Production and characterization of sustainable aluminium matrix composites reinforced with industrial waste materials via stir casting for lightweight and high-strength applications

Pradeep Kumar Krishnan*, *Bashair* Mohammed Al Kindi, *Abdulshafi* Mohammed Al abri

Mechanical and Industrial Engineering, National University of Science and Technology, Muscat, Oman

Abstract. The present research work deals with the fabrication and characterization of AMC-based composites through the addition of industrial wastes in the form of iron (Fe) and copper (Cu) particles by stir casting. The investigation covers their microstructure evolution, mechanical properties, and porosity. With the optimized stirring parameters adopted in the study, three composites were fabricated: as-cast scrap industrial aluminum alloy (SIAA), Al-Fe, and Al-Cu. Accordingly, the Al-Fe composite exhibited a higher tensile strength of 117.6%, which rose to 148 MPa from that of the as-cast SIAA with a value of 68 MPa. This is attributed to the presence of a refined microstructure, homogeneous dispersion of Fe particles, and subsequent intermetallic formation. Its ductility was compromised in the range of 0.5–1% elongation. The Al-Cu composite exhibited an intermediate strength of 95.36 MPa and demonstrated better ductility in the range of 3–3.5% elongation. However, it exhibited higher submicron porosity of 13.7% along with interfacial oxides, as revealed from SEM and elemental mapping. Microstructural studies further established that the superior performance of Al-Fe is attributed to the pore-free interfaces and the segregation of Fe-Si at the grain boundaries, whereas the limitations in case of Al-Cu arise due to the presence of nano-porosity and Cu-Mg-O clustering. These results demonstrate the feasibility and acceptability of waste-based reinforcement in AMC fabrication. Specifically, the Al-Fe composite emerges as a high-strength and sustainable class. This work contributes toward the development of eco-friendly composites by establishing a relation between processing parameters, interfacial chemistry, and associated mechanical properties. It also demonstrates promising information for industrial applications pertaining to lightweight engineering.

* Corresponding author: pradeepkrishnan@nu.edu.om

1 Introduction

The need to develop lightweight materials has been escalating in different fields, such as in aerospace, automotive, and construction industries, owing to the increasing demand for improved energy efficiency and decreasing carbon footprints [1]. Among a large host of lightweight materials, aluminium alloys have emerged for their superior mechanical properties, corrosion resistance, and good formability[2]. On the whole, though the properties of aluminium alloys are desirable, their intrinsic properties can be further enhanced by incorporating reinforcements in them; hence, the emergence of AMC's.

AMC has attracted much interest in recent times due to their superior mechanical properties compared with conventional aluminum alloys[3]. Normally, these composites are produced by the integration of a secondary phase material into the aluminum matrix, and this action enhances the strength, stiffness, and wear resistance significantly[4]. The combinations of aluminum with various reinforcement materials, such as ceramic particles, metal fibers, or even waste materials, create possibilities for applications in demanding environments.

Application of various reinforcement materials, which is made from waste materials, enhances the mechanical properties of aluminum composites and promises a solution to environmental hazards brought about by waste disposal and recycling challenges [5]. Materials such as iron and copper are commonly regarded as industrial waste but may be used as reinforcement materials. Their application in AMC decreases the demand for virgin raw materials while contributing to mechanical properties enhancement [6].This tenet addresses the sustainability perspective of this approach, in line with global trends for circular economies in material engineering and manufacturing [7].

In manufacturing these aluminum composites, the stir casting method is usually used because of its cost-effectiveness and ease of processing[8]. During this process, the melting of the aluminum matrix occurs, followed by the addition of solid reinforcement particles into the melt and stirring vigorously to distribute the reinforcement uniformly within the matrix [9]. The economic advantage of stir casting is its versatility for different shapes and sizes of components, which again fosters industrial applications.

Many researchers have investigated the mechanical properties of AMC with various reinforcement materials; and a wide range of mechanical improvements was observed. For example, sic particle addition to the base aluminum alloy significantly enhanced the hardness and tensile strength, which confirms the effectiveness of the particulate reinforcement [10]. In another work, it was reported that the reinforcement of aluminum with Al_2O_3 improved its wear resistance and fatigue life [11]. However, detailed information about the effects of using waste material, especially iron and copper particles, on the mechanical behavior of amcs is still needed.

