Research Article

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Wear Performance of Hybrid Ceramic Strengthened Nano-aluminium Composites for Potential Application in Brake Discs

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ABSTRACT

Hybrid ceramic-reinforced nano-aluminum composites are emerging as a superior material for brake discs for use in automobiles because of their remarkable qualities. The inclusion of ceramic particles significantly enhances wear resistance, thermal stability, and mechanical strength, ensuring efficient heat dissipation and reducing the risk of brake fade. In this study, aluminium alloy 7075 (AA7075) is reinforced with equal proportions of nano silicon carbide (nSiC) and zirconium oxide (ZrO_2) to reduce vehicle weight, improve fuel efficiency, and extend the brake disc lifespan. The powder metallurgy (PM) method is adopted for fabricating the composites with 3 wt.% of nSiC and 7.5% ZrO_2 with polyvinyl alcohol (PVA) as a binder. The fabricated specimen was subjected to wear studies in pin-on-disc (PoD) apparatus as per ASTM G99 standard. Higher axial load (AL), sliding velocity (SV), and sliding distance (SD) intensify the wear loss (WL) of the hybrid composite. The hybrid composite can sustain more AL and SV than the base alloy due to the reinforced ceramics that form a protective tribo-layer on the composite surface under increased stress and frictional heat. The WL of nanocomposite tends to lower by 10.42%, 10.29%, 8.57%, and 11.38% when compared with base alloy (624.78, 856.47, 1087.38, and 1156.72 g) when the AL is 5, 10, 15, and 20 N. similarly, when the SV is altered (2.5, 3, .5, and 4 m/s) the WL is reduced by 8.43%, 7.73%, 6.26%, and 6.85%. The wear mechanisms of the nano-composites are analyzed by observing the abrasive wear, adhesive wear, and oxidative wear.

Keywords: Hybrid ceramic nano-composite; AA7075; Powder metallurgy; Wear studies; Tribolayer; Wear mechanism.

1. INTRODUCTION

The demand for aluminum-based composites in automobile applications arises from their unique combination of properties that address key challenges in vehicle design and performance. Aluminum composites offer significant advantages over conventional materials like steel due to their lower density, which helps reduce vehicle weight and improve fuel efficiency (Khan *et al.* 2024). This weight reduction also contributes to lower emissions, supporting environmental goals. Additionally, aluminum composites exhibit good corrosion resistance, which enhances the longevity and durability of automotive components, reducing maintenance costs over the vehicle's lifespan. Furthermore, these composites can be tailored with reinforcements such as ceramics or fibers to enhance specific mechanical properties like strength, stiffness, and thermal stability, making them suitable for critical components like engine parts, chassis components, and structural elements (Ragupathy *et al.* 2021). As automakers continue to pursue lighter, more efficient, and environmentally friendly vehicles, the demand for advanced aluminum composites is expected to grow, driving innovation in their production and application across the automotive industry (Oda *et al.* 1997).

Metal matrix composites (MMCs) are progressively being explored as potential materials for brake discs in automobiles due to their superior performance characteristics. Aluminum-based MMCs, reinforced with nano ceramic particles offer a compelling combination of lightweight properties, high thermal conductivity, and improved wear resilience associated with traditional cast iron discs (Bracamonte *et al.* 2018). These nano-composites can withstand the high temperatures and intense friction associated with braking, making them ideal for enhancing vehicle performance and efficiency. The development and optimization of these nano-MMCs focus on achieving the best balance between weight reduction, cost-effectiveness, and enhanced braking performance, matching the car industry's fuel efficiency and emission reduction targets.

