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Mechanical Properties and Microstructural Investigation of AA2024-T6 Reinforced with Al_2O_3 and SiC Metal Matrix Composites

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Abstract: Aluminium metal matrix composites (AMMCs) using alumina (Al_2O_3) and silicon carbide (SiC) as reinforcement elements are gaining significant interest in various applications because of their excellent properties. In this study, Al_2O_3/SiC with compositions (0.5 wt.%, 1.5 wt.%, and 2.5 wt.% for each) were used as reinforcement elements in an aluminium alloy (AA2024-T6). The samples prepared were AA2024-T6 + (0.5Al_2O_3/0.5SiC), AA2024-T6 + (1.5Al_2O_3/1.5SiC), and AA2024-T6 + (2.5Al_2O_3/2.5SiC) using a stir-casting technique. The experimental study included density calculation mechanical properties, such as tensile strength, compressive strength and hardness. The study also included a microstructure examination of the fracture surface of the tensile specimens. The results showed that incorporating Al_2O_3/SiC as reinforcement materials into aluminium AA2024-T6 significantly improved its properties. Hence, increasing the reinforcement with compositions of 2.5Al_2O_3/2.5SiC into AA2024-T6 showed a drop in density and increased mechanical properties, such as ultimate tensile strength, compressive strength and hardness, compared to the base alloy (AA2024-T6). Furthermore, the scanning electron microscopy analysis revealed the uniform distribution of the reinforcement particles resulting in strong bonding with the matrix. The findings suggest that Al_2O_3/SiC reinforced with AA2024-T6 can be used in applications where a combination of lightweight and high strength is needed.

Keywords: aluminum metal matrix composites; Al2024-T6; alumina; silicon carbide; mechanical properties; microstructure

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1. Introduction

Aluminium composites are used in various fields, including aerospace, structural, and automotive industries. Alumina matrix composites are favoured for industrial applications because they have high strength, precise stiffness, and fatigue strength [1]. These innovative materials possess attractive features such as corrosion resistance, high strength, wear resistance, and light weight [2]. Reinforcement additives are available in the form of fibres [2], particles [3] and whiskers [4,5]. Particles and whiskers play a significant role due to their accessibility, high elastic modulus, thermal and chemical stability, and compatibility within the matrix [5]. Additionally, aluminium metal matrix composites (AMMCs) play a vital role due to their affordability, abundant availability, and casting ability [6]. Casting is economical among different production techniques, while stir casting is frequently recognized as a commercially tested method. Additionally, stir casting enables replacing and integrating a traditional metal processing method, which reduces costs. While using the stir casting technique, several factors must be carefully considered when producing metal matrix composites, including the difficulty of attaining proper distribution of reinforcement material and the porosity of the cast metal matrix composites [7].