Different parameters, such as the percentage of reinforcement, distribution of the particles, and the processing parameters during the manufacture, can affect the mechanical properties of the aluminum composites [12]. Precise characterization of these properties is an important prerequisite for understanding how modifications in the composite composition and processing conditions lead to the desired results. Moreover, studying the microstructural changes that result from reinforcement incorporation helps explain the mechanism involved in the improvement of the properties observed [13].

Another important factor affecting the mechanical performance of AMC is porosity. A very high content of porosity can result in early failure and loss of load-carrying capability [14]. Hence, great care must be taken during the casting process to minimize the porosity of the manufactured products. For the production of high-quality AMC, it is very essential to understand the relationship between processing conditions and porosity formation[15].

The optimisation of aluminium composites through waste material incorporation opens up excellent perspectives in relation to mechanical properties and further sustainability. Although several studies have been conducted using different industrial wastes as reinforcements, there is a gap in the literature with regard to a direct and comparative analysis of Fe-rich and Cu-rich sludges within the same aluminum matrix system. Therefore, this work represents a systematic study of aluminum composites reinforced with these specific types of industrial wastes. The core novelty of our work embodies the direct comparison of how Fe and Cu waste particles, originating from industrial sludge, uniquely affect the microstructure, mechanical properties, and porosity of a scrap industrial aluminum alloy (SIAA) matrix. In the present work, three composites-as-cast SIAA, Al-Fe, and Al-Cu-will be produced by a stir casting method and their respective properties will be assessed and compared. The obtained results are expected to give important insights into the selective utilization of certain waste streams for the development of high-performance, sustainable composites and thus contribute to innovative and ecologically aware solutions in materials engineering.

2 Materials and methods

2.1 Composite fabrication

The composites were produced from the following materials:

Matrix Material: The matrix used was a Scrap Industrial Aluminum Alloy (SIAA), which is a cast Al-Si alloy. Its chemical composition in wt.% is given as: Al (Balance), Si 0.20-0.60, Fe ≤0.35, Cu ≤0.10, Mn ≤0.10, Mg 0.45-0.90, Cr ≤0.10, Zn ≤0.10, Ti ≤0.10, and other elements ≤0.15% total.
Reinforcements: Particles of industrial wastes were employed as reinforcements. Fe-rich waste particles were in the size range of 50-150 μm, whereas Cu-rich waste particles had sizes in the range 20-75 μm.

All composites were designed with 70 wt.% of an aluminium matrix and 30 wt.% reinforcement particles. In order to ensure a homogeneous distribution of reinforcements within the matrix, composite fabrication was done using a computerized stir casting system. The complete fabrication process is represented in Figure 1. Schematic diagram of the stir casting process used for composite fabrication. The major steps involved are the SIAA matrix material is melted in a graphite crucible located in a resistance furnace. Reinforcing particles (Fe-rich and Cu-rich wastes) are preheated to remove moisture and enhance their wettability. Molten metal is stirred at controlled speed (600 rpm) to generate a vortex, into which preheated reinforcements are introduced. Stirring is continued for a sufficient period of time to distribute the particles uniformly within the molten matrix. Finally, the obtained composite slurry is poured into a preheated metallic mould to solidify into the required shape.

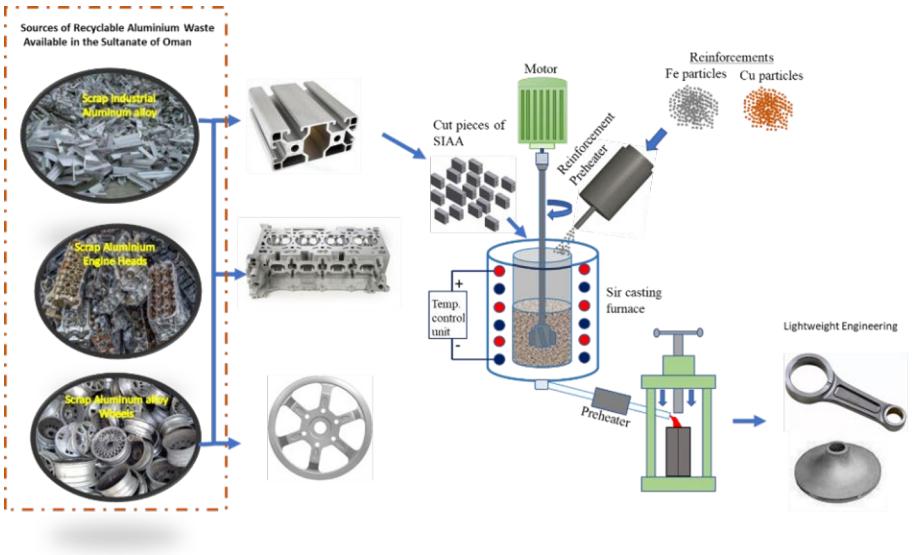

Fig. 1. Graphical representation of the stir casting process for fabricating Al composites.

