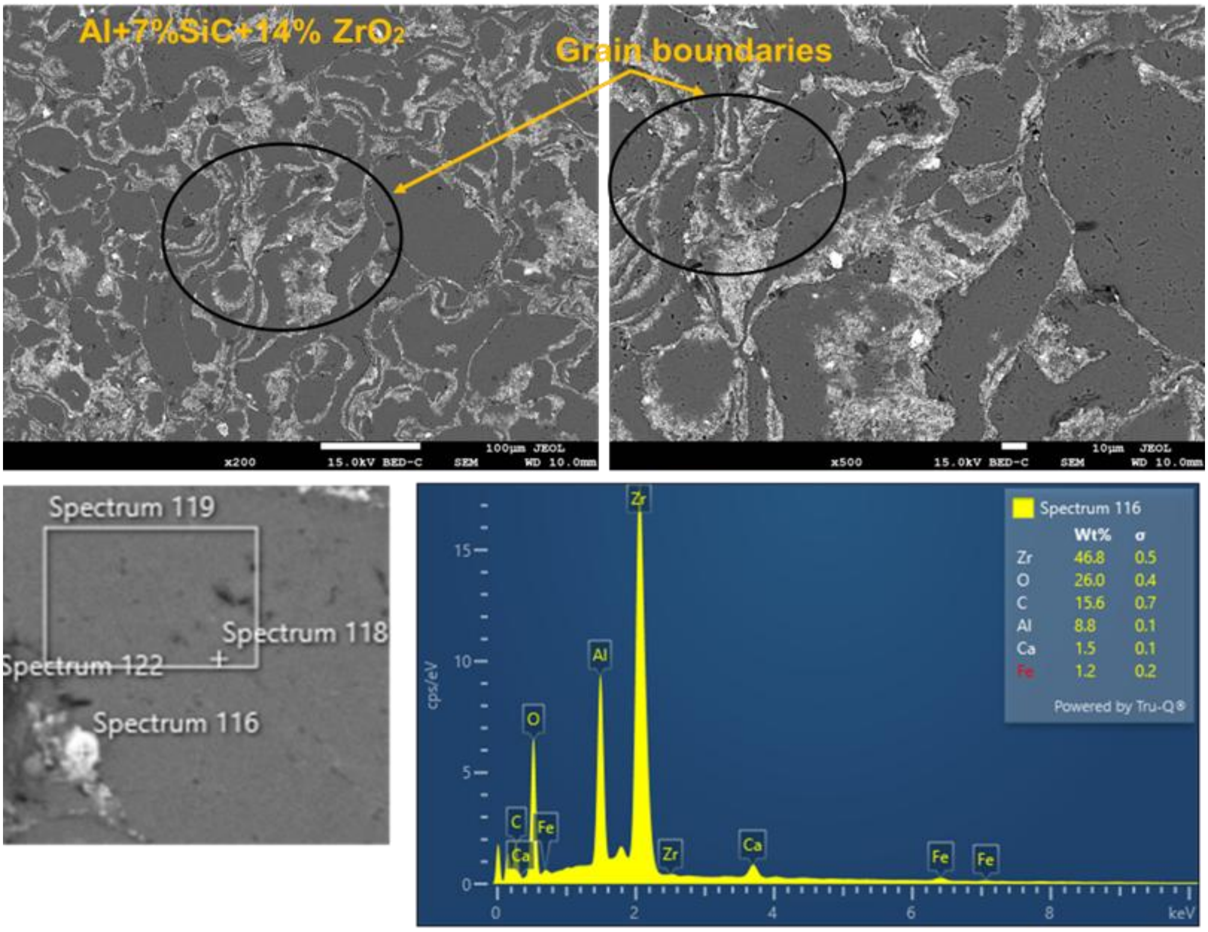


Fig. 3. SEM-EDS results for the manufactured MMCs at fabrication conditions 10 (Al+7 wt.%SiC+14wt.%ZrO_2) [24]

3. RESULTS AND DISCUSSION

Table 2 presents the average COF for 25 numbers of hybrid MMCs. SiC and ZrO_2 reinforcement particles boost hardness by generating a robust interfacial connection through the matrix material, resulting in a reduction in COF as the fraction of reinforcement increases. Increasing hardness improves load-bearing capacity and wear resistance [25]. Fig. 4 illustrates the change in COF with experimental conditions. Lowest and highest COF values of 0.4518 and 0.8403 were achieved for the fabrication conditions 10 and 14, respectively.

