Letters on Materials 16 (1), 2026 pp. 92-99 www.lettersonmaterials.com

Received 27 June 2025; Accepted 26 January 2026
https://doi.org/10.48612/letters/2026-1-92-99 https://elibrary.ru/tqvlho

Image-based microstructural characterization and mechanical behavior of hybrid Al 5083 MMC reinforced with SiC, Mg, and Sr

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Abstract: This study investigates the mechanical and microstructural performance of Al-5083 composites fortified with hybrid reinforcements featuring 2 to 12 wt.% SiC, Mg, and Sr particulates, synthesized by stir casting technique, in contrast to earlier research that typically utilize single reinforcement or fine compositional ranges. The outcomes of the optical microscopy and SEM-EDS, as well as the tensile, flexural, impact, and wear tests, substantiate the evaluation of matrix reinforcement, elemental incorporation, and particle dispersion. The mechanical performance improved with increasing reinforcement, and the best strength, toughness, and wear resistance are shown at 10 wt.% composition. The successful addition of hybrid particles and then resulting improvement of the aluminum matrix is confirmed by elemental mapping and microstructural analysis. The hybrid SiC-Mg-Sr reinforcement provides experimental insight into how multicomponent reinforcement affects microstructure and properties, and it enhances Al-5083 performance. Matrix regions are localized by the addition of hybrid reinforcement, produces alternative sound structures that were observed across all compositions. Effective stress transfer between the particles and matrix confirmed by the uniform rise of load bearing capacity as the reinforcement level increases. These observations highlight the appropriate stir casting for manufacturing hybrid MMCs with reasonable engineering relevance. The insights gained from this investigation may assist in designing lightweight components where simultaneous improvements in strength and wear resistance are required.

Keywords: metal matrix composites, machine learning (ML), image-based analysis, particle dispersion, structure–property relationship, Aluminum 5083, microstructural characterization, high-performance materials, EDS mapping

Acknowledgment: *The authors would like to thank GITAM Deemed to be University and Andhra University for their invaluable support and assistance in conducting this research.*
Funding: *This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.*

1. Introduction

Metal Matrix Composites (MMCs) are an important category of advanced structural materials compared with the conventional monolithic alloys due to their excellent stiffness, strength, wear resistance, and thermal stability [1, 2]. These improvements develop from mixing the ceramic or metallic particles within a metal matrix, which customize the mechanical functional response of the composite [3]. Aluminum composites are widely used because of their low density, corrosion resistance, and ease of fabrication compared to various other MMCs [4]. However, the mechanical performance of Al-5083 can be further improved through adding suitable reinforcement particles which are commercially important alloys [5, 6].

The excellent corrosion resistance and good strength of Al-5083 are significantly used in marine, automotive, and lightweight structural applications [7]. In Al-5083 alloys, microstructure-property correlations have also been investigated in recent work. The susceptibility of this alloy system to microstructural refinement was emphasized by annealing-induced modification of lamellar structures to govern mechanical properties in Al-5083 [8]. Biryukova et al. further confirmed the relevance of structural control in Al-5083 based systems, indicating that laminated composites produced through accumulative roll bonding displayed superior performance attributable to to micro structural modification [9]. Its performance enhancement has been stated with reinforcement additions such as Magnesium (Mg) and Strontium (Sr). Workability improvement and strengthening are contributed by Mg, while the intermetallic- phases alterations and grain structure refinement are attributed by Sr, thereby improving castability and the mechanical properties [3,10 – 12]. Further enhancement in load-bearing capability, wear resistance, and hardness were attained using ceramic reinforcements such as Silicon Carbide (SiC). For producing aluminum MMCs, stir casting persists in a widely adopted and efficient method because it facilitates incorporation of reinforcement phases into the molten alloy with relatively homogeneous dispersion [13,14].

Fewer works have methodically investigated the synergistic impacts of hybrid accompaniments such as Mg, Sr, and SiC on Al-5083, although various studies have assessed the influence of individual reinforcement on aluminum alloys, predominantly across a wide range of refinement percentages. The detailed correlations remain inadequately reported in the literature about the collaboration of these three reinforcements, which is estimated to govern solidifying behavior, microstructure refinement, and ultimately mechanical attributes. It is imperative to address this gap for optimizing hybrid composite inventions for structural applications.