2.2 Methods of composite production

The composites were produced using a computerized stir casting method. This method was selected for its cost-effectiveness and efficiency in producing metal-matrix composites. The specific process parameters were carefully chosen and optimized to achieve a uniform distribution of reinforcement particles and to minimize porosity in the final castings. A temperature of 750°C was selected to maintain the aluminium matrix in a semi-solid state. This state is crucial as it reduces the turbulence of the melt, which minimizes gas entrapment and porosity. It also lowers the viscosity, facilitating a more uniform integration and distribution of the reinforcement particles. A stirring speed of 600 rpm was optimized to create a sufficient vortex for effectively drawing the reinforcement particles into the melt. This speed ensures adequate shear force to break up particle agglomerates and achieve a homogeneous mixture, without causing excessive turbulence that could lead to air entrapment or slag formation. A duration of 10 minutes was determined to be optimal to ensure the reinforcement particles were fully wetted by the molten aluminium and distributed uniformly throughout the matrix. This time allows for thorough mixing while preventing excessive exposure to the atmosphere, which could increase oxidation. Preheating the Fe and Cu waste particles to 250-300°C serves two primary purposes. First, it removes any residual moisture, thereby eliminating a key source of gas-induced porosity. Second, it reduces the thermal shock when the particles are added to the molten aluminium, improving wettability and minimizing the formation of undesirable clusters. The metal die was preheated to 200°C to control the solidification rate of the composite. A preheated die ensures a more uniform and controlled cooling process, which reduces thermal gradients, minimizes solidification shrinkage defects, and improves the overall soundness of the cast component. To further improve the wettability between the ceramic-like reinforcement particles and the molten aluminium, 1 wt.% magnesium was added to the mixture, as magnesium is known to enhance interfacial bonding. Before stirring, impurities floating on the top layer of the melt were removed to ensure the purity of the composite. Also, a graphite non-stick coating was applied to the stirrer rod and thermocouple, together with the inner wall of the mould, when the

furnace reached 300°C to prevent the sticking of the composite to the equipment. The computerized stir casting parameters are summarized in Table 1.

Table 1. Computerized casting process parameters.

S.No	Process parameters	Values
1	Temperature of stirring	750 ºC
2	Stirring speed	600 RPM
3	Stirring time	10 mins
4	Preheating temperature of reinforcement particles	250-300 ºC
5	Permanent die preheating temperature	200 ºC

2.3 Mechanical testing

Each composite's mechanical properties are analyzed by performing tensile tests under ASTM E8 standards. Prepared samples with standard dimensions were used for consistency in testing.

2.4 Density and porosity calculation

The theoretical density of each composite is calculated based on the rule of mixtures, while the experimental density is determined using Archimedes' principle. The percentage of porosity is determined by:

$$Porosity\ (\%) = \frac{\text{Theoretical Density}}{(\text{Theoretical Density} - \text{Experimental Density})}\ X\ 100 \quad (1)$$

2.5 Microstructural analysis

The microstructure of the composites is studied through optical microscopy and SEM. The optical micrographs give information on the overall structure and distribution of the reinforcements, while the SEM analysis provides detailed information on porosity and interfacial bonding.

