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Enhanced Mechanical Performance of Al7075/ 3–9 wt % SiC and 2 wt % Al_2O_3 Hybrid Composites Through T6 Heat Treatment

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ABSTRACT

The applications of aluminium metal matrix composites (AMMCs) using Al7075 as the base alloy are increasing in the automobile and aerospace industries due to their superior strength-to-weight ratio. Al7075, being a heat-treatable alloy, offers scope for enhancing mechanical properties through suitable reinforcement and heat treatment. In this study, hybrid AMMCs were fabricated using Al7075 alloy reinforced with silicon carbide (SiC) and aluminium oxide (Al_2O_3) particles through the stir casting process. The stir casting process involves melting preheated Al7075 alloy at 650°C and further heating it to 780°C for complete liquefaction. Preheated reinforcements (650°C) are then added and stirred thoroughly for uniform blending. Subsequently, 2 g of magnesium powder is introduced into the slurry to improve wettability. After solidification, the material is removed from the mould to produce samples using a wire-cut electrodischarge machine. SiC was added in varying proportions of 3, 5, 7 and 9 wt %, while Al_2O_3 was maintained at a constant 2 wt % for all samples. The T6 heat treatment of the samples involved solutionizing at 530°C, holding time for 8 h, ageing at 165°C for 8 h and cooling by water quenching. Mechanical and metallurgical properties were examined for both as-cast and heat-treated (T6) composites. The results revealed that the inclusion of SiC and Al_2O_3 significantly improved the tensile strength and hardness of the composites compared to the base alloy. The heat-treated specimens exhibited superior performance compared to as-cast samples, achieving a maximum tensile strength of 553.1 MPa (70% increment) and hardness of 204.5 VHN (71.8% increment), compared to 325 MPa and 119 VHN for the as-cast samples. SEM micrographs confirmed uniform dispersion of reinforcements and refined grain structures in heat-treated composites. The strengthening mechanisms in metal matrix composites mainly include load transfer, Hall–Petch strengthening and Orowan strengthening. Strengthening occurs by load transfer from the ductile matrix to the hard reinforcement particles, Hall–Petch strengthening by an increase in the number of grain boundaries to obstruct dislocations and Orowan strengthening, in which dislocations form loops around reinforcements, obstructing dislocation movement. The developed hybrid AMMCs demonstrate excellent potential for structural applications in the aerospace and automotive sectors.

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1 | Introduction

Composite materials have become the modern solution to develop a material with tailored properties to suit the required application by combining materials with different properties in optimum proportions. Metal matrix composites (MMCs) are widely substituted in place of heavy metals like steel to obtain lightweight, as well as a good strength-to-weight ratio, along with other enhanced properties from the composition. The main advantage of composite materials is that any material, be it metal, polymer or ceramic, can be mixed with each other through proper fabrication techniques. A study by Manocha & Bunsell [1] revealed that 200 materials out of 1600 materials available in the market were composite materials in 1980. At present, the percentage of composites used has increased manyfold, as almost all sectors such as aero, automobile, construction and marine extensively apply composites to fabricate structural and functional elements. Among the lighter metals like aluminium, magnesium and copper, aluminium, particularly its alloys, is widely used for developing MMCs. Al7075 is one such aluminium alloy, which finds wide applications in sports, aero, transportation, marine and other industries, as it can be made to provide desired properties by an optimum mix of the reinforcement materials. Past literature shows that with the inclusion of appropriate ceramic material(s), strength-to-weight ratio, tensile strength and wear resistance of the Al7075 could be increased further [2, 3]. It was also understood that the selection of appropriate reinforcement, method of synthesis and percentage of mixing composition are crucial for obtaining the desired level of properties. The objective of this study is to investigate the impact of SiC and Al_2O_3 ceramics on the mechanical behaviour of the Al7075 alloy that would pave the way for new applications.

Past research types have shown that MMCs produced using aluminium/aluminium alloys provide higher strength, lower wear and endurance at elevated temperatures compared to the base matrix [4]. Another study reveals that particle size and their distribution pattern have a great impact on the properties of aluminium MMCs [5, 6]. An investigation was made to compare the effect of single and hybrid (double) reinforcement with different percentages of inclusions on the mechanical and metallurgical properties of aluminium nanocomposites. In the single reinforcement composites, the ceramic particles were added only after preheating them to different temperatures (400°C, 500°C and 600°C) to fabricate three separate composites. In the case of hybrid composites, the ceramic inclusions were preheated to 500°C and then added to the matrix. The experimental outcomes showed that uniform distribution of reinforcements was achieved only up to 2% reinforcement addition and at a preheating temperature of 500°C, after which clustering of particles occurred [7]. Arunachalam et al. [8] have carried out an extensive review by analysing past literature on MMCs, particularly works that employed different types of stir casting techniques. Various problems pertaining to stir casting methods have been discussed in this article, such as variations in furnace design, arrangement of stirrer, squeeze facility attachment and also suggestions were provided to overcome such issues. Moreover, the outcomes of using different matrices, reinforcement materials and wetting agents in the production of MMCs were discussed in the report. It has also highlighted the issues to be resolved in the production of MMCs. Aluminium alloy nanocomposites were produced with SiC particles using the stir casting technique. It was observed that the wettability and embedding of SiC particles into the aluminium matrix were good due to the nanosize of the reinforcement particles. The enhancements in the outcomes were found to be a 125% increase in hardness, a 45% increase in tensile strength, a 41% increase in yield strength and an improvement in compressive strength to 603 MPa from 311 MPa for 5% SiC inclusion. Analysis of fractography showed that debonding and cracking had caused the fracture (Tanwir Alam et al., 2017). The work of Mahadevan et al. [9] revealed that uniform dispersion of reinforcement particles in the matrix could be achieved when the wetting (interfacial bonding) between the reinforcement and matrix material was good. Pradeep Devaneyan et al. [3] produced hybrid composites containing Al7075/SiC + TiC with different reinforcement percentages using the powder metallurgy technique. The highest microhardness (52.12HV) was obtained from the composition of Al 7075 + 8% TiC + 4% SiC. The composites also showed good wear resistance as both TiC and SiC possess good hardness. Different types of reinforcements have been utilized to produce MMCs with high wear resistance. Anubhav Coyal et. al [10] fabricated aluminium metal matrix composites (AMMCs) using Al6061 + SiC + jute ash through the stir casting method. The samples were made with individual reinforcements and also as a hybrid composite having both SiC and jute ash particles. The wear resistance was found to be four times higher than the matrix material, and the SiC-reinforced composites gave the best wear resistance. Researchers have also used vegetable ashes as reinforcements along with ceramic particles to produce composites. Afnan Haider Khan et al. [11] have fabricated ternary-reinforced composites by reinforcing ash of rice husk (RHA) and carbonized egg–shell (CES) along with SiC in the matrix of Al7075. The samples were found to have enhanced tensile strength, hardness and impact strength. Shivaramakrishna et al. [12] have used Fe_3O_4 as the reinforcement material for producing Al7075 MMCs by adding 2% to 10% of reinforcement by weight. Good wettability and distribution were observed, which enhanced tensile strength, compression strength, wear strength and hardness of the composites. It was also noticed that an increase in the percentage of Fe_3O_4 improved the properties of these composites. It would be pertinent here to discuss the effects of heat treatment on some ferrite alloys too. Doomra et al. [13] investigated the effects of different heat inputs and postweld heat treatment on the impact toughness and tensile strength of electron beam-welded AISI 409 ferritic stainless steel. Heat input produced a 46% reduction in impact toughness at the top weld region, but in the bottom section, it was 83%. Postweld heat treatment enhanced impact toughness by 35% and 24%, respectively, for high and low heat inputs. Moreover, tensile strength in the bottom section increased by 26% compared to the base metal. Doomra and Sandhu [14] studied the effect of postweld heat treatment (550°C/75 min) on the mechanical behaviour of electron beam-welded AISI 409 stainless steel plates. In the bottom section, grain refinement was observed and X-ray diffraction also showed a reduction in martensite after heat treatment. A tensile strength of 532 MPa was found at the bottom section, while the weld joint's overall impact toughness was 37% lower than the base metal. However, an enhanced impact toughness of 31 J was observed at the top section after heat treatment. As the hybrid composites like Al7075–SiC–Al_2O_3 contain more than one kind of reinforcement, the combined characteristics of these materials may lead to both advantageous

