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Catalysts of Strength: Unveiling the Mechanical and Tribological Mastery of Al-2024 MMC with Fly ash/TiB2/SiC Reinforcements

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ABSTRACT

The current work investigates the mechanical and tribological characteristics of a hybrid aluminum matrix composite. Aluminum AL-2024 alloy was used as the base material, it was reinforced by fly ash, Silicon Carbide (SiC), and Titanium diboride (TiB2) particles with varied weight percentages. The composition of the Al 2024 alloy emphasizes its applicability for applications needing high strength-to-weight ratios and fatigue resistance, including aircraft components. Stir casting was used in the manufacturing process to ensure that the reinforcements were evenly distributed throughout the molten mixture. Tensile testing indicates considerable increases in ultimate tensile strength using SiC, fly ash, and TiB2, demonstrating the efficacy of the reinforcing technique. With respect to microhardness rating, rises are apparent at higher TiB2 concentration levels, expressing the greater extent of mechanical performance. The wear of composites was evaluated using a pin-on-disk tribometer. TiB2 has such a significant effect on lowering wear rates. The obtained results, which attribute the reinforcement content effect on the mechanical and tribological properties, help to design composites in application areas where high performance is significantly required.

1. Introduction

In the present era of engineering, the introduction of composite materials has gained notable credibility in that the objective is to improve mechanical properties while also widening the boundaries of their applicability. The application of aluminum matrix composites (AMCs) of types like those based on 2024 alloy is one of the areas that can be incorporated to attain a better outcome in varied industrial functions. The intelligent combination of the reinforcing items (such as fly ash, TiB2, and SiC particles), which is a typical approach to fabricating materials to meet the specific demands of applicants, there are many previous studies about enhancing aluminum matrix alloys using different particles [1]. Mahesh, V.P. et al. [2] investigate B4C-reinforced 6061 aluminum matrix composites for neutron shielding. Challenges in B4C dispersion and interfacial stability during processing are addressed via optimized liquid-metal stir-casting. Preheating B4C at 250°C achieves uniform dispersion, while interfacial characterization reveals reaction products like AlB2, Al3BC, AlB12, and AlB10. Karabacak, A. H. et al. [3] fabricated Al-based metallometric nanocomposites boosted by hexagonal boron nitride (h-BN). The well dispersion of H-BN nanoparticles up to 4 wt.% enhanced both the mechanical strength and resistance to corrosion resistance. The nanocomposite reinforced with 4 wt.% demonstrated the highest level of hardness and tensile strength, providing improved corrosion and wear characteristics compared to the unreinforced base alloy Naguib, G. [4,5] used ZrO2 fractions (2–8%), while B4C and Al2O3 were fixed at 5 wt.% and 10 wt.%, respectively. Tensile toughness tests revealed significantly enhanced mechanical properties with the addition of ZrO2, which promises improved aerospace and automotive applications. Furthermore, the study investigates how Al-7075 with B4C, Al2O3, and ZrO2 reinforced the wear behavior, indicating enhanced wear resistance with higher ZrO2 fractions in nanocomposites blended with Yati Lin, F., et al. [6] used powder metallurgy to fabricate Al2024-Titanium Carbide(TiC)-Graphene nano plates (GNPs) hybrid composites, which increased wear resistance compared to unreinforced Al2024 and single-reinforced composites of TiC and GNPs, with synergistic effects significantly increasing wear resistance, indicating the potential a hybrid composite has for different applications. Deya, D. et al. [7] studied Al2024 alloy and its different composites like Al2024-SiC and Al2024-TiB2 by stir casting, observing the physical, mechanical, and tribological properties. Microstructural analysis confirmed the equal distribution and strong bonding of the reinforcements in the matrix. Al2024-TiB2 exhibited high corrosion resistance with minimal plastic deformation, confirming its effective workability. Ghanbari, D. et al. [8] investigated the fabrication of AA2024/SiC nanocomposites by friction stir processing with different passes. The heat-treatment effect on the damage behavior was that a hardness decrease was observed in the stir zone, which increased due to the larger S-phase, but post-heat treatment increased the hardness due to the disintegration of the larger S-phase, and it enhanced the composites. The study emphasizes the role of microstructural changes, especially in S-phase precipitate, in improving mechanical properties and corrosion resistance. Nurcihan, K. investigated [9] Al2024 composites with various hybrid reinforcements by vacuum infiltration and evaluated their hardness and microstructure after disintegration and aging processes. The study reported increased hardness, peaking at a 5% reinforcement ratio after 6 hours of aging. Optimum results were observed in a 2.5% B4C + 2.5% SiC composite, which exhibited homogeneous reinforcement distribution and desired wettability. The present paper represents a detailed study of three AL-2024 MMC reinforcements, which are fly ash, SiC, and TiB2, covering microstructural, mechanical, and tribological aspects. The rationale for the use of these reinforcements is based on their special characteristics, especially their high hardness and low density. This, in turn, can have a synergistic effect on increasing composites. Understanding the feedback between matrix and reinforcement is important to help us have high-quality materials for mechanical and tribological loads.