3 Results and discussion

3.1 Mechanical properties

The tensile test results reveal that the Al-Fe composite shows improved mechanical strength compared to the as-cast SIAA. The tensile properties of the composites, as shown in Figure 2, demonstrate drastic changes in strength and ductility. The tensile strength for the as-cast aluminium alloy SIAA was 68 MPa, whereas for the Al-Fe composite (aluminium alloy reinforced with Fe particles) the strength was drastically higher at 148 MPa, corresponding to an increase of 117.6%. Correspondingly, the strength of the Al-Cu composite was only 95.36 MPa; the aluminum alloy was therefore intermediate in strength and contains Cu particles. Ductility, as described by elongation at break, also showed a significant variation. Limited plasticity was given to the as-cast SIAA, showing elongation between 2-2.5%. In its turn, the brittle behavior was exhibited by the Al-Fe composite, which fractured at 0.5-1% elongation due to intermetallic phases hindering plastic deformation. On the other hand, improved ductility was observed for Al-Cu composite, showing elongation in the range 3-

3.5%, hence more favorable balance between strength and deformability. These results confirm that reinforcement particles play a critical role in tailoring mechanical properties: while the additions of Fe improve the strength at the expense of ductility, the additions of Cu provide an optimal compromise between strength and ductility. The superior strength of the Al-Fe composite may be attributed to finer microstructural features and the formation of strengthening intermetallic compounds during processing.

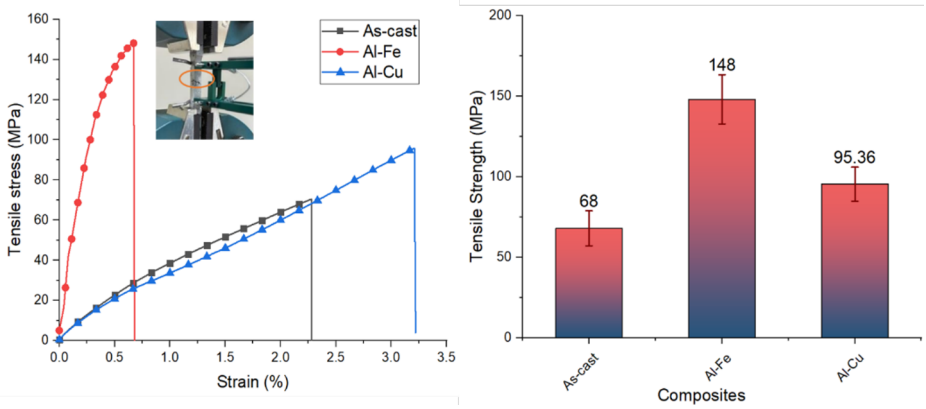

Fig. 2. Tensile strength of different composites.

3.2 Porosity analysis

The porosity percentages of the composites were quantitatively assessed by comparing theoretical and experimental densities. The rule of mixtures was applied to calculate the theoretical density for each material, and the experimental density was obtained using Archimedes' principle.As shown in Figure 3, maximum porosity was found in as-cast SIAA, which was 12.41% and reflects its mechanical property weaknesses. The porosity of Al-Fe composite was lower, 8.21%, due to better conditions of processing to minimize gas entrapment during solidification. The Al-Cu composite showed the highest porosity, 13.7%, which might indicate difficulties with achieving uniform dispersion or maintaining melt integrity during processing. These clearly indicate the critical impact of porosity on mechanical properties, whereby the stronger capability of Al-Fe, at 148 MPa, corresponds to its relatively more compact microstructure.

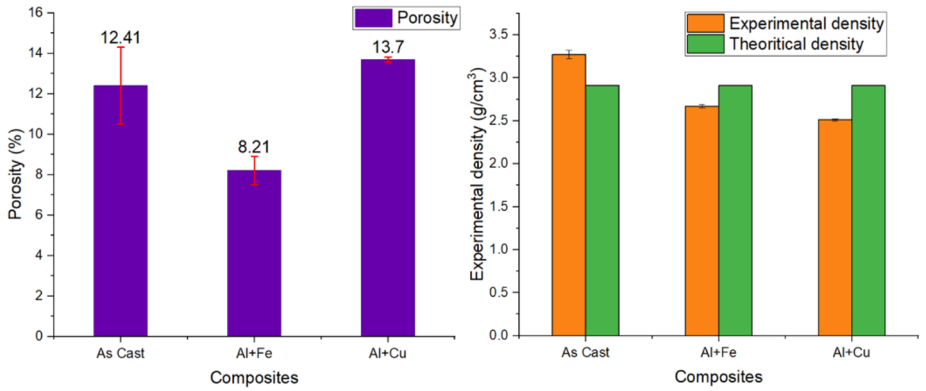

Fig. 3. Porosity percentage of different composites.