Thermophysical characteristics of MMCs based on aluminum (Al-10La and Al-10Ce) reinforced with SiC were studied by Lattanzi and Awe (2024) concerning the impacts of Ni, Cu, La, and Ce. Intermetallic phases, such as Al_3Ni and $Al_{11}(La,Ce)_3$, are formed when alloying elements are added to an alloy. These phases influence the base alloy's thermal and physical characteristics. Incorporating Ni enhanced the ambient temperature elastic modulus by 180% while incorporating Cu improved it by 300%. As the temperature rose, the improvement diminished. To assess the impact of hybrid particles on dry sliding, Zheng *et al*. (2020) examined the wear behaviour of aluminium composites (ASC); 80% aluminium, 20% silicon was used as a matrix material, supplemented with SiC particles and ceramic waste. In comparison to the base alloy, ASC showed higher Brinell hardness and flexural strength. A mechanical transfer layer consisting of ASC is formed by the ceramic waste particles; this layer is beneficial for preserving the ultrafine wear fragments over the worn surface. Several blends of heat-treated aluminum MMCs (Al6082-SiC-TiO_2 composites) were studied and evaluated in terms of mechanical characteristics and high-temperature sliding wear behaviour by Singh *et al*. 2024. The hybrid composite outperformed the other materials in terms of ultimate tensile strength, hardness, and percentage of elongation. Regardless of the temperature, the hybrid composite demonstrated superior wear resistance compared to the material samples under other settings. Bharathi and kumar (2023) fabricated hybrid composites containing varying proportions of SiC and constant B_4C in aluminium matrix using a powder metallurgy route. The composite's hardness increased as a result of grain refining and dislocation movement resistance. The presence of SiC particles in the Al matrix enhanced the composites' hardness. One way to significantly boost the AMCs' compressive strength is to include SiC and B_4C reinforcements into the Al matrix alloy. The synergistic effect of reinforcing particles was seen as assisting the improvement of wear resistance.

Hybrid ceramic-reinforced (brown pumice, and coal ash) nano aluminum composites with AA6061 matrix show promising potential for application in brake discs (Ibrahim *et al*. 2024). These materials combine the lightweight properties of aluminum with the high-temperature resistance and wear characteristics of ceramics. By incorporating nano-SiO_2 and micron sized ceramic (WC) particles or fibers into an aluminum matrix (AA6061), these composites achieve enhanced mechanical strength, thermal stability, and wear resistance compared to traditional brake disc materials (Senthilkumar *et al*. 2024). This makes them suitable for demanding automotive applications where performance under high temperatures and intense frictional forces is crucial for safety and durability, where composites of aluminium incorporated with ceramic particles and nano fillers (AA1100+TiC+nanoclay) is used extensively (Srinivasan *et al*. 2024). Brake discs from lightweight hybrid composite were manufactured by Tan *et al*. (2022) using friction-stir processing. The discs had a top layer composed of A357/SiC AMMC and a bottom base made of AA6082 alloy. Microstructures are refined by a consistent distribution of SiC particles and supplementary particles, which reduces the initiation of cracks and increases durability against external stresses and inner thermal stress. The existence of hard SiC particles enhance wear resistance, particularly at higher temperatures, hardness increases. Hybrid composites reinforced with B_4C particles and naturally existing ilmenite mineral particles ($FeTiO_3$) in LM13 alloy matrix were manufactured by Gupta *et al*. (2023) using the stir-casting process. The rate of wear increased as the working temperature rose. Beyond 200℃, there was a noticeable increase in the wear rate. Particles of ilmenite decreased the coefficient of friction, enhanced strong interfacial bonding, and oxidized the sliding surface early, while B_4C improved grain refinement and boosted tribo-layer stability. Employing liquid metallurgy, Babu *et al*. (2024) reinforced zirconium diboride (ZrB_2) and B_4C dual ceramic particles in AA2014. Hybrid composites exhibited improved hardness, tensile strength, and wear resistance with increasing ZrB_2 weight% and B_4C incorporation. Surfaces that showed signs of wear at greater applied loads were mostly adhesive for matrix alloys and exhibited abrasive wear with minimal plastic deformation in hybrid composites. The tribological characteristics of AA2618+B_4C+Gr were tested at temperatures ranging from 50 to 300℃ by Nagaraju *et al*, 2023. At temperatures ranging from 50 to 300℃, the combination of Al2618 +15wt.%B_4C+10wt.% Gr increases the wear resistance by 16.45%. This is because a larger amount of Gr solid lubricants is incorporated with B_4C. Wear tolerance was sufficient due to the glazed layer's thickness and durability.