Several studies have been conducted in this regard. For instance, Pugalenthi et al. [8] employed the stir-casting method to create the composites, where the components were added incrementally until the desired composition was achieved. In their experiments, the physical characteristics related to the mechanical behaviour of the metal matrix composites were analysed, including the tensile strength and hardness. The investigation revealed that including silicon carbide (SiC) and alumina (Al_2O_3) reinforcements led to a rise in the microhardness and tensile strength of the Al7075 alloy. Pitchayyapillai et al. [9] prepared Al6061 matrix composites with varying amounts of nano-silver (1% and 2%) using the stir-casting method. The samples underwent testing for hardness, tensile strength, compression strength, and wear resistance. Based on the study, the Al6061-nano-silver blend demonstrated an increase in mechanical properties and displayed the potential to substitute conventional materials, ultimately enhancing efficiency and extending the lifespan of the composites. Raju et al. [10] analysed the effect of incorporating nano-sized Al_2O_3 particles on the fatigue life of an aluminium nanometal matrix composite. The liquid metallurgy method was used in conjunction with powder metallurgy to produce the composites, where the reinforcements were added to the molten metal through a two-stage mechanical stirrer. The composite specimens underwent tensile and fatigue testing, with the amount of reinforcement ranging from 0% to 2% by weight in increments of 0.5%. They found that tensile strength increased when adding 1.5 wt.% of Al_2O_3 reinforcement material to Al2024. Annigeri and Kumar [11] studied the characteristics of composites made of the aluminium metal matrix, focusing on their density, hardness, and wear behaviour. The study found that an increase in the density of the composites was observed with the addition of higher-density reinforcement particulates. Furthermore, the inclusion of reinforcement materials enhanced the composites' wear resistance and hardness properties. In another study, Daramola et al. [12] investigated the mechanical characteristics of Al6063 metal matrix composites that were strengthened with agro-waste silica particles. The composites were fabricated using double-stir casting, and different volume fractions of agro-waste silica particles (2%, 4%, 6%, and 8%) were added to the Al6063 metal matrix. The results indicated that the use of silica reinforcement led to an improvement in mechanical properties while reducing density. However, the percentage elongation and fracture toughness gradually decreased as the volume fraction of silica increased beyond 6–8%. They found that agro-waste silica particles have great potential as low-cost reinforcement materials for manufacturing aluminium matrix composites. Furthermore, Subramaniam et al. [13] analysed the mechanical characteristics of hybrid aluminium matrix composites (HAMC), which consisted of Al7075 alloy reinforced with boron carbide (B_4C) and coconut shell fly ash (CSFA) particles. The study found that the addition of 12 wt.% B_4C and 3 wt.% CSFA to the Al7075 alloy increased the hardness of the composites by 33% and the tensile strength by 66%. However, further additions of reinforcements led to a decrease in tensile strength, and the elongation of the composites decreased as the amount of B4C and CSFA reinforcements increased in the matrix. Sivananthan et al. [14] studied the physical characteristics of the mechanical behaviours of metal matrix composites made of Al6061 alloy reinforced with silicon carbide particles, which were produced using the stir-casting method. The study assessed the hardness, tensile strength, and compression strength of the composites with varying weight percentages of SiC particles ranging from 0 to 4%. The outcomes revealed that adding SiC particles to the Al6061 alloy matrix enhanced the hardness, tensile strength, and compression strength of the composite. The maximum increment noted was 25% in hardness, 25.6% in tensile strength, and 12% in compression strength compared to Al6061 alloy.

Hence, the current study is based on the introduction of different samples with AA2024-T6 as base alloy and Al_2O_3/SiC as reinforcement with different compositions, including AA2024-T6 + (0.5Al_2O_3/0.5SiC), AA2024-T6 + (1.5Al_2O_3/1.5SiC), and AA2024-T6 + (2.5Al_2O_3/2.5SiC) using the stir-casting technique. This study was based on the calculation of density, measurement of hardness, XRD analysis, and mechanical properties, such as tensile and compressive tests. The study also includes the microstructure examination of the fracture surface of the tensile samples. The objective was to introduce different Al_2O_3/SiC reinforcement compositions into AA2024-T6 to enhance its properties for applications where lightweight and high strength are needed.

2. Materials and Methods

2.1. Sample Preparation

In this study, aluminium alloy (AA2024-T6) was selected as the matrix material due to its high tensile strength, durability, and ability to resist wear and corrosion. Alumina (Al_2O_3) and silicon carbide (SiC) in powder form with a particle size of 400-mesh were added as reinforcements. These reinforcements were selected to enhance the mechanical properties, wear resistance and make the final material more suitable for high-performance applications. The specific weight percentages of the aluminium metal matrix composites (AMMCs) are detailed in Table 1.

Table 1. Weight percentages of aluminium metal matrix composites.