2. Materials and method

2.1. Materials

The hybrid aluminum matrix composite examined employs the aluminum AL-2024 alloy as its primary material. This alloy was chosen for its aptness in applications demanding exceptional strength-to-mass ratio and outstanding fatigue resistance, such as aircraft components (wings and frames). The composition of the used alloy is elaborated on in Table 1. The reinforcements used in this study are fly ash (Fig. 1a) particle size of 20 μm and density 1.85 g/mL, SiC (Fig.1b) particle size of 15 μm-density 2.53 g/mL, and TiB2 (Fig. 1c) particle size of 10 μm and density of 4.51 g/mL. All reinforcements were supplied by Sigma Aldrich. Fly ash integrated into the composite is a residual product of coal combustion, it contains oxides like SiO2, Al2O3, and Fe2O3, sourced from emissions from coal-burning power plants. It is widely used in the construction industry, fly ash serves to lower costs in the production of concrete structures, bricks, and materials for road construction. The composition of fly ash is detailed in Table 2. Different samples were chosen with varied weight ratios or proportions of fly ash, SiC, and TiB2. These samples were chosen to investigate the influence of varying proportions of reinforcements on the properties of the alloy. The sample weight percentage compositions are included in Table 3.

2.2 Fabrication of composite

The stir casting method is utilized for the manufacturing of aluminum matrix compositions. Several techniques were applied during the production process to facilitate the creation of metal matrix composites that, to the full extent, can overcome the capabilities of unreinforced AL-2024 matrix material. Primarily, the fly ash, SiC, and TiB2 particles were chosen to boost the metal matrix composite. The particles of the reinforcement materials were heated to 220°C to be mixed and immersed into the liquid molten matrix. The AL-2024 alloy underwent melting in a clay crucible. The crucible temperature inside an induction furnace is from 695°C to 725°C. The preheated hybrid particles at a specific temperature were added bit-by-bit into the liquid matrix under controlled conditions with the aim of getting good mixing. The entire system keeps a stirrer as a prime component that encourages the distribution and dispersion of reinforcement particles uniformly in a molten aluminum matrix. Temperature control was of utmost importance to prevent the heating of the products and ensure a uniform mixture. Temperature and heat energy were monitored using a thermocouple and a digital meter. Stirring of the matrix alloy and reinforcement particles caused interactions among the chemical components, which promoted the formation of solid adhesion points and enhanced mechanical properties. This process was over once the material had been homogenized before being transferred into a preheated mold and allowed to cool down and turned into solid. The subsequent processes involved in improving the product include cooling and preparation for annealing to identify and remove the residual stresses, then improving the mechanical properties. The adopted stir casting process achieves good development at a low cost, resulting in the resulting in the casting production of hybrid aluminum matrix composites (AMCs) with customized properties for different applications

Fig.1 Reinforcements used within metal matrix, a) Fly ash b) TiO2 c) SiC

Table 1 Composition of base metal

Element	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Percentage	90-90.75	0.50	0.50	3.9-4.8	0.30-0.8	1.3-1.9	0.10	0.26	0.17

