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Fabrication and Mechanical Behaviour of Aluminium Alloy 2219-Sic-Flyash Hybrid MMC's by Stir Casting

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Abstract: The development of hybrid metal matrix composites (HMMCs) has gained significant attention in material science due to their superior mechanical properties and adaptability for structural applications. This study focuses on the fabrication and evaluation of Aluminium 2219-based metal matrix composites reinforced with a fixed quantity of silicon carbide (5g) and varying amounts of fly ash (5g, 10g, 15g, and 20g) using the stir casting technique. Key process parameters such as stirring speed, temperature, and reinforcement feed rate were optimized to ensure uniform particle dispersion. The primary aim was to enhance the physical and mechanical properties of the base metal by combining the strength of reinforcements with the toughness of the matrix. Mechanical characterization included Vickers hardness testing, compression strength assessment, and corrosion resistance evaluation in a 5% HCl environment. The results demonstrated that increased reinforcement content improved hardness and compressive strength significantly, with the highest performance observed in the Al-75g + SiC-5g + Fly Ash-20g composition. However, an increase in reinforcement also led to a reduction in corrosion resistance, as evidenced by higher weight loss over time. The findings confirm that aluminium metal matrix composites can be engineered to achieve a desirable balance of strength, toughness, and durability, making them suitable for advanced structural and engineering applications.

1. Introduction

Composite materials are engineered combinations of two or more distinct phases—typically a reinforcing phase embedded within a continuous matrix. These materials are designed to deliver enhanced mechanical, thermal, and structural properties that are superior to those of the individual constituents. Composites can be classified based on their matrix and reinforcement combinations—such as metal-metal, metal-ceramic, polymer-polymer, or ceramic-polymer. Their growing significance is attributed to advantages like high strength-to-weight ratio, corrosion resistance, and design flexibility, making them indispensable across aerospace, automotive, marine, biomedical, and construction sectors. Based on the geometry and nature of the reinforcement, composites are broadly categorized into **particle-reinforced**, **fiber-reinforced**, and **structural composites**. Particle-reinforced composites use ceramic or hard particulates like carbon black or aluminum oxide to enhance stiffness and wear resistance, while fiber-reinforced composites utilize high aspect ratio fibers—either continuous or discontinuous—to provide high tensile strength and directional stiffness. Structural composites, such as laminar and sandwich types, integrate multiple layers or cores to optimize load distribution, thermal insulation, or resistance to bending and shear forces. The orientation, volume fraction, and distribution of the reinforcement critically determine the composite's performance. Among all composites, **metal matrix composites (MMCs)**—particularly **aluminum-based particle-reinforced MMCs (PMMCs)**—have emerged as promising candidates due to their unique combination of mechanical robustness, thermal conductivity, and resistance to wear and high temperatures. MMCs are particularly valuable in demanding applications like aerospace and defense, where weight reduction and structural integrity under thermal cycling are essential.