3.3 Microstructural analysis

The optical microstructures shown in Figure 4 substantiate the quantitative measurements of porosity, where distinct morphological differences among composites are evident. Image 4a [as-cast SIAA] contains several pores that can be seen at both magnifications of 100X and 1000X, corresponding to the high porosity measured at 12.41%, which is responsible for acting as a stress concentrator that reduces tensile strength in the alloy to 68 MPa. On the other hand, image 4b (Al-Fe) features a refined grain structure with minimal evident porosity in both the low and high magnification images, confirming its low porosity at 8.21% and higher strength at 148 MPa. The absence of pores and the presence of fine intermetallic phases, which are clearly visible at 1000X, create an effective network for bearing the load, while the ultra-fine grain structure at a scale of 50µm further enhances mechanical properties through grain boundary strengthening. Image 4c, representing Al-Cu, indicates larger grains than Al-Fe but fewer pores than the as-cast alloy; however, the unexpectedly high porosity of 13.7% suggests either sub-surface defects or particle inhomogeneity, which cannot be fully reflected in 2D micrographs. Such microstructural inconsistency gives rise to an intermediate tensile strength at 95.36 MPa because the positive effects of grain refinement are partially offset by the hidden porosity. Among the three composites, Al-Fe demonstrates the best processing conditions, wherein minimum porosity of 8.21%, ultra-fine grains, and homogeneously distributed intermetallic evident in 1000X images, act synergistically to enhance the mechanical properties.

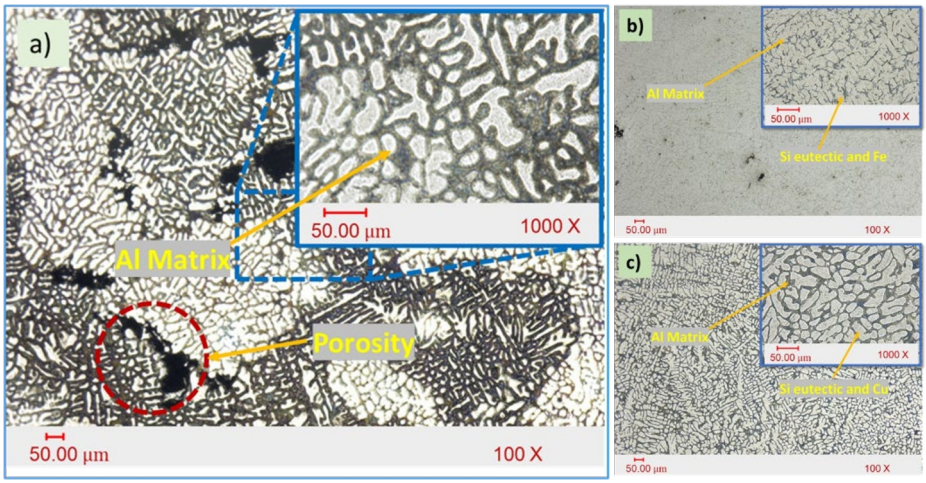

Fig. 4. Optical microstructure.

3.4 SEM analysis

The SEM micrographs in Figure 5 provide nanoscale validation of the porosity trends observed in density measurements. Image 5a (as-cast SIAA) at 100X clearly shows large keyhole-type pores (>5µm), consistent with its 12.41% porosity, which serve as fracture initiation sites under tensile loading. At 2000X, the Al-Fe composite (5b) reveals a clean Al-Fe interface with well-dispersed Fe particles and complete absence of microporosity, explaining its 8.21% porosity and maximum strength. The Al-Cu composite (5c), while showing good Cu particle distribution at 2000X, contains sub-micron pores (0.5-2µm) along grain boundaries, accounting for its higher 13.7% porosity. These nanoscale voids preferentially nucleate cracks during plastic deformation, resulting in its intermediate strength. The 2000X images reveal critical interfacial differences – Al-Fe (5b) exhibits sharp,

continuous interfaces between the Al matrix and Fe reinforcements without interfacial porosity, enabling effective load transfer. In contrast, Al-Cu (5c) shows both intra-granular pores and partial interfacial decohesion around Cu particles. This microstructural evidence directly correlates with the tensile data: Al-Fe's pore-free microstructure and strong interfaces maximize strength, while Al-Cu's combined nano-porosity and weaker interfaces limit its performance despite grain refinement benefits.

