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Microstructural, Mechanical, and Tribological Behaviour of Stir-Cast LM13 Hybrid Metal Matrix Composites Reinforced with Silicon Carbide and Fly Ash

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Abstract- The present study focuses on the fabrication and characterization of LM13-based hybrid metal matrix composites reinforced with silicon carbide (SiC) and fly ash. Three hybrid compositions containing a constant 5 wt.% fly ash and varying SiC contents of 3, 6 and 9 wt.% were developed using the stir casting method. Microstructural observations revealed significant refinement of dendrite arm spacing and homogeneous dispersion of reinforcement particles within the matrix, indicating enhanced interfacial bonding. Mechanical characterization demonstrated notable improvement in hardness and tensile strength with increasing SiC content; the as-cast matrix alloy exhibited the lowest properties whereas Composite-3 (9 wt.% SiC + 5 wt.% fly ash) achieved the highest hardness (74.23 HV) and tensile strength (252.58 MPa), albeit at the expense of ductility. Tribological studies conducted under dry sliding conditions indicated that all hybrid composites possessed lower wear rates compared to the unreinforced alloy, with wear resistance improving progressively with SiC addition. Enhanced performance was attributed to the load-bearing capability of SiC, the formation of a mechanically mixed tribo-layer, and the abrasive resistance imparted by fly ash. Overall, the synergistic reinforcement strategy effectively upgraded the microstructure, mechanical properties and wear resistance of LM13 alloy, making Composite-3 the most suitable for high-performance automotive applications such as pistons and sliding components.

Key words: LM13 alloy, Silicon carbide, Fly ash, Hybrid metal matrix composites, Microstructure, Mechanical properties, Tribology

I. INTRODUCTION

Aluminium (Al) alloys are widely used in vehicle, marine, and aviation industries because of their excellent corrosion resistance, low weight, and relatively low costs compared with many other structural metals [1,2]. Nonetheless, their relatively limited performance mechanically limits their direct application in demanding engineering environments. These limitations are reduced by reinforcing aluminium alloys with ceramic particles to make Aluminium Matrix Composites (AMCs). Reinforcements are usually ceramic particles, fibers, or whiskers [3]. Al_2O3, SiO_2, SiC, TiO_2, TiB_2, B_4C, ZrB_2, AlN, and Si_3N_4 are popular reinforcements because they increase material strength, hardness, and wear resistance while remaining lightweight [4]. SiC, Al_2O_3 and B_4C provide excellent mechanical qualities at cheap manufacturing costs, making them appropriate for braking rotors, drive shafts, pistons, and cylinder liners. The matrix-reinforcement interface and manufacturing process substantially affect AMC performance. Consequently, these composites are gradually replacing the use of monolithic materials in aerospace, marine, automotive, electronics, and space exploration fields, mainly because they have an engineered synthesis of high modulus, high strength, low thermal deformation, and wear resistance [5]. Despite these obvious benefits, AMCs have not yet been exploited sufficiently on a commercial scale due to high costs in manufacturing and the challenges in achieving a homogeneous distribution of reinforcement. Lightweight metals such as magnesium, aluminium, and titanium are generally adopted as matrices owing to their favourable density-to-strength ratios [6]. Stir casting is one of the most cost-effective and scalable AMC production technologies. In this process, ceramic particles (up to 30 vol.% or more) are added into molten metal and dispersed by mechanical stirring. However, the mechanical performance of the final composite is hindered by major problems such as reinforcement settlement during casting and poor interfacial bonding. Parameters such as holding