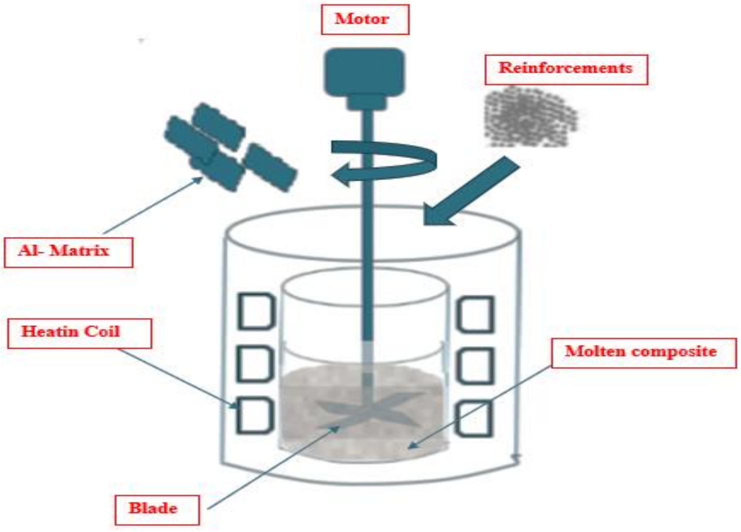

Fig.2 Stir casting Schematic.

Table 2: Composition of Various Fly Ash

Reinforcement Material	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	CaO (%)
Fly Ash	36.5	28	32.05	6.68

Table 3. Weight percentage [wt.%] of material composition.

Sample no.	Al-2024	SiC	Fly ash	TiB_2
1.	100	0	0	0
2.	75	10	15	0
3.	70	10	15	5
4.	67	10	15	8
5.	65	10	15	10

2.3 Tensile testing

Tensile samples were cut into bone-shaped in adherence to ASTM standard E8/E8M-011, and the outcomes are illustrated in Figure 3. The ultimate tensile strength (UTS) and percentage elongation were assessed using a computerized universal testing machine, specifically the WAW-300B model (with a capacity of 300 kN), produced by Zhejiang Jingyuan Mechanical Equipment.

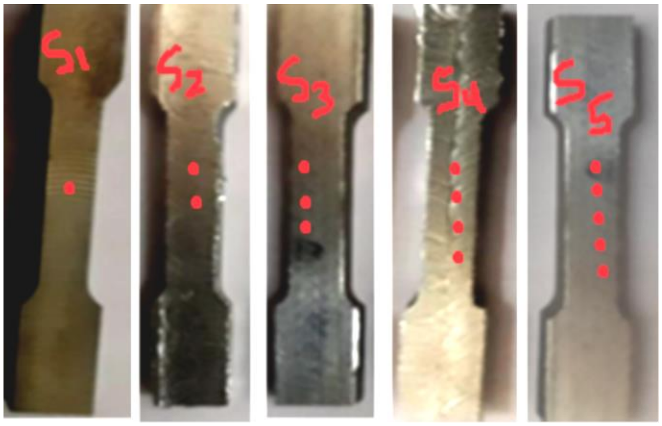

Fig. 3 Tensile Test Samples

2.4 Microhardness

The Brinell hardness test was conducted following the procedures outlined in the ASTM E10 standard. A 50-gram load was applied over a 15-second period. Microhardness assessments were performed at four distinct points on each sample. The resulting microhardness value for each sample was obtained by calculating the average of these four measurements.

2.5 Wear testing

Figure 4 presents the pin-on-disc wear tester laboratory stand, which comprises the hybrid composite aluminum, demonstrating wear behavior followed by the standards developed by American society for the testing of materials and specifically for the dual line bearing test (DUCOM, TR 20LE). The wear disk diameter is 100 mm, then the disc is performing the balance by means of a weighing device mounted on the wheel body. The tribometer contains a counter-face of 60 HRC hardened steel, which was measured in the slide wear experiments and conducted under dry sliding. The test was conducted under different load conditions (10N, 20N, 30N, and 40N). The sliding speeds of the test were 1.9, 3.7, 5.2, and 7 m/s, respectively, and 10 m was the was the total time consumed to run the experiment. Samples were carefully subjected to the polishing process, then samples were conducted with acetone and finally with ethanol. The run time was raised or lowered to match the level of speed required for the selected amount of runtime. Materials under consideration were subject to the calculated amount of wear and friction coefficient. Composite samples were weighed in points via pin scale before and after each run, quantifying weight loss. A further simulation included capturing on the screen and dragging force with the monitor to be used in the results and data analysis part of the experiment.