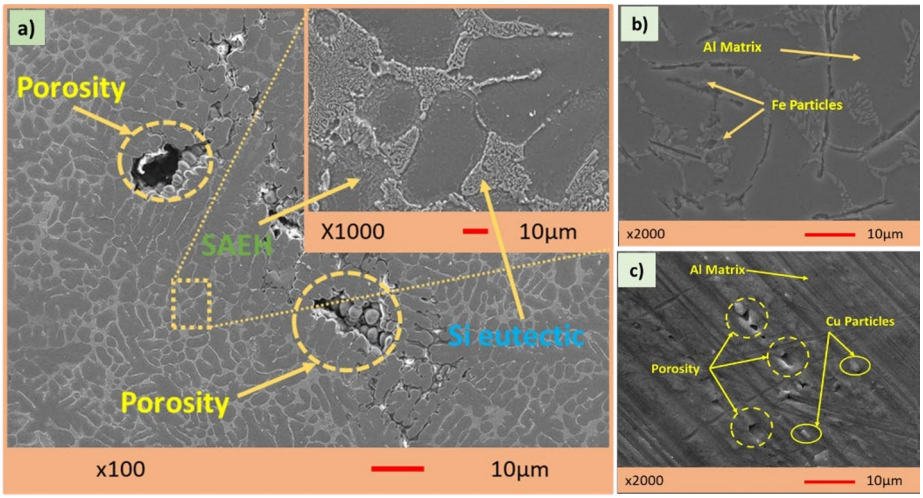

Fig. 5. SEM analysis.

3.5 Elemental mapping analysis

Elemental mapping in Figure 6, reveals distinct compositional variations across the composites. In the as-cast SIAA, 6a, grain boundary segregation is evident as Spectrum 1 shows carbon enrichment (5 at. %) compared to the matrix (Spectrum 2, 90 at. % Al), indicating the potential impurity accumulation at the interfaces. The Al-Fe composite, 6b, has a heterogeneous distribution of Fe (10 at. %) and Si (50 at. %) along grain boundaries in Spectrum 28, while the matrix (Spectra 27 & 29) is Al-dominated (90 at. %), indicating partial Fe-Si intermetallic formation. In contrast, the AlCu composite, 6c, has significant Cu (20 at. %) and Mg (30 at.%) segregation at grain boundaries in Spectrum 2, accompanied by oxygen (5 at. %), indicating oxide formation therein. The matrix, Spectra 1 & 3, retains high Al content of 95 at. %, but with detectable Cu and Si, 20 at. % each, indicating limited solid solubility.