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temperature, stirring speed and, impeller geometry are hypothesized to be critical in controlling these effects [7, 8].LM13 aluminium–silicon alloy is widely utilized in automotive and marine components due to its excellent castability and thermal stability; however, its moderate wear resistance under high-stress and dry sliding conditions has motivated the development of particulate-reinforced metal matrix composites. Among the various reinforcements investigated, silicon carbide (SiC) remains one of the most effective ceramic particles for improving hardness, strength, and tribological performance of LM13[9]. Studies on LM13/SiC composites report that the incorporation of SiC particles enhances the load-bearing capacity of the alloy, suppresses plastic deformation, and reduces material removal during sliding, which collectively lead to a significant decrease in wear rate as the SiC content increases[10]. Researchers also observed refined microstructure and better interfacial bonding between SiC particles and the LM13 matrix, with improvements in hardness and tensile strength being directly proportional to SiC weight fraction[11]. Erosive and abrasive wear investigations further confirmed that the addition of SiC minimizes pit formation and crack propagation through the matrix, demonstrating superior durability compared to the unreinforced alloy[12]. Parallel to ceramic reinforcement, fly ash has gained substantial attention as a cost-effective and lightweight secondary reinforcement for aluminium composites[13]. Fly ash additions in LM13 reduce overall density while simultaneously increasing hardness and improving wear resistance[14]. Its particulate morphology provides additional abrasive resistance and helps restrict surface deformation under mechanical loading[15]. Studies on Al–SiC–fly ash systems indicate that the presence of fly ash reduces the overall production cost while contributing to improved tribological performance[16]. Although fly ash typically offers lower strengthening ability per unit weight compared to SiC, its addition assists in stabilizing the microstructure and distributing stresses more uniformly across the matrix. Recent research has particularly focused on the hybrid reinforcement strategy, in which SiC and fly ash are simultaneously introduced into the LM13 matrix to achieve synergistic strengthening. In LM13/SiC/fly ash hybrid composites fabricated through stir casting, SiC contributes to enhanced hardness and wear resistance whereas fly ash helps reduce density and cost while improving damping characteristics [18]. The primary objective of this study is to fabricate LM13-based hybrid metal matrix composites reinforced with silicon carbide (SiC) and fly ash through the stir casting technique, and to systematically investigate the influence of varying SiC content (3, 6 and 9 wt.%) on their microstructural evolution, mechanical properties, and tribological performance. The study aims to establish the correlation between reinforcement content and the resulting enhancements in strength, hardness, and wear behaviour to identify the optimum hybrid composition suitable for high-performance engineering applications.

II. EXPERIMENTAL DETAILS

2.1. Matrix material

This study involves the fabrication and characterization of LM13-based hybrid metal matrix composites reinforced with silicon carbide (SiC) and fly ash. Three hybrid compositions containing a constant fly ash content of 5 wt.% and varying SiC content (3, 6 and 9 wt.%) were prepared through stir casting. The compositions of the fabricated composites are listed in Table 1. LM13 (Al-Si-Mg) alloy, commonly used in piston applications due to its low melting point, castability and dimensional stability, was procured in ingot form from M/s Fen fee Metallurgicals Pvt. Ltd., Bengaluru. The chemical composition and physical properties of LM-13 alloy are shown in Table 2.

Table 1: Composition of hybrid composites

Material	Composition
Matrix	LM13 Alloy
Composite-1	LM13 + 3 wt.% SiC +
Composite-2	LM13 + 6 wt.% SiC +
Composite-3	LM13 + 9 wt.% SiC +

Table 2: Properties of LM-13

Property	Values
Density (g/cm^3)	2.7
Tensile strength (MPa)	170-200
0.2% proof stress (MPa)	160-190
Elongation %	0.5
Solidus Temperature (°C)	560-525
Thermal Conductivity (cal/cm^2 /cm/°C at 25°C)	0.28

2.2. Reinforcements

SiC and fly ash was selected as reinforcements owing to their high hardness, thermal stability, chemical inertness and suitability for wear-resistant applications. SiC contributes to load-bearing and abrasive resistance, whereas fly ash provides low density and enhances tribo-layer formation during sliding. The physical properties of SiC and fly ash are summarized in Table 2.