Table 4 Wear test conditions

Evaluate Conditions	Values
Load	10,20,30,40 N
Pin Diameter	10 mm
time	10 min
Sliding speed	1.9, 3.7, 5.2, 7 m/s
Disc Roughness	0.2 µm
Disc Hardness	60 HRC

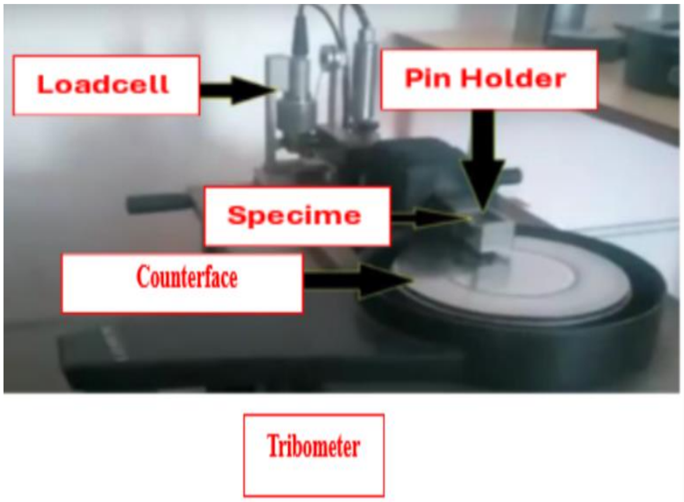

Fig. 4. Pin on disk tribometer.

3 Results and discussion

3.1 Tensile strength

The influence of the amount of reinforcement on the tensile strength measurements is shown in Figure 5. Since ASTM E8M is the standard test method, tensile tests were performed accordingly. The results achieved during the mechanical testing show a distinct improvement in the mechanical performance of the hybrid aluminum matrix composite with the variation in the composite composition. The sample 5, which possesses a tensile strength of 141.03 MPa, is the most remarkable one, with an increase in tensile strength of 43.9% in comparison with the initial sample observed in sample 1, characterized by a tensile strength of 98.04 MPa. These are the concrete results of how modularity is used to improve tensile strength with reinforcing detailing. The added result will be a more effective modularity approach. The observed increase in the level of tensile strength across the various samples, starting from Sample 2 with a reinforcement content of 17.5% to Sample 5, which has a content of 43.9%, all of which vary in value compared to Sample 1, can be the cause of the significant effect of reinforcement content on mechanical properties. This finding points out the possibility of simultaneously altering the mechanical parameters of aluminum matrix composites by means of the selection of the type and concentration of reinforcing agents. This contributes not only to the inclusion of a superior level of innovation into composite design but also to the development of knowledge and optimization of design for applications where a high level of mechanical performance is required.