An error analysis was carried out for the microhardness and COF measurements of the manufactured hybrid MMCs to confirm the validity of the experimental findings. To take into consideration local compositional and microstructural changes, the Vickers microhardness tests were performed at several points on each sample surface. A comparatively high degree of repeatability was indicated by the observed variation in microhardness values across different locations, with values staying within ±5%. A pin-on-disc tribometer was employed to measure the COF while maintaining a constant normal load and sliding velocity. For each sample, the variation in COF values was determined to be within ±0.2 throughout three repeated tests.

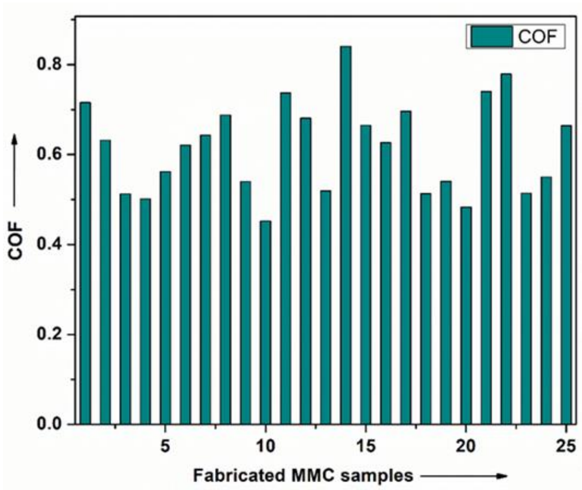


Fig. 4. Variation of COF measurements at all 25 fabrication conditions

Composites with a greater wt.% possess a better wear resistance than composites with a lower wt.%

of reinforced particles under the identical load [26]. Increased SiC and ZrO_2 content leads to varying wear severity. Scratching and grooving are more noticeable when MMCs include a low wt.% of reinforcing particles.

Composites with a higher wt.% of reinforcement particles consistently have lower COF values, demonstrating that ceramic particles like SiC and ZrO_2 improve both load-bearing capability and resistance to material loss. Previous research [27] has described the creation of a protective tribolayer during sliding, which could potentially explain the reduction in friction. Samples with reduced reinforcing content, on the other hand, had increased COF and wear, most likely due to larger real contact areas and a greater sensitivity to microcutting.

Table 2. Experimental combinations for the production of hybrid Al-SiC-ZrO_2 MMCs, together with the associated COF and microhardness [24]