Table 2: The physical properties of SiC (Silicon Carbide) and Fly ash

Sl. No.	Property	SiC (Silicon Carbide)	Fly Ash
1	Density (g/cm³)	3.10 – 3.21	2.10 – 2.30
2	Hardness (Mohs)	9.0 – 9.5	~5 – 6
3	Melting Temperature	~2700 °C	Not clearly defined (main constituents soften ~1200–1400 °C)
4	Coefficient of Thermal Expansion ($\times 10^{-6}$ /°C)	4.0 – 4.5	8.5 – 10.0
5	Color	Black/green	Light gray to dark gray

2.3. Melting and Casting

The composites were fabricated using the stir casting technique. LM13 ingots were charged in a graphite crucible and melted in an electric resistance furnace. The molten matrix was degassed at ~780 °C using hexachloroethane. SiC particulates preheated to 320 °C were gradually introduced into the melt during stirring to promote uniform dispersion. Mechanical stirring was carried out for 10 min until vortex formation indicated homogeneity. The melt was then poured into preheated and mold-coated cast-iron finger molds maintained at ~300 °C. The casting was allowed to solidify under ambient conditions. The electrical melting furnace with stir cast setup, LM13 ingot and cast composite is in the figure 1

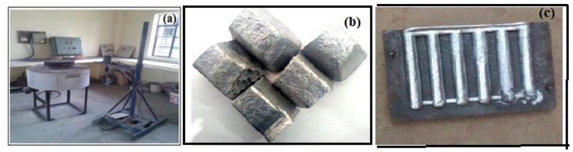


Figure1. Electrical melting furnace with stir cast setup, (b) LM13 ingot and (c) cast composite

2.4. Microstructural Specimen Preparation

Metallographic samples were sectioned from the cast specimens using an abrasive cutter, followed by grinding with successive grades of emery papers. Final polishing was performed using diamond paste on a cloth wheel. Keller's reagent (2.5 ml HNO_3 + 1.5 ml HCl + 1 ml HF + 95 ml H_2O) was used for etching. The etched specimens were examined under an optical microscope to evaluate matrix–reinforcement distribution and interfacial integrity.

2.5. Hardness measurement

Figure 2 shows the Vickers micro hardness tester. The micro-hardness testing was carried out using a diamond indenter with an applied load of 300 g and a dwell time of 10 s. Three measurements at different locations on each specimen were averaged for micro-hardness evaluation.

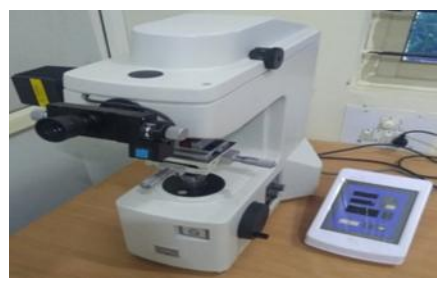


Figure 2. Vickers micro hardness (Mitotoya) tester

2.6. Tensile test

Tensile specimens machined according to ASTM E8 standards were tested using a 1-ton universal testing machine (TEC-SOL, India). Ultimate tensile strength (UTS) and percentage elongation were recorded. The photograph of UTM machine and tensile test specimen is shown in the Figure 3.

