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# Characterization of Aluminium 2024 Composites Reinforced with Silicon Carbide and Fly Ash

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**Abstract -** *Aerospace, automotive and structural engineering would desire a lighter, stronger material, so people are considering hybrid metal matrix composites. In this paper, stimulated-casted Al-2024 hybrids are considered with SiC and fly ash. The tests indicate that 10 percent SiC and 10 percent FA provide the highest tensile strength (290 3N/mm 2 ) and Brinell hardness (96.6 BHN). Subsequent density decreases to 2.09 g/cm 3. We constructed some Response Surface Methodology (RSM) models to determine the extent to which each reinforcement can be of assistance. The ANOVA indicates that 55.41% of the increase in strength is caused by SiC and 36.14% by FA. One type of reinforcement is not as good as a two slim one in power and mass. Thus hybrid composites are suggested by the study to be used as aerospace components that require being light and strong.*

**Key Words: Aluminum 2024, Silicon Carbide, Fly Ash, Stir Casting, Hardness, Tensile Strength, Hybrid Composite, RSM.**

## INTRODUCTION

Rapid progress in high-efficiency industrial objectives based on the push of advanced engineered materials has become insane within recent years. Aerospace, automotive, marine, and structural gears all demand the ability to have something stronger, lighter, heat-resistant and durable. The big deal is to balance between weight loss and mechanical stability. Metal matrix composites (MMCs) have the ability to blend a number of phases to achieve bespoke performance, thereby cool substitutes of normal metals. Plain alloys continue to experience some bummer issues even after centuries of development. They lose their stamina and become extremely bulky under heavy loads and err when it gets hot. Pure metals are super-ductile and conducting due to crystal structure but not very great under stress. Engineers are now into hybrid structures, with reinforcements into a matrix to provide intriguing new material behaviors. That is the essence of composite science: play phase interactions to create high-performance stuff that is capable of meeting modern loads. Aluminum is an attractive melt-processing material, and ALU has high specific strength, good strength/weight ratio, inherent corrosion resistance, and low cost and can be processed in large scale, which makes the Al- matrix composite (Al-MMCs) a hot bet. Al 2024 is an engineering hero since the copper content of the alloy enhances fatigue, tensile and machining characteristics. This is what is typical in aircraft components fuselage skins, wings, landing gear and all the delicate load-carrying components where a failure is a large sinks. Al‑2024 does have limits, though. It cannot survive in hard tribological locations as it can be easily worn out, it can be bent easily with pressure, and its surface hardness is not very good. The reduction in the weight of aircrafts to increase engine efficiency has made people seek methods to increase the alloy strength and decrease the drop density. That is why the research is performed on the enhancement of Al alloys including ceramic particles and industrial by-products.

### 1.1 Research Need and Motivation

A research gap in the hybrids with FA and SiC in Al-2024 still exists. Not so many people apply RSM to simulate mechanical behaviors such as tensile, hardness, and density and even few separate out individual and interaction effects. The absence of sound statistical framework prevents forecast of mechanical trend, appropriate ratios of reinforcement and industrial acceptance. The hybrids may strike incredibly efficient synergies, yet there is no proof of this in a hard experimental way.

### 1.2 Purpose and Scope of Present Study

The present paper bridges that gap by preparing Al 2024 hybrids containing 010wt% SiC and FA via controlled stir casting. Each sample is measured in terms of tensile strength, hardness, and density. RSM modeling informs us of the precise contribution of each reinforcement and what proportion of the overall contribution it brings. The models also provide equations of future behavior as a form of prediction in the form of a form of equations which are expressed as polynomial. The aim is to make aircraft parts, vehicle brakes, marine propellers, and advanced military materials; lightweight, mechanically better, and cost effective hybrids. We are investigating how to develop the hybrid metal matrix composites to be more effective,

through design using real experiments. This is aimed at increasing structural efficiency, ensuring it is safe and being gentler to the planet- and demonstrating to the industry how to use greener composite technology.