Samples	Base Metal	Reinforcement	
	AA2024-T6	Al_2O_3	SiC
AA2024-T6	100	-	-
AA2024-T6 + (0.5Al_2O_3/0.5SiC)	99	0.5	0.5
AA2024-T6 + (1.5Al_2O_3/1.5SiC)	97	1.5	1.5
AA2024-T6 + (2.5Al_2O_3/2.5SiC)	95	2.5	2.5

The plates of AA2024-T6 were cut using a milling machine. The reinforcement particles (Al_2O_3/SiC) in the powder form were mixed using the planetary ball mill process for 36 h with a ball mill speed of 180 rpm. The ball mill process was used to ensure the uniform dispersion of reinforcement powders before casting. After the ball mill process, the reinforcement powders were placed in a drying oven at 100 °C for 4 h to reduce and resist the moisture before adding to the aluminium alloy molten AA2024-T6. A digital weighing scale was used to weigh the required samples. It is worth mentioning that the reinforcements were kept warm for 2 h at 500 °C, which helped decrease the porosity of the composite. The pre-heated reinforcement was then added to the molten aluminium alloy, which was kept in a graphite crucible. The molten alloy temperature was maintained at 850 °C; however, the furnace was heated up to 1100 °C and cover flux was used to prevent hydrogen absorption. Figure 1 shows the setup of the furnace with graphite crucible and stirrer while the final prepared samples are shown in Figure 2.

Subsequently, the molten alloy was cooled to 660 °C, reaching a semi-solid state to prevent the settling of the reinforcement particles. The pre-heated Al_2O_3 and SiC particles were then introduced into the semi-solid alloy and stirred uniformly at a rotational speed of 400–500 rpm for 10 min. The speed of rotation plays a crucial role in the casting process. Higher speeds contribute to improved refinement, while lower speeds can lead to porosity and instability in the molten material. Previous studies recommend a rotational speed of 400 rpm for stir casting [15], while the operational temperature for AMMC was maintained at 600 °C for 2 h to ensure homogeneity [7]. The molten metal was then poured into sand moulds and solidified under natural convection. The solidified samples were subsequently machined for further analysis, as discussed in the preceding sections. Table 1 shows the compositions of these AMMCs.

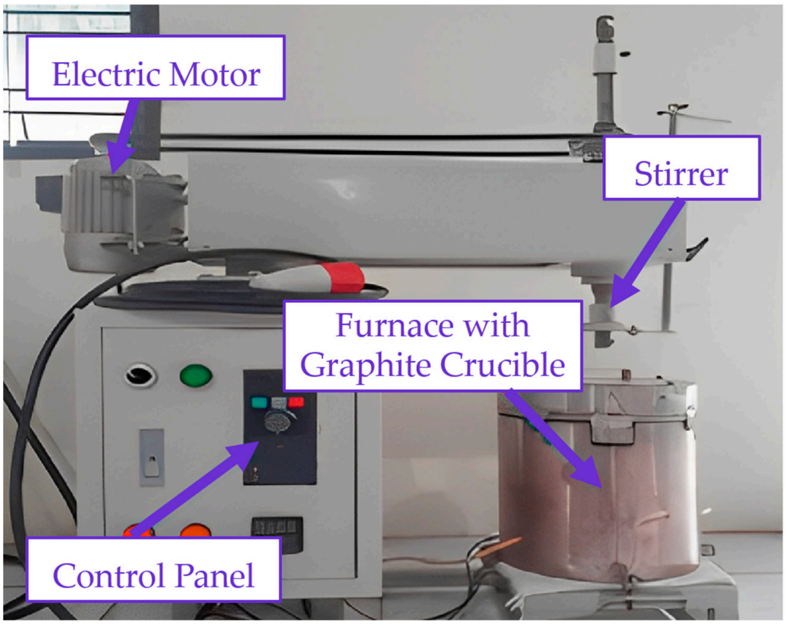

Figure 1. Setup of furnace with graphite crucible and stirrer.

Figure 2. Prepared samples.

2.2. X-Ray Diffraction (XRD)

In the current study, the specimens were analyzed through X-ray diffraction (XRD) analysis to confirm the added reinforcements. XRD spectra were recorded with a graphite mono-chromatic Cu-K radiation (=1.5406 Å) in the 2 range from 5 to 70° with a 2°/min scan rate.