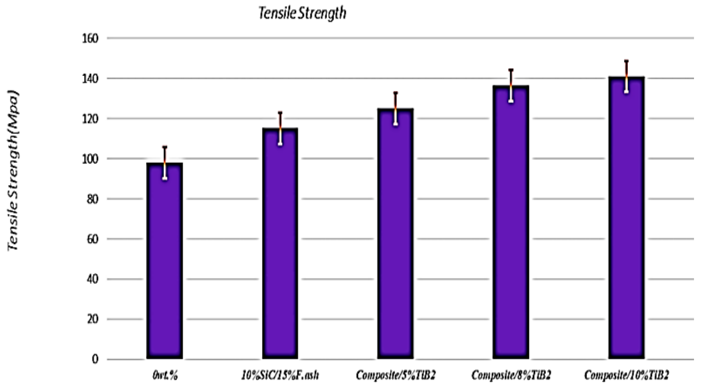

Figure 5 tensile test results

3.2 Microhardness

Fig. 6 shows the relationship between reinforcement weight percent and their effect on the results of microhardness values. It could be obtained that sample 1 made of 100% Al-2024 alloy without enhancement has a microhardness corresponding to 64.5 HV. Sample 2 contains 75% Al-2024-alloys along with 10% SiC/silicon carbide, 15% fly ash, and 0 wt.% TiB2, which shows the growth of microhardness to 71.2 HV. Also, sample 3, consisting of 70% Al-2024 alloy/10% SiC/15% fly ash/5% TiB2, exhibits much further progress in microhardness, and its measurement is 73.6 HV. Composite four, having 67% Al-2024 alloy/10% SiC/15% fly ash/8% TiB2, hit a high of 77.4 HV in microhardness, an obvious improvement. While the specimen containing 65% Al-2024 alloy/10% SiC and 15% fly ash/10% TiB2 possesses the utmost microhardness value among all samples, the value reached 81.05 HV. These results exemplify that the enhanced microhardness values refer to an upsurging chemical reaction that works better when there is a higher concentration of TiB2 in the composite. The current microhardness outcomes in Sample 5 are a result of synchronization of the bearing effect of the TiB2 with the target attributes affecting the mechanical properties of the aluminum matrix composite. This obtained data assists in fabricating the composite according to the necessary demands for desired applications [13–16].

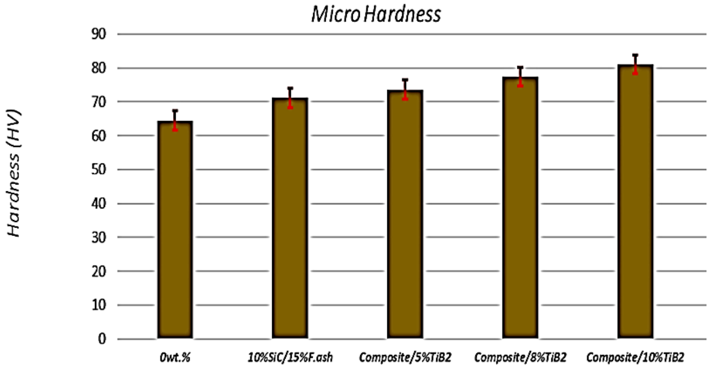

Figure 6 hardness values of MMCs/different wt.% reinforcements

3.3 Wear

3.3.1 wear rate vs applied loads at different sliding speeds of MMCs/Reinforcements.

Figures 7–10 show the variances in the wear rate during the dry sliding tests, with the sliding speeds achieved ranging from 1.8 to 6.5 m/s and the weights exerted ranging from 10 to 40 N. Here, the study can identify that the wear rate of the base alloy and its different reinforcements increases proportionally with applied loads at low speeds. The plastic deformation zone size area within the free surfaces of the investigated sample enlarges with growing load. Delamination occurs due to the degradation of the adhesive bonding of matrix and reinforcements. The counterface hardness as well as slippage under high loads and speeds, along with fractures in between the reinforcement elements and the base material, have a direct negative impact on the wear mechanism. Just looking at the Al-2024, 10% SiC, 2% fly ash, and 10% TiB2 composite, the wear resistance in that case is much better than other aluminum nanocomposites that have been used before. TiB2 leads to a decrease in the wear rate for all types of loads. This shows the versatility of the MMCs. The findings are in accordance with the trends observed in previous studies [17–24].