## LITERATURE REVIEW

### 2.1 Introduction

Various studies on aluminum-based metal matrix composites have emerged over the past three decades due to the demand by firms to have lighter components that can withstand more than usual metal. In order to reinforce them with tensile strength, hardness, wear resistance, fatigue endurance, and thermal stability, researchers have attempted to reinforce them with the use of ceramic particles, metal powders, and industrial by-products. The combination of Aluminum 2024 alloy (Al- 2024) with Silicon Carbide (SiC) and Fly Ash (FA) is becoming the subject of a lot of academic research due to its low cost, versatility, and durability. The key scientific achievements in aluminum MMCs, SiC reinforced composites, FA reinforced systems and hybrids reinforced with both will be presented in this chapter. I will point out the research findings, research methodologies, main findings, issues, and the research gaps that induced me to carry out this research.

### 2.2 Early Investigations on Fly Ash Reinforced Aluminium Alloys

Rao et al. (2012) published the first large-scale article on the use of fly ash in aluminum alloys. They stir-cast Al 2024 composites containing 2-10 wt.% FA. Their results were that the FA decreased the size of the grains, which reduced density and increased the hardness and compressive strength. SEM demonstrated that the FA was evenly distributed thus the matrix-reinforcement bond became stronger. This groundbreaking research demonstrates that FA might be an effective waste-based reinforcement and preconditioned the studies on hybrid MMC. In addition, Selvam and colleagues (2013) later combined FA 0-12 percent and AA6061. Since the FA had a uniform blend, the hardness and ultimate tensile strength increased. XRD had no bad intermetallic, thus chemical compatibility. According to their data, FA enhanced the mechanical properties without affecting the structure. Kountouras et al. (2015) conducted investigation on FA-reinforced aluminum composites with respect to microstructure, corrosion, thermal expansion, and wear. They discovered moderate levels of FA increased the hardness and wear resistance but over 40 percent FA resulted in the separation of particles- hence, there is a maximum point to the concentration of FA to be added. Their corrosion tests demonstrated that FA in NaCl formed a passive layer, which proved to be more resistant. Dinaharan et al. (2016) applied friction stir processing to AA6061 containing 0 (0) to 18 (18) vol.% FA. The grains were refined; the alloy hardened, and wears reduced by the process. The presence of the FA in the stir zones showed solid-state reinforcement works as EBSD itself revealed that the FA was uniformly distributed across the zones. Razzaq et al. later investigated AA60632020 Next, compression-casting and sliding-wear tests of AA60632020 were performed (Razzaq et al., 2017, 2018, 2020). They observed increased FA percentage redoubled microhardness, porosity, and wear resistance, but decreased density and impact energy- indicating that FA simultaneously varies mechanical and physical properties.

### 2.3 Research on Silicon Carbide Reinforced Aluminium MMCs

Yet another branch of research was on SiC due to its high heat conductivity, hardness, and strength. Cast and age-hardened Al-SiC MMCs with 3-12-percent SiC were prepared by Alaneme and Aluko (2012) who reported that aging of the materials enhanced tensile properties. According to them, SiC blocks the dislocations in the matrices hence increasing the yield strength and fracture toughness. The substance is even more brittle when subjected to greater masses. Rahman and Al -hashed (2014) stir-cast Al alloys containing 0 -20 kg/SiC. Alloys became stronger, tougher and wear-resistant. A major challenge is the problem of dispersion; at large levels of SiC their microscopic examination revealed mild clumping and porosity. Dandekar and Shin (2013) attempted the laser-assisted machining of SiC reinforced A359 MMCs and discovered that increase in machining temperature lowers the tool wear and cutting forces- good news to industry. Rajeswari et al. (2015) investigated hybrids of Al-7075/SiC/Al 2 O3 and discovered that the percentage of reinforcement, stirring speed, as well as process temperature, had a significant impact on the mechanical behavior and the formation of defects. Mohanavel et al. (2018) mixed AA6351 with 0-20 wt.% SiC and enhanced the density, hardness, and impact strength. Optical micrographs ensured there was a regular distribution at good enough levels of reinforcement.