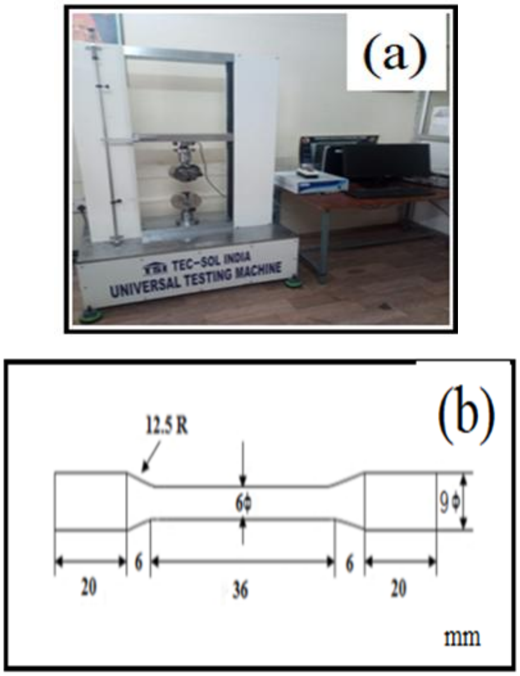
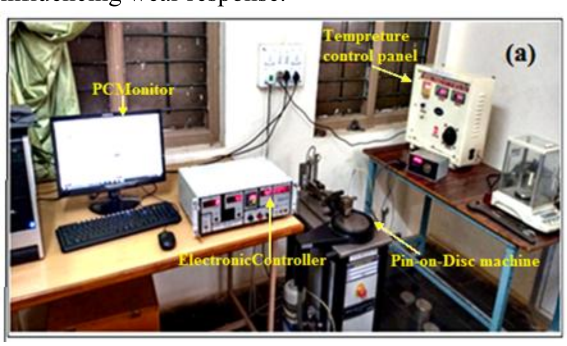


Figure3. (a) Universal Tensile testing machine (b) Tensile test specimen .

2.7. Wear study

Dry sliding wear studies were carried out using a pin-on-disc tribometer complying with ASTM G133-05 standards. Cylindrical test pins (6 mm diameter and 15 mm length) were slid against a stationary wear plate (40 × 40 × 5 mm). The process parameters—applied load, sliding speed and sliding distance—were varied as per the test matrix presented in Table 3.5. Weight loss was determined using a precision digital balance by comparing the weights of specimens before and after testing. The wear rate and frictional behaviour were analysed to establish the dominant factors influencing wear response.



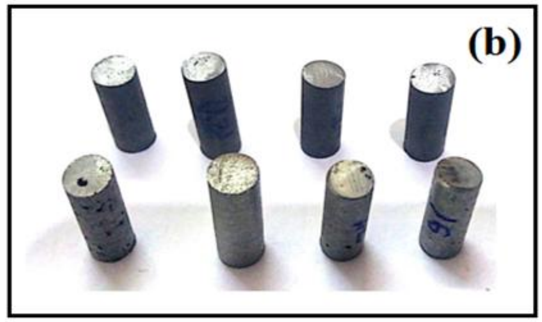


Figure 4. (a) Pin- on- Disc wear testing machine and (b) wear test specimen

III. RESULTS AND DISCUSSION

1.1. Microstructure study

Figure 5 shows the details of the microstructure examination carried out on as-cast LM-13 alloy. It can be observed that the matrix consists of primary aluminum dendrites having an average size of around 15 microns. Eutectic silicon appears like plate like structure. Figure 6 presents the microstructure of LM-13 alloy reinforced with SiC and fly ash. Compared with the as-cast matrix alloy, the hybrid composites exhibit a refined microstructure with reduced dendrite arm spacing. The refinement indicates that the addition of reinforcements acts as nucleation sites during solidification, resulting in a finer and more uniform distribution of grains. The homogeneous dispersion of SiC and fly ash particles also improves the interfacial bonding between the matrix and reinforcement.

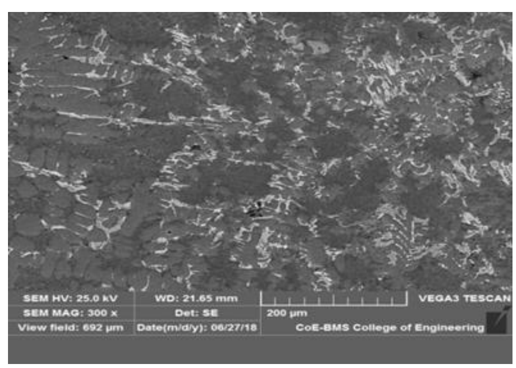


Figure 5. SEM Microstructure (Matrix (LM-13) alloy

Figure 6 shows the microstructure of the LM-13 alloy subjected to reinforcement (SiC and Fly ash) additions. It is observed from the figure that the dendrite arm spacing has been reduced finer structure is observed compared with the as cast alloy indicating that the reinforcement addition has an effect on the microstructure of the casting.