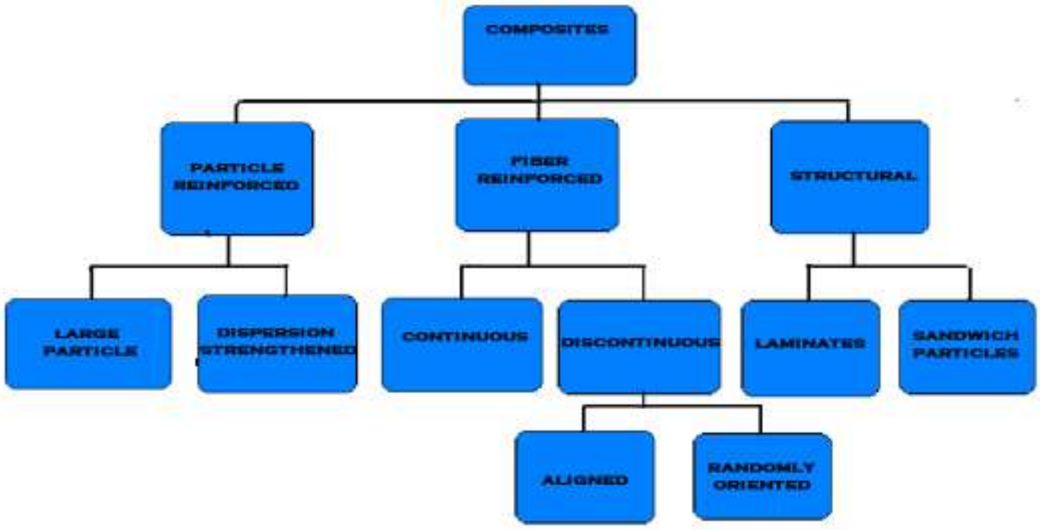

Fig 1.1 Schematic representation of composite classification

Reinforcements such as silicon carbide, boron, and carbon fibers have expanded the possibilities of MMCs by improving dimensional stability and high-temperature tolerance. Aluminum matrix composites stand out for their low cost, machinability, and compatibility with existing manufacturing processes. The **stir casting technique** is one of the most effective and economical methods for fabricating PMMCs. It involves mechanically stirring the molten metal to create a vortex that uniformly distributes the reinforcement particles before solidification. However, challenges such as particle clustering, poor wettability, and porosity need to be addressed for optimal mechanical performance. Despite these challenges, stir casting remains widely adopted due to its scalability and flexibility. Additional fabrication methods like infiltration, powder metallurgy, squeeze casting, and diffusion bonding are also employed to meet specific structural and functional requirements. In summary, composite materials—particularly aluminum-based PMMCs—represent a transformative class of engineering materials that continue to evolve through advancements in processing techniques and material selection. Their benefits, including high strength-to-weight ratio, corrosion resistance, thermal stability, and adaptability, enable their usage in high-performance sectors such as aerospace, automotive, electronics, biomedical, and structural engineering. The present research focuses on the fabrication and characterization of aluminum–carbon particle-reinforced composites, with a specific emphasis on evaluating their corrosion resistance and hardness compared to pure aluminum, carbon, and Al–C alloys.

2. Literature Review

Numerous studies have explored the development and characterization of aluminum-based metal matrix composites (MMCs) reinforced with various particles to enhance their mechanical, thermal, and wear properties. Maurya et al. examined the addition of SiC particles to Al 6061 using electromagnetic stir casting and reported a uniform dispersion of SiC and increased density due to the higher density of the reinforcement. Boopathi et al. focused on hybrid composites of Al 2024 with SiC and fly ash, highlighting improved physical properties. Kumar et al. fabricated both mono and hybrid composites using Al 2024 reinforced with varying weight percentages of B_4C and a fixed amount of graphite via powder metallurgy, resulting in improved performance. Nair and Faisal used liquid metallurgy to produce LM6 alloy composites with B_4C and graphite and evaluated enhanced hardness and compressive strength. Kumaraswamy et al. developed Al 2024–boron fiber–graphite composites through optimized stir casting, employing magnesium to improve wettability. Selvam et al. reinforced AA6061 with fly ash using compo casting and confirmed successful incorporation through XRD without intermetallic formation. Kumar et al. used high entropy alloy particulates (HEAp) in AA2024 to enhance strength and interface bonding. Rao et al. demonstrated the feasibility of AA2024–fly ash composites for cost-effective automotive applications via stir casting. Balasubramanian and Maheswaran reported increased tensile and sliding resistance in AA6063–SiC composites produced through stir casting. Lastly, Vanam and Rao investigated the effect of TiB_2 additions on Al6061 MMCs and found improved microstructure and wear resistance.

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Collectively, these studies confirm that the selection of suitable reinforcements and optimized processing techniques significantly influence the mechanical and structural behavior of aluminum matrix composites.