### 2.4 Research on Hybrid Composites Reinforced with SiC and Fly Ash

The initial idea of applying the hybrid reinforcements with ceramic material and industrial by-products was introduced by Ravesh and Garg (2012). Tensile strength, toughness, and hardness increased step-wisely when SiC and FA were added to AA6061. This initial research demonstrated that hybrids were able to beat single-reinforcement. Mahendra Boopathi et al. mixed SiC, FA and Al 2024 into hybrids and discovered that a 5 percent of SiC and 10 percent of FA reduced the density and hardness of the samples (Mahendra Boopathi et al., 2013). Their findings highlight an upper limit of composition beyond which

reinforcement ceases to be effective- essential to take note of. Dwivedi et al. (2014) created A356/SiC/FA hybrids with high interfacial bonding and dispersion uniformity using electromagnetic stir-casting, and optimally with 15 per cent SiC and 5 per cent FA. The upper limit of corrosion potential and current density in the Al-5083/SiC/FA composites was found to increase with increased reinforcement of the material by Gowda (2017). Al 6082 hybrids with 2.5-7.5 wt.% SiC + FA were stir-casted by Reddy and Srinivas (2018). Due to hard-phase strengthening, reinforcement proportionally divides the wear resistance, tensile strength, and hardness.

### 2.5 Specific Research on Al-2024 Hybrid Reinforcement

A variety of scholars, including Boopathi et al. (2014), Singh and Chauhan (2016), Kurapati and Kommineni (2017), Kurapati (2018), and Kumar (2020) bridged the gap of Al-2024 hybrid composites. These experiments all demonstrated that SiC and FA can reinforce Al -2024 parts, making them stronger, tougher, and more wear-resistant than those reinforced with one or none. SiC was uniformly distributed in the SEM work, but not FA, which means that it is necessary to work on better processing.

The combination of their works preconditions this study and demonstrates the following gaps:

- Lack of research on the overall contribution of each of the types of reinforcements.
- No forecasting mathematical modeling.
- Poor experimental optimization through Response Surface Methodology.
- No systematic reporting of density-strength.

The gaps are rationalizing the experimental and statistical work we are presently doing.

### 2.6 Summary

It has been demonstrated in literature that adding a touch of SiC and FA to the aluminum alloys effectively renders them tougher and lighter thus being a boon to the environment and the budget. Even the hybrid MMCs, particularly the ones filled with Al 2024, have little sound research, much less undergone statistical testing. Here we have applied RSM-based modeling and experimental calibration to nail down the most effective mixture of the reinforcement and provided a rigorous measure of performance providing us with new concepts of material design.

## MATERIALS AND METHODOLOGY

In regards to this project I am focusing on developing and testing hybrid aluminum metal matrix composites (HMMCs) made of Aluminum 2024 alloy and reinforced with SiC and Fly Ash. The methodology assures uniform distribution of reinforcement, reduces processing errors such as porosity and makes the structure solid as the composite remains in liquid. The chapter discusses the way we selected the materials, constructed the composite, made the specimens and conducted tests of tensile strength, surface hardness and density.

### 1.3 Materials Used

As the base material, we began with the powerful alloy of aluminum, 2024 (Al -2024 ), since the alloy is a popular choice of high-performance aerospace components. It is harder and easier to work than standard grades due to the copper content and this is the reason we selected it. 250 mesh Silicon Carbide (SiC) powder was the primary ceramic reinforcement super strong, wear-resistant and tough in high temperatures. The fine alumino-silicate fly ash is produced by combustion of powdered coal, and we used it to decrease the density of the composite, to cast easily, and recycle industrial waste. The reinforcements were added using weight portions of 0, 5 and 10 percent to observe individual and individual joint effect. Precisely 1.5 wt.% Mg was sprinkled on the surface to assist the ceramic particles to stick to the molten aluminum..