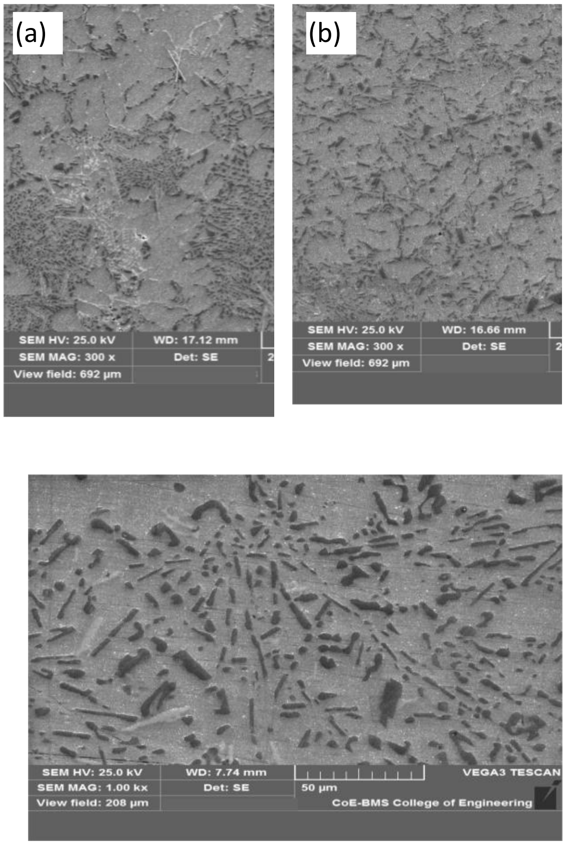


Figure 6. SEM Microstructure of Hybrid Composites (a) composite1,(b) composite-2and (c) composite-3

3.2. Mechanical properties

Table 3 shows the mechanical properties of matrix and composites. The hardness measurements were carried out using Vicker's hardness testing machine. An average of 3 readings across the cross section has been considered for the analysis. It can be seen from the Table that the cast matrix alloy exhibits the least hardness value of 54.78 With reinforcement additions, the hardness values have also improved with increased addition levels of the reinforcement. Addition of Sic and fly ash has resulted in improved interfacial bonding strength, resulting in enhanced resistance against deformation. Maximum hardness of 74.1 VHN is seen for the composite-3. This indicates that the reinforcement addition has an influence in improving the hardness values. An increase of 38.5% with the highest level addition of reinforcement compared with matrix alloy. This may be attributed to the refinement of grain structure and fewer chances of crack nucleation which has taken place with the reinforcement addition and the heat treatment carried out.

The variation of UTS matrix and composites as shown in the Table 4 that as-received alloy exhibits lower tensile strength values whereas the composites shows higher UTS values. Further, increase in the reinforcement addition also has resulted in improved UTS values. The highest UTS value of 252.6 N/mm^2 in composite-3. The trend in tensile strength (UTS) follows a similar pattern to hardness. The as-cast alloy shows the lowest UTS (180 N/mm^2), whereas Composite-3 reaches the highest value (252.58 N/mm^2). The significant enhancement is due to the mechanically and thermally stable reinforcement–matrix system, which exhibits good wettability and clean interfaces. Preheating of reinforcements further contributed to improved bonding. Although UTS increases with reinforcement content, ductility decreases from 5% (matrix) to 1.9% (Composite-3), which is expected due to the presence of hard, non-deformable particles restricting plastic deformation.

Table 3: Mechanical properties of matrix and composites

Compos	Hardness(	UTS	YS	Ductil
Matrix	54.78	180	126	5
Compos	59.2	225.5	136	3
Compos	65.89	242.5	143	2.5
Compos	74.23	252.5	134	1.9

3.3. Tribological Studies

Dry sliding wear tests were conducted using a Pin-on-Disc setup to evaluate the influence of reinforcement on wear resistance.