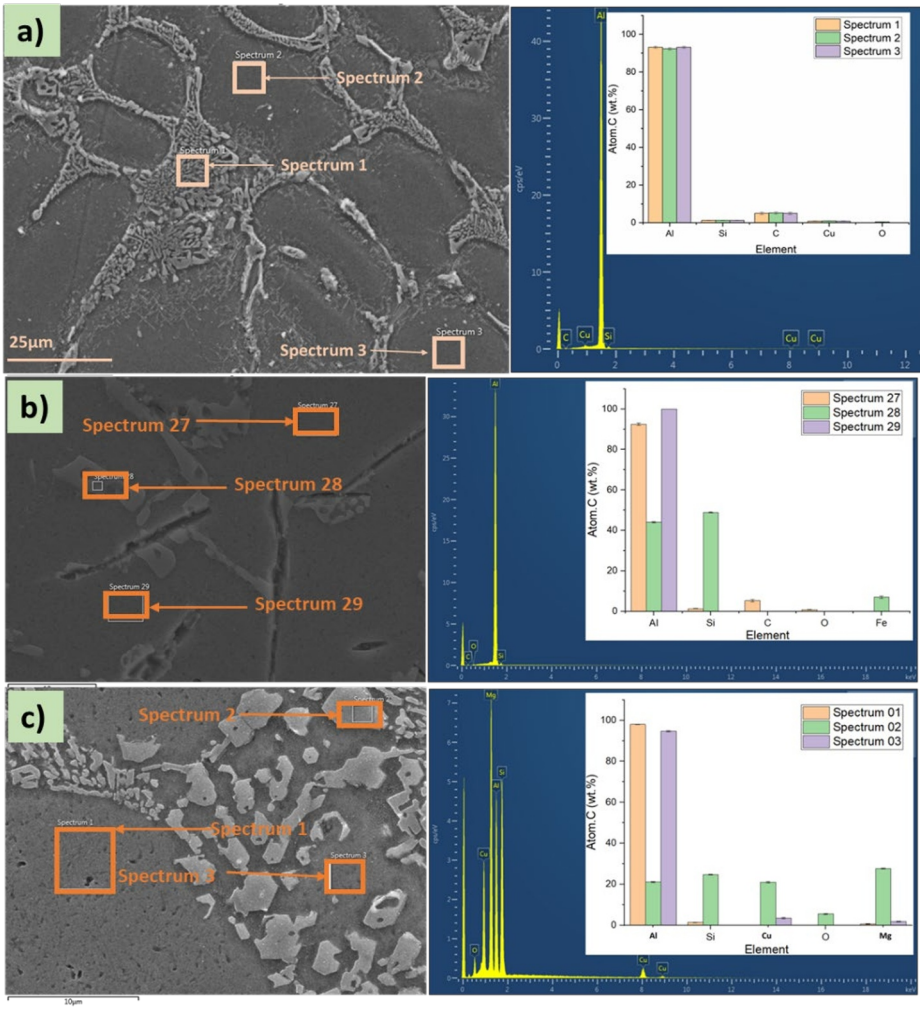

Fig. 6. Elemental mapping analysis.

4 Conclusion

This study highlights the prospects of using industrial waste materials as reinforcement in aluminum composites. The addition of waste iron and copper displayed superior mechanical properties than the SIAA as cast. From the results obtained, it is evident that improved performance of aluminum composites could be achieved by controlled microstructural attributes, which falls under the principles of sustainability and recycling in material science.

- The Al-Fe composite exhibited excellent enhancement in tensile strength to 148 MPa, which corresponds to an increase of 117.6%, over the as-cast SIAA material (with 68 MPa), owing to its refined features and intermetallic phase. Its ductility was poor with only 0.5-1% elongation due to the constitutional sacrifice between strength and plasticity in particle-reinforced systems.
- The superior mechanical performance of the Al-Fe composite, represented by 148 MPa in tensile strength, is directly related to its lower porosity of 8.21%, hence

proving how optimization in processing conditions can effectively minimize gas entrapment and improve material density.

- Microstructural characterisation shows that porosity and reinforcement distribution induced by processing are the key variables controlling the mechanical performance, with the optimal strengthening architecture being achieved as a result of fine porosity (8.21%) and uniformly dispersed Fe in the Al-Fe composite, unlike the porous as-cast SIAA or the interface-compromised Al-Cu composite.
- The superior integrity of the particle-matrix interfaces, together with its exceptional microstructural homogeneity, sets a benchmark for the design of aluminium composites, where porosity minimization and interfacial engineering both need to be addressed to achieve peak mechanical properties.
- Elemental mapping analysis proves that segregation of reinforcement-specific behaviour in interfacial chemistry at grain boundaries includes clustering of Fe-Si in Al-Fe, hence enhancing cohesion, while for Al-Cu, it promotes interfacial weakening through Cu-Mg-O complexes – directly relating to the differences in mechanical performance of the tested composites.
- Some specific future research directions are consequently recommended in view of the results obtained in the present work, as follows: Systematic optimization of process parameters-stirring speed, temperature, and reinforcement preheat temperature-by means of statistical techniques such as the Taguchi DOE with a view to minimizing porosity and further improving mechanical properties.
- Investigation of the hybrid reinforcements by combining Fe and Cu wastes in various ratios to achieve an optimized balance between the high strength provided by Fe and the potential Cu ductility.
- Long-term corrosion and wear studies on these composites will help to understand their durability for real industrial applications.

The valuable support and funding by the Research Grant No. (URG-2024), Project ID: (BFP/URG/EI/24/067) from The Research Council of Oman is greatly acknowledged, which helped us to complete this research. We would like to take this opportunity to express our heartfelt gratitude for the confidence and financial resources entrusted in the research grants that have been instrumental in enabling this study.