### 1.4 Composite Fabrication Using Stir Casting

The synthetic composite materials were produced in the hybrid composite specimens by stir casting, which is a cost-efficient and scalable liquid metallurgical process in industries. Aluminum 2024 alloy was melted in graphite crucible at 720 0 C through an electrical resistance furnace. Preheat of SiC and FA was done at 300oC during three hours to remove moisture and make them more wettable before combining them together to prevent clumping and gasses entrapment. Mechanical stirring, using a mild-steel impeller, formed a vortex within the molten alloy. The stirring took between 5 and 7 minutes with 200 rpm. The reinforcement mix was fed slowly on the vortex wall, in order to maintain uniformity. The molten composite slurry was poured in a permanent steel mold heated to 680 o C and left to cure in the air. Redoing the same procedure provided less flaws, reduced turbulence, and improved particle dispersion.

### 1.5 Specimen stir furnace Preparation

The castings that had solidified were machined into standard lab test shapes. ASTM dog-bone shaped tensile specimens were 36mm in length. Hardness samples were sliced into disk and polished in order to remove scaling. The pieces were wiped down with each piece being degreased so that no dirt was left on it.

### 1.6 Mechanical Testing of specimen

Simulations on tensile tests were performed on a 20 ton Universal Testing Machine (UTM). The ultimate tensile strength was calculated using load-displacement curves of the tests, and the results were tested at 5mm/min until the material failed. Surface hardness measurement was done by means of Brunel Hardness (ASTM E10) using hardened steel indenter of 10mm diameter and 10 kg load at 10 highly required dwell time. The indentation diameter was measured under optical microscope and values of hardness were calculated.

The principle of Archimedes was applied to the determination of the composite density by weighing the mass of both air and water with high-precision digital scales to consider the effects of buoyant forces.

## TESTING OF COMPOSITES

### 1.7 Tensile Strength Test

#### 1.7.1 Introduction

Tensile testing is a fundamental mechanical characterization technique used to determine the load-bearing capability, ductility, and fracture behavior of aluminum hybrid metal matrix composites (HMMCs). The present study evaluates the tensile properties of Al 2024 reinforced with Silicon Carbide (SiC) and Fly Ash (FA), fabricated through the stir casting route. The test provides insight into the influence of reinforcement percentage on the ultimate tensile strength (UTS) of the composite system.

#### 1.7.2 Simulation Using RSM

Simulation of tensile behavior was conducted using Response Surface Methodology (RSM) to develop a predictive mathematical model.

The strength model derived from regression analysis is:

$$\text{Strength } (\text{N/mm}^2) = 242.083 + 3.08333(\text{SiC}) + 2.51667(\text{FA}) - 0.03(\text{SiC} \times \text{FA})$$

**Key simulated findings:**

- Tensile strength increases with increasing SiC and FA content.
- Interaction term (SiC×FA) shows marginal negative influence (0.09% contribution).
- ANOVA results confirm SiC (55.41%) has the highest influence, followed by FA (36.14%).

#### 1.7.3 Tensile Test Specimens

The specimens were machined according to ASTM E8 with a gauge length of 36 mm.

- A total of nine specimens were prepared, each representing a unique reinforcement combination (0, 5, 10 wt.% of SiC and FA).
- Specimen surfaces were polished to remove oxides, burrs and contaminants before testing.

Images of fabricated tensile samples are shown in Figure 3.3(a) in the project report.

#### 1.7.4 Testing Procedure

- Equipment: Universal Testing Machine (UTM), calibrated per ASTM E4, E74, and E83.
- Maximum load capacity: 20 tons.
- Crosshead speed: 5 mm/min.
- Sampling rate**:** 9.103 points/sec.
- Tests conducted at ambient laboratory conditions.
- Each specimen was loaded until fracture and load-displacement curves were recorded.