2. Methodology

Manufacturing cost, energy efficiencies, economic productivity are impacted by the friction and wear that reports for macro-energy defeats substantially. To ease wear effects and improve mechanical functioning the present work sought to fabricate Al-5083 reinforced with Mg, Sr, and SiC particles. A viable and effective methodology in preparation of the composite material was absorbed by the stir casting method, typically with eddy current as shown in Fig. 1.

3. Material design and manufacture

The chemical composition of Al-5083 used in this study is consistent with that reported in [15]namely Al-5083, that has been reinforced with Silicon Carbide (SiC, containing major elements such as Mg (≈4.0%), Mn (≈0.7%), and trace amounts of Si, Fe, Cu, and Zn. The hybrid reinforcement was composed of SiC, Mg, and Sr which were added at the same wt.% level (2–12 wt.%) individually to the Al-5083 matrix, and all reinforcement contents were given in weight percentage (wt.%). The subsequent phases designate the manufacture of composite using stir casting method: A refractory container of graphite crucible used to melt the Al 5083 alloy by means of a controlled temperature of 800°C of a three-phase electrical resistance furnace. Mg, Sr, and SiC, particles were pre-heated to approximately 400°C before being introduced into the molten Al. Instead of a mechanical stirrer, eddy current stirring was employed to induce a non-contact Lorentz force-driven vortex within the molten metal. This technique improves particle dispersion, minimizes agglomeration, and reduces porosity due to more uniform temperature and solute distribution throughout the melt. The electromagnetic stirring system was operated at an optimized current setting equivalent to ≈600 RPM stirring intensity for a duration of 60-75 seconds. The molten composite was poured into a pre-prepared cylindrical mold using the bottom-pouring technique and allowed to solidify naturally. The same procedure was followed to prepare unreinforced matrix material for comparative analysis.

3.1. Experimental procedure — preparation of specimens

To prepare test specimens, the fabricated Al-5083 composites underwent preheating via the stir casting method, as depicted in Fig. S1a (supplementary material). Continuous stirring of the alloy was carried out until it reached a preheating temperature of 610°C, which took about two hours. The reinforcements were added to the molten metal as a vortex was created by eddy current stirring, allowing non-contact, uniform dispersion of particles through electromagnetic induction. After reaching the target temperature, the molten Al-Mg-Sr-SiC composite was gently transferred into pre-prepared moulds, as illustrated in Fig. S1b. As shown in Fig. S1c the liquid solidified into a Nano Metal Matrix Composite (NMMC) in the course of 10 to 15 minutes a specific consideration was given to the four holes in the molds throughout procuring process which directed the molten material. After the meticulous heating and stirring of the Al-Mg, Sr, and SiC alloy was prudently poured into molds

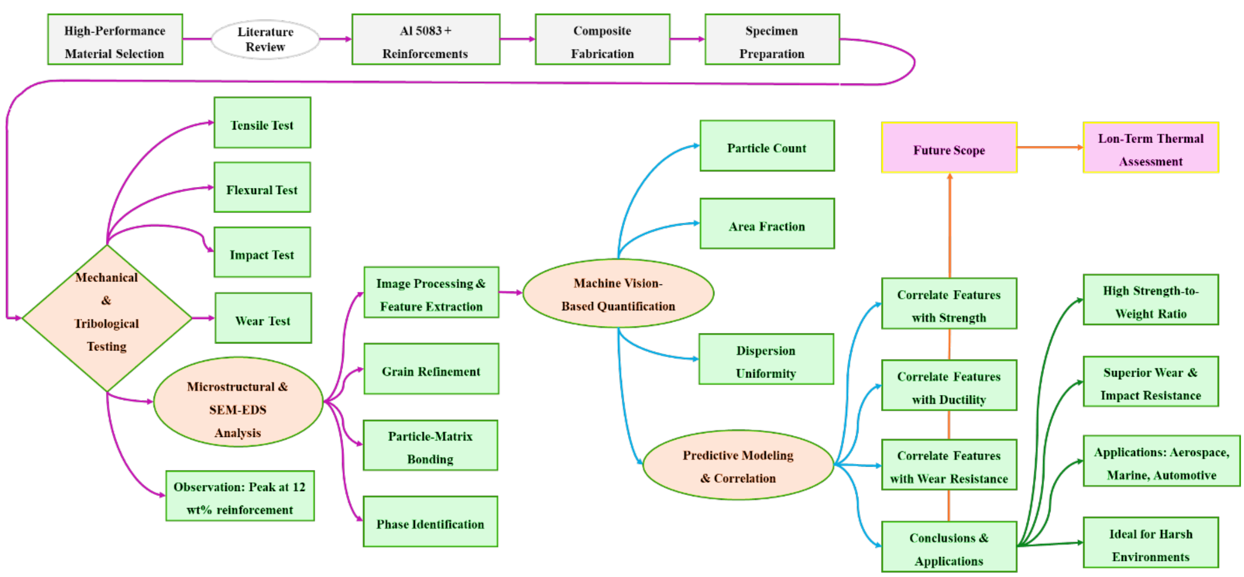

Fig. 1. (Color online) Methodology.