Despite the promising potential of hybrid ceramic nano-aluminium composites (HCNAC) for application in automobile brake drums, several literature gaps need to be addressed. There is limited data on the effects of environmental factors on the temperature stability and wear of these composites. Wear studies on hybrid ceramic composites have shown encouraging outcomes in terms of enhanced wear resistance and durability. The influence of the type, size, and distribution of ceramic reinforcements on the wear mechanisms is not fully understood, necessitating further investigation into optimizing composite formulations for different applications. The interaction between different wear mechanisms, such as abrasive, adhesive, and fatigue wear, in hybrid ceramic composites also requires more detailed exploration. Hence, this study emphasizes the wear behaviour of HCNAC containing 3 wt.% of nSiC and 7.5% of ZrO_2 prepared through the powder metallurgy technique, which makes this research unique.

2. MATRIX MATERIALS AND REINFORCEMENTS

AA7075 aluminum alloy is well-known for its outstanding physical and mechanical features, making it a popular choice in various high-performance applications, including the automotive industry. AA7075 is characterized by its high strength-to-weight ratio, higher resistance to fatigue, and good machinability. With 2.81 g/cm³ density, it is significantly lighter than steel, contributing to overall vehicle weight reduction and improved fuel efficiency (Khalid *et al*. 2023). AA7075 exhibits impressive tensile and yield strength of 530 MPa and 460 MPa. Also, it has good toughness and resistance to stress-corrosion cracking, although it is less resistant to corrosion than some other aluminum alloys. In the automotive sector, AA7075 is utilized in critical components, such as suspension parts, chassis components, and high-stress structural elements. Its excellent mechanical properties make it ideal for enhancing vehicle performance, safety, and fuel economy (Miller *et al*. 2000).

Nano silicon carbide (nSiC) has an impressive tensile strength, which can exceed 340 MPa. These particles exhibit excellent thermal stability, with a melting point of approximately 2,730℃, allowing them to perform reliably under high-temperature conditions. nSiC also has a high thermal conductivity, around 145 W/mK, which facilitates efficient heat dissipation. It has a density of 3.21 g/cm³, which contributes to weight reduction in composite materials *(Biscay et al.* 2021*)*. Ceramic particles made of silica are widely used in MMCs, that are employed in high-performance brake discs, engine components, and other critical parts where enhanced wear resistance, thermal stability, and lightweight properties are essential (Wang and Monetta, 2023). Zirconium dioxide (ZrO_2) possesses a density of 5.68 g/cm³ and has high wear resistance and toughness making them ideal for applications such as brake discs, pistons, and valve seats, where durability and performance under high-stress conditions are paramount. Zirconia's thermal stability and low thermal conductivity also make it suitable for thermal barrier coatings, enhancing the efficiency and lifespan of engine components by protecting them from heat and thermal degradation (Fedorov and Yarotskaya, 2021; Senthil *et al*. 2024). The average size of nSiC is 50 to 60 nm, whereas ZrO_2 is 30 to 50 µm.

3. POWDER METALLURGY

The powder metallurgy (PM) route was adopted for fabricating the HCNAC containing powders of AA7075, and 3 wt.% of nSiC and 7.5 wt.% of ZrO_2. Initially, the powders were ball-milled for uniform dispersion using carbide balls.

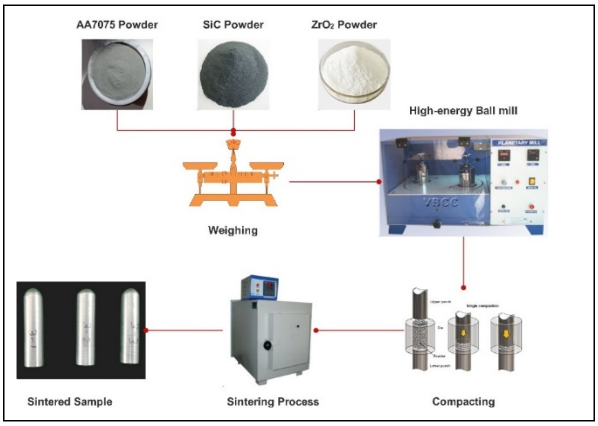

Fig. 1: Procedure of powder metallurgy

The ball-to-powder weight ratio (BPR) considered is 10:1 with 300 rpm of milling speed for 2 hrs. The blended powders were filled in a die and then subjected to a compaction process, typically using a uniaxial or isostatic pressing method, to form a green compact with the desired shape and density (Deepanraj *et al*. 2023). This compact is subsequently sintered at elevated temperatures (500 ℃) for one hour with controlled heating rate of 20°C/min in an inert atmosphere, below the melting point of aluminum to facilitate diffusion bonding between the particles and achieve a dense, cohesive composite material. After cooling the part inside the furnace to atmospheric temperature, the component was ejected from the die (Mussatto *et al*. 2021). For binding during sintering, polyvinyl alcohol (PVA) was used. The PM process is depicted in Fig. 1.