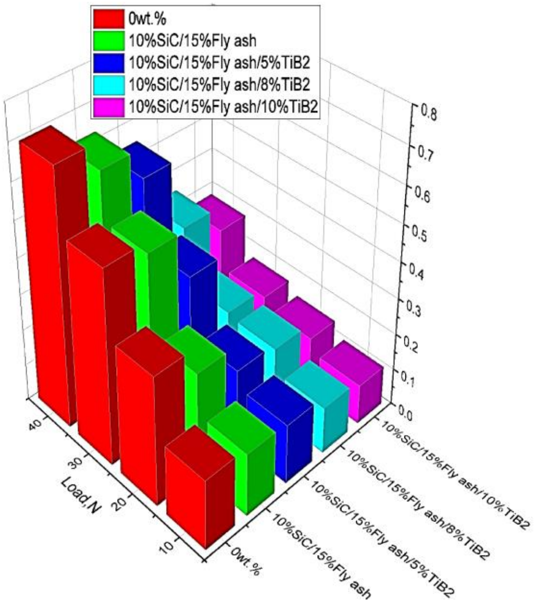

Figure 7 variation in the wear rate vs load of at sliding speed of 1.9 m/s

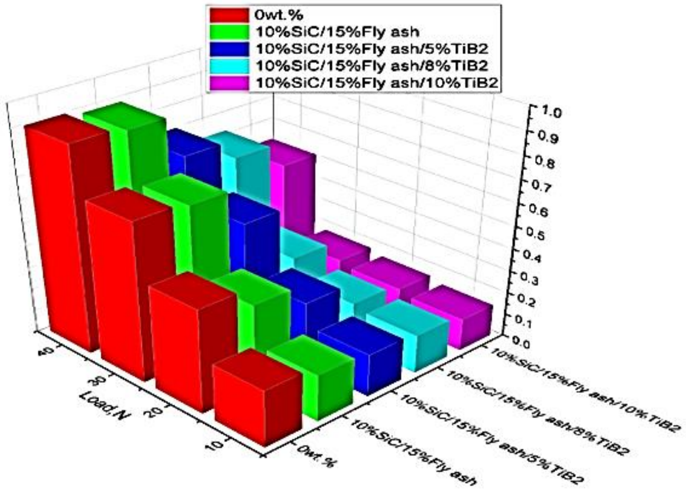

Figure 8 variation in the wear rate vs load of at sliding speed of 3.7 m/s

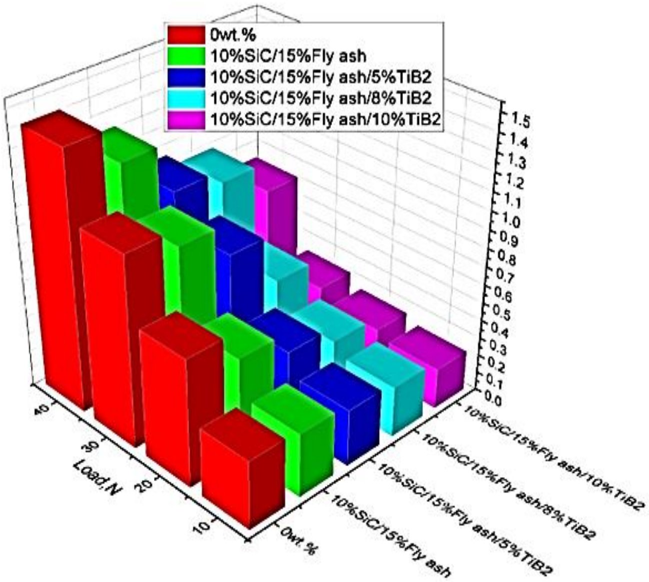

Figure 9 variation in the wear rate vs load of at sliding speed of 5.2 m/s

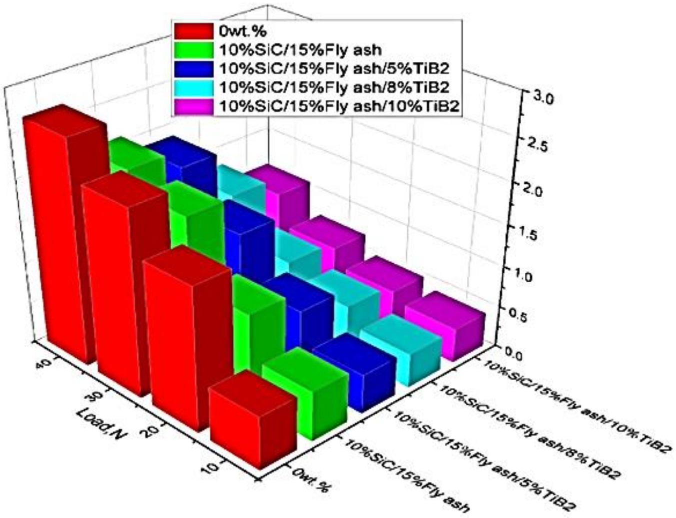

Figure 10 variation in the wear rate vs load of at sliding speed of 7 m/s

3.3.2. wear rate vs applied loads at constant high sliding speed of MMCs/Reinforcements.