within timeframe. The preparation process commenced with the creation of fly ash moulds with dimensions of 20.5 mm in diameter and 210 mm length, as shown in Fig. S1c. These moulds transitioned from wet to dry states by applying a gas flame to ensure complete drying before subsequent use.

3.2. Mechanical properties

Widespread research has directed on how the production process influences the properties to appreciate the factors that stimulus the features of particulate-reinforced MMCs [16,17]. The features such as modulus, strength, creep resistance, and wear resistance can significantly be enhanced by recognised various reinforcements [18]. To understand the mechanical behavior of the developed composites, tensile and impact tests were conducted, and the corresponding fracture mechanisms were evaluated.

Tensile tests were performed on flat dogbone specimen with gauge length 50 mm, width 12.5 mm as per ASTM E8 using an INSTRON-1195 universal testing machine with a 100 kN load capacity. Impact strength was measured using Charpy tests following ASTM E23 standards. Fractographic analysis of failed tensile specimens revealed key fracture mechanisms-matrix void nucleation, particle fracture, and interface debonding. Micro-void coalescence (MVC) was the predominant mode, indicating the matrix–reinforcement interaction during loading. All mechanical property values are reported as mean ±SD, and error bars are represented in figures.

3.3. Effect of reinforcement content (wt.%)

The reinforcement content (wt.%) influences the mechanical performance of MMCs. Strength generally increases with reinforcement content up to an optimum level, beyond which further additions offer little benefit. At very low reinforcement contents, the matrix dominates the load transfer, leading to reduced strength. Thus, selecting an appropriate reinforcement content is essential for balancing matrix and particle contributions. Representative specimens with 2% and 4% reinforcement are shown in Fig. S2 – S4.

3.4. Microstructural analysis

Sliced specimens were examined under an optical microscope to evaluate the distribution of Mg, Sr, and SiC particles within the Al matrix. The analysis confirmed a uniform dispersion of reinforcement particles, even with varying reinforcement contents (wt.%), ensuring consistency in the composite's mechanical and wear properties.

4. Results and discussion

4.1. Tensile test

The strength-to-weight ratio was the primary focus of the tensile testing conducted on this specimen, which was conducted in compliance with ASTM standards for Al 5083 reinforced with Mg, Sr, and SiC particles. The reinforcement percentage indicated corresponds to identical individual wt.% additions of SiC, Mg, and Sr.

Table 1 summarizes the tensile strength of Al-5083 composites. Strength increases with reinforcement content from 114.0 MPa to a peak of 173.9 MPa at 10 wt.%, as shown in Fig. 2. At 12 wt.%, it decreases slightly to 167.8 MPa, indicating an optimum near 10 wt.%. The drop at 12 wt.% is attributed to excess Sr, which promotes brittle Al_4Sr formation and porosity due to poor wettability, consistent with reported literature [10,19].

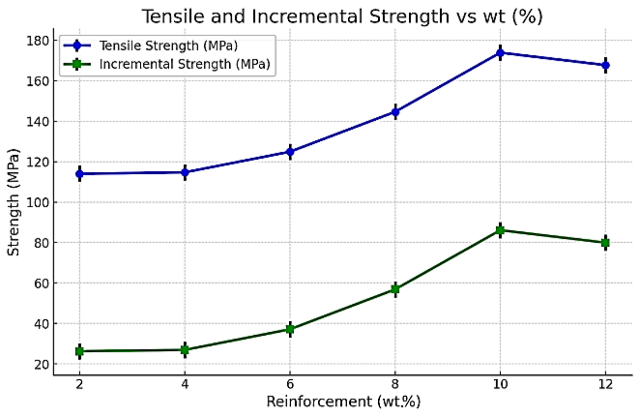

Fig. 2. (Color online) Tensile and incremental strength vs reinforcement wt.%.