4. PIN-ON-DISC APPARATUS

The pin-on-disc apparatus is a widely used experimental setup for evaluating the wear characteristics of materials, particularly in tribological studies. The setup typically consists of a stationary pin, which can be made of the material being tested, and a rotating disc, often made of a counter material (Thirumalvalavan and Senthilkumar, 2019). During the test, the pin was made to be in contact with the rotating disc under a specified normal load, while the apparatus controls parameters such as rotational speed and sliding distance. The frictional force generated was continuously measured, and the wear rate of the materials was determined by assessing the volume or weight loss of the pin or disc after the test (Sundaraselvan *et al*. 2024; Verma *et al.*, 2022). The pin-on-disc apparatus is particularly useful for simulating sliding wear conditions, making it an essential tool in material development and selection for components subjected to friction and wear, such as automotive brake systems and bearings (Federici *et al*. 2018; Ganapathy *et al*. 2015). An EN31 steel disc of size 55 mm in diameter and 8 mm thick hardened to 58–63 HRC was rotated. A cylindrical specimen of Ø10 mm and 32 mm in length was positioned vertically within a specimen holder (Mishra and Srivastava, 2017). The wear tests were performed under different sliding velocities (SV), applied (AL), and sliding distance (SD). Fig. 2 presents the PoD apparatus and test pins used in this study.

5. RESULTS AND DISCUSSION

After fabricating the HCNAC, microstructural studies were conducted to visualize the dispersion, and grain structure of the composite. The AA7075 matrix is interspersed with nSiC and ZrO_2, which are near uniformly distributed to enhance the properties of the composite which significantly influence its overall performance (Sabbar *et al*. 2021). Fig. 2 illustrates this, the nSiC particles act as a reinforcement that improves load transfer between the aluminum matrix and ZrO_2 particles. Due to its high hardness, rigidity, and nSiC enhances interfacial bonding by reducing the difference in thermal expansion between the aluminum matrix and ZrO_2, thereby minimizing internal stresses during thermal cycles. The high surface area of nSiC particles also promotes better interfacial contact with aluminum and ZrO_2, which leads to improved particle dispersion and reduced porosity within the composite (Sundaraselvan *et al*. 2020). The matrix-reinforcement interface is critical, as a strong bond at this interface enhances load transfer and improves mechanical properties such as strength and stiffness. Some voids are visible due to particle removal but no micro-cracks are visible (Tahamtan *et al*. 2014). It is observed that no clustering of reinforcements (nSiC, ZrO_2) is seen from the SEM image, which directly correlates with near homogeneous distribution of reinforcements.