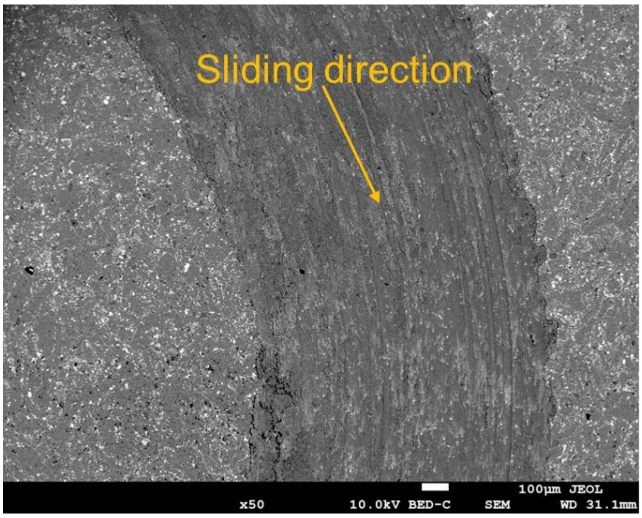
Expt. No.	Fabrication Condition					Microhardness (VHN)	COF
	wt.% of SiC	wt.% of ZrO_2	Sintering Temperature (∘C)	Sintering Time (min)	Milling Time (min)		
1	3	2	500	80	20	36.4±2.32	0.7157
2	3	5	530	90	40	42.2±2.14	0.6319
3	3	8	560	100	60	47±2.8	0.5123
4	3	11	590	110	80	52.4±4.58	0.5017
5	3	14	620	120	100	46.6±4.84	0.5621
6	7	2	530	100	80	36.4±1.95	0.6209
7	7	5	560	110	100	49.4±3.84	0.6430
8	7	8	590	120	20	41.8±4.64	0.6879
9	7	11	620	80	40	61.2±4.31	0.5396
10	7	14	500	90	60	86.6±2.85	0.4518
11	11	2	560	120	40	34.2±3.84	0.7369
12	11	5	590	80	60	41.6±3.19	0.6811
13	11	8	620	90	80	68.8±3.31	0.5194
14	11	11	500	100	100	30.6±2.55	0.8403
15	11	14	530	110	20	44±2.47	0.6649
16	15	2	590	90	100	45±4.38	0.6264
17	15	5	620	100	20	41.6±3.77	0.6961
18	15	8	500	110	40	65.2±3.52	0.5129
19	15	11	530	120	60	61.8±3.22	0.5402
20	15	14	560	80	80	75.2±4.12	0.4831
21	19	2	620	110	60	55±2.59	0.7406
22	19	5	500	120	80	52.4±2.28	0.7793
23	19	8	530	80	100	54.4±2.17	0.5138
24	19	11	560	90	20	46.2±4.31	0.5502
25	19	14	590	100	40	44.6±3.55	0.6640

Sharp edges on contact surfaces cause abrasion, resulting in scratches. Wear resulted from the material pushing out of the groove in both directions and remaining there when tiny wedge-shaped fragments came into contact with abrasive particles. Continuing sliding caused fractures beneath the surface, leading to significant wear [28]. Following the tribology test, worn composite samples were evaluated.

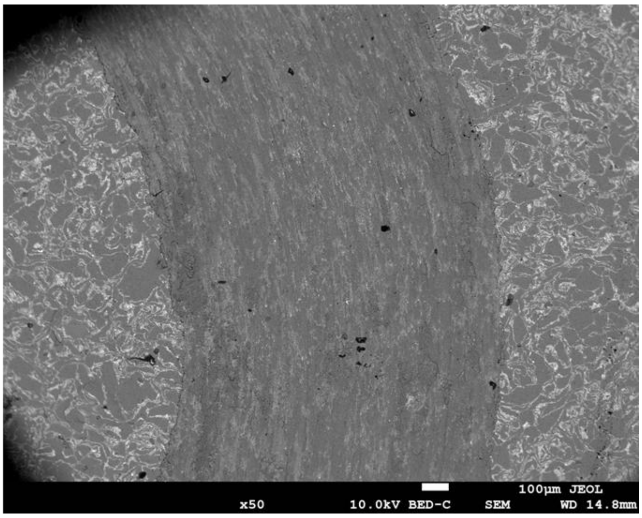
Microcracks and wear debris were visible in the worn surface's SEM pictures. Fig. 5 presents the worn surface of MMCs at various fabrication conditions. Because of the greater wt.% of reinforcement particles, the COF value decreased.

However, fewer fractures were seen, and the surface was smoothened, increasing the COF. Microcracks and delamination on the wear track are caused by extreme plastic distortion of the composite surface, resulting in greater wear rates. SEM pictures demonstrate the existence of adhesion wear generated by cold welding amid asperities of contact surfaces, which then rips the composite's surface in the designated location.

