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INFLUENCE OF T4 AND T6 HEAT TREATMENTS ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF STIR CAST AL6061–SIC COMPOSITES

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Abstract: This study investigates the influence of T4 and T6 heat treatments on the microstructure and mechanical properties of Al6061–SiC metal matrix composites fabricated via stir casting. The composite was reinforced with silicon carbide (SiC) particles and subjected to T4 (solution treatment and quenching) and T6 (solution treatment, quenching, and artificial aging) heat treatments. Microstructural analysis was carried out using optical microscopy, revealing significant changes in grain structure, particle distribution, and porosity across the different conditions. Mechanical properties were evaluated through Vickers microhardness testing following the ASTM E92-23 standard and compressive strength measurements. The results showed minimal change in hardness between the as-cast and T4-treated samples, with a notable increase in the T6-treated sample due to precipitation hardening. Compressive strength improved progressively from 217.91 MPa in the as-cast condition to 264.28 MPa in the T4-treated, and reached 301.84 MPa in the T6-treated condition. The study confirms that T6 heat treatment significantly enhances both the microstructural refinement and mechanical performance of stir cast Al6061–SiC composites.

1. Introduction:

Aluminum matrix composites (AMCs) have emerged as a class of advanced materials offering superior mechanical, thermal, and wear-resistant properties, making them suitable for aerospace, automotive, and structural applications.[1]–[3] Among various aluminum alloys, Al6061 is widely preferred due to its balanced combination of strength, corrosion resistance, machinability, and heat treatability.[4]–[6] Al6061 is a precipitation-hardenable alloy containing magnesium and silicon, which allows enhancement of its properties through suitable thermal treatments such as T4 (solution treatment followed by natural aging) and T6 (solution treatment followed by artificial aging).[7] The incorporation of ceramic reinforcements, particularly silicon carbide (SiC), into the Al6061 matrix using stir casting—a liquid metallurgy process—further enhances the mechanical performance of the alloy.[8], [9] Stir casting is recognized for its cost-effectiveness, simplicity, and ability to produce near-net shape composite materials with fairly uniform reinforcement distribution. The use of preheated SiC particles during stirring reduces thermal mismatch and helps achieve a homogenous dispersion, minimizing defects like porosity and agglomeration[10]. In this study, Al6061 is reinforced with silicon carbide particles through stir casting, and the fabricated composites are subjected to hardness testing, compressive strength evaluation, and optical microstructure analysis. Additionally, the effect of post-fabrication heat treatment under T4 and T6 conditions is investigated. Prior research indicates that T6-treated Al6061 composites exhibit significant improvements in hardness and strength due to the formation of coherent Mg2Si precipitates[11], [12]. For instance, the hardness of Al6061 improves from 65 BHN in T4 to 95 BHN in T6, while tensile strength increases from 241 MPa to 310 MPa respectively. Previous investigations showed that the addition of 5 wt% SiC particles to Al6061 enhanced hardness by approximately 12.5% and improved tensile strength up to 288 MPa, attributing the improvement to the strong interfacial bonding and load-bearing capacity of the SiC particles.[13] Similarly, the compressive strength of Al6061-SiC composites also increases with higher reinforcement content due to the load transfer mechanism and dislocation pinning effect[14]. Heat treatment further influences the microstructural refinement and mechanical performance of the composites. The T6 treatment, in particular, promotes precipitation hardening and better stress distribution at the matrix-reinforcement interface, thereby increasing both strength and wear resistance.

This research aims to provide a comprehensive analysis of Al6061–SiC composites prepared by stir casting, focusing on the impact of SiC reinforcement and heat treatment (T4 and T6) on mechanical properties such as hardness, compressive strength, and microstructure. By understanding these effects, the study seeks to contribute to the development of high-performance aluminum composites for structural applications.

2. Materials and methods:

2.1. Materials:

The matrix material used was commercially available Al6061 alloy, chosen for its excellent mechanical properties and response to heat treatment[7], [15]. The reinforcement used was silicon carbide (SiC) particles with 50 µm in 5 wt%, selected due to their high hardness, wear resistance, and compatibility with aluminium[4], [16], [17].

Table 1: Chemical composition of Al6061 alloy (wt%):

Sample	Si	Cr	Cu	Fe	Mg	Mn	Ti	Zn	Al
Al6061	0.6	0.23	0.18	0.36	0.93	0.12	0.14	0.22	Bal

3. Experimental setup:

Al6061 alloy ingots were charged into a graphite-coated crucible and melted in an electric resistance furnace. The furnace temperature was maintained at 800°C, which ensured complete melting and appropriate fluidity of the matrix alloy. A manual stirring technique was employed to ensure uniform mixing of the reinforcement particles. The stirrer rod used for this purpose was coated with graphite to avoid contamination and unwanted reactions with the molten metal[18]. Stirring was conducted at regular intervals for an adequate duration to promote even distribution of SiC particles and reduce agglomeration. Preheated SiC particles were gradually added to the molten metal during the stirring process to improve wettability and reduce thermal shock. After adequate stirring, the molten composite was poured into a preheated sand mould of dimensions 30 mm × 100 mm × 20 mm. The sand moulds were chosen for their simplicity and ability to replicate near-net shapes with acceptable surface finish. The mould cavities were prepared to withstand thermal loads and were dried thoroughly before pouring. The poured molten composite was allowed to cool at room temperature under ambient conditions. After solidification, the composite samples were removed from the mould and subjected to further processing.