Figure 11 shows that the positioning of SiC, flyash, and TiB2 reinforcements within the metal matrix composite has a substantial influence on the wear rate of various composites. The graphic shows the wear rate fluctuation of multiple MMCs under a constant load of 30 N and varying sliding velocities. The graph demonstrates that adding SiC, fly ash, and TiB2 significantly reduces wear rate, particularly at a high sliding speed of 7 m/sec. Furthermore, increasing the content of TiB2 in the base alloy enhances wear resistance. When 10 wt.% TiB2 is added to the Al-2024 metal matrix alloy, the wear resistance rises by 67.5% at a high sliding speed of 7 m/s and a constant load of 30 N.

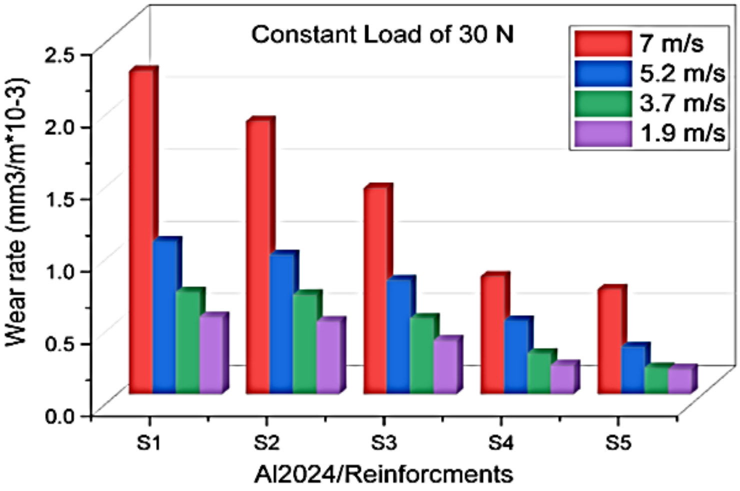

Figure 11 variation in wear rate vs MMCs/reinforcements wt.% at constant load of 30N

3.3.3 The impact of applied load and fillers content/Coefficient of friction.

Figure 12 demonstrates the variation in friction coefficient over various percentages of MMCs/reinforcements. The graph indicates that as the load increases, the friction coefficient rises. Furthermore, adding reinforcements, specifically TiB2, lowers the friction coefficient. This phenomenon is explained by the presence of strong and evenly distributed TiB2 particles. At a load of 30 N, the friction coefficient gradually decreases as reinforcements increase. TiB2 has varying weight percentages. The friction coefficient changes between loads of 20, 30, and 40 N. This suggests an elevated capability of resistance to wear.

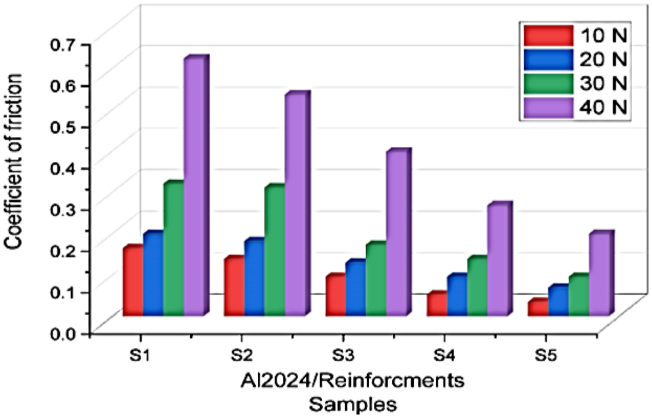

Figure 12 the variation in friction coefficient vs MMCs/reinforcements wt.% at constant load of 30N