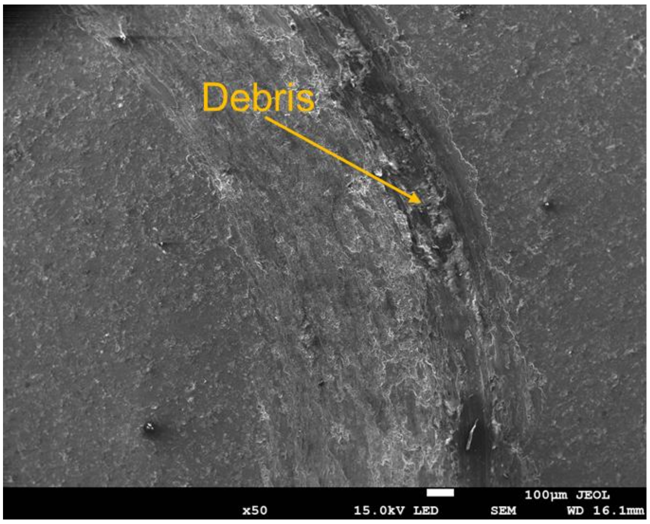
Abrasive wear is the primary wear mechanism seen in the manufactured hybrid MMCs, according to the SEM examination of worn surface morphology. Parallel grooves and ploughing lines in the sliding direction are indicative of this, especially in samples with higher reinforcement content, where hard particles helped to micro-cut the matrix and counterface. Minor delamination features, such as subsurface fissures and localized material pull-out, were also noted in certain samples, particularly those with weaker interfacial bonding or reduced reinforcement dispersion. Nevertheless, under the tested conditions, delamination was not the predominant process.



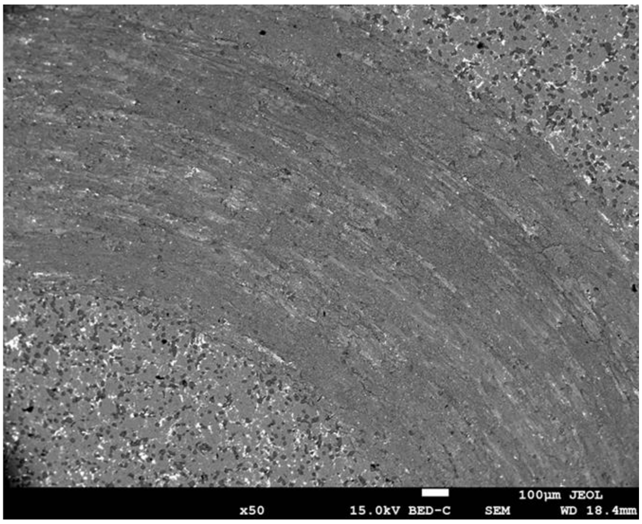
(a) Fabrication condition: 1



(b) Fabrication condition: 10



(c) Fabrication condition: 14



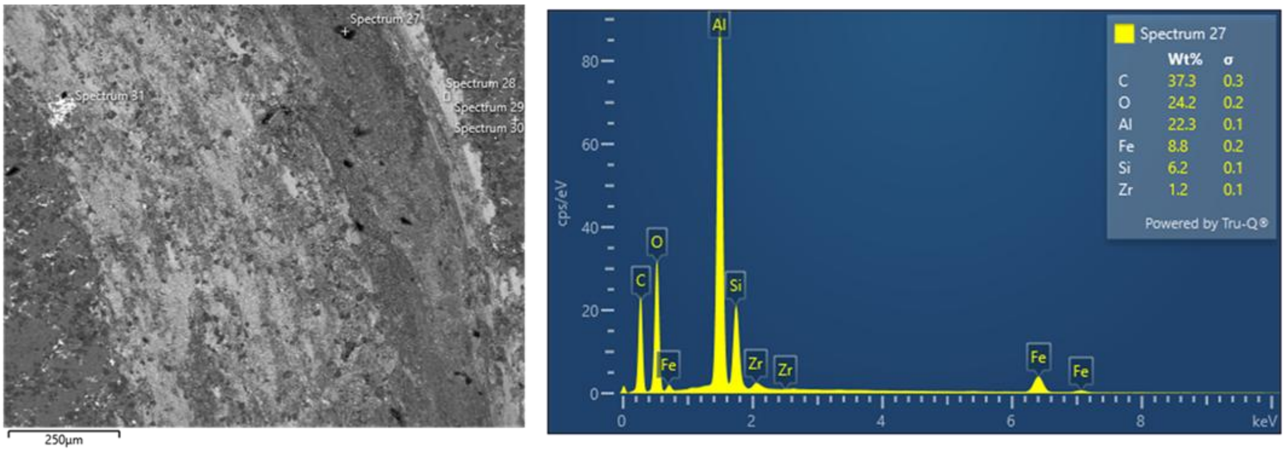
(d) Fabrication condition: 20

Fig. 5. SEM images of the worn surface of the hybrid MMCs developed at various manufacturing conditions