3.3.1. Effect of Applied Load

Figure 7 shows that the weight loss increases with an increase in load for all materials. However, wear loss in composites is significantly lower than the matrix alloy due to their higher hardness. Composite-3 exhibits the least material loss because of the maximum reinforcement content and superior microstructural integrity.

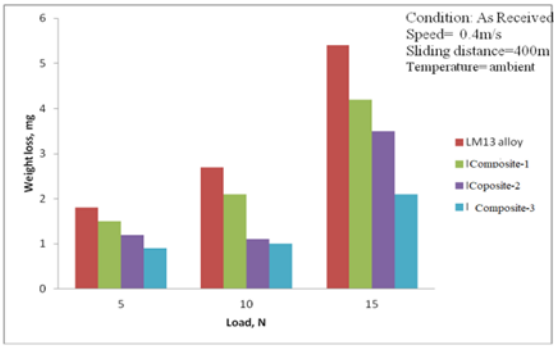


Figure7. Variation of weight loss with applied load

3.3.2 Effect of Sliding Speed

Figure 8 shows that weight loss increases with sliding speed. The matrix alloy exhibits the highest wear rate, whereas Composite-3 shows the least. Higher speed leads to increased frictional heat, weakening the surface. The presence of SiC and fly ash suppresses surface softening and restricts micro-cutting, improving resistance to wear.

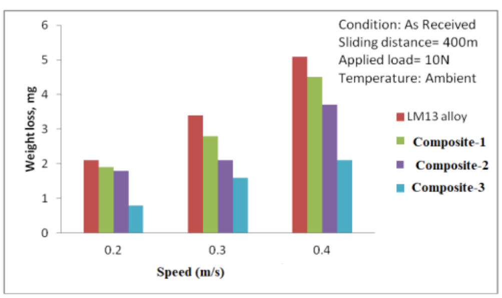


Figure8. Variation of weight loss with sliding speed

3.3.3 Effect of sliding distance

Figure 4.5 indicates an increasing trend in weight loss with sliding distance. The matrix alloy undergoes severe wear, while composites display lower wear rates. For larger sliding distances, composite specimens form a mechanically mixed protective layer, which significantly improves wear resistance. Composite-3 exhibits the best performance due to the higher reinforcement content and improved interfacial integrity.

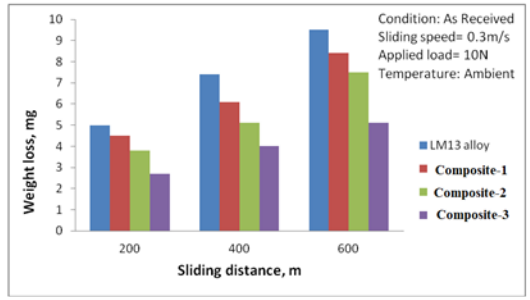
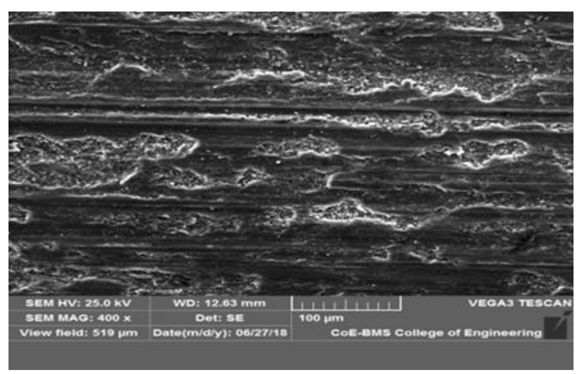