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and disadvantageous effects on the final properties of the MMC. Sridhar et al. [15] investigated the tribological properties of Al7075–SiC–Al_2O_3 composites and found considerable enhancement in hardness for 9 wt % SiC and 5 wt % Al_2O_3 composition and increased tensile strength for 6 wt % SiC + 5 wt % Al_2O_3 sample. It was also observed that the addition of more than 6 wt % SiC reduced tensile strength due to clustering. It was also inferred that a higher range of reinforcement materials in the composite resulted in clustering, porosity, etc., and reduced mechanical properties. Pugalenthi et al. [16] evaluated the mechanical properties of Al7075–SiC–Al_2O_3 composites and observed that both hardness and tensile strength increased steadily with the increase in reinforcement material, while ductility decreased. It was observed from the review of past studies in the area of AMMCs that there are many external and internal factors which influence the end properties of the composites. These factors include load transfer mechanism, microstructural homogeneity, grain refinement, bonding and interfacial strength, control of grain boundaries, porosity, nature of reinforcement, Orowan strengthening mechanism and variation in coefficient of thermal expansion of the matrix and reinforcement materials. The literature study revealed that composites having the combination of Al7075 with the reinforcements of SiC and Al_2O_3 have not been developed and investigated much. Also, the specific reinforcement proportions (3, 5, 7 and 9 wt % of SiC and 2wt % of Al_2O_3) were not explored. The reinforcement particle sizes were as small as possible (30–40 μm) for homogeneous mixing in the matrix. Also, Al7075 is a heat-treatable alloy and the properties of the composites made with it can further be enhanced by heat treatment. The main objective of this research is to produce Al7075 + SiC + Al_2O_3 composite samples through the stir casting method and investigate their mechanical properties in the as-cast and heat-treated conditions through different tests. Hence, the results of this investigation would be beneficial to the aerospace and automotive industries that are seeking to use suitable aluminium composites with a good strength-to-weight ratio and enhanced mechanical properties.

2 | Experimentation

2.1 | Preparation of Test Specimens

The Al7075 alloy used as matrix material was bought in the form of rods, and the reinforcements in powder form (Hindustan Traders, Chennai). The rods were melted, and the SiC and Al_2O_3 particles were mixed into them under the hot conditions of the base alloy. Al7075 alloy, in terms of weight percentage of elements, is given in Table 1.

The ceramic particles of SiC and Al_2O_3 used for reinforcement were of 30/40-micron size, which were poured into the base alloy and stirred well in the stir casting process. The schematic of the stir casting arrangement with various units is illustrated in Figure 1.

The aluminium rods were cut into smaller pieces and preheated to 400°C before being placed into a 6″ graphite crucible. The preheating would ensure good blending with reinforcement particles. The SiC and Al_2O_3 particles were preheated in a separate crucible of 2″ size. As the temperature of the crucible was gradually increased, the Al7075 alloy melted at 650°C, and at 780°C, it attained the liquid state. Now, the preheated reinforcement particles (650°C) were poured into the electric furnace containing the base alloy and mixed thoroughly using the stirrer. A small quantity of magnesium powder (2 g) was then mixed in the slurry to enhance interface wettability. The mixing ratio was 2 g of magnesium for 500 g of Al7075 alloy, and all values are shown in Table 2. At elevated temperatures, the tendency for gas absorption and porosity increases. The addition of magnesium supports the degassing procedure and reduces the gas absorption effects considerably. The hybrid composite is superheated above the melting point (liquidus) of Al7075 to improve fluidity. This superheat compensates for thermal losses during transfer from the furnace to the die, ensuring that the slurry retains sufficient temperature to avoid premature solidification and enables proper mould filling.

The motor-operated stirrer can reach a speed of 480 to 500 rpm within 32 s during each spell. The speed was kept at 450 rpm, and the stirring time was 2 min per spell. For double stirring, a 2-min stirring spell was carried out twice. After mixing, the molten slurry was poured into a square die having a size of '100 × 100 × 10' mm. The slurry was then allowed to solidify and then removed from the mould. In the same way, samples of different compositions (3, 5, 7 and 9 wt.% of SiC with 2 wt.% of Al_2O_3 in each) were produced. Figure 2 shows the stir casting facility used for the experiments. Double-stirring method and appropriate temperature control by employing a thermocouple were followed to prevent agglomeration of micro-sized reinforcement particles.

Milling (milling machine) and cutting (wire-cut electrodischarge machine) operations were used for preparing tensile test specimens as per ASTM E8M04 dimensions. A universal testing machine was used to carry out tensile tests, the crosshead displacement rate was kept constant for all the tests, and the atmospheric temperature was 25°C. Mechanical properties like ultimate tensile strength (UTS) and ductility were evaluated. During the tensile test, the specimen stretches before it breaks and the elongation is expressed as a percentage of its original length; i.e., percentage elongation was tested and the values were recorded. Microhardness tests were also carried out (ASTM B557M standard) on the specimens. For microstructural examination, a small portion was cut from the casting, ground (belt-grinding), polished (emery papers of different grades), repolished (using clothes), washed, dried and finally etched using Keller's solution. Now the samples were micrographed under optical microscope (OM) and scanning electron microscope (SEM) for microstructural analysis of different compositions. The broken tensile specimens were also photographed under SEM for fractography analysis. SiC agglomerations were found at the fractured parts. The portion having hard ceramic particles could have initiated the failure, which would then have propagated through the large ductile matrix portion to end up in fracture.

The sample compositions and the name assigned to each sample are given in Table 3.

The important properties of the Al7075 alloy are given below in Table 4.

Figure 3 below shows the specimens prepared for micrographic examination.

The variation in density of MMCs can be calculated from Equation (2) based on Archimedes principle and illustrated in

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TABLE 1 | Chemical compositions of Al7075.

Metals	Zn	Mg	Cu	Si	Mn	Fe	Cr	Ti	Al
Weight %	5.1	2.185	1.690	0.179	0.146	0.476	0.193	0.045	89.986

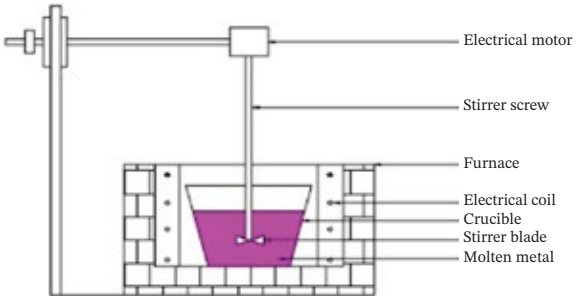


FIGURE 1 | Schematic diagram of stir casting setup.

Table 5. An electronic balance (Make: SHIMADZU BL-220H; accuracy of 0.001 mg) was used to weigh the initial mass of the samples:

$$d_{\text{mmc}} = \frac{m_a}{m_a - m_w} \times d_w. \quad (1)$$

where d_{mmc} = hybrid composite's density

m_a = composite specimen's mass (in air)

m_w = composite specimen's mass (in water)

d_w = water density

Heat treatment process: The heat treatment was carried out by solutionizing at 530°C, holding for 8 hours, ageing at 165°C for 8 hours and cooling through water quenching. During the ageing process, Mg Zn_2 (intermetallic compound) precipitate into the porosities and grains, imparting hardness to the base alloy/composite. The quantity and size of precipitates have an impact on improving the hardness of the base alloy/composite. The interface zone is the nucleation site for precipitates where the particles gather, leading to heterogeneous nucleation, which obstructs the dislocations and strengthens the composite. The cooling rate (method of quenching) plays a vital role in controlling the amount and size of the intermetallic precipitates [17, 18].