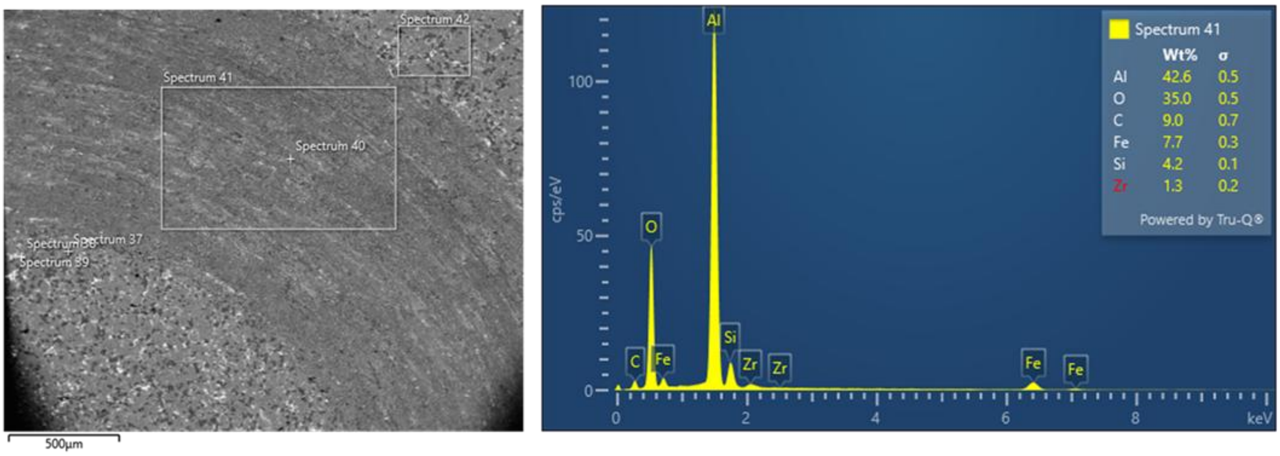
Distinct abrasive grooves that follow the sliding direction are present on the hybrid MMCs' worn surface as observed in Fig. 5. These grooves are sharp and closely spaced, indicating a primary abrasive wear process, most likely induced by hard reinforcing particles contained in the counterface, scratching the softer aluminum matrix. Furthermore, delamination cracks perpendicular to the sliding direction are detected, implying cyclic fatigue under repeated loading conditions. These fissures may aid in the separation of material pieces, contributing to an enhanced wear rate. The coexistence of these features explains the moderate increase in the COF values observed during the steady-state sliding phase.

Fig. 6 shows the worn surfaces' SEM and EDS spectra after dry wear analysis. The ploughing of ceramic SiC and ZrO_2 reinforcement particles onto the counter EN31 steel pin produced continuous grooves analogous to a sliding way. In dry conditions, the occurrence of direct contact between the asperities on the HMMC disc and the counter pin surface caused thermal softening of the disc surface, resulting in considerable wear of the disc.

Also, increased reinforcing particle content reduced wear as well as the COF value in HMMC specimens. As shown in the EDS spectra, adding SiC and ZrO_2 elements to the composites caused the development of oxide layers under increased stresses, which oxidized the pin and disc interfaces. These oxide coatings reduced wear due to their self-lubrication properties. As the sintering temperature increased, the wear rate increased due to the distortion of asperities at the pin and disc counter surfaces. Furthermore, strong ceramic reinforcing particles on the composite disc surface broke down and dispersed into smaller abrasive particles. Ceramic particles on the composite surface can originate and propagate microcracks, causing the HMMC surface to delaminate and wear. Microcracks and a separated bulk surface in the form of laminates indicate delaminating wear. The applied load affects the localized stress concentration near the asperities' contact, causing disc surface wear. The SEM/EDS study also revealed no discernible development of a mechanically mixed layer (MML). Instead of material transfer and mixing at the interface, the lack of a stable tribo-layer indicates that two-body abrasive interaction dominated the wear process.