### 1.7.5 Tensile Strength Values

**Table: Experimental Tensile Strength Results**

| Sample | SiC (%) | FA (%) | Strength (N/mm$^2$) |
|---|---|---|---|
| 1 | 0 | 0 | 240 |
| 2 | 5 | 5 | 280 |
| 3 | 0 | 10 | 265 |
| 4 | 0 | 5 | 253 |
| 5 | 10 | 5 | 288 |
| 6 | 5 | 10 | 282 |
| 7 | 5 | 0 | 258 |
| 8 | 10 | 0 | 268 |
| 9 | 10 | 10 | **290** |

### 1.7.6 Tensile Test Results and Discussion

The results indicate a clear improvement in UTS with the incorporation of reinforcements:

- Baseline alloy (0% SiC, 0% FA) recorded 240 N/mm$^2$.
- Maximum strength (290 N/mm$^2$) was observed for 10% SiC + 10% FA, demonstrating the synergistic effect of dual reinforcement.
- SiC contributes significantly due to its superior stiffness and load transfer capability.
- FA reduces density and moderately improves strength due to its aluminosilicate composition.

Overall, the hybrid composite exhibited enhanced mechanical performance suitable for aerospace and automotive applications requiring high strength-to-weight ratios.

## 1.8 Hardness Testing

### 1.8.1 Introduction

Hardness testing evaluates the resistance of a material to localized plastic deformation, which correlates with wear resistance and surface durability. The Brinell Hardness Test (BHT) was selected for this study due to its effectiveness in characterizing cast aluminum-based composites.

### 1.8.2 Simulation Model for Hardness (RSM)

The hardness model derived is:

$$\text{Hardness (BHN)} = 82.7889 + 0.446667(\text{SiC}) + 0.1(\text{FA}) + 0.1(\text{SiC} \times \text{FA})$$

Findings:

- Hardness increases with both SiC and FA content.
- Interaction effect contributes positively to hardness.
- SiC is the primary strengthening phase due to its extreme hardness (~2500 HV).

### 1.8.3 Hardness Test Specimens

- Disc-shaped specimens were prepared from each cast composite.
- Surfaces were finished smoothly to ensure accurate indentation measurement.
- Figure 3.3(b) in the report depicts the hardness testing specimens.

### 1.8.4 Testing Procedure

- Standard followed: ASTM E10.
- Indenter: 10 mm steel/ carbide ball.
- Load applied: 10 kg (suitable for aluminum alloys).
- Dwell time: 10–30 seconds.
- BHN determined by measuring indentation diameter using optical measurement equipment.
- Load-to-indentation surface area ratio yields BHN.

### 1.8.5 Hardness Results

**Table: Experimental Hardness (BHN) Values**

| Sample | SiC (%) | FA (%) | Hardness (BHN) |
|---|---|---|---|
| 1 | 0 | 0 | 82.7 |
| 2 | 5 | 5 | 90.4 |
| 3 | 0 | 10 | 89.2 |
| 4 | 0 | 5 | 86.1 |
| 5 | 10 | 5 | 94.9 |
| 6 | 5 | 10 | 91.8 |
| 7 | 5 | 0 | 88.5 |
| 8 | 10 | 0 | 93.7 |
| 9 | 10 | 10 | **96.6** |

### 1.8.6 Hardness Test Discussion

The results exhibit a consistent rise in BHN with increasing reinforcement content:

- Pure Al 2024 alloy records the lowest hardness (~82 BHN).
- Maximum hardness of 96.6 BHN is obtained at 10% SiC + 10% FA.
- SiC improves hardness due to its ceramic nature and strong load-bearing properties.
- FA contributes by refining grain boundaries and enhancing particle dispersion.

The improved hardness indicates enhanced wear resistance, making the hybrid composites favorable for applications involving sliding, abrasion, and surface stresses.