3. Methodology

In this study, pure aluminum was used as the matrix material and reinforced with graphite, silicon carbide (SiC), and fly ash particles to fabricate metal matrix composites (MMCs) through the stir casting technique. The carbon particles were generated using conventional lathe filing methods, while SiC and fly ash reinforcements were preheated to remove moisture. The aluminum alloy was melted in a crucible furnace at 700–820°C, and alloying elements including 0.5% zinc, 1.5% magnesium, and 2% phosphorous were added to improve wettability and prevent floatation of graphite particles. The reinforcements were added gradually using a spoon at a rate of 10–20 g/min, while stirring was maintained at 500–800 rpm for uniform distribution, followed by casting into a preheated cast iron die designed to produce cylindrical specimens of 100 mm length and 12 mm diameter.

Fig 3.1 Drilling machine used for casting

Fig 3.2 Molten metal

Fig.3.3 Furnace

Fig.3.4 Furnace

Four different compositions were fabricated by varying the proportions of fly ash while keeping SiC constant at 5%, producing Al matrix composites with 5–20 wt.% fly ash. Mechanical characterization involved hardness and compression testing. Micro Vickers hardness tests were performed using a UHL tester with a 500 gm load and 10-second dwell time; average values were calculated from three readings per sample. Compression tests were conducted using a Universal Testing Machine (UTM) according to ASTM standards to assess compressive strength and modulus. For corrosion testing, samples were exposed to 5% HCl solution for durations ranging from 2 to 8 hours, with periodic weight loss measurements recorded using a Dhona 200D electronic balance. The extent of corrosion was evaluated by comparing the mass loss over time, and the data were used to plot weight loss vs. exposure time to analyze corrosion behavior in acidic environments. The experimental setup and testing conditions were optimized to ensure repeatability, homogeneity, and reliable property assessment of the fabricated composites.

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Table 3.1. Composition Percentage

S.No	Aluminum Alloy 2219 (Matrix) g	SIC (Reinforcement-1) g	Fly Ash (Reinforcement-2) g
1	90	5	5
2	85	5	10
3	80	5	15
4	75	5	20

3.3.1. Hardness Test

Hardness tests were conducted using a UHL Vickers micro hardness testing machine in accordance with ASTM standards for metallic materials. A consistent load of 500 grams was applied for a dwell time of 10 seconds to determine the microhardness values of the composite samples. To ensure reliability and reduce experimental error, a minimum of three indentations were taken on each sample, and the average value was calculated. Variations in hardness values were attributed to factors such as cooling rate, gravitational effects, and non-uniform distribution of reinforcement particles in the metal matrix. Among the tested samples, Sample 1 exhibited the highest hardness, which was primarily due to the uniform dispersion of SiC particles. The presence of finer SiC particles contributed significantly to the increase in hardness, and the inclusion of hard fly ash particles further enhanced the composite’s resistance to deformation. These results confirm the reinforcing effect of ceramic particulates on the mechanical behavior of aluminum matrix composites**.**

Fig 3.5 Micro Vickers Hardness Test Equipment

Fig 3.6 Al-90%+Sic-5%+Flyash-5%

Fig.3.7Al-80%+Sic-5%+Flyash-15%


Fig 3.8 Al-85%+Sic-5%+Flyash-10%


Fig3.9 Al-75%+Sic-5%+Flyash-20%


Fig 3.10 Aluminium Alloy 2219

3.3.2. Compression Test

Compressive strength tests were conducted on aluminium specimens and their composites using a computerized Universal Testing Machine (UTM) in accordance with ASTM standards. For each composition, three samples were tested and the average value was taken as the representative compressive strength. These tests are vital for evaluating the elastic and compressive fracture properties of brittle or low-ductility materials. In addition to compressive strength, the tests also help determine important mechanical parameters such as the modulus of elasticity, proportional limit, compressive yield point, and compressive yield strength, which are crucial for understanding the deformation behaviour and structural integrity of the metal matrix composites under compressive loading.