2.2 | Limitations and Potential Sources of Error in the Experimental Procedure

The limitations and potential sources of error in the experimental procedure of AMMCs are many and could be at any stage, such as the fabrication process, specimen preparation and testing methods. These include uniform distribution of reinforcement, clustering tendency of ceramic particles, wettability issues, interfacial reactions, application of different fabrication processes, gas entrapment issues in the stir casting method, porosity formation, internal stresses caused by thermal variations, contamination in materials used, surface quality and dimensional variations in specimens, environmental influence and equipment errors, among others. However, during this research, efforts have been taken to avert all potential sources of error.

3 | Results and Discussion

3.1 | Effects of Process Parameters on Properties of the Composite

As the fabrication of MMCs involves two different materials such as metals and ceramics that have completely different characteristics, getting a homogeneous output becomes a challenging task. Hence, for obtaining a quality composite from the stir casting method, each input parameter should be at an optimum level. The process parameters of the stir casting method mainly involve stirring speed, stirring time, stirring temperature, preheating of reinforcement and the matrix and percentage of reinforcement material added. All these parameters should be kept in the optimum range to obtain improved properties from the composites.

The stirring speed of 450 rpm and the stirring time of 4 min are in the optimum range and hence produced a homogeneous composite that has shown improved properties. If the limits were below the optimum level, reinforcement clusters would have formed, and for higher limits, porosity could have occurred. The stirring temperature (780°C) has improved the fluidity of the Al7075 base alloy and the wettability of the SiC and Al_2O_3 ceramic particles with the matrix. The preheating of the reinforcement (650°C) could avert a mismatch in temperature difference with the matrix, enhancing wettability, which would otherwise lead to thermal shock and isolation of reinforcement particles as clusters. Preheating of the mould also helped in the flowability of the slurry and prevented solidification defects. Also, there is an optimum range for adding reinforcement materials with the matrix, and when the limit is exceeded, the end

TABLE 2 | Processing parameters for fabrication of hybrid-reinforced A17075 alloy composite.

Parameter	Value/range	Remarks
Matrix material	Al7075	Base alloy
Reinforcements	SiC, Al_2O_3	Hybrid reinforcement
Melting temperature	660°C–750°C	Furnace melting range
Preheating temperature (Particles)	300°C–400°C	To remove moisture and improve wettability
Stirring speed	480–500 rpm	Mechanical stirring
Stirring time	3 min	Uniform dispersion of particles
Magnesium (Mg) addition	2 g	Improves wettability (specify exact value)

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FIGURE 2 | Stir casting machine.

TABLE 3 | Samples' names and compositions.

Sl. No.	Sample name	Composition
1	S1	Al7075 + 3% SiC+ 2% Al_2O_3
2	S2	Al7075 + 5% SiC+ 2% Al_2O_3
3	S3	Al7075 + 7% SiC+ 2% Al_2O_3
4	S4	Al7075 + 9% SiC+ 2% Al_2O_3

properties may be degraded. In the present experiments, the percentage of reinforcement addition (3, 5, 7 and 9 wt % of SiC particles + 2 wt % of Al_2O_3 as constant in all samples) is within the optimum limit in all samples, as the results show enhanced results for all the samples. Also, the gradual addition of the reinforcement particles into the molten base material helped to obtain homogeneous composite specimens.

The matrix material, Al7075, is a heat-treatable aluminium alloy that gets strengthened by precipitation hardening. Hence, the Al7075–SiC–Al_2O_3 composite was heat-treated (solutionizing temperature at 530°C, holding for 1 h, ageing at 165°C and cooling by water quenching) to further enhance the properties. From the results, it was observed that the heat-treated samples produced much improved property values than the as-cast samples. Hybrid composites are fabricated to combine the favourable properties of different reinforcement materials in a single composite. In the Al7075–SiC–Al_2O_3 composite, the combined effect of hardness enhancement from SiC and the improved strength and thermal stability from Al_2O_3 contributes to an overall enhancement of the properties of the composite.

3.2 | OM and SEM Micrograph Analyses

The density difference between the reinforcement and the matrix affects the pattern of distribution. The heavier reinforcement particles may settle down at the bottom, and lighter particles may float on top and join together. The quantity of reinforcement distribution may differ from place to place in the casting, and the manner of pouring also has great influence over this factor. Homogeneous casting is crucial for good quality casting. Hence, OM and SEM micrographs were taken to analyse the distribution of SiC and Al_2O_3 particulates in the Al7075 alloy matrix and check the homogeneity. Figure 4 (S1, S2, S3 and S4) shows the optical micrographs of the composite specimens with different wt % of reinforcements. Good homogeneity, along with changes in grain size and orientation, could be observed here, and the patterns are further discussed below.

The micropictures of the OM of the heat-treated (to T6 condition) composite specimens show an even distribution of silicon carbide and alumina particles in the matrix of Al7075 alloy. The homogeneous distribution of the reinforcement particles eliminates stress concentration and results in enhanced isotropic (equal magnitude in all directions) mechanical properties. It was noted that heat-treated samples showed a smaller number of reinforcement clusters than the as-cast composite samples. The heat applied during heat treatment could be the cause of such even distribution. The findings of Alaneme and Aluko [19] agree well with our results. Their report states that the stir casting method yielded very few particle clusters, as observed in the micrographs of the Al6063/SiC composite, demonstrating the effectiveness of the production method. The analysis of the optical micrographs in Figure 4 shows fewer clusters for all compositions. However, the agglomeration counts slightly increased with the increase in the percentage weight of reinforcement particles. The isolated presence of SiC and Al_2O_3 could also be seen in the matrix at some places in the micrographs as dark spots. Figure 4 (S1–S4) gives the micropictures of various as-cast Al7075/SiC/Al_2O_3 compositions with a magnification of 100X. Uniform pattern of reinforcement distribution can be seen here and this homogeneous mix of the composite is achieved through the stir casting process, employing the double-stirring method. In the SEM micrographs, SiC particles typically appear white, while Al_2O_3 particles appear in black colour. However, due to the homogeneous distribution of the reinforcement materials within the Al7075 matrix, it becomes difficult to distinctly identify and differentiate them in the micrographs.

The micrograph in Figure 4-S1 is of Al7075/3 wt % of SiC/2 wt % of Al_2O_3. It shows uniform distribution of both SiC and Al_2O_3 particles in the Al alloy matrix, where the grains are close-packed. The micrograph of Figure 4-S2 having Al7075/5 wt % of SiC/2 wt % of Al_2O_3 composition also shows homogeneous distribution of reinforcements, but the grain patterns are a bit longer and some clusters are also seen. If the test area falls in these places, the results may be completely different from the homogeneous areas. Figure 4-S3 is of the Al7075/7 wt % of SiC/2 wt % of Al_2O_3 composite. The reinforcement homogeneity is comparatively lower here, and agglomerations are also witnessed along with irregular grain orientation. The increase in SiC percentage could be the cause of these effects. Figure 4-S4

TABLE 4 | Important properties of Al7075.

Alloy	Tensile strength (MPa)	Yield strength (MPa)	Percentage elongation (%)	Vickers hardness (VHN)
Al7075	220–280	100–150	10–20	60–80

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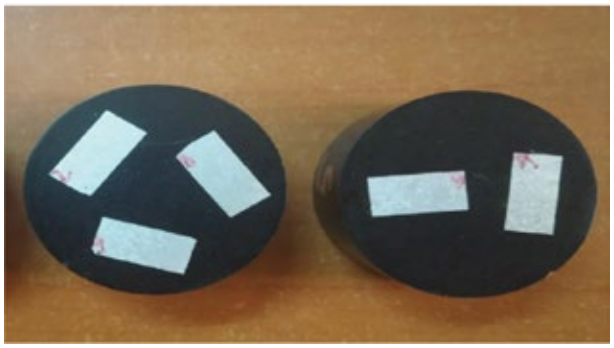


FIGURE 3 | Samples prepared for micrographic study.