## RESULTS AND DISCUSSION

This part assesses the mechanical performance of Aluminum 2024 hybrid MMC reinforced with SiC and Fly Ash. After stir casting, we were able to measure tensile strength, Brinell hardness, and density experimentally and analyses them using RSM. The primary matrix Al -2024 was used and nine specimens embraced the entire factorial reinforcement combinations of 0%10% SiC and FA. This paper will demonstrate the effect of each of the reinforcements on the mechanical characteristics and demonstrate that hybrid systems perform better than single-reinforced and unreinforced matrices.

### 1.9 Tensile Strength Behavior Analysis

All the tensile strengths of the nine samples are indicated in Table 4.1a in the paper. The data verify that strength is increased with the addition of reinforcement. Sample 1 (0% SiC, 0% FA) had the lowest tensile strength value (240 N/ mm 2) and was used as the control. The addition of 5 5 -percent SiC and 5 -percent FA (Sample 2) increased the strength by 16.7 percent to 280 N/mm 2, which is higher than the plain alloy. Sample 6 containing 5% SiC and 10% FA recorded 282 N/mm 2, which states that both reinforcers are beneficial in that they distribute loads and also make the interface between the matrix and particles hard.

Sample 9 (10 per cent SiC, 10 per cent FA), in which dual reinforcement was observed, and had the highest tensile strength of 290 N/mm Hex 2 which is 20.8 per cent higher than the tensile strength of the unreinforced Al-2024 matrix. The tensile strength is evidently increased by a hybrid reinforcement over the single one, as observed in Sample 8 (10 percent SiC, 0 percent FA: 268 N/mm 2) and Sample 3 (0 percent SiC, 10 percent FA: 265 N/mm 2). Another advantage is that Fa and SiC have a stronger elastic modulus and hardness, which influence tensile behavior whereas Fa stabilizes microstructure and minimizes density.

The key strengthening mechanisms are:

- Preventing the build-up of dislocation at the reinforcing and matrix interface
- High modulus of SiC increases the transfer of loads
- even microstructure due to FA particle dispersion
- deformation is prevented by pinning of particles

This is because of the reinforcement particles that absorb deformation energy and form additional crack-bending paths during hybridization that diminish micro-porosity and crack propagation.

### 1.10 Tensile Strength Model and ANOVA Interpretation

Accordingly, under the tensile strength section, I re grassed the reinforcement content in a second-order regression with the aid of RSM to determine the relevance of the same.

$$Strength = 242.083 + 3.08333 \times SiC + 2.51667 \times FA - 0.03 \times (SiC \times FA)$$

As the equation indicates, both SiC and FA strengthen in a linear fashion with a duration coefficient that is slightly negative which can be said to signify that there is a small amount of cross-effect between the two. Since 55.41% of the variance is attributed to Silicon Carbide, it happens that that is the largest in the ANOVA (see Table 4.1b). Fly Ash contributes 36.141354 and the interaction is merely 0.091, thus we are dealing with additive but not multiplicative effects. We may have confidence in the model in that the F-value is 18.43 with a p-value less than 0.0039 that informs us that the reinforcement actually strengthens the alloy. The error value of 8.36 is also a residual value and indicates that all was stable in the experiment and uncontrolled variability was also minimal.

### 1.11 Response Surface and Contour Analysis

By checking Figures 4.1(a) and 4.1(b), 3D surface plot and the contour plot both show an upward trend in the direction of the upper right quadrant. That essentially translates to the fact that at high concentration levels of SiC and FA, you achieve the optimum tensile strength. The smooth curve in plot indicates that the strength continues to rise, in a straight-line with reinforcement, up to 10 per cent. That is, there are no clustering effects there. Similarly, the absence of saddle points is an indication of a plateau or a wear-out area beyond the existing range, and, thus, the material cannot continue to get stronger beyond some point.

### 1.12 Hardness Behavior

When we measured the number of Brinell Hardness (BHN) using a 10-kg indenter, the findings replicated those of tensile strength. The hybrid reinforcement prevents the localized plastic deformation and also hardens the surface. Sample 9 containing 10 per cent SiC and 10 per cent FA was the hardest with 96.6 per cent BHN. The second hardest was sample 5 with 10% SiC and 5% FA at 94.9BHN. Only 82.7 BHN made the base alloy the softest.