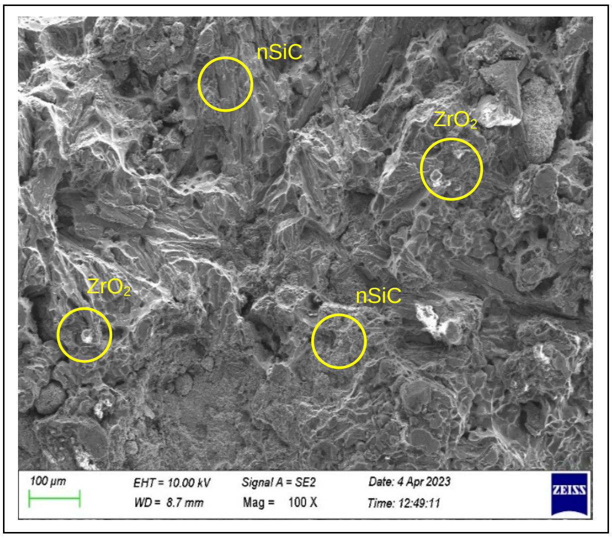

Fig. 2: SEM micrograph of fabricated specimen

The influence of AL on the WL of the fabricated specimen is presented in Fig. 3. It shows that as the AL increases, the WL tends to increase. This behavior is primarily attributed to the elevated pressurized interaction between the composite material and the opposing surface as the AL intensifies (Pali and Dwivedi, 2017). The increased load results in a greater degree of material deformation, resulting in a greater rate of material extraction. Additionally, the elevated load can cause the composite's reinforcement particles to either fracture or detach, which further contributes to the WL. Consequently, the total wear resistance of the composite diminishes as the AL increases, leading to a more pronounced WL (Sundara and Senthilkumar, 2018). nSiC enhances hardness, reducing friction, and increasing resistance to material removal. nSiC's exceptional hardness reinforces the composite structure, making it more resistant to abrasive and adhesive wear mechanisms. nSiC acts as a wear-resistant barrier that inhibits the propagation of micro-cracks and reduces the rate of material loss. Additionally, the fine dispersion of nSiC particles improves the composite's surface hardness and minimizes direct metal-to-metal contact under sliding or abrasive conditions, which reduces friction (Ragupathy *et al*. 2018). The thermal stability and high thermal conductivity of nSiC further support wear resistance by preventing localized heating and softening of the aluminum matrix during wear, preserving structural integrity under high-load or high-temperature conditions.

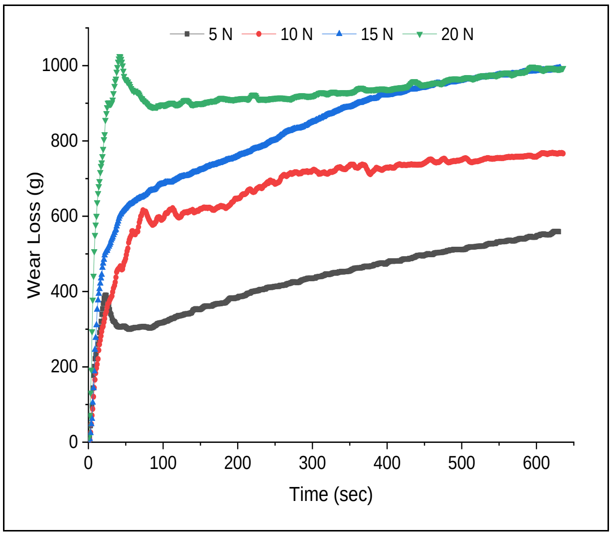

Fig. 3: WL on specimens subjected to different AL

As the AL rises, the contact area between the composite material and the counterface also grows, leading to more intense interaction at the surface level. This heightened interaction can cause an increase in frictional forces, which manifests as a higher CoF (Akutagawa *et al*. 1987), as depicted in Fig. 4.

Additionally, the increased load can generate more heat at the interface, potentially altering the surface characteristics of the composite and contributing to the rise in the CoF. Consequently, the composite's resistance to sliding becomes more pronounced as the AL increases, leading to an elevated CoF (Gupta *et al*. 2022). As the AL increases, the WL tends to increase. attributed to the elevated contact pressure between the composite material and the opposing surface resulting in a greater degree of material deformation, leading to a higher rate of material removal and particle fracture or delamination. This also causes an increase in frictional forces, which manifests as a higher CoF.