Fig 3.11 Compression Test Equipment


Fig 3.12 Al-90%+Sic-5%+Flyash-5%


Fig 3.13 Al-80%+Sic-5%+Flyash-15%

Fig 3.14 Al-85%+Sic-5%+Flyash-10%

Fig 3.15 Al-75%+Sic-5%+Flyash-25%

Fig 3.16 Aluminium Alloy 2219

3.3.3. Corrosion Test

The corrosion behavior of the fabricated samples was evaluated by subjecting specimens of 8 mm diameter and 12 mm length to hydrochloric acid (HCl) environment with a concentration of 5%. The samples were immersed in a beaker containing the HCl solution, and weight loss was measured at regular time intervals to assess corrosion resistance. Specifically, samples were withdrawn after 2, 4, 6, and 8 hours, and both the initial and final weights were recorded using a Dhona 200D electronic balance with a least count of 0.001 g. The metal loss due to corrosion was calculated from the difference in weights before and after exposure to the corrosive medium. Based on the weight loss data, graphs of weight loss versus time were plotted to analyze the corrosion behavior of the composite samples under acidic conditions

Fig 3.17 Corrosion Test Setup

Fig 3.18 HCL Reaction with composite material

4. Results and Discussions

4.1.1. Hardness

The Vickers hardness values show a clear improvement with the addition of SiC and fly ash reinforcements. The base aluminum alloy (Al 2219) recorded the lowest average hardness of 42.29 HV**.** Introducing 5g SiC and increasing fly ash from 5g to 20g progressively enhanced the hardness, reaching a peak of 53.35 HV for the 75% Al + 5% SiC + 20% Fly Ash composite. This increase in hardness can be attributed to the uniform distribution of hard SiC and fly ash particles within the matrix, which enhances resistance to indentation.

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S.No	Composition	Trail-1	Trail-2	Trail-3	Average
1.	Aluminum (Al 2219)	40.91	42.03	43.95	42.29
2.	Al-90g+Sic-5g+Fly Ash-5g	47.19	40.42	45.54	44.38
3.	Al-85g+Sic-5g+Fly Ash-10g	52.60	51.15	50.73	50.95
4.	Al-80g+Sic-5g+Fly Ash-15g	51.17	50.08	51.62	51.49
5.	Al-75g+Sic-5g+Fly Ash-20g	54.61	52.65	52.81	53.35

Table 4.1 Summary of hardness value for Al and SiC& Fly Ash composites.