**Hardness goes up because:**

- Ceramic SiC alloys withstand dislocations.
- FA dispels the stress and alleviates the depression.
- Higher interface bonding decreases the depth of ductile dentation.

The reinforcement content and hardness ratings go hand in hand indicating that the reinforcement is evenly distributed.

### 1.13 Density Behavior

As we increase the reinforcement, we know that the density measurements decreases by Archimedes principle. The maximum density of the unreinforced alloy is 2.71 0 g/cm 2, and 2.09 0 g/cm 2 in the hybrid specimen with 10 0 SiC + 10 0 FA. That downturn is extremely significant to the airplane and auto industries since lighter frameworks increase fuel efficiency and cargo.

**Overall Performance Summary**

| Specimen | Strength ($N/mm^2$) | Hardness (BHN) | Density ($g/cm^3$) |
|---|---|---|---|
| 0% SiC + 0% FA | 240 | 82.7 | 2.71 |
| 10% SiC + 10% FA | 290 | 96.6 | 2.09 |

### 1.14 Major Observations

- Composites that have hybrid reinforcement are stronger.
- SiC is the big deal because it is hard.
- FA enhances density optimization and refinement.
- The hybrid design is less weighty and provides mechanical strength.

## CONCLUSION

To observe the mechanical characteristics of casting on an Aluminum 2024 hybrid matrix composite with Silicon Carbide (SiC) and Fly Ash (FA), we did stir casting on the same. To determine the effect of reinforcement on tensile strength, hardness and density, we installed nine trials with the help of RSM. The data demonstrated that hybrid reinforcements enhance the performance of alloy. The 10 96.6 BHN 10 290 N/mm 2 sample achieved the best tensile strength (290 96.6 BHN 10 290 N/mm 2), hardness (96.6 96.6 BHN 10 290 N/mm 2), and low density (2.09 2.09 BHN 10 290 N/mm 2) compared to both single reinforced and unreinforced base alloy samples. Tensile strength and FA increase 55.41 and 36.14 respectively with minimal interaction involving SiC andFA in the ANOVA. That informs us that FA is good at reducing weight, and spreading the plastic flow, and that SiC is the strongest due to being tougher. The research further demonstrates that hybrid reinforcement refines the microstructure, combats dislocations and adsorbs energy hence load performance is enhanced. In aerospace, automotive, military applications, where a long life with minimal weight is required, Al-2024 hybrid MMCs are very attractive. This study confirms that structural efficiency, costs and sustainability are balanced through the use of industrial waste as a reinforcement.

## FUTURE SCOPE

Although this work provides strong evidence of the benefits of hybrid Al2024 composites with SiC and FA, which are mechanical, there is still more to be done. This paper has considered tensile strength, hardness and density only, but the practical application requires information on fatigue life cycle, impact toughness, fracture behavior, and the high-temperature performance. Future studies might consider SEM, TEM, XRD, and EDS to examine microstructure, particle-matrix bonding and fracture morphology. One more thing we can investigate the impacts of the rate of sliding, load, ambient temperature, and shape of the specimen on tribological characteristics of these hybrids in the dry and lubricated wear experiments. The reinforcement ratio may exceed 10% to locate the sweet spot and a point at which excessive reinforcement renders the material either porous or brittle. The nano-sized reinforcements may assist in the particle packing and interface diffusion. The data with the digital twin modeling, FEM, ANN-based predictions, and other simulations could also be increased with future experiments. Squeeze casting, friction stir processing, powder metallurgy, and additive manufacturing can also be put on the table but on industrial scale. Lastly, the environmental benefit of waste fly ash reuse in engineering material must be further studied in terms of their recyclability and environmental impact. These recommendations may transform hybrid MMCs to the preferable next-generation structural material.

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