4.2. Impact test

The impact energy increases as the reinforcement increases from 2 to 12%. The particle strengthening resulted in the highest resistance to crack propagation of 58.90 J at 12 wt.%. However, literature reports also suggest that excess reinforcement, especially Sr, can induce porosity, which disrupts matrix continuity and may reduce ductility and toughness under certain conditions [20]. Despite this, the current composites show a smooth increasing trend in impact energy, indicating that porosity has not yet critically affected toughness up to 12%.

The data were fitted with a second-order polynomial, yielding a high correlation (R^2≈0.98), confirming the

Table 1. Tensile strength of the Al-Sr, Mg, SiC samples.

Wt.%	Tensile Strength (MPa)	Incremental Strength (MPa)	Impact Energy (J)	Flexure Strength (GPa)	Wear Rate (10^{-11} m^2/N)
2	114.0	+26.2	26	638.1	6.085
4	114.7	+26.9	30	677.7	4.980
6	124.9	+37.1	36	730.4	4.097
8	144.7	+56.8	45	796.3	3.434
10	173.9	+86.1	56	875.2	2.991
12	167.8	+79.9	59	897.2	3.068

consistency of the trend. As shown in Fig. 3 and corresponding to Table 1, Sr, Mg, and SiC particles, which may act at stress concentration locations, can be attributed to the reduced impact strength of Al base alloy MMCs. It is important to note that very high Sr levels in other systems have been associated with formation of brittle intermetallic (e.g., Al_4Sr) and ductility loss [20].

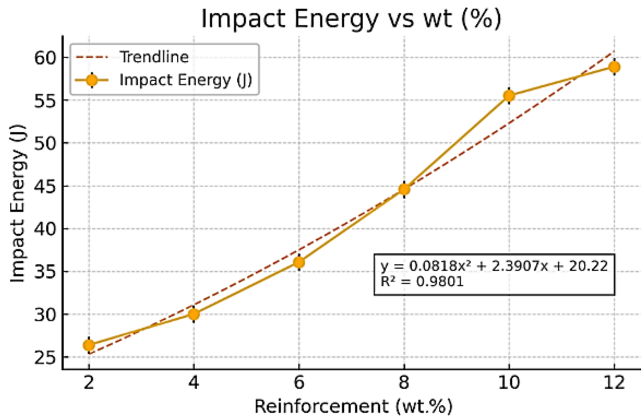

Fig. 3. (Color online) Impact energy vs reinforcement wt.% of Al-5083 composites with fitted polynomial trendline (R^2 = 0.9801).

4.3. Flexure test

The flexural behavior of the Al-5083-based composites was evaluated using a universal testing machine in accordance with ASTM E290 standards and measured their resistance to bending forces. The measured flexural strength of Al-5083 composites with different contents of Sr, Mg, and SiC reinforcements is presented in Table 1.

A progressively increase of the flexural strength from 638.1 MPa at 2 wt.% to 897.2 MPa at 12 wt.% of Sr, Mg, and SiC. This composite exhibits good bending resistance, reflecting efficient load distribution between the matrix and reinforcement phases. Figure 4 confirmations that the flexural strength of the 4 wt.% composition material was higher than 2 wt.% composition associated with the base metal and graphically presents the relationship between reinforcement percentage and flexural strength.

The uniform upward trajectory shows the increased particle content enhances bending resistance due to better

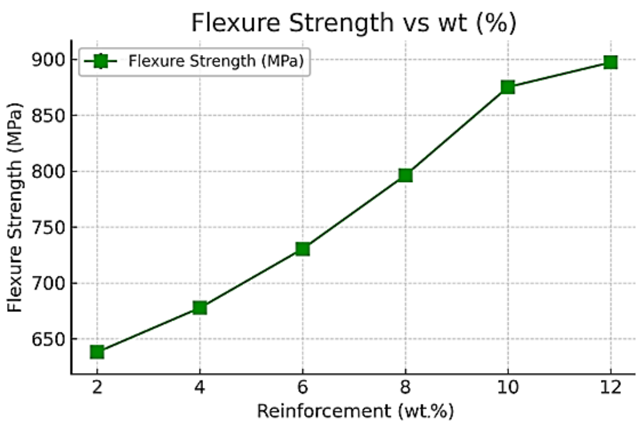

Fig. 4. (Color online) Flexure strength vs reinforcement wt.% of Al-5083 composites. Error bars appear visually small.

particle distribution and matrix stiffening. While the experimental results show steady increase in flexural strength, the impact of porosity becomes imperative to consider at higher reinforcement levels. Porosity acts as a stress concentrator in composite matrices, reducing both tensile and flexural strength [21]. There is no visible reduction in flexural performance up to 12 wt.%, indicating effective particle distribution, or porosity below critical limits.