(a) Fabrication condition: 14



(b) Fabrication condition: 20

Fig. 6. EDS examination of the hybrid MMCs' worn surfaces under varied manufacturing settings

When compared with the results of other researchers [29,30], the current work has obtained significantly improved microhardness and wear resistance for Al-based MMCs reinforced with SiC and ZrO_2. In comparison to the 86.6 HVN found in the current study under ideal conditions (7 wt.% SiC + 14 wt.% ZrO_2), a maximum microhardness of roughly 67 ± 4 HV was reported for microwave-sintered Al–5 wt.% SiC with up to 9 wt.% ZrO_2 [20].

Nayak et al. [29] obtained microhardness values in the range of 80–104 VHN for Al–ZrO_2–SiC composites with Gr particles. Additionally, the present study's SEM examination revealed an abrasive wear mechanism, which is consistent in matching with the findings of other studies and indicates that harder surfaces and abrasive wear are usually the outcomes of keeping higher ceramic reinforcement content. Surface durability under sliding conditions is improved by the efficient use of SiC and ZrO_2 particles.

4. CONCLUSION

In this study, tribological analysis was successfully done for the fabricated 25 numbers of hybrid Al-based MMCs with SiC and ZrO_2 reinforcement particles. The following findings can be highlighted:

- Al-based MMCs with SiC and ZrO_2 reinforcing components have been successfully hybridized using the powder metallurgy technique with the aid of ball milling and conventional sintering operations.
- SiC and ZrO_2 reinforcing components spread uniformly throughout the Al matrix in all the fabricated composites, which directly influenced the mechanical and tribological properties.
- Increased interfacial bonding and improved physical characteristics of the composites were the outcomes of sintering at higher temperatures. The highest 86.6 HVN and lowest 30.6 HVN microhardness values for fabrication conditions 10 and 14, respectively, were achieved.
- MMCs with 7 wt.% SiC and 14 wt.% ZrO_2 particles showed the lowest wear possibility with a COF value of 0.4518. Also, the SEM study of the worn surface revealed abrasive wear mechanisms.

Such Al-based hybrid MMCs equipped with suitable tribological properties can find potential applications in automotive, aerospace, and other industrial domains. The possible future research avenues may be on exploring other performance characteristics of Al MMCs, investigating the effect of different compression and sintering techniques, modeling and optimization of process parameters using machine learning, comparison of MMC properties obtained by different techniques, and sustainability interventions in Al MMC manufacturing.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

REFERENCES

[1] J. Krstić, J. Jovanović, S. Gajević, S. Miladinović, N.M. Vaxevanidis, I. Kiss, B. Stojanović, Application of metal matrix nanocomposites in engineering. *Advanced Engineering Letters,* 3(4), 2024: 180-190. https://doi.org/10.46793/adeletters.2024.3.4.5

[2] A.T. Oyewo, O.O. Oluwole, O.O. Ajide, T.E. Omoniyi, M. Hussain, A summary of current advancements in hybrid composites based on aluminium matrix in aerospace applications. *Hybrid Advances*, 5, 2023: 100117. https://doi.org/10.1016/j.hybadv.2023.100117

[3] P.V. Reddy, G.S. Kumar, D.M. Krishnudu, H.R. Rao, Mechanical and wear performances of aluminium-based metal matrix composites: A review. *Journal of Bio- and Tribo-Corrosion*, 6, 2020: 83. https://doi.org/10.1007/s40735-020-00379-2

[4] S. Gajević, S. Miladinović, B. Stojanović, Metallic nanocomposites: An introduction. *Nanotechnology in the Automotive Industry,* 2022: 155–161. https://doi.org/10.1016/B978-0-323-90524-4.00008-6