References

1. X. Wu, W. Zhang, A review on aluminum matrix composites' characteristics and applications for automotive sector, Heliyon 10 (2024) e38576. https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e38576.
2. Z.J. Wang, Z. Zheng, M.W. Fu, Aluminum matrix composites: Structural design and microstructure evolution in the deformation process, J. Mater. Res. Technol. 30 (2024) 3724–3754. https://doi.org/https://doi.org/10.1016/j.jmrt.2024.03.237.
3. D.M. Mishra, A Review of Manufacturing Processes for Aluminum-Lithium Alloys and Their Applications, Prem. J. Eng. (2025) 1–7. https://doi.org/10.70389/pje.100007.
4. W. Zhang, J. Xu, Advanced lightweight materials for Automobiles: A review, Mater. Des. 221 (2022) 110994. https://doi.org/https://doi.org/10.1016/j.matdes.2022.110994.
5. P.K. Krishnan, J.V. Christy, R. Arunachalam, A.H.I. Mourad, R. Muraliraja, M. Al-Maharbi, V. Murali, M.M. Chandra, Production of aluminum alloy-based metal matrix composites using scrap aluminum alloy and waste materials: Influence on microstructure and mechanical properties, J. Alloys Compd. 784 (2019) 1047–1061. https://doi.org/10.1016/j.jallcom.2019.01.115.

6. S. Al-Alimi, N.K. Yusuf, A.M. Ghaleb, M.A. Lajis, S. Shamsudin, W. Zhou, Y.M. Altharan, H.S. Abdulwahab, Y. Saif, D.H. Didane, I. S T T, A. Adam, Recycling aluminium for sustainable development: A review of different processing technologies in green manufacturing, Results Eng. 23 (2024) 102566. https://doi.org/https://doi.org/10.1016/j.rineng.2024.102566.
7. A. Diaz, J.-P. Schöggl, T. Reyes, R.J. Baumgartner, Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management, Sustain. Prod. Consum. 26 (2021) 1031–1045. https://doi.org/https://doi.org/10.1016/j.spc.2020.12.044.
8. A. Kumar, R.C. Singh, R. Chaudhary, Recent progress in production of metal matrix composites by stir casting process: An overview, Mater. Today Proc. 21 (2020) 1453–1457. https://doi.org/10.1016/j.matpr.2019.10.079.
9. T.N. Mishra, A. Kumar, S.B. Prasad, A Recent Innovation in Stir-Cast Aluminium Metal Matrix Composites to Improve Mechanical and Wear Properties with Potential Applications: A Review, JOM (2025). https://doi.org/10.1007/s11837-025-07570-1.
10. T. Ye, Y. Xu, J. Ren, Effects of SiC particle size on mechanical properties of SiC particle reinforced aluminum metal matrix composite, Mater. Sci. Eng. A 753 (2019) 146–155. https://doi.org/10.1016/j.msea.2019.03.037.
11. A.M. Sadoun, M.M. Mohammed, A. Fathy, O.A. El-Kady, Effect of Al2O3 addition on hardness and wear behavior of Cu–Al2O3 electro-less coated Ag nanocomposite, J. Mater. Res. Technol. 9 (2020) 5024–5033. https://doi.org/https://doi.org/10.1016/j.jmrt.2020.03.020.
12. F.A.R. Rozhbiany, S.R. Jalal, Reinforcement and processing on the machinability and mechanical properties of aluminum matrix composites, J. Mater. Res. Technol. 8 (2019) 4766–4777. https://doi.org/https://doi.org/10.1016/j.jmrt.2019.08.023.
13. T.Y.T. Su, R. Aguiar, N.D. Sansone, C. Hao, N. Yan, P.C. Lee, Green, Sustainable, and Melt-Compoundable PLA Composites Reinforced with Spray-Dried Lignocellulosic Nanofibrils for Enhanced Barrier and Mechanical Properties, Chem. Eng. J. 515 (2025) 163183. https://doi.org/https://doi.org/10.1016/j.cej.2025.163183.
14. Z. Song, K. Xiao, S. Xiao, K. Du, Z. Mao, T. Li, B. Wang, Effect of porosity on the tensile strength and Micromechanisms of laminated stitched C/C-SiC composites, Mater. Des. 247 (2024) 113429. https://doi.org/https://doi.org/10.1016/j.matdes.2024.113429.
15. P. Korban, A. Wąsik, B. Leszczyńska-Madej, Advancing Sustainability in Alloy Production: The Role of Recycled Materials and Barbotage in Enhancing EN AC-46000 Castings, Sustainability 17 (2025). https://doi.org/10.3390/su17114755.