The suitability of reinforcing Sr, Mg, SiC in Al-5083 confirms these findings for structural applications requiring high bending strength. It is recommended for microstructural investigation to quantify porosity and interfacial bonding for compositions beyond 12 wt.% [22].

4.4. Analyzing wear and tear

A series of experiments were conducted following an L9 orthogonal array to investigate how the dry sliding wear characteristics of Al-5083 affect the sliding speed, applied load, sliding distance, and reinforcement content as shown in Fig. 5. The wear rate reduces uniformly from 6.085 $\times 10^{-11}$ m^2/N to 2.991$\times 10^{-11}$ m^2/N at 2 wt.% to 12 wt.% of Sr, Mg, and SiC. An enhancement in wear resistance due to reinforcement is specified in Table 1. An excessive reinforcement may introduce porosity or interfacial defects, resulting in a slight increase of wear rate at 12 wt.%. According to Hamid et al. [22] and Islam & Farhat [21], excessive reinforcement in MMCs increases porosity, leads to crack initiation, subsurface damage, and reducing tribological performance. It is confirming the overall beneficial effect of Sr, Mg, and SiC additions up to an optimal range.

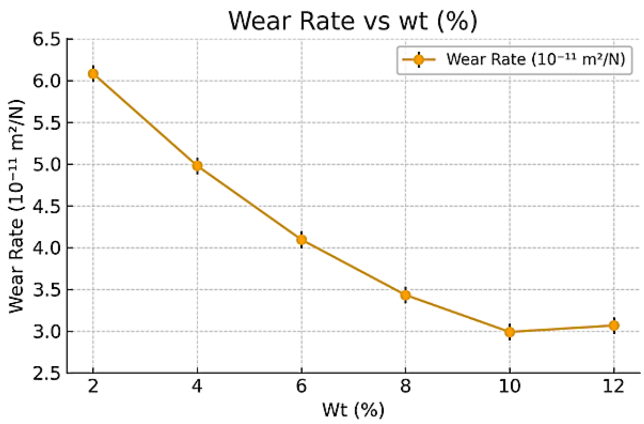

Fig. 5. (Color online) Wear rate vs reinforcement wt.% of Al-5083 composites.

4.5. SEM and EDX Analysis of Al-5083-Mg, Sr, and SiC Composites

SEM micrograms of the reinforced composites Fig. 6. give a close analysis of the interface between the matrix and the reinforcement and also the distribution of the secondary phases. The SEM images show SiC particles spread within the matrix and enhanced regions in Mg and Sr. The effective incorporation of the hybrid reinforcements is substantiated by the subsequent EDX spectrum, which is confirmed by the elemental peaks correlated with SiC, Mg, and Sr at the analyzed locations.

Further substantiating the localization of SiC, Mg, and Sr throughout various microstructural regions, supplementary EDX Spectra from the reinforcement-rich sites are shown in Fig. 7. The mechanical results show that composite with up to 10 wt.% reinforcement manifests enhanced tensile, flexural, and impact performance, which is strengthened by the absence of substantial agglomerates or voids.

The enhancements in mechanical properties bestowed in sections 4.1-4.4 are justified by the performance of this microstructure. An explicit phenomenological empathetic of the strengthening mechanisms effective in the hybrid Al-5083 composites is presented by the microstructural tendencies attained from image-based analysis, while this study does not endeavor to establish a predictive quantity to model.

4.6. Image-based microstructural analysis and property interpretation

The SEM micrographs and the associated EDS elemental maps indicate the effects of microstructural characteristics induced by reinforcement on the response of the hybrid Al-5083 composites to support both the mechanical testing and microstructural analysis of the images. The present investigation concentrates on establishing qualitative trends and evaluating the applicability of using microstructure derived morphology characteristics for further data-driven studies instead of developing a predictive model which requires a large data set and multiple compositions.

4.6.1. Image feature extraction

To enhance future visibility in both optical and SEM micrographs, image preprocessing steps, including grayscale normalization, noise filtering, and contrast enhancement were applied. The particle recognition and the spatial metric extraction are shown in Fig. 9, utilizing a representative example of the segmented microstructure. The workflow of segmentation according to the processed SEM-EDS grids is depicted in Fig. 7, and the corresponding particle highlight overlays are provided in Fig. 8 and which are only used in the verification of segmentation.