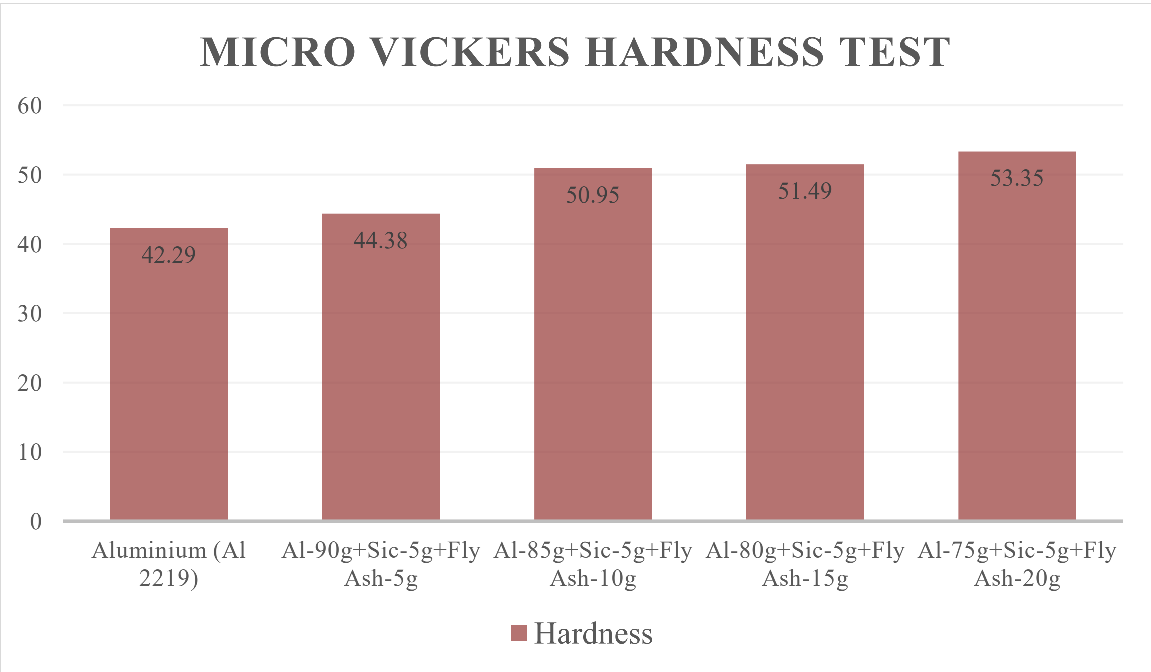

Fig 4.1 Micro Vickers Hardness Test

4.2. Compressive Strength

The compressive strength of the composite materials showed significant improvement with the addition of SiC and fly ash reinforcements. The base Al 2219 alloy had the lowest compressive strength of **70.0 kN**. As the fly ash content increased from 5g to 20g (while keeping SiC constant at 5g), the compressive strength also increased, reaching up to **85.0 kN**. This trend highlights the reinforcing effect of fly ash and SiC particles, which enhance the load-bearing capacity of the matrix by increasing its resistance to deformation under compression.

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Table 4.2. Summary of hardness value for Al and SiC& Fly Ash composites.

S.No	Composition	Trail-1 (KN)	Trail-2 (KN)	Average (KN)
1.	Aluminum (Al 2219)	69.0	71.0	70.0
2.	Al-90g+Sic-5g+Fly Ash-5g	70.0	80.0	75.0
3.	Al-85g+Sic-5g+Fly Ash-10g	75.0	85.0	80.0
4.	Al-80g+Sic-5g+Fly Ash-15g	78.75	87.5	83.0
5.	Al-75g+Sic-5g+Fly Ash-20g	90.0	80.0	85.0

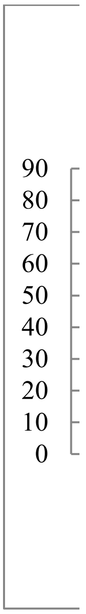

Fig 4.2 Compression Test

4.3. Corrosion Test

The bar chart titled "Weight Loss vs Time" represents the corrosion behavior of aluminum-based metal matrix composites with varying fly ash content (5g to 20g) while keeping SiC content constant at 5g. Over a 72-hour immersion period in HCl solution, all samples showed gradual weight loss, indicating corrosion.

The initial weight ranged from 35.5g (for Al-90%) to 26g (for Al-75%), and all samples experienced progressive weight reduction over 24, 48, and 72 hours. The Al-90g+SiC-5g+Fly Ash-5g sample showed the least weight loss, dropping from 35.5g to 31g, while the Al-75g+SiC-5g+Fly Ash-20g sample exhibited the maximum weight loss, reducing from 26g to 22g.

This trend suggests that higher fly ash content increases the corrosion susceptibility of the composite, likely due to non-uniform distribution or increased porosity. In conclusion, while fly ash improves certain mechanical properties, excessive content may adversely affect corrosion resistance, and an optimal reinforcement ratio is essential for balancing mechanical strength and corrosion behavior.

Table.4.3. Summary of weight loss in grams for Al and SiC& Fly Ash composites

S.No	Composite	5% of concentration of HCL			
		Initial Weight (g)	Weight (g) at 24 hrs	Weight (g) at 48 hrs	Weight (g) at 72 hrs
1	Al-90g+Sic-5g+Fly Ash-5g	35.5	34.0	32.5	31.0
2	Al-85g+Sic-5g+Fly Ash-10g	35.0	33.5	32.0	30.5

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3	Al-80g+Sic-5g+Fly Ash-15g	31.5	30.0	27.5	27.0
4.	Al-75g+Sic-5g+Fly Ash-20g	26.0	24.0	22.5	22.0