(composition: Al7075/9 wt % of SiC/2 wt % of Al_2O_3) presents a uniform distribution of reinforcements, among which SiC's presence looks prominent.

The porosity of these composites should be lower, as a homogeneous distribution of reinforcements is seen in the SEM pictures (Figure 5), and the addition of magnesium would provide good wettability, ensuring enhanced properties. The SEM pictures of the above samples are provided in Figure 5 (S1, S2, S3 and S4). The pictures clearly exhibit even dispersion of reinforcement particles in the matrix, and the surface homogeneity ensures excellent interface bonding. The heat energy imparted during heat treatment has also caused grain refinement, which can be seen.

The SEM pictures in Figure 5 (S1–S4) are at higher magnification (500X), which again clearly reveal the homogeneity of the composites and good interface wettability attained through the stir casting process of composite fabrication. These metallurgical factors, such as lower porosity, homogeneous composition, strong interfacial bonding and refined grains, ensure enhanced final properties of the composite compared to the base alloy. The research conducted by Rajesh et al. [20] on the material characterization of Al7075/SiC + Al_2O_3 hybrid composites (samples having 5% SiC/5% Al_2O_3, 10% SiC/10% Al_2O_3 and 15% SiC/15% Al_2O_3 reinforcements) observed SEM pictures showing uniform distribution of reinforcements and attributed it to the separation of clustered SiC/Al_2O_3 particles caused by the hydrodynamic forces generated locally in the stir casting process. These results agree well with our findings.

3.2.1 | Varying Trends in Microstructural Features

The variations found in the microstructural features of the SEM micropictures of various heat-treated compositions of Figure 5 are explained below.

Figure 5a–Composition: Al7075 + 3% SiC+2% Al_2O_3

TABLE 5 | Density of the Al7075/SiC/Al_2O_3 composites.

Sample no.	Experimental density (g/cm^3)	Theoretical density (g/cm^3)
S1	2.799	2.810
S2	2.806	2.818
S3	2.816	2.826
S4	2.823	2.834

The reinforcement particles are evenly dispersed in this condition with minimum clustering and visible matrix continuity. The uniform distribution ensures good interface bonding between the matrix and the reinforcement materials. Fine precipitates are found due to heat treatment. The grain size of the composite is refined and reduced to an extent.

Figure 5b–Composition: Al7075 + 5% SiC + 2% Al_2O_3

The reinforcement particles are dispersed in a fairly uniform manner, showing a tendency for clustering. The interfacial bonding is moderately strong for this composition. Also, the grain size is found to be refined and uniform, with a slight increase in heterogeneity.

Figure 5c–Composition: Al7075 + 7% SiC + 2% Al_2O_3

The reinforcement particles are dispersed in a moderately uniform manner, showing localized clustering at some sites. For this higher reinforcement composition too, grain refinement could be seen as particles act as nucleation sites restricting growth of grains. The interfacial bonding is weak at some interfaces due to increased tendency for clustering as the reinforcement percentage increases.

Figure 5d–Composition: Al7075 + 9% SiC + 2% Al_2O_3

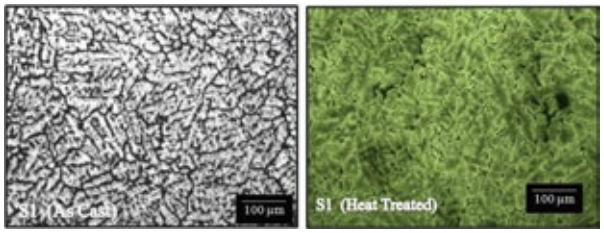
The dispersion of reinforcement particles is not uniform, with an increased number of clusters observed. This is due to reduced wettability between the matrix and the reinforcement particles. The weak interfacial bonding and the thermal variations between the matrix and the reinforcement also create microvoids at the interfacial sites, which are observed in the SEM picture.

3.2.2 | High-Resolution SEM and EDAX Analysis of the Specimen S4

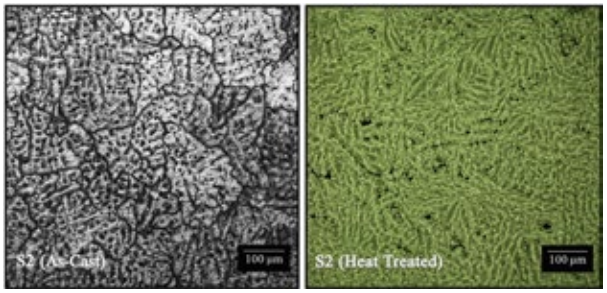
Figure 6 is the high-resolution SEM micrographs of Sample S4 (Al7075 + 9% SiC + 2% Al_2O_3) at different magnifications. (a) Low magnification showing overall homogeneous microstructure; (b) medium magnification highlighting uniform dispersion of SiC and Al_2O_3 particles; (c) higher magnification revealing grain refinement and particle–matrix interfaces; (d) very high magnification showing strong interfacial bonding and reduced porosity. At low magnification, the overall microstructure appears homogeneous, while higher magnifications reveal refined grains, reduced porosity and clean reinforcement–matrix interfaces. SiC particles typically appear as bright phases, whereas Al_2O_3 appears as darker regions. The heat-treated composites display more uniform dispersion with fewer agglomerates compared to the as-cast condition, which can be attributed to the combined effect of optimized stir casting parameters (stirring speed, double stirring, preheating) and the T6 heat treatment that enhances wettability and diffusion.

The functional roles of the reinforcements are evident in the microstructural observations. SiC, being a hard ceramic, contributes to increased hardness and wear resistance by resisting dislocation motion and acting as a load-bearing phase. Al_2O_3 enhances thermal stability and contributes to grain refinement, preventing grain coarsening during heat treatment. Together, the hybrid reinforcement system enables a balance of strength, hardness and stability in the composites. These effects are reflected in the improved tensile strength and hardness values, but

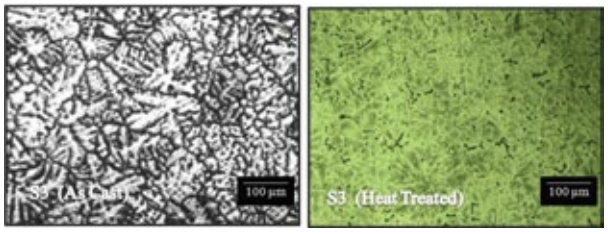
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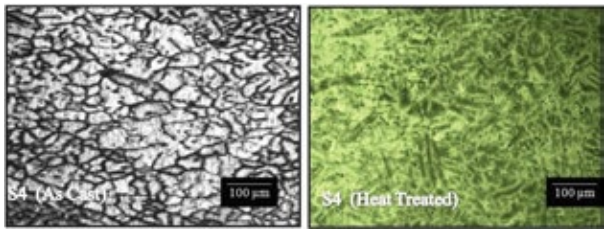
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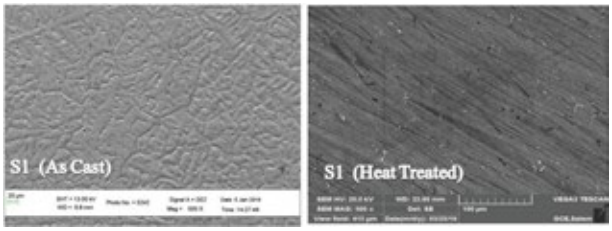


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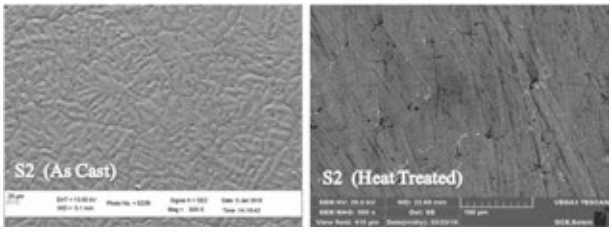


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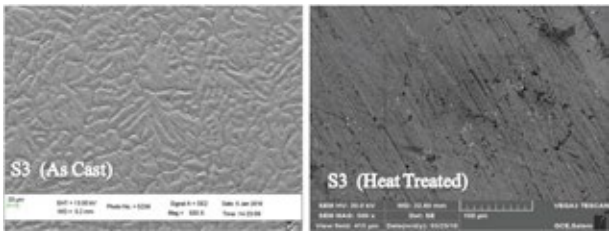
FIGURE 4 | Optical micropictures of as-cast and heat-treated composites with various compositions. (a) Al7075 + 3% SiC + 2% Al_2O_3. (b) Al7075 + 5% SiC + 2% Al_2O_3. (c) Al7075 + 7% SiC + 2% Al_2O_3. (d) Al7075 + 9% SiC + 2% Al2O3.