[5] S. Veličković, S. Miladinović, B. Stojanović, R.R. Nikolić, B. Hadzima, D. Arsić, Influence of load and reinforcement content on selected tribological properties of Al/SiC/Gr hybrid composites. *Production Engineering Archives*. 18(18), 2018: 18-23. https://doi.org/10.30657/pea.2018.18.03

[6] V.K. Sharma, V. Kumar, R.S. Joshi, Experimental investigation on effect of RE oxides addition on tribological and mechanical properties of Al-6063-based hybrid composites. *Materials Research Express*, 6, 2019: 0865D7. https://doi.org/10.1088/2053-1591/ab2504

[7] A. Hegde, R. Nayak, G. Bolar, R. Shetty, R. Ranjan, N. Naik, Comprehensive investigation of hardness, wear, and frictional force in powder metallurgy engineered Ti-6Al-4V-SiCp metal matrix composites. *Journal of Composite Science*, 8(2), 2024: 39. https://doi.org/10.3390/jcs8020039

[8] A. Saxena, K.K. Saxena, V.K. Jain, S.K. Rajput, B.N. Pathak, A review of reinforcements and process parameters for powder metallurgy-processed metal matrix composites, *Materials Today: Proceedings*, 2023. https://doi.org/10.1016/j.matpr.2023.02.227

[9] R. Sreenivasa, B.T. Ramesh, J. Giri, M.K. Al-Sadoon, A. Bongale, T. Sathish, A.R. Banagar, Optimizing process parameters to minimize wear-induced material loss in bronze-based hybrid metal matrix composites using the

Taguchi method. *AIP Advances*, 14, 2024: 095104. https://doi.org/10.1063/5.0203081

[10] K.C. Nayak, K.K. Rane, P.P. Date, T.S. Srivatsan, Synthesis of an aluminum alloy metal matrix composite using powder metallurgy: Role of sintering parameters. *Applied Sciences*, 12(17), 2022: 8843. https://doi.org/10.3390/app12178843

[11] P. Raghuvaran, M. Suresh, S. Abilash, M. Asfaq, R.D. Tejash, C. Dinesh, Reviews on properties of silicon carbide reinforced composite materials made by liquid metallurgy technique. *AIP Conference Proceedings*, 2527, 2022: 020018. https://doi.org/10.1063/5.0108405

[12] M.Y. Zhou, L.B. Ren, L.L. Fan, Y.W.X. Zhang, T.H. Lu, G.F. Quan, M. Gupta, Progress in research on hybrid metal matrix composites. *Journal of Alloys and Compounds*, 838, 2020: 155274. https://doi.org/10.1016/j.jallcom.2020.155274

[13] G. Marmol, D.P. Ferreira, R. Fangueiro, Automotive and construction applications of fiber reinforced composites. *Fiber Reinforced Composites*, 2021: 785–788. https://doi.org/10.1016/B978-0-12-821090-1.00009-0

[14] P. Chakrapani, T.S.A. Suryakumari, Mechanical properties of aluminium metal matrix composites—A review. *Materials Today: Proceedings*, 45(Part 7), 2020: 5960-5964. https://doi.org/10.1016/j.matpr.2020.09.247

[15] B. Abbasaipour, B. Niroumand, S.M. Monir Vaghefi, M. Abedi, Tribological behavior of A356–CNT nanocomposites fabricated by various techniques. *Transactions of Nonferrous Metals Society of China*, 29(10), 2019: 993–2004. https://doi.org/10.1016/S1003-6326(19)65107-1

[16] A. Sharma, V.M. Sharma, J. Paul, A comparative study on microstructural evolution and surface properties of graphene/CNT reinforced Al6061–SiC hybrid surface composite fabricated via friction stir casting processing. *Transactions of Nonferrous Metals Society of China*, 29(10), 2019: 2005–2026. https://doi.org/10.1016/S1003-6326(19)65108-3

[17] S. Suresh, G.H. Gowd, M.L.S.D. Kumar, Advances in aluminum-based hybrid composites: A review. *Advanced Composites and Hybrid Materials*, 2, 2019: 530–539.