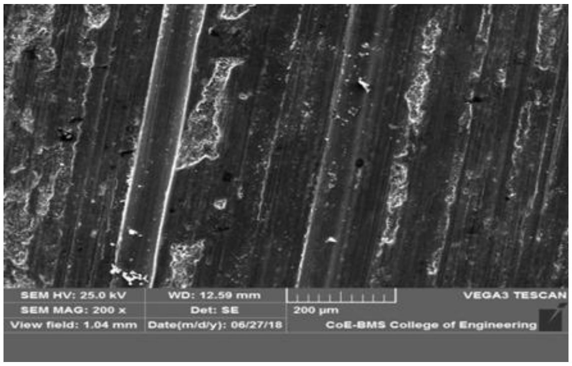
Figure 9. Variation of weight loss with sliding distance

3.4. Surface morphology of worn surfaces

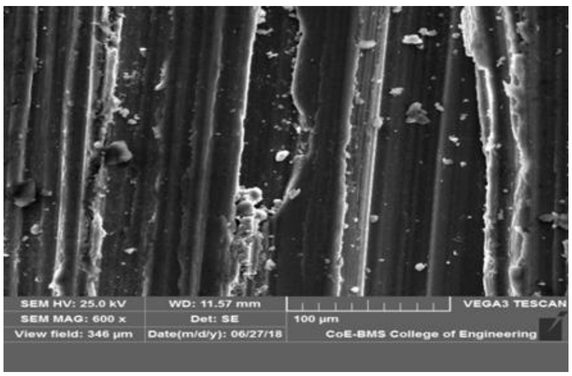
SEM wornout surfaces of matrix and composites are shown in figure10. SEM analysis of worn surfaces provides insight into the dominant wear mechanisms. The LM-13 matrix alloy displays severe abrasion, deep grooves, plastic deformation and crack nucleation around micro-pores, leading to delamination and fracture. In contrast, the worn surfaces of composites exhibit shallower grooves, reduced damage and fewer debris particles. The hard SiC and fly ash particles are well retained during sliding and act as load-bearing constituents, protecting the softer matrix from direct contact with the counter surface. The precipitation of reinforcement particles during sliding further contributes to the formation of a protective layer, thereby improving wear resistance.



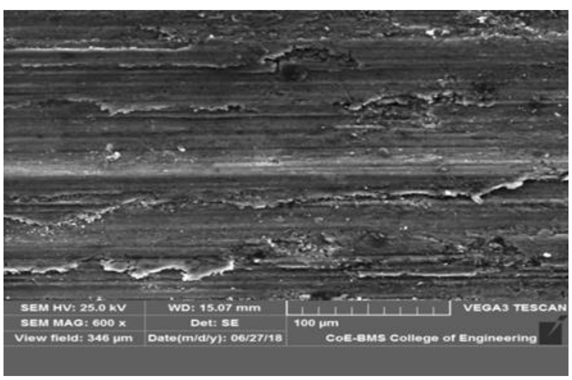
(a)



(b)



(c)



(d)

Figure10. SEM worn surfaces of (a) Matrix, (b) Composite-1,(c)Composite-2 and (d) Composite-3

IV. CONCLUSION

- The LM-13 matrix alloy reinforced with 3, 6 and 9 wt.% SiC and a constant 5 wt.% fly ash was successfully fabricated using the stir casting process.
- Microstructural analysis confirmed a uniform distribution of reinforcement particles with clear presence of α-Al phase and eutectic silicon in the matrix.
- The addition of SiC and fly ash transformed the morphology from acicular to fibrous and finally to a finer structure, indicating improved solidification and strong interfacial bonding.
- Mechanical testing showed that the as-cast alloy exhibited the lowest hardness and tensile strength, while all hybrid composites demonstrated significant property enhancements.
- Higher SiC content contributed to further increases in hardness and tensile strength by restricting dislocation motion and reducing crack initiation.
- Tribological studies revealed that hybrid composites displayed superior wear resistance compared to the unreinforced alloy, with wear loss decreasing consistently as SiC content increased.
- Among all compositions, Composite-3 (9 wt.% SiC + 5 wt.% fly ash) showed the best overall performance in terms of mechanical strength and wear resistance.
- The study establishes that the combined addition of SiC and fly ash effectively enhances the microstructure, strength and tribological behaviour of LM-13 alloy, making the developed hybrid composites suitable for high-performance applications such as pistons and automotive components.