The solidified samples were divided into three sets: as-cast, T4-treated, and T6-treated. T4-treated: Samples were solution treated at approximately 490°C for 2 hours, followed by natural aging at room temperature. T6-Treated: Samples were solution treated at 490°C for 2 hours, followed by artificial aging at 210°C for 4 hours to achieve precipitation hardening.

The fabricated and heat-treated samples were tested for hardness, compressive strength, and microstructural features. Brinell hardness was measured using a standard tester with a steel ball indenter. Compressive strength was evaluated using a Universal Testing Machine (UTM) in accordance with ASTM standards. For microstructural analysis, specimens were polished, etched, and examined under an optical microscope to observe the distribution of SiC particles and grain structure.

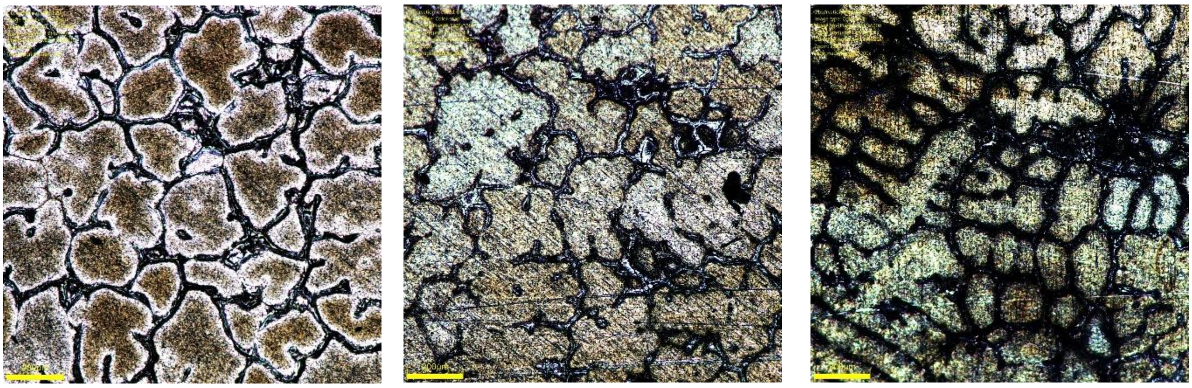
4. Results and discussions:

4.1 Porosity:

Fig. 1: Porosity in stir casted Al6061 + SiC (5 %wt) sample

The observed porosity in the stir-casted composite can also be attributed to incomplete degassing of the molten alloy and oxidation during stirring, which traps gases like hydrogen within the matrix. The high surface area of SiC particles can further contribute to gas entrapment, especially if they are not preheated properly before addition. These pores typically appear as rounded or irregular voids in the microstructure and are often concentrated near particle clusters or regions of turbulence. Porosity not only weakens the mechanical integrity but also acts as a stress concentrator, potentially leading to early failure under load [19]. To minimize porosity, careful control of stirring speed, melt temperature, particle preheating, and degassing techniques is essential during processing.

4.2 Optical Microscopy:



(a) (b) (c)

Fig. 2:Optical microscopy image of (a) stir casted(b) T4-treated (c) T6-treated Al6061 + SiC sample

Based on optical micrography observations taken at 200X magnification, the microstructural evolution of the stir-casted Al6061–SiC composite under different conditions—As-Cast, T4-treated, and T6-treated—has been clearly noted. In the As-Cast condition, the microstructure reveals a dendritic α-Al matrix with a non-uniform distribution of SiC particles[20]. There is noticeable porosity and micro-segregation resulting from solidification, along with the presence of coarse intermetallic compounds and grain structures. Additionally, due to limited wettability during casting, SiC particles appear to cluster in certain regions. After T4 heat treatment (solution treatment followed by quenching), the grain boundaries become more homogenized and the SiC particles are more evenly dispersed. This is due to the dissolution of secondary phases during solutionizing, which also leads to a reduction in segregation. Slight coarsening of the grains is observed, along with a decrease in microvoids. Upon applying the T6 heat treatment (T4 followed by artificial aging), the microstructure further refines, showing fine and uniformly distributed precipitates such as Mg_2Si and AlFeSi. The grain structure appears uniform, with well-dispersed SiC particles and significantly reduced porosity. The aging process also introduces finely distributed precipitates that enhance the grain boundary strength and improve the overall particle–matrix interface. These observations confirm a progressive improvement in microstructural uniformity and integrity from the As-Cast to the T6-treated condition.