2.3. Density and Hardness

The density was measured according to the ASTM standard B962-15 [16], which outlines the procedures for determining the density of cast composites. In addition, Rockwell hardness was measured according to ASTM standard E-18. Rockwell hardness machine was used with a steel ball indenter with a diameter of 1/16 inch. Initially, a light load of 10 kgf on the sample was applied to the surface to minimize the effects of minor flaws. Then, after a dwell time of 15 s, a load of 100 kgf was applied. The data were collected at three different locations on the surface of the samples to ensure accuracy and consistency.

2.4. Tensile and Compression Tests

A 100 KN universal testing machine was used to examine the tensile strength according to ASTM standard E-8/E8M. The gauge length of the samples was marked, and the samples were securely mounted in the tensile testing machine using appropriate grips/wedges. After performing tests, samples were removed from the grips of the machine. In addition, the compression tests were conducted as per the ASTM standard E9.

2.5. Microstructural Examination

A scanning electron microscope (SEM) was used to examine the fractured surfaces of tensile specimens after failure. The micrographs were taken for AA2024-T6 alloy containing Al_2O_3/SiC particles with varying weight percentages to observe the distribution and interaction of Al_2O_3 and SiC reinforcement particles within the AA2024-T6 alloy matrix.

3. Results and Discussion

3.1. X-Ray Diffraction Analysis

Figure 3 shows an X-ray diffraction (XRD) pattern for different compositions of Al_2O_3/SiC reinforced AA2024-T6 metal matrix composite. The XRD pattern showed the existence of Al, Al_2O_3, and SiC phases with peaks intensity varying with the compositions. The peak shift was detected with the increase in wt.% of Al_2O_3/SiC reinforcements, suggesting the distribution of phases. To analyse the presence of different phases, the peaks were compared with the standard diffraction. Peaks at 2θ values of approximately 37.60°, 45.32°, 65.13°, 78.71° and 82.65° correspond to Aluminium AA2024-T6 phase, which is comparable to the JCPDS No. 85-1327. The Al_2O_3 phase is confirmed from the peaks at 35.81°, 43.03°, 68.32°, and 66.42° that match with JCPDS card No. 10-0173, while SiC peak at 28.62°, 44.18°, 60.32°, and 69.83° confirmed with the JCPDS No. 29-1128. The less intense peaks found were due to the fine dispersion of reinforcement particles formed during the reaction at the interface between Al and SiC particulates [17–20]. The XRD analysis confirms the successful incorporation of Al_2O_3 and SiC into the AA2024 matrix, which could influence the material's mechanical properties.

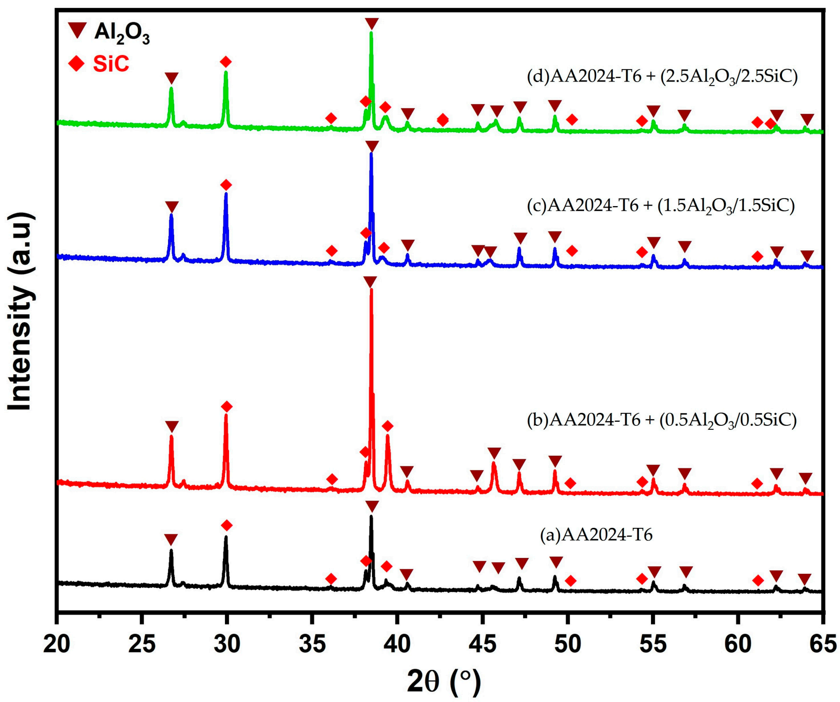

Figure 3. X-ray diffraction (XRD) analysis.