REFERENCES

[1] Singh, R., & Chauhan, A. (2020). Aluminium alloys for lightweight structural applications: A review. *Materials Today: Proceedings, 28*, 1140–1146.

[2] Prasad, S. V., & Asthana, R. (2019). Aluminium alloys for automotive, aerospace, and marine applications. *Journal of Materials Engineering and Performance, 28*(2), 602–616.

[3] Suresh, S., & Ranganathan, S. (2021). Reinforcement mechanisms in aluminium matrix composites: A critical review. *Composites Part A: Applied Science and Manufacturing, 143*, 106309.

[4] Sharma, P., & Gupta, N. (2018). Mechanical and wear behaviour of ceramic particle reinforced aluminium composites: A comprehensive review. *Ceramics International, 44*(17), 21543–21556.

[5] Kumar, P., & Murugan, N. (2020). Aluminium matrix composites for aerospace and high-performance applications: Current trends and future prospects. *Progress in Materials Science, 110*, 100626.

[6] Lee, J., Park, S., & Kim, H. (2019). Lightweight metal matrix systems for emerging engineering applications. *International Journal of Lightweight Materials and Manufacture, 2*(1), 23–33.

[7] Hashim, J., Looney, L., & Hashmi, M. S. J. (2017). Stir casting parameters and reinforcement distribution in metal matrix composites. *Journal of Materials Processing Technology, 119*(1–3), 329–335.

[8] Zhang, X., & Chen, B. (2021). Influence of stirring speed and impeller design on particle distribution in stir cast aluminium composites. *Materials Characterization, 174*, 110996.

[9] Babu, R., & Gopalakrishnan, S. (2020). Mechanical and wear behaviour of LM13/SiC composites fabricated via stir casting. *Transactions of the Indian Institute of Metals, 73*(10), 2651–2659.

[10] Dinesh, S., & Sharma, R. (2021). Effect of SiC content on wear rate and load-bearing capacity of LM13-based composites. *Wear, 484–485*, 204033.

[11] Rao, M. N., & Reddy, T. K. (2021). Microstructure and strength evolution in SiC reinforced LM13 aluminium alloy. *Materials Today Communications, 26*, 101999.

[12] Patel, S., & Shanmugam, K. (2018). Erosive and abrasive wear response of LM13–SiC particulate composites. *Tribology International, 126*, 94–104.

[13] Gupta, M., & Rohatgi, P. (2017). Fly ash reinforced aluminium composites: A review. *Journal of Composite Materials, 51*(9), 1261–1280.

[14] Srinivas, S., & Reddappa, H. (2019). Mechanical and wear behaviour of fly ash reinforced LM13 aluminium alloy. *Materials Research Express, 6*(8), 0865a4.

[15] Venkatesh, G., & Ramesh, C. (2020). Influence of fly ash on abrasive resistance and surface deformation of aluminium composites. *Surface Topography: Metrology and Properties, 8*(3), 035007.

[16] Sharma, S., & Kumar, A. (2022). Tribological behaviour of Al–SiC–fly ash hybrid composites under dry sliding conditions. *Tribology International, 171*, 107520.

[17] Rajesh, P., & Balaji, N. (2023). Hybrid reinforcement of aluminium with SiC and fly ash: Synergistic effects on microstructure and mechanical behaviour. *Materials Today: Proceedings, 72*, 1989–1996.

[18] Dhanasekaran, S., & Sunil, B. (2022). Stir-cast LM13/SiC/fly ash hybrid composites for automotive applications: Microstructure and wear performance. *Journal of Alloys and Compounds, 910*, 164918.