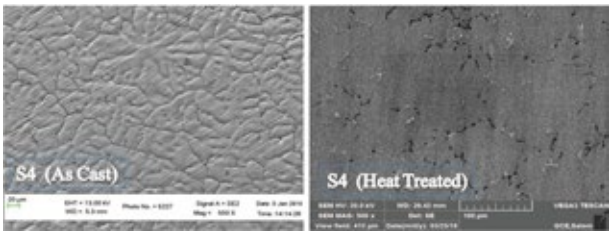
(a)



(b)



(c)



(d)

FIGURE 5 | SEM micropictures of as-cast and heat-treated the composites with various compositions. (a) Al7075 + 3% SiC + 2% Al_2O_3. (b) Al7075 + 5% SiC + 2% Al_2O_3. (c) Al7075 + 7% SiC + 2% Al_2O_3. (d) Al7075 + 9% SiC + 2% Al_2O_3.

also in the reduced ductility due to the brittleness imparted by the ceramics.

In addition to SEM, EDAX elemental analysis was carried out to validate the presence and distribution of reinforcements, as shown in Figure 7. The EDAX spectrum confirmed the dominance of Al in the matrix, along with Si and O corresponding to SiC and Al_2O_3 reinforcements. Minor peaks of Mg, Zn and Cu correspond to alloying elements of Al7075 that support precipitation hardening, while traces of Ti, Cr and Fe represent compositional inclusions typical of Al7075 alloys. The uniform distribution of Si and O in the EDAX elemental maps confirms that reinforcements were incorporated effectively into the Al7075 matrix without significant clustering. This consistency between SEM and EDAX results demonstrates that the processing parameters (optimized stirring speed, temperature and Mg addition) successfully promoted homogeneous distribution and strong matrix–particle bonding.

The strengthening mechanisms operating in these composites can be interpreted from the combined microstructural and elemental analysis. Load transfer from the softer Al7075 matrix to the hard SiC/Al_2O_3 particles enhances tensile strength. The presence of fine reinforcements provides Orowan strengthening by resisting dislocation movement. Precipitation hardening, assisted by Mg and Zn from the matrix, is evident after T6 heat treatment, where intermetallic precipitates contribute to hardness and strength. Grain refinement, as observed in SEM, further increases strength by restricting dislocation motion. The combination of these mechanisms results in the significant property improvements observed in heat-treated composites.

The dominant Al peak corresponds to the matrix, while Si and O peaks confirm the presence of SiC and Al_2O_3 reinforcements. Minor peaks of Mg, Cu and Zn represent alloying elements of

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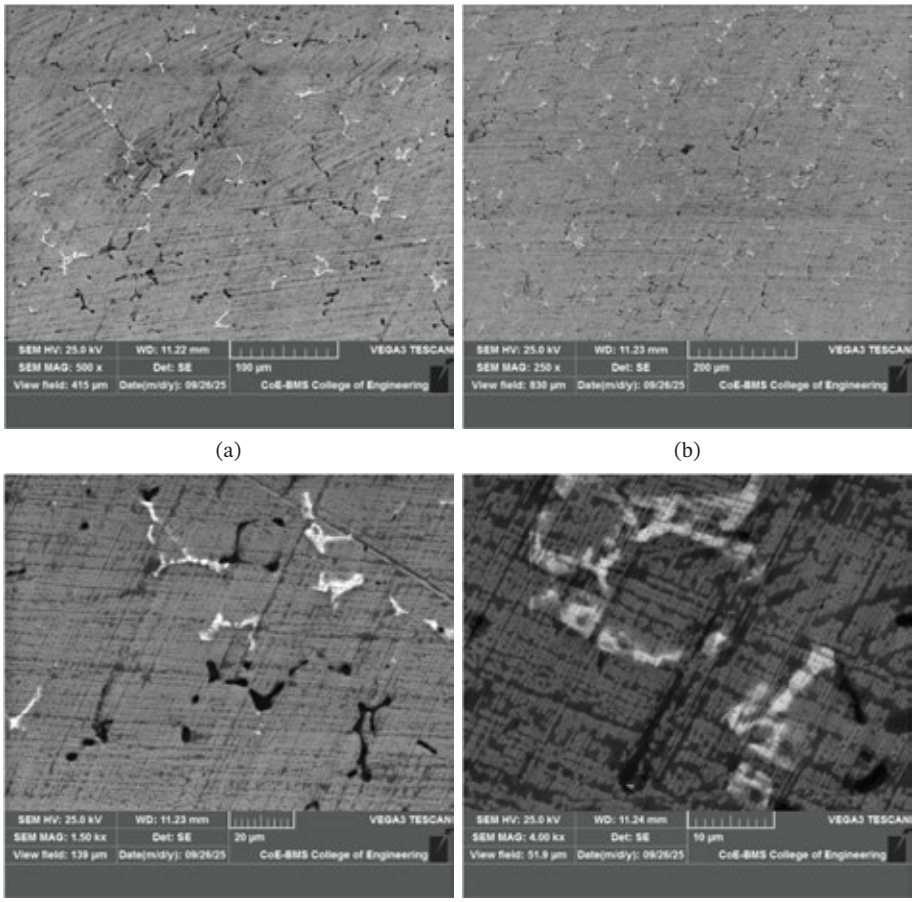
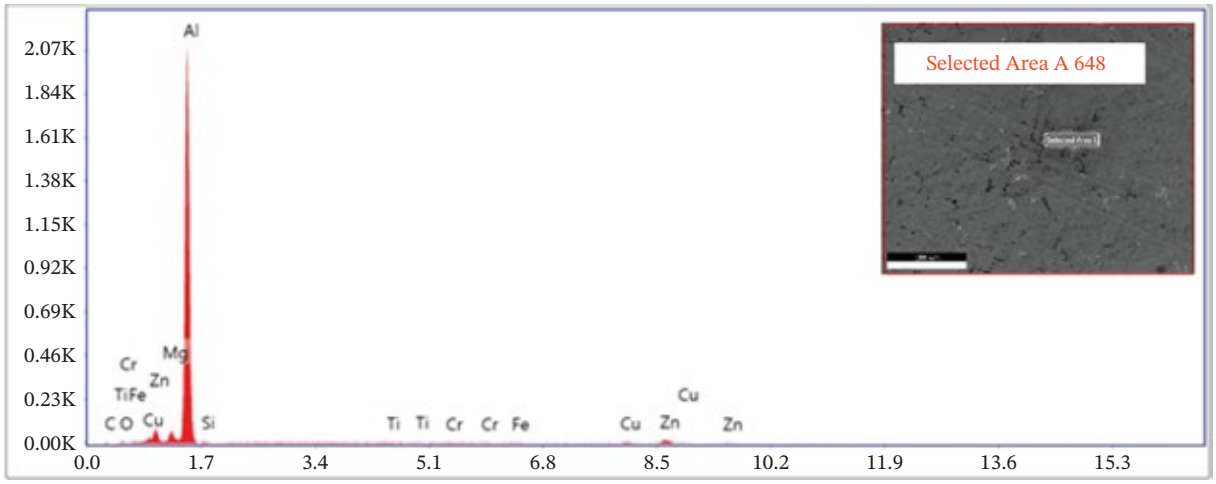


FIGURE 6 | High-resolution SEM micrographs of sample S4 (Al7075 + 9% SiC + 2% Al_2O_3) at different magnifications. (a) Low magnification showing overall homogeneous microstructure; (b) medium magnification highlighting uniform dispersion of SiC and Al_2O_3 particles; (c) higher magnification revealing grain refinement and particle–matrix interfaces; (d) very high magnification showing strong interfacial bonding and reduced porosity.