The extracted image features comprise particle count, measured area ratio, delineated particulate zones, and the qualitative distribution uniformity. The descriptive summary is presented in Table S1 (supplementary material), and these parameters were obtained for the 4 wt.% composite (as an example to define the process). The type of microstructural metrics obtainable from image analysis are illustrated from these values, which are not used for quantitative correlation.

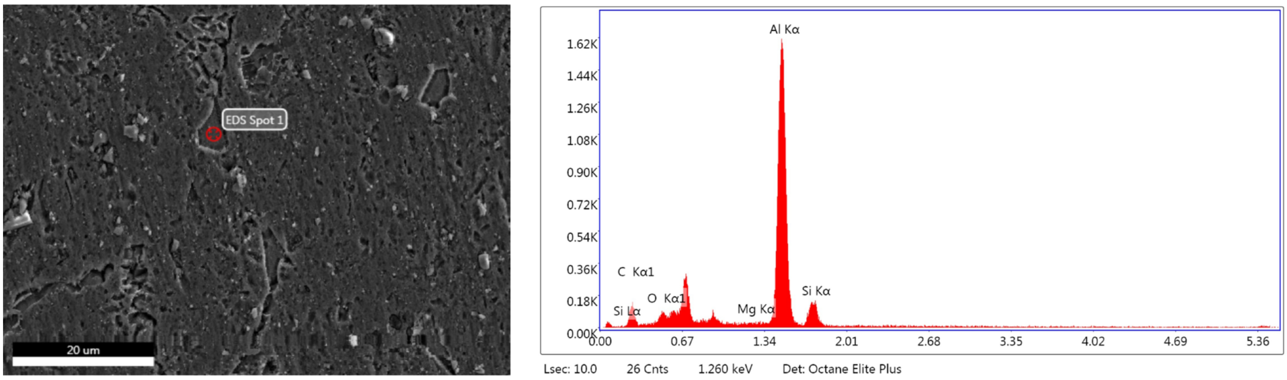

Fig. 6. (Color online) SEM micrograph and EDS spectrum of Al-5083/Mg, Sr, and Sic, composite at EDS Spot 1, revealing elemental peaks corresponding to Al matrix and reinforcement particle sites.

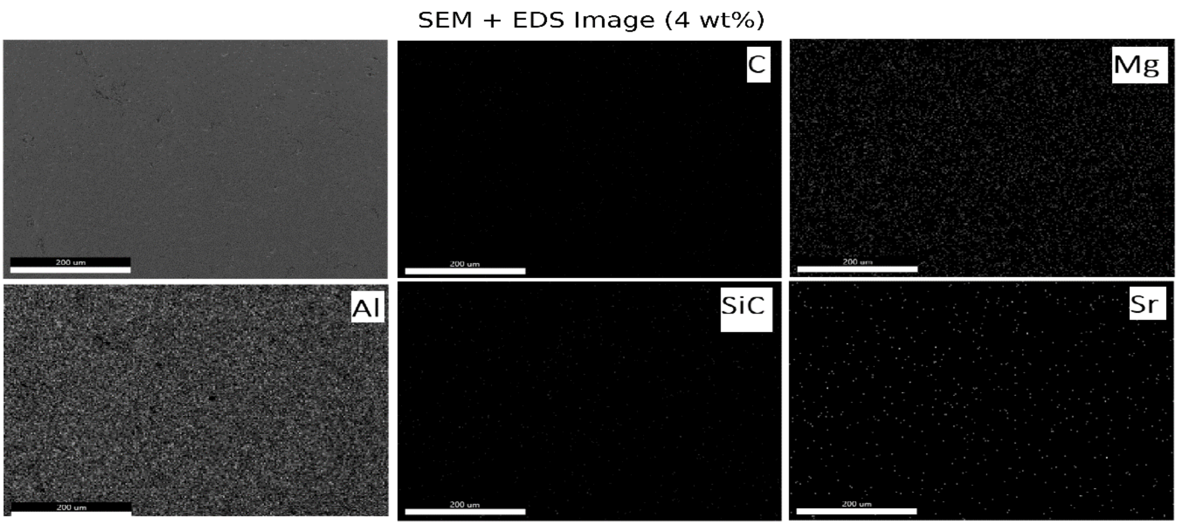

Fig. 7. SEM + EDS image grid (original).