[18] G.T. Danappa, C.R. Raghavendra, R.P. Swamy, K. Naik, Dry sliding wear behaviour of Al7075/Gr/nano TiO_2 MMC using RSM. *Materials Today: Proceedings*, 38(Part 5), 2021: 2797–2802. https://doi.org/10.1016/j.matpr.2020.08.736

[19] P. Raghuvaran, J. Baskaran, C. Aagash, A. Ganesh, S.G. Krishna, Fabrication and evaluation of Al-based MMC using stir casting process. *Materials Today: Proceedings*, 45(Part 2), 2021: 1914–1918. https://doi.org/10.1016/j.matpr.2020.09.191

[20] A. Khan, M.W. Abdelrazeq, M.R. Mattli, M.M. Yusuf, A. Alashraf, P.R. Matli, R.A. Shakoor, Structural and Mechanical Properties of Al-SiC-ZrO_2 Nanocomposites Fabricated by Microwave Sintering Technique. *Crystals*, 10(10), 2020: 904. https://doi.org/10.3390/cryst10100904

[21] A. Sridhar, K.P. Lakshmi, C.V.S. Raju, Microstructure, Mechanical and Tribological Properties of Al7075/SiC/Graphite Hybrid Metal Matrix Composites. *Journal of Bio-and Tribo-Corrosion*, 8, 2022: 84. https://doi.org/10.1007/s40735-022-00680-2

[22] S. Suresh, G.H. Gowd, M.D. Kumar, Tribological behavior of Al 7075/SiC metal matrix nano-composite by stir casting method. *Journal of the Institution of Engineers (India): Series D*, 100, 2019: 97–103. https://doi.org/10.1007/s40033-018-0167-2

[23] S. Liu, Y. Wang, T. Muthuramalingam, G. Anbuchezhiyan, Effect of B_4C and MoS_2 reinforcement on microstructure and wear properties of aluminum hybrid composite for automotive applications. *Composites Part B: Engineering*, 176, 2019: 107329. https://doi.org/10.1016/j.compositesb.2019.107329

[24] P. Sarmah, S. Pawanr, K. Gupta, Fabrication of novel hybrid Al-SiC-ZrO_2 composites via powder metallurgy route and intelligent modeling for their microhardness. *Ceramics*, 8(3), 2025: 91. https://doi.org/10.3390/ceramics8030091

[25] X. Canute, M. C. Majumder, Mechanical and tribological behaviour of stir cast aluminium/boron carbide/fly ash composites. *Journal of Engineering Science and Technology*, 13(3), 2018: 755–777.

[26] D.O. Folorunso, S.S. Owoeye, Influence of quarry dust–silicon carbide weight

percentage on the mechanical properties and tribological behavior of stir cast ZA-27 alloy-based hybrid composites. *Journal of King Saud University - Engineering Sciences*, 31(3), 2019: 280–285. https://doi.org/10.1016/j.jksues.2017.07.003

[27] T. Liu, W. Lyu, Z. Li, S. Wang, C. Liu, J. Jiang, X. Jiang, A Review of Research Progress on the Fretting Fatigue Mechanism and Protection Measures of Metal Matrix Composites. *Coatings,* 13(2), 2023: 365. https://doi.org/10.3390/coatings13020365

[28] P. Sarmah, P. K. Patowari, Mechanical and tribological analysis of the fabricated Al 6063-based MMCs with SiC reinforcement particles. *Silicon*, 15, 2023: 2781–2796. https://doi.org/10.1007/s12633-022-02175-8

[29] S. Nayak, T. Mahanta, J. Sahoo, A. Mishra, Mechanical Properties and Wear Characteristics Al-ZrO_2-SiCp and Graphite Hybrid Metal Matrix Composites. *IOP Conference Series: Materials Science and Engineering*, 338, 2018: 012029. https://doi.org/10.1088/1757-899x/338/1/012029

[30] S.P. Dwivedi, A. Saxena, I. Haider, S. Sharma, Effect of zirconium diboride addition in zirconium dioxide reinforced aluminum-based composite fabricated by microwave sintering technique. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 238(4), 2023: 1708-1722. https://doi.org/10.1177/09544089231164272