4.3Hardness:

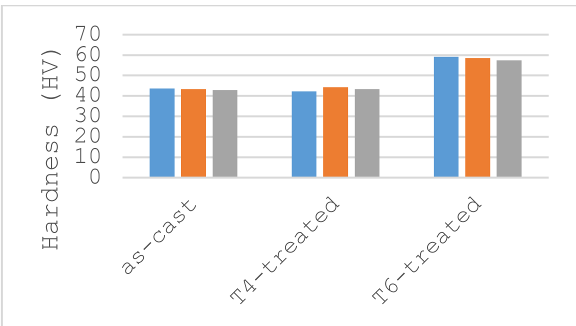


Fig. 3: Hardness comparison of as cast, T4-treated and T6-treated composite

The microhardness of the stir-casted Al6061–SiC composite was evaluated in accordance with the ASTM E92-23 standard using the Vickers hardness testing method. The results revealed notable differences in hardness across the three conditions: As-Cast, T4-treated, and T6-treated. In the As-Cast condition, the average hardness was measured to be 42.26 HV, reflecting the baseline mechanical properties of the composite in its solidified state, with limited precipitation and the presence of casting defects such as porosity and micro segregation. Following T4 heat treatment (solution treatment and quenching), the hardness remained nearly unchanged at 42.23 HV, indicating that while the structure was homogenized and segregation reduced, the absence of aging meant no significant precipitation strengthening occurred. However, with the application of T6 heat treatment (T4 followed by artificial aging), the average hardness increased significantly to 58.33 HV. This marked improvement is attributed to the formation of fine, uniformly distributed Mg_2Si precipitates during aging, which enhance the composite's resistance to localized plastic deformation. These findings confirm that the T6 condition provides the greatest improvement in hardness due to effective precipitation hardening mechanisms.

4.4 Compressive strength:

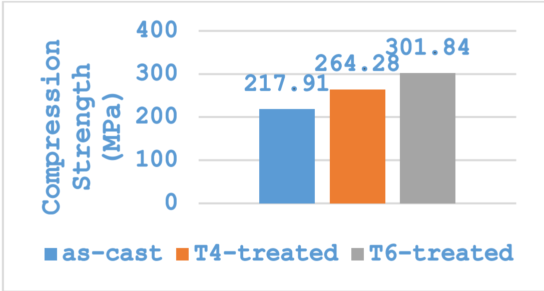
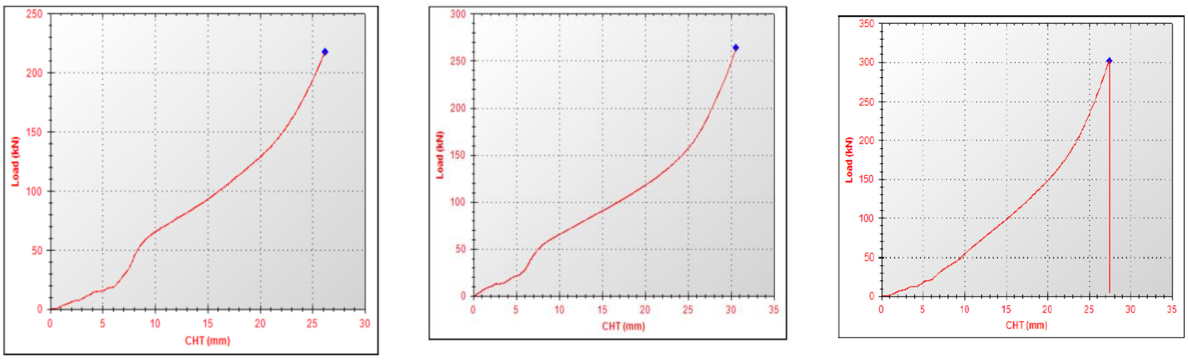


Fig. 4: Compression strength comparison of as cast, T4-treated and T6-treated composite

The compressive strength of the stir-casted Al6061–SiC composite increased with heat treatment. The As-Cast sample showed a strength of 217.91 MPa, limited by casting defects and coarse structure. After T4 treatment, the strength improved to 264.28 MPa due to microstructural homogenization and better SiC dispersion. The highest strength was observed in the T6-treated sample at 301.84 MPa, resulting from precipitation strengthening and improved particle–matrix bonding.



(a) (b) (c)

Fig. 5: Load vs Deflection graph of (a) as-cast (b) T4-treated (c) T6-treated Composite

5. Conclusion:

The present study highlights the significant influence of T4 and T6 heat treatments on the microstructure and mechanical properties of stir cast Al6061–SiC composites. Key findings are as follows

- As-cast samples exhibited coarse dendritic structures, uneven SiC particle distribution, and visible porosity under 200X magnification

- T4 heat treatment improved the uniformity of the microstructure and enhanced particle dispersion
- T6 treatment further refined the microstructure through the formation of fine precipitates and stronger particle–matrix bonding
- The average Vickers microhardness values were 42.26 HV for as-cast, 42.23 HV for T4-treated, and increased significantly to 58.33 HV for T6-treated composites due to effective precipitation hardening
- Compressive strength improved from 217.91 MPa in the as-cast condition to 264.28 MPa after T4 treatment and further to 301.84 MPa with T6 treatment

Overall, while T4 treatment improves structural uniformity, T6 treatment results in significant enhancements in both hardness and compressive strength, making it highly effective for structural and load-bearing applications of Al6061–SiC composites.

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