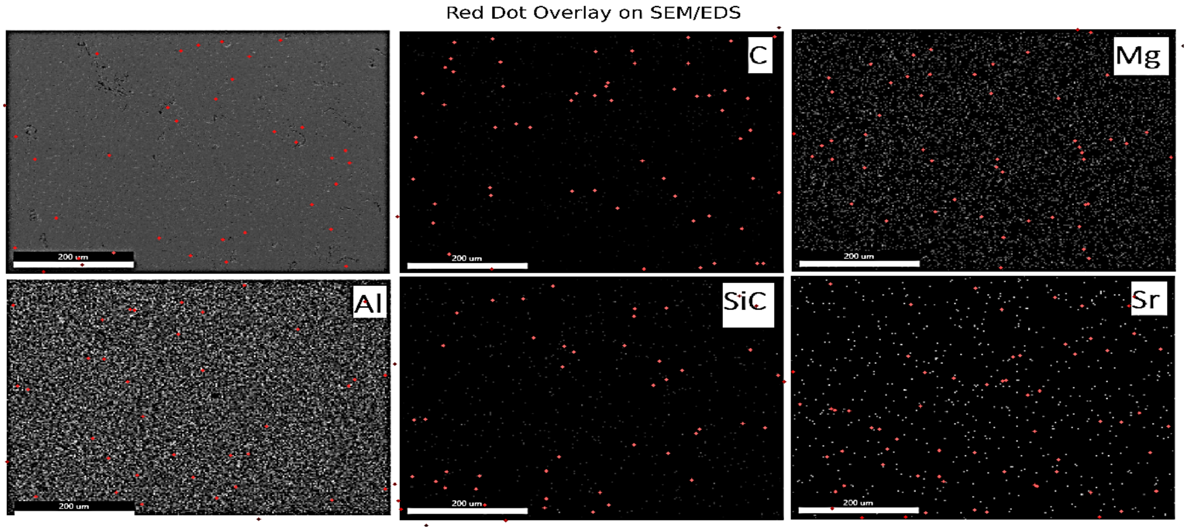

Fig. 8. (Color online) Red dot overlay highlighting particles.

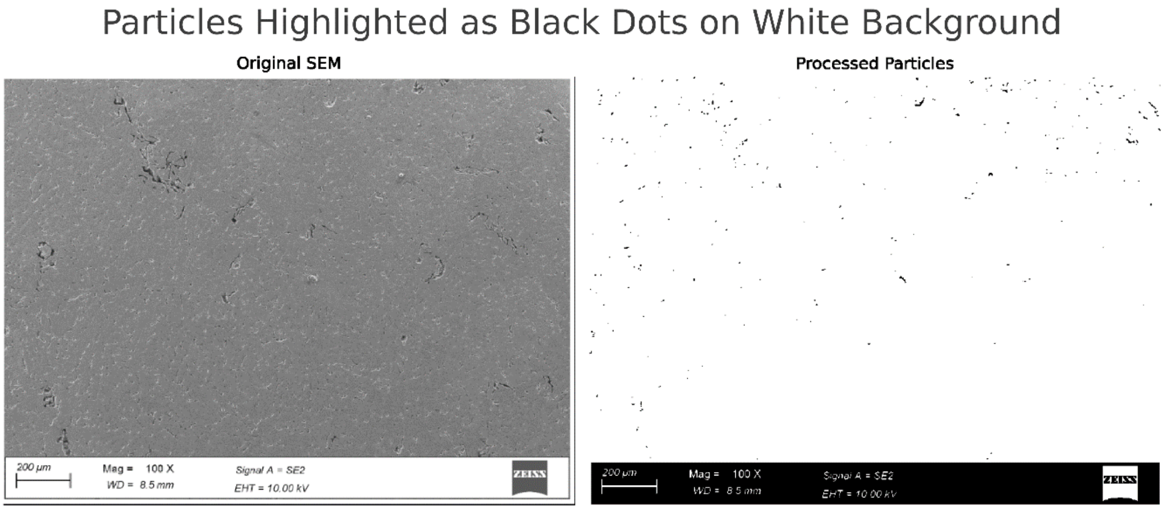

Fig. 9. Processed wear SEM — particles in white background.

4.6.2. Qualitative correlation with mechanical properties

The image features obtained were qualitatively compared with mechanical properties discussed in section 4.1–4.4. The correlation analysis should be interpreted as indicative rather than fully predictive due to the study considering a limited set of enforcement compositions. The micrographs specify that improving reinforcement content results in a more diverse matrix and finer structure regions, which is consistent with the segmentation output in Fig. 9 and the SEM-EDS based microstructural features.