Al7075, and traces of Ti, Cr and Fe correspond to typical compositional inclusions. The spectrum validates the homogeneous incorporation of reinforcements without significant clustering, supporting the microstructural observations from SEM. Overall, the multiscale SEM analysis together with EDAX mapping provides a comprehensive picture of reinforcement distribution, elemental composition and interface quality. These results confirm microstructural homogeneity, thermal stability, wear



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FIGURE 7 | EDAX spectrum of Sample S4 (Al7075 + 9% SiC + 2% Al_2O_3).

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resistance contribution and interfacial bonding in Al7075–SiC–Al_2O_3 hybrid composites.

3.3 | Testing of Mechanical Properties

Tensile specimens were prepared (as per ASTM E8M04 standard) to test the tensile strength of the fabricated hybrid composites, as shown in Figure 8, and the specimens after completing the tests are shown in Figure 9. Apart from tensile tests, Vickers microhardness tests were also carried out on the specimens. The results are given in Table 6.

All the samples were tested using computerized universal testing machine (MTS Insight: Electromechanical and 100 KN standard length), in which the force can be increased constantly at room temperature.

In the Vickers hardness test (VHN), the specimen is indented with a diamond indenter, having the shape of a right pyramid on a square base and 136° angle between opposite faces, with different load settings (1 Kgf to 100 Kgf) applied for about 15 s. The dimensions of the two diagonals made by the indenter on the surface of the specimen are measured by an inbuilt microscope for calculating the average value. Vickers hardness is generally calculated by dividing the load (in Kgf or N) by the square of indentation area (in mm) as shown in the following equation:

$$\mathrm{VHN} = 2\mathrm{P}\sin\frac{(\theta/2)}{D^2}, \tag{2}$$

where P is the applied load in Newtons, D is the mean diagonal of the indenter in mm, and θ is the angle between opposite faces of the diagonal (136°). For each specimen, readings have been taken in three places and the average calculated. The tests were carried out with an applied load of 0.49 kg and for 15 s.

An analysis of the above results reveals that an increase in the SiC addition has improved the tensile strength and the hardness of the composites. The tensile strength has increased from 248 (for 3wt % of SiC) to 325 MPa (for 9wt % SiC), which shows an gradual increase in tensile strength as the hard SiC particles. Improvement in yield strength shows a similar pattern. It is quite obvious that the hardness of the reinforcement particles contributes to the increment of hardness values as the addition of SiC is increased.

Many researchers, including [21], have shown in the past that the inclusion of hard ceramic particles in lighter materials like Al and its alloys significantly increases the hardness of the composite. Sujan et al. [22] investigated the mechanical properties of as-cast Al7075–SiC and Al7075–Al_2O_3 composites separately and observed significant improvements in tensile strength and

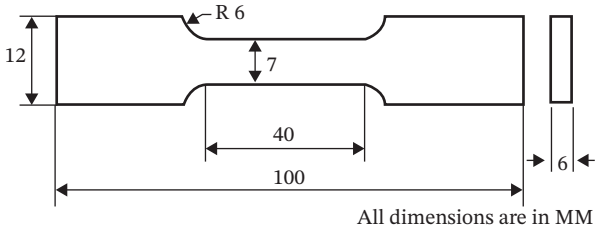


FIGURE 8 | Schematic drawing of tensile specimen (as per ASTM E8M04 standard).



FIGURE 9 | Photograph of fractured tensile specimens.

hardness. The tensile strengths obtained were 262.2 MPa for 5% Al_2O_3, 276 MPa for 10% Al_2O_3 and 282.9 MPa for 15% Al_2O_3, as well as 258.8 MPa for 5% SiC, 293.3 MPa for 10% SiC and 310.5 MPa for 15% SiC. However, the hybrid composite, which contains both SiC and Al_2O_3 reinforcements in lower proportions, can yield superior results, as observed in Table 6 of our study. Similarly, Sridhar et al. [15] studied the tribological properties of Al7075–SiC–Al2O3 composites for gear fabrication and obtained VHNs of 66 for Al 7075 + 3% SiC + 5% Al_2O_3, 73 for Al 7075 + 6% SiC + 5% Al_2O_3 and 98 for Al 7075 + 9% SiC + 5% Al2O3. The corresponding tensile strengths were 166 MPa, 366.45 MPa and 228.6 MPa, respectively. A comparison with our study, as shown in Table 6, demonstrates superior results with lower reinforcement proportions, which could be attributed to the effectiveness of the stir casting method employed. Ramakoteswara Rao et al. [23] conducted mechanical and wear tests on Al7075–SiC–Al_2O_3 composites with different proportions and found that the composite with 5 wt % SiC and 5 wt % Al_2O_3 produced superior results compared to other compositions. It can be observed from the results that the elongation percentage (strain-to-failure) has been reduced from 3.4 (Specimen 1) to 2.1 (Specimen 4). This is because hard ceramic particles impart brittleness to the composite and reduce ductility of the composite in proportion to their inclusion. Weak interface bonding may also cause ineffective load transfer and contribute to the reduction in elongation property of the composite. The property values of the four samples (tensile, yield, percentage elongation and microhardness) are provided in graphical form in Figure 10 above.

The composite that contained the highest percentage of reinforcement (9 wt % SiC + 2wt % Al_2O_3) shows maximum values of tensile and yield strengths (325 MPa and 107 MPa, respectively), which amounts to an increase of 70.15% in tensile strength and 37.17% in yield strength compared to base alloy values (tensile strength: 191 MPa and yield strength: 78 MPa) for the same. It can also be noticed that all composites show higher tensile and yield strength than the base alloy because of the inclusion of hard reinforcement materials. Also, improvement in hardness contributes to an increase in tensile strength. It can be observed from Table 6 that heat-treated composites show a substantial enhancement in tensile strength, yield strength and hardness compared to as-cast samples. The heat treatment of the base matrix material as well as the hybrid composites has produced good results after heat treatment. The composite with the maximum percentage of reinforcements (9wt % SiC + 2wt % Al_2O_3) has shown tensile strength and yield strength values of

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TABLE 6 | Mechanical test results of AMMC specimens.

Sample name	Sample identification	UTS (MPa)		YS (MPa)		Percentage elongation		Hardness (VHN)	
		As cast	Heat-treated	As cast	Heat-treated	As cast	Heat-treated	As cast	Heat-treated
S1	Al7075 + 3% SiC+ 2% Al_2O_3	248	506.2	81	428.9	3.4	1.68	96	186
S2	Al7075 + 5% SiC+ 2% Al_2O_3	272	522.6	90	439.25	2.5	1.3	105	191
S3	Al7075 + 7% SiC+ 2% Al_2O_3	294	538.3	99	453.12	2.4	1.24	112	197
S4	Al7075 + 9% SiC+ 2% Al_2O_3	325	553.1	107	465.5	2.1	1.1	119	204.5

553.1 MPa (16.2% increment) and 465.5 MPa (17.6% increment), respectively, compared to the base alloy values of 476.2 MPa and 396 MPa for tensile and yield strengths, respectively. The formation of close-packed grains due to heat treatment could be attributed as the reason for this effect. Heat-treated specimens of the base alloy as well as the reinforced composites have provided enhanced tensile and yield strengths compared to as-cast samples. Ravikumar et al. [24] conducted wear and mechanical tests on heat-treated Al7075–SiC–Al_2O_3 hybrid composites and reported VHN of 113 for 3% SiC/2% Al_2O_3, 116 for 6% SiC/2% Al_2O_3 and 120 for 9% SiC/2% Al_2O_3 at a heat treatment temperature of 180°C. Since our heat treatment was carried out under T6 conditions (460°C–530°C), the process has produced higher values.