3.2. Density and Hardness

Figure 4a demonstrates that density also fluctuated with varying weight percentages of Al_2O_3/SiC. The result showed that the density decreases by increasing the weight percentages of Al_2O_3 and SiC. Hence, the Al_2O_3/SiC reinforced samples showed less density than AA2024-T6. AA2024-T6 + (2.5Al_2O_3/2.5SiC) gave density of 2.601 g/cc, which was less than AA2024-T6 with density of 2.784 g/cc. Therefore, the potential of such materials is useful in many applications where less density is required. In addition, the hardness of the hardness values with varying compositions of Al_2O_3/SiC selected in this study is illustrated in Figure 4b. The study showed that the Al_2O_3/SiC reinforced samples had higher hardness than the AA2024-T6. It is expected that these particles act as bonding agents in aluminium composites; hence, increasing the hardness of the resulting composites. The highest hardness value was obtained at AA2024-T6 + (2.5Al_2O_3/2.5SiC). It is likely that the increased constraint to plastic matrix deformation during the hardness test results from the addition of stiffer and harder Al_2O_3 reinforcement. As a result, the comparatively higher hardness of Al_2O_3/SiC might be responsible for enhancing the hardness of composite materials [21].

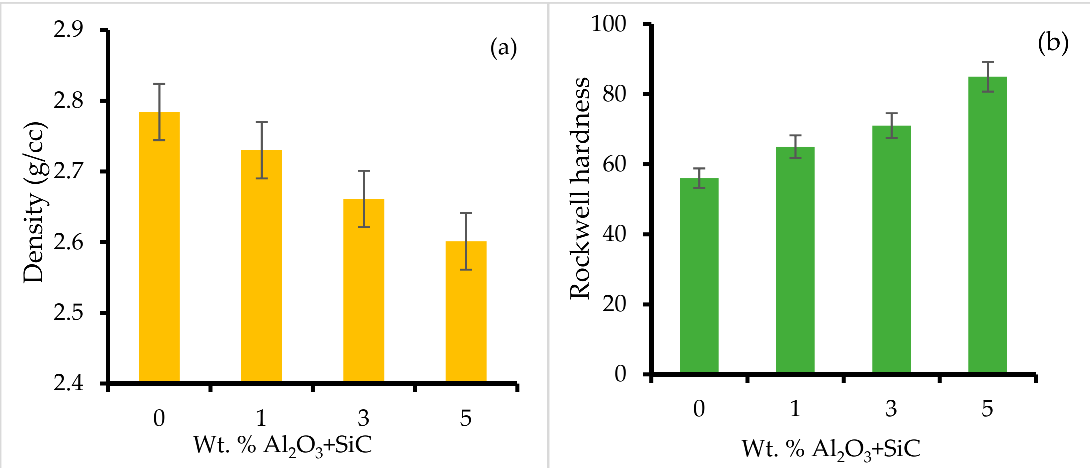

Figure 4. Variation in properties of AA2024-T6, AA2024-T6 + (0.5Al_2O_3/0.5SiC), AA2024-T6 + (1.5Al_2O_3/1.5SiC), AA2024-T6 + (2.5Al_2O_3/2.5SiC): (**a**) density, (**b**) hardness.