The experimentally observed increases in tensile strength, flexural strength, and impact energy up to 10 wt.% reinforcement aligned with these qualitative microstructural refinements. The case for grain boundary hardening and increased stress transfer is strengthened by the presence of reinforcement induced zones and the decrease of visual large matrix regions.

4.6.3. Statistical trend observation

A preliminary analysis was conducted to explore the possible relationships between mechanical properties and microstructural features. The growing patterns in tensile and the flexural strength up to 10 wt.% reinforcement showed characteristic agreement to the optical and SEM features, including matrix reinforcement, particle-dense zones, and particle dispersion.

A change toward smaller structural features at higher reinforcement levels indicates histogram-based distributions of feature counts within segmented particle areas shown in Fig. 10. This shift can be found in the reinforcement trends which are observable in the segmented SEM-derived features of Fig. 9.

4.6.4. Limitations and future scope

The predictive model does not consistently in the present analysis, and it is exploratory. The ability to develop statistically

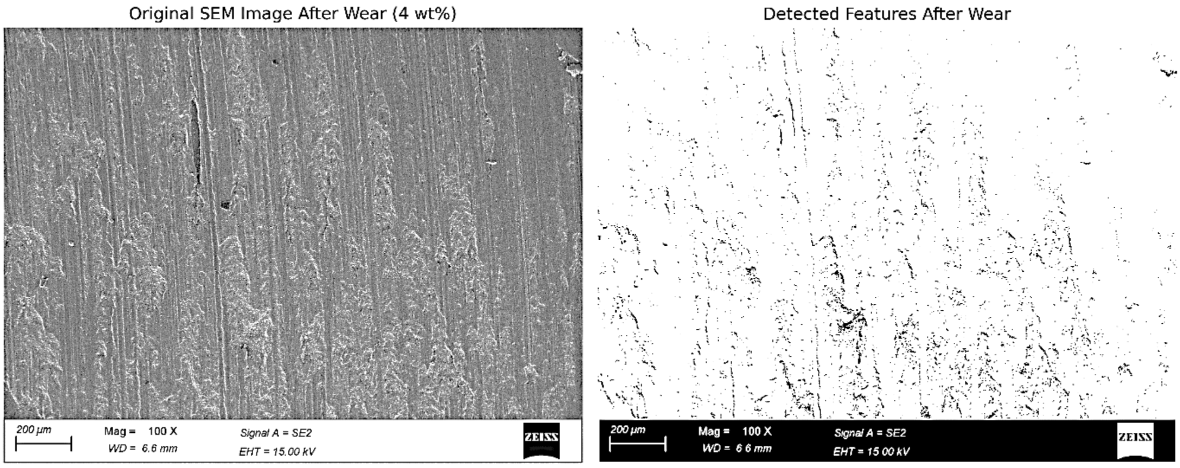

Fig. 10. SEM (wear) with particle detection in black on white.

reliable correlations is restricted by the lack of multiple fields of view per composition, the limited number of reinforcement compositions, and the absence of quantitative grain size measurements. Moreover, the fully variability of the composites cannot be represented by the microstructural features extracted from single SEM or optical images.

Future work will involve building robust statistical or machine learning based predictive models by acquiring additional micrographs at multiple locations, expanding the data set across more reinforcement levels, quantifying grain size and the particle dispersion using automated segments and integrating mechanical, imaging, and process parameters.

5. Conclusion

The present study confirms that Sr, Mg, and SiC reinforcements substantially improve the mechanical and tribological performance of Al-5083 composites. Key findings include:

– The composite with higher reinforcement content exhibited significantly enhanced tensile strength, impact toughness, flexural strength, and wear resistance.

– Incremental refinement of the Al matrix with higher reinforcement percentage and successful integration of hybrid particles are confirmed by the SEM-EDS based microstructural analysis.

– The strength, hardness, and resistance to crack initiation are improved because the reinforcements functioned as various nucleation sets.

– The analysis of image-based microstructures helped to understand the observed mechanical behaviour and provided qualitative forms of particle distribution.

– Consistently the mechanical properties are improved by the combination of microstructural refinement and the hybrid reinforcement.

– It is potentially capable of use in lightweight structures and wear resistant components suggested by the improvement in strength and wear characteristics.

Future work needs to contain variable grain size measurement, expansion of reinforcement levels, wide-range microstructural sampling to support statistically enabled structure property modelling.

Supplementary material: *The online version of this paper contains supplementary material available free of charge on the journal's website https://lettersonmaterials.com.*

Conflict of interest: *the authors declare no conflicts of interest related to this study.*

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