The amount of reinforcement added (weight fraction) and the interface strength (wettability level) impact the elongation property of the hybrid composite. The base alloy comprising metals has good ductility (% elongation is 4), but the effect of heat treatment reduces it (% elongation is 2.1); apart from the effect of adding hard reinforcement particles, the hardness imparted by heat treatment can also be attributed to it. The heat-treated base alloy reveals 2.1% elongation, while the composite with maximum reinforcement composition (9 wt % SiC + 2wt % Al_2O_3) provides a meagre 1.1% elongation, showing a reduction of 52% in ductility. The heat-treated composites have provided only about 50% of the elongation values compared to as-cast samples. The resistance to ductile deformation caused by hard ceramic particles resists elongation in as-cast composites, while grain refinement and microstructural changes due to heat treatment further reduce ductility and increase hardness. Prasad et al. [25] stated that A356 + SiC composites exhibited significantly less elongation compared to its base material and attributed this to the addition of hard ceramic reinforcements.

The values of hardness of the fabricated samples obtained through Vickers hardness tests are given in Table 6. The maximum improvement in hardness is 21.4% for the composition of Al7075 + 9 wt % SiC + 2 wt % Al_2O_3, as can be seen from the graphs of Figure 10a–d. The effect of the addition of hard ceramic particles (SiC and Al_2O_3) is evident from the results, as the hardness values increase gradually with increasing reinforcement in both as-cast and heat-treated specimens. Dislocation movements/deformation mechanisms that lead to failure of ductile materials are resisted by the reinforcement materials added to the base ductile alloy at the interfaces. This effect was explained by a 3D model by Ayyar and Chawla [26], which is also referred to as the Orowan strengthening mechanism that increases the yield strength of the composite.

3.4 | Fracture Analysis of Tensile Failure Specimens

Analysis of the fractured surface of the tensile specimen revealed that the base ductile alloy produces a greater number of dimples due to prolonged deformation, while the composite fracture shows a lower number of dimples. This is because failure in composites is caused at clustered reinforcement particles, where cracks begin and propagate due to the concentration of stress at these points. With an increase in reinforcement percentage in the composite, the dislocations occurring due to load at many zones in the ductile matrix material are resisted in large numbers. This

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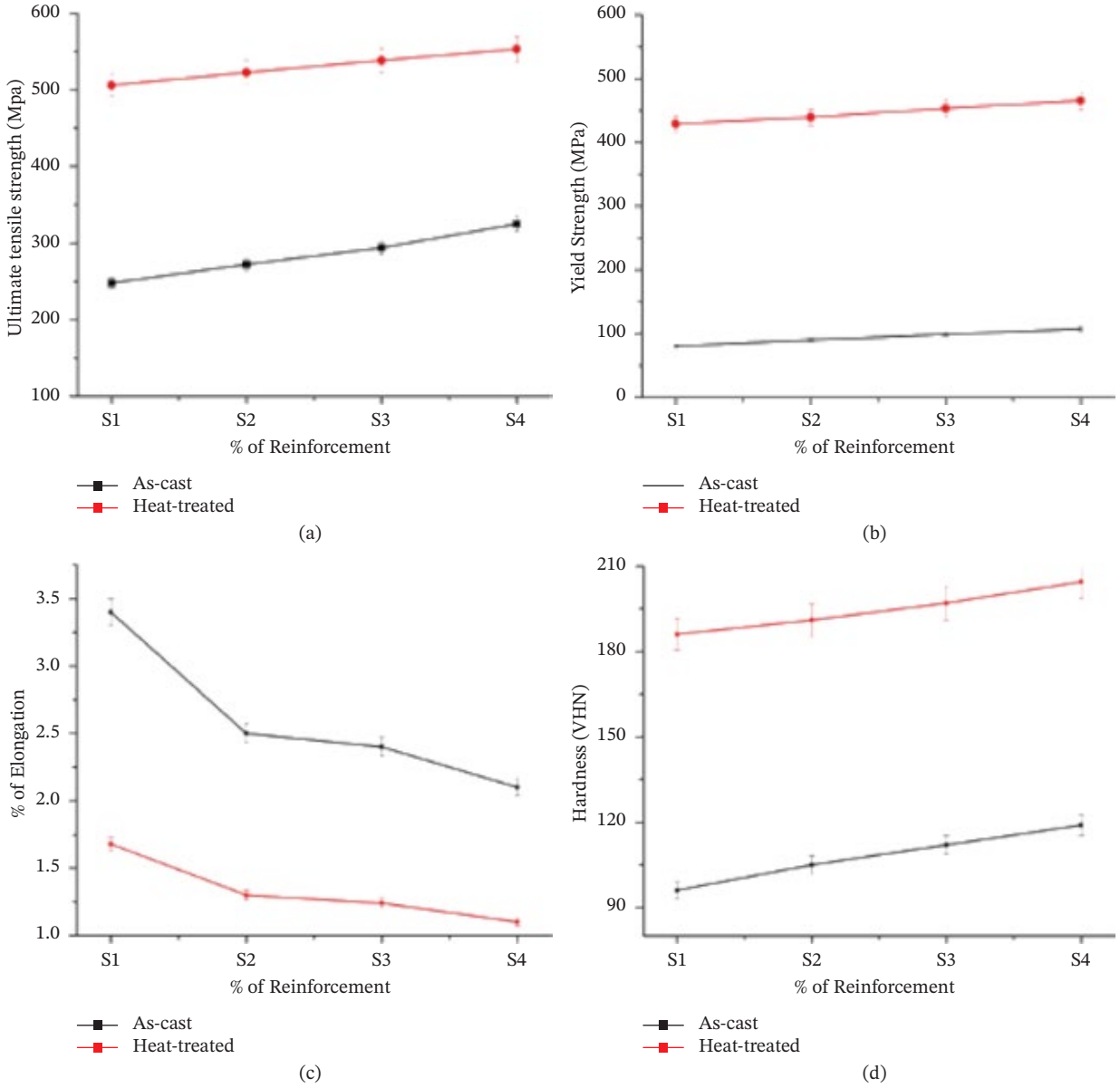


FIGURE 10 | (a) Ultimate tensile strength of as-cast and heat-treated AMMC specimens. (b) Yield strength of as-cast and heat-treated AMMC specimens. (c) Percentage elongation of as-cast and heat-treated AMMC specimens. (d) Hardness of as-cast and heat-treated AMMC specimens.

causes dislocations to pile up, creating high dislocation density. In such areas, the occurrence of deformation is very low, and the failure is of a brittle type [27–29]. Figure 11 (S1–S4) presents the SEM fractographs of as-cast Al7075/SiC/Al_2O_3 composites taken using fractured tensile test samples.

It can be observed that the composite breaks in a transgranular fashion, as it mostly contains ductile matrix material that can absorb energy until final failure. Initiation of cracks happens at the reinforcement zone, where cracks join together to form a larger crack, forming a void. These further progress to cause failure in ductile–brittle mode, as a composite contains both ductile (matrix in bulk) and hard (reinforcement in lesser quantity) materials. The SEM picture of S1 (composition: Al7075 + 3 wt % SiC + 2% Al_2O_3) depicts reinforcements in a river-like pattern caused by intermetallic precipitation formed during heat treatment, and such a tendency can be seen in other compositions also. With an increase in reinforcement material, the tendency for brittle failure of the composite increases. The as-cast micrographs show separated particles unlike the river patterns found in the heat-treated samples. Conducted tensile fractography on Al7075–Al_2O_3–SiC hybrid composites and observed particulate fractures of the reinforcements and pullouts. These findings align with our fractographic analysis, which reveals that stress concentration at clustered reinforcement particles initiates cracks and ultimately leads to failure.

3.5 | Strengthening Mechanisms

3.5.1 | Hall–Petch Strengthening (Through Grain Refinement)

The inclusion of SiC and Al_2O_3 particles promotes heterogeneity in the composition, leading to increased nucleation during solidification, which results in grain refinement.