3.3. Tensile Strength and Compressive Strength

In this study, the tensile testing results showed that the tensile strength increased as the weight percentage of Al_2O_3/SiC increased. AA2024-T6 + (2.5Al_2O_3/2.5SiC) showed the maximum ultimate tensile strength (UTS). The Al_2O_3/SiC components contributed to the improved strength of the aluminium alloy in the matrix. The brittleness of the soft matrix was affected due to the hard components that allow it to sustain higher-directed loads. These particles contributed to increasing the strength of the composites. According to the Hall–Petch strengthening process [22], adding micro-particles to the aluminium matrix reduces the composites' grain size, which increases their strength. Figure 5 depicts the variation in UTS of the AA2024-T6 alloy samples reinforced with different weight percentages of Al_2O_3 and SiC. The AA2024-T6 alloy exhibits a UTS of 97.80 MPa. With 0.5 (0.5Al_2O_3/0.5SiC), the tensile strength increases to 109.23 MPa. Further addition of (1.5Al_2O_3/1.5SiC) enhances the tensile strength to 115.31 MPa. The maximum tensile strength of 125.18 MPa is achieved with (2.5Al_2O_3/2.5SiC). Hence, the tensile strength of the composites increases with the increasing weight percentage of Al_2O_3 and SiC. Similarly, the compression strength of AA2024-T6 reinforced with Al_2O_3 and SiC are depicted in Figure 6. The AA2024-T6 showed a compressive strength of 284.78 MPa. With the addition of (0.5Al_2O_3/0.5SiC), the compressive strength increased to 314.54 MPa. The values further increased to 352.71 MPa with the addition of (1.5Al_2O_3/1.5SiC), with the highest compressive strength of 390.45 MPa recorded when the reinforcement was (2.5Al_2O_3/2.5SiC). Hence, the findings suggest a significant impact of Al_2O_3 and SiC contents on the compressive strength of AA2024-T6.

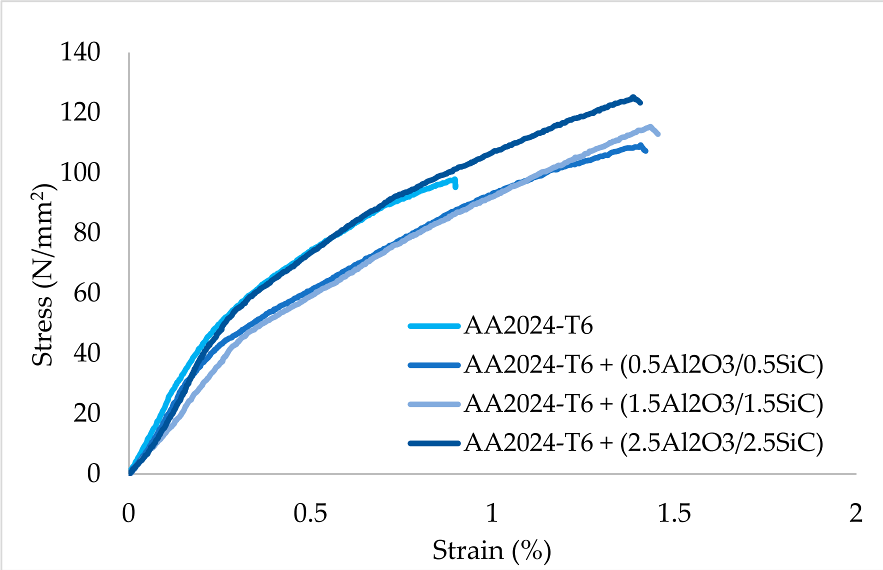

Figure 5. Tensile strength.