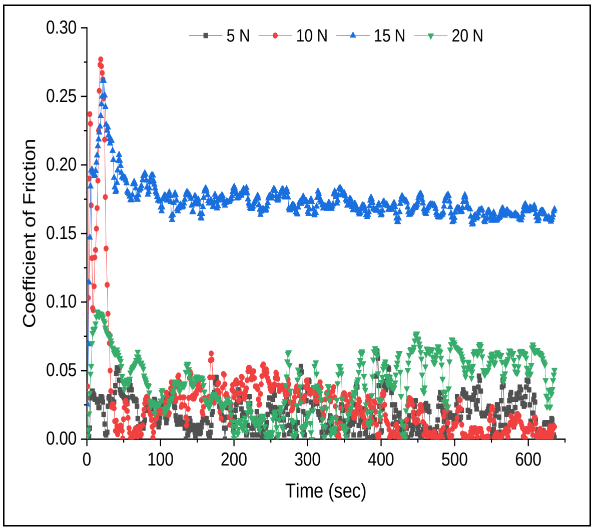

Fig. 4: CoF attained during wear tests subjected to different AL

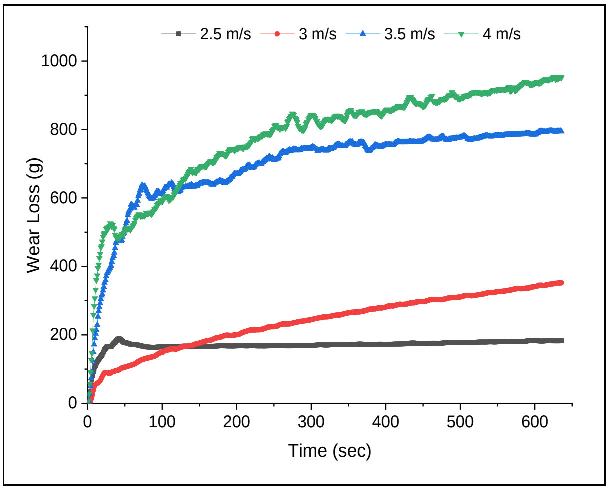

Fig. 5: WL on specimens subjected to different SV

The WL generally increases with rising SV, as shown in Fig. 5. As the SV increases, the relative motion between the composite material and the counterface becomes more aggressive, leading to greater frictional heat generation at the contact surface. This heat can soften the matrix material, increasing the likelihood of distortion and material loss. (Mao *et al*. 2020). Additionally, the increased SV can lead to more frequent and severe abrasive interactions, where hard reinforcement particles may become dislodged or fractured, further contributing to wear. As a result, the combination of higher temperatures and intensified mechanical interactions at higher SVs leads to an accelerated rate of WL in the composite material (Ammisetti and Kruthiventi, 2024).

The CoF tends to increase with rising SV during wear tests as seen in Fig. 6. Higher SVs intensify frictional interactions and generate more heat at the contact surface, which can soften the matrix material and increase surface adhesion. This, combined with more frequent abrasive interactions, leads to a rougher surface, resulting in a higher CoF as the SV increases (Boggarapu *et al*. 2023). The WL generally increases with rising SV, and the relative motion between the composite material and the counterface becomes more aggressive, leading to greater frictional heat generation which softens the matrix material, making it more susceptible to deformation and material removal and severe abrasive interactions, Higher SVs intensify frictional interactions and generate more heat at the contact surface, when combined with more frequent abrasive interactions, leads to a rougher surface, resulting in a higher CoF as the SV increases.

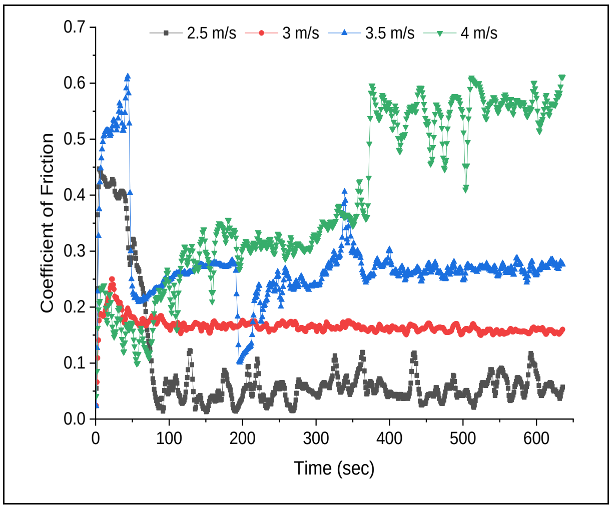

Fig. 6: CoF attained during wear tests subjected to different SV

During wear testing of metal matrix composites, WL tends to increase with greater SD as depicted in Fig. 7. As the SD extends, the contact between the composite material and the opposing surface becomes prolonged, leading to more extensive material interaction and degradation (Yilmaz, 2019). Over time, repeated contact exacerbates the wear process, causing more material to be removed from the surface. Additionally, with longer SDs, the cumulative effects of frictional heating, abrasion, and potential fatigue of the composite material become more pronounced, further accelerating WL. Consequently, the overall wear of the composite material increases as the SD increases, resulting in a higher WL (Rao and Das, 2011).