4. SEM of MMCs worn Surfaces

Figure 13(a–d) gives data from SEM images of the worn surfaces of Al2024 with reinforcement and matrix alloys at room temperature. Different layers were observed on these materials, which show that abrasive wear is the main mechanism. Looking closely at both alloy and composite worn surfaces at low magnification, it will be noticed that distinct patterns of grooves and ridges are running parallel to each other in the direction of slip. As in the image of the un-strengthened Al2024 alloy, it could be seen that the composite continues to carry grooves. The surface shows significant staining and cracking in places where there may be some problems due to the fabrication of the new composites. It could be for varied reasons: the iron-ceramic parts may not have bonded properly, they may not have mixed properly, or the difference in density between the aluminum base and the solids caused a crack. Different boundaries between titanium and aluminum are clearly seen. Even in these cases of mixing, the new composites are produced from the air bubbles and holes (porosity and shrinkage) that can sometimes form during manufacturing. This is a great advantage because it makes the material stronger and wider (stretchable). In samples containing 10% titanium, this ceramic reinforcement was spread uniformly throughout the material [25–30]. When these materials were tested with long-term rubbing on a metal counter, the surface of the standard metal appeared to be smooth compared to the new one. This is likely because titanium particles do not cause surface deformation (micro-pulling) during the wear of their material. Other materials and conventional metals develop these parallel lines when worn, but when subjected to greater pressure, these grooves become deeper. These findings agree with previous studies [31–36].

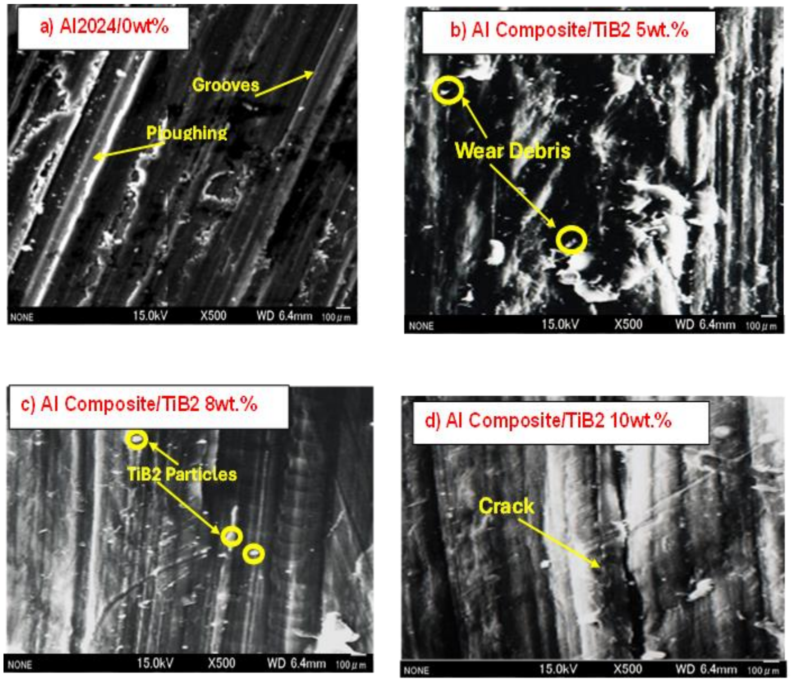

Fig.13 SEM worn surfaces of aluminum MMCs.

5. Conclusions

This research examined the mechanical characteristics and wear performance of hybrid Al-matrix composites (HMMCs) reinforced with SiC, fly ash and TiB2 particles. By means of investigation of tensile strength, microhardness, wear rate, and friction coefficient, the following results could be obtained:

Tensile Strength Enhancement: The addition of TiB2 to the MMC composites significantly increased the tensile strength. This confirms the effectiveness of TiB2 as a powerful agent for improving the characteristics of the aluminum matrix alloys.

Microhardness Improvement: Microhardness exhibited a direct relationship with the wt.% of SiC/fly ash/TiB2. Sample 5 displayed the highest microhardness value among all samples, highlighting the role of TiB2 in enhancing material hardness, crucial for high corrosion resistance applications.

Reduction in Wear Rate: The addition of TiB2 significantly reduced wear rate under all loading conditions, indicating its ability to enhance wear characteristics of Al2024/hybrid reinforcements, suitable for severe applications involving moderate abrasive wear.

Decrease in Friction Coefficient: TiB2 showed benefits in reducing friction and enhancing overall performance of the composites.

In summary, the research confirms the efficacy of TiB2 in enhancing mechanical characteristics, wear performance, and tribological properties of hybrid Al-matrix composites, making them promising materials for various engineering applications.

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