Hall–Petch expression is as follows:

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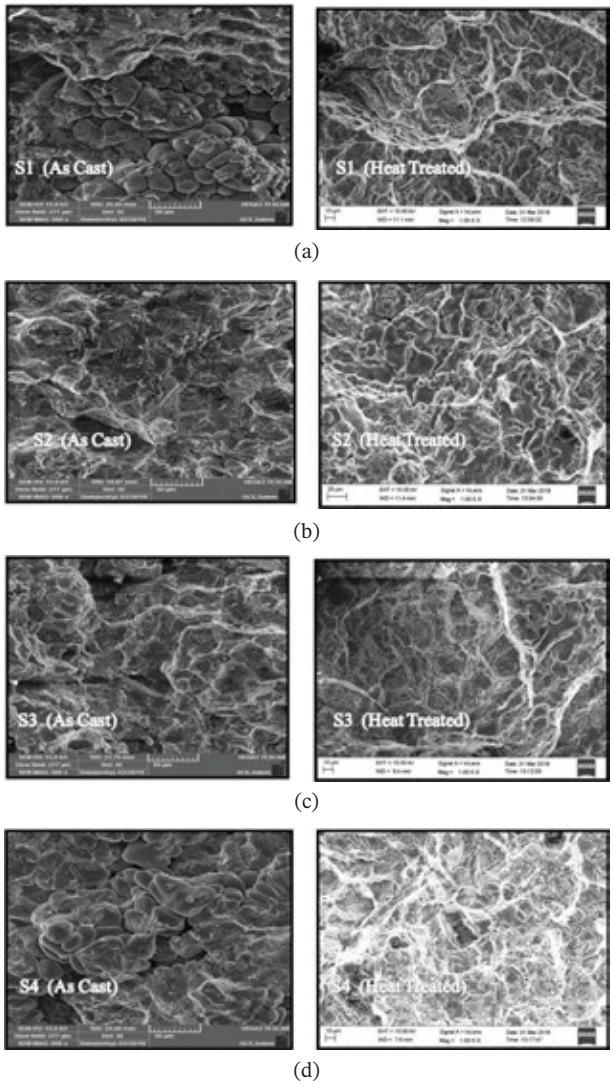


FIGURE 11 | (S1–S4): Fractured images of as-cast and heat-treated composites with various compositions. (a) Al7075 + 3% SiC + 2% Al_2O_3. (b) Al7075 + 5% SiC + 2% Al_2O_3. (c) Al7075 + 7% SiC + 2% Al_2O_3. (d) Al7075 + 9% SiC + 2% Al_2O_3.

$$\sigma_y = \sigma_0 + kd^{-1/2}, \tag{3}$$

where

- σ_y = yield strength
- σ_0 = friction stress
- k = Hall–Petch constant
- d = average grain size

The increased percentage of SiC (3 wt % to 9 wt %) reduces grain size due to an increased number of nucleation sites during the T6 heat treatment of the composites. The number of grain boundaries increases as the grain size is reduced, which increasingly restricts dislocation movement. Thus, the strength of the composite increases with the increase in percentage of reinforcement particles.

3.5.2 | Orowan Strengthening (Particle Strengthening)

The hard, brittle, nonshearable fine particles of SiC and Al_2O_3 can restrict dislocation motions and strengthen the composite.

The expression is as follows:

$$\Delta\sigma_{(\text{Orowan})} \propto \frac{Gb}{\lambda}\ln\left(\frac{r}{b}\right), \tag{4}$$

where

- G = shear modulus
- b = Burgers vector
- λ = interparticle spacing
- r = particle radius

As per the Orowan strengthening mechanism, the increased percentage of reinforcement particles (particularly SiC) decreases interparticle spacing (λ) and this smaller spacing increases obstruction, leading to higher strength. The reduced interparticle spacing forces the dislocations to form loops around the particles, which increases the stress required to cause plastic deformation.

3.6 | Combination of Mechanisms for Strengthening the Composites

The overall strengthening is the combined effect of Hall–Petch's grain refinement, Orowan looping, load transfer from matrix to reinforcement and an increase in dislocation density caused by thermal mismatch between the matrix and the reinforcement during the heat treatment process.

3.7 | Explanation for High SiC Success Without Clustering

The uniform distribution of SiC particles even at higher weight percentages (9 wt %) can be attributed to many factors.

Good processing parameters such as stirring speed and time, preheating of particles and inclusion of wetting agents like Mg (Al7075 contains Mg) have contributed to resisting clustering.

The addition of Al_2O_3 (constant 2 wt % in all compositions) can act as a dispersion stabilizer minimizing SiC agglomeration and also promoting a more homogeneous microstructure.

The strong interfacial bond formed between the matrix and reinforcements due to the above optimal parameters can reduce particle mobility during solidification, preventing clustering.

The SEM micrographs also reveal a fairly uniform dispersion of reinforcements with very little clustering even at 9 wt % of SiC, indicating homogeneous particle inclusion in the composites.

4 | Conclusions

The objective of this research is to investigate the effect of the T6 heat treatment on the mechanical properties of the Al7075/3–9 wt % SiC and 2 wt % Al_2O_3 hybrid composites that are fabricated through the stir casting method. The results showed considerable improvement in the mechanical performance of these hybrid

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MMCs. The composite with the highest reinforcement percentage is the optimum composition that provided the maximum property value.

The significant conclusions arrived at from the investigation on Al7075/SiC + Al_2O_3 hybrid composites are listed below. The reinforcements enhanced the hardness of the hybrid composites, which in turn improved the mechanical properties in as-cast condition. These composites when subjected to heat treatment, attained higher hardness due to the formation of intermetallic precipitates and refinement of grains caused by thermal energy.

- Stir casting can be successfully employed to produce homogeneous Al7075+ SiC + Al_2O_3 hybrid composites.
- Addition of magnesium powder during casting enhances wettability, resulting in uniform dispersion of reinforcements in the composite.
- The mechanical properties such as tensile strength, yield strength and hardness of the composites were enhanced due to the addition of hard SiC and Al_2O_3 ceramic particles into the ductile Al7075 base alloy in as-cast as well as in heat-treated conditions.
- The percentage elongation of the composites decreased with the increase in the reinforcement percentage, as they impart hardness and reduce the ductile property.
- Study of microstructures of the composites showed the regular distribution of reinforcements in the base alloy matrix.
- The combination of high-resolution SEM and EDAX elemental mapping provided strong evidence for the successful incorporation and uniform dispersion of SiC and Al_2O_3 reinforcements within the Al7075 matrix. Multiscale SEM images confirmed grain refinement, reduced porosity and clean reinforcement–matrix interfaces, while EDAX spectra validated the presence and homogeneous distribution of the reinforcements alongside the base alloying elements.
- The fracture analysis revealed that the addition of hard ceramic particles like SiC and Al_2O_3 could cause a ductile + brittle mode of failure in the composite, depending on the proportion of inclusion of the reinforcements.

This area of AMMC offers a lot of research potential, as different reinforcement materials in different proportions can be explored, or the parameters of the stir casting process optimized for enhanced property outcomes.

4.1 | Limitations of the Present Study

The present investigation is limited to the evaluation of basic mechanical properties such as tensile strength, yield strength, elongation and hardness, along with qualitative microstructural analysis and study of the influence of T6 heat treatment under a single set of heat treatment parameters due to limitations of time and resources.

4.2 | Scope for Future Work

Future work in this area could focus on the study of tribological behaviour, fatigue performance and corrosion resistance of the hybrid composite to obtain complete material characterization data. Moreover, a scalability study would be beneficial for industrial applications.

Author Contributions

Pugalenthi Palanisamy conceived and designed the experiments and writing. Subburam Venkatajalapathy performed the experiments and supervised. Gunasekaran Raji analysed the data and materials/analysis tools. Haiter Lenin Allasi reviewed and edited. All authors reviewed the manuscript. All authors were involved in editing the final manuscript.

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Disclosure

All authors read and approved the final manuscript.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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