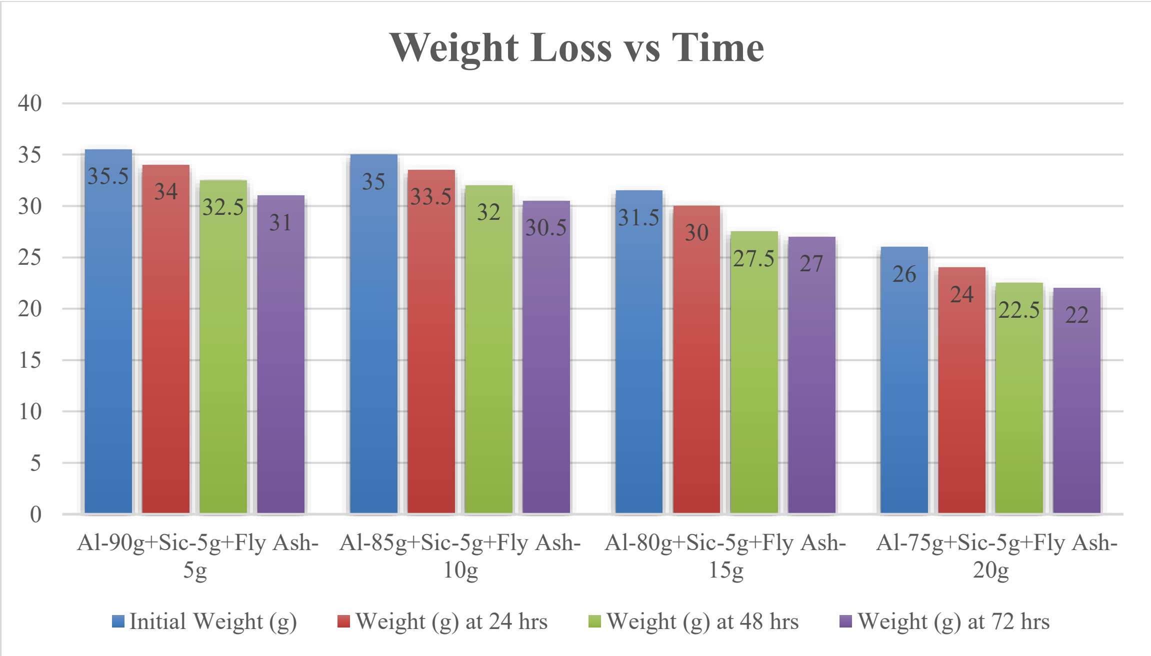

Fig 4.3 corrosion behavior of Al-SiC-Fly Ash at 5% Concentration of HCL for composites

5. Conclusions

Processing Parameters Matter: The successful fabrication of metal matrix composites depends significantly on critical process parameters such as holding temperature, stirring speed, stirrer size and position, particle concentration, and mixing time. Optimal control of these factors ensures uniform distribution of reinforcement and improved composite properties.

Hardness Improvement: Incorporation of reinforcements such as SiC and fly ash into the Al 2219 matrix significantly enhances hardness. The sample with the highest reinforcement content (Al-75g + SiC-5g + Fly Ash-20g) achieved a hardness of **53.79**, showing a **27% increase** compared to the unreinforced Al 2219 alloy which had a hardness of **42.29**.

Enhanced Compressive Strength: The addition of reinforcements also improved the compressive strength of the composite. The maximum compressive strength recorded was **85 kN** for the composite with the highest reinforcement, compared to **70 kN** for the base alloy, reflecting a **21.4% increase**.

Corrosion Resistance Decreases with Reinforcement: While mechanical properties improved, the corrosion resistance decreased with increasing reinforcement. The weight loss in HCl solution was higher for composites with greater fly ash content, indicating **reduced corrosion resistance** possibly due to increased porosity or galvanic effects between the matrix and reinforcement.

Trade-off Between Strength and Corrosion Resistance: Overall, the study demonstrates that while SiC and fly ash reinforcements effectively improve the mechanical performance of Al 2219 composites, they compromise corrosion resistance. Hence, **a balance must be struck between mechanical enhancements and environmental durability** depending on the intended application.

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