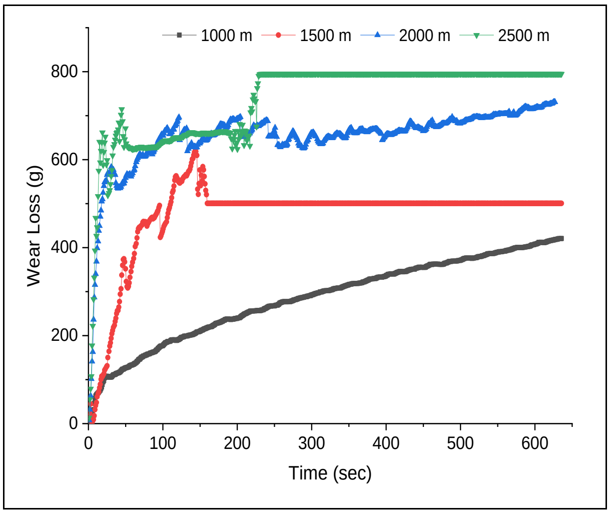

Fig. 7: WL on specimens subjected to different SD

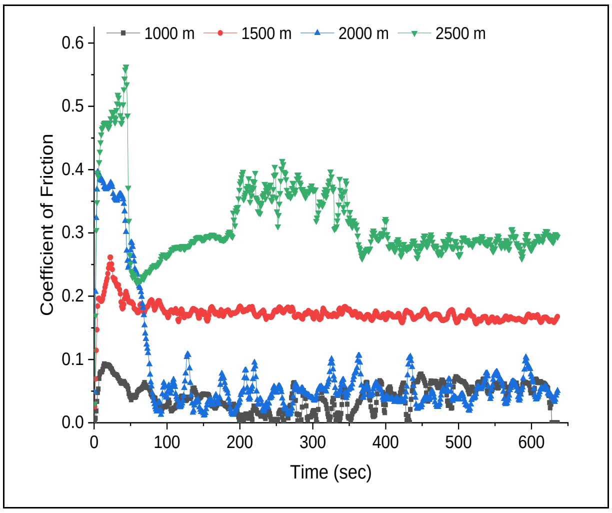

Fig. 8: CoF attained during wear tests subjected to different SD

The CoF in MMCs generally tends to increase with increasing SD during wear tests, but a moderate SD produces lower CoF as presented in Fig. 8. As the SD increases, the prolonged interaction between the composite material and the counterface can lead to surface roughening, wear debris accumulation, and changes in surface characteristics (Pillari *et al*. 2024). These factors contribute to an increase in frictional resistance, which elevates the CoF. Overextended SDs, and wear debris may become embedded in the contact surfaces, creating a more abrasive environment that further enhances friction. Additionally, the sustained sliding can cause surface fatigue, leading to microstructural changes that increase friction. Consequently, as the SD increases, the CoF is likely to rise due to the cumulative effects of these surface interactions (Meghwal *et al*. 2023). The WL tends to increase with greater SD leading to more extensive material interaction and degradation. With longer SDs, the cumulative effects of frictional heating, abrasion, and potential fatigue of the composite material become more pronounced, further accelerating WL. The CoF in MMCs generally tends to increase with increasing SD during wear tests, but a moderate SD produces lower CoF Over extended SDs, wear debris may become embedded in the contact surfaces, creating a more abrasive environment that further enhances friction.

6. CONCLUSION

The wear studies performed on the fabricated HCNAC subjected to various AL, SV, and SD are investigated and the outcomes obtained are that increasing the AL, SV, and SD increases the WL and CoF. The AA7075 matrix strengthened with nSiC and ZrO_2, is uniformly distributed to enhance the composite's properties which significantly influence the overall performance of the composite. A strong bond at the interface enhances load transfer, some voids are visible due to particle removal but no micro-cracks are visible. The fabricated HCNAC can withhold the damage caused by increase in AL, WL, and SV, which in turn increase the CoF.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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