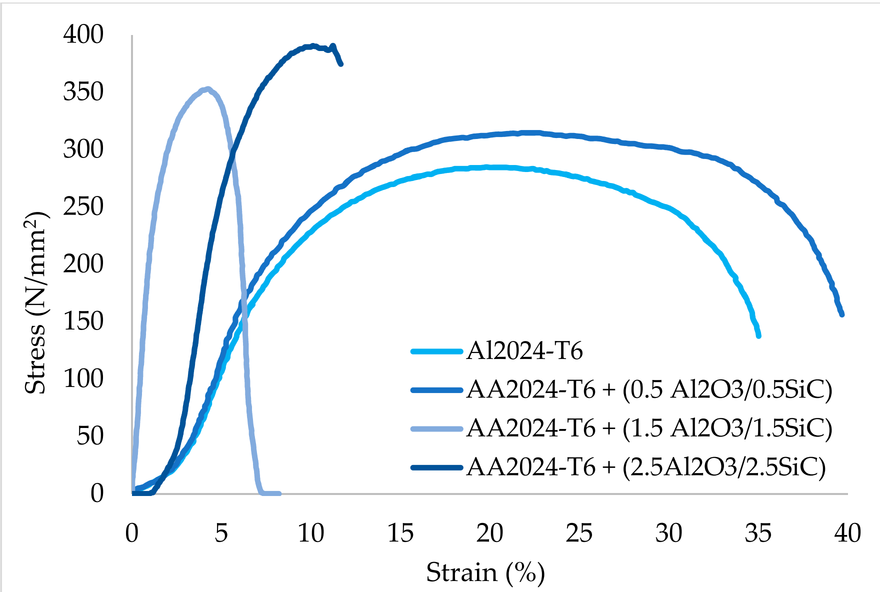

Figure 6. Compressive strength.

The increase in tensile strength can be attributed to the effective load transfer from the aluminium matrix to the harder Al_2O_3 and SiC particles. These particles act as obstacles to dislocation movement, thereby strengthening the composite. The reinforcement not only improves the tensile strength but also significantly enhances the compressive strength of the composite. The uniform distribution of these particles and their strong interaction with the matrix material are key factors contributing to the improved mechanical properties. These findings indicate the potential of these composites for applications requiring high strength and durability.

3.4. Microstructure Examination

The micrographs of the fractured surface of all the samples selected in this study are given in Figure 7a–d. Figure 7a presents a SEM image of the fractured surface of the

AA2024-T6 alloy. The SEM image suggests a ductile fracture. The microstructure appears homogeneous, indicating the absence of reinforcement particles, and confirms that the material is a pure alloy without any reinforcing elements, contributing to its ductile nature. Similarly, Figure 7b shows the SEM image of AA2024-T6 + (0.5Al_2O_3/0.5SiC). The image shows small clusters of Al_2O_3 and SiC particles indicating the initial stages of reinforcement and irregular fractured surface compared to the AA2024-T6 alloy. The fracture surface has fewer voids, suggesting a transition towards a brittle fracture. Figure 7c presents the SEM image of the fractured surface of the AA2024-T6 + (1.5Al_2O_3/1.5SiC). The surface shows that Al_2O_3 and SiC particles appear more evenly distributed with minimal clustering. The presence of dimples and voids indicates a mixed fracture mode. The mixed fracture mode suggests that the material retains some ductility while gaining strength from the reinforcement particles, leading to enhanced overall mechanical properties. The more uniform distribution of reinforcement particles improves the load-bearing capacity and structural integrity of the composite. Figure 7d shows the SEM image of the fractured surface of the AA2024-T6 + (2.5Al_2O_3/2.5SiC). The surface exhibits a uniform distribution of dimples and a smoother appearance than previous samples. Al_2O_3 and SiC particles are uniformly dispersed, which improves the composite's mechanical properties. The uniform particle distribution and strong matrix particle bonding contribute to the composite's superior mechanical properties. Hence, the transition from a pure alloy to reinforced composites indicates that improved particle dispersion and uniform distribution at higher reinforcement contents lead to enhanced mechanical performance. This uniformity is crucial for achieving consistent mechanical properties and enhancing the composite's overall performance. The SEM results support the mechanical testing data, showing that adding reinforcement particles improves the mechanical properties by altering the fracture behaviour.

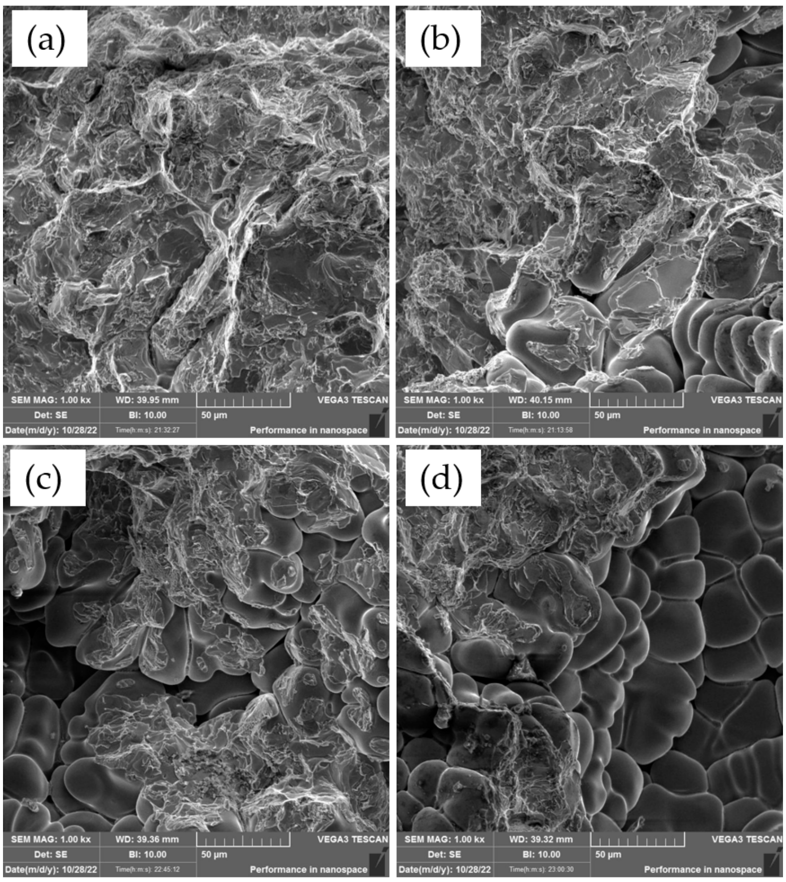

Figure 7. SEM micrographs: (**a**) AA2024-T6, (**b**) AA2024-T6 + (0.5Al_2O_3/0.5SiC), (**c**) AA2024-T6 + (1.5Al_2O_3/1.5SiC), (**d**) AA2024-T6 + (2.5Al_2O_3/2.5SiC).

4. Conclusions

This study used the stir-casting method to investigate AA2024-T6 aluminium alloy composites reinforced with varying weight percentages of Al_2O_3 and SiC. AA2024-T6 + ($0.5Al_2O_3/0.5SiC$), AA2024-T6 + ($1.5Al_2O_3/1.5SiC$), and AA2024-T6 + ($2.5Al_2O_3/2.5SiC$) were used for experimental study including density calculation, mechanical properties, such as tensile strength, compressive strength and hardness. In addition, the microstructure of the fracture surface of the tensile samples was studied using scanning electron microscopy. The conclusions drawn from the results included that the density of the composites decreases by increasing the concentration of reinforcing materials with the lowest density found at AA2024-T6 + $2.5Al_2O_3/2.5SiC$. The results also showed that inclusions of Al_2O_3/SiC as reinforcement into AA2024-T6 improved the mechanical properties. The hardness of the composite materials was enhanced by increasing the weight percentages of reinforcing materials with the maximum hardness found in the composite with $2.5Al_2O_3/2.5SiC$. Furthermore, AA2024-T6 + $2.5Al_2O_3/2.5SiC$ showed the highest tensile strength and compressive strength compared to the base alloy (AA2024-T6). Furthermore, the scanning electron microscopy analysis revealed the uniform distribution of the reinforcement particles resulting in strong bonding with the matrix. The findings suggest that with improved mechanical properties and light weight, Al_2O_3/SiC reinforced with AA2024-T6 can be used in applications where a combination of light weight and high strength is needed.

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