Microstructural and Mechanical responses of Al6061 alloy matrix composite reinforced with yttria particles

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Abstract

The increasing need for materials that can improve the overall performance of automotive and aerospace components has driven the development of composite materials. Aluminium Metal Matrix Composites (AMMC) have become a popular alternative due to their ability to satisfy the changing needs of industries. This study investigates the mechanical characteristics of AMMC (Aluminium Matrix Metal Composite) made using the stir casting method. The study examines the effects of different amounts of Y_2O_3 *(yttria/YO) reinforcement, specifically at 1wt%, 2wt%, and 3wt%, when combined with aluminium alloy 6061. By conducting thorough evaluations of density, hardness, and tensile strength, it was shown that the composite containing 3wt% of yttria demonstrates superior characteristics in comparison to base aluminium. The hardness and ultimate tensile strength of composite having 3wt% of yttria is 26% and 42.2% more than the base alloy Al6061. The microstructural characteristics of the composites were meticulously examined employing Scanning Electron Microscopy (SEM). The uniform dispersion of the reinforcement within the matrix has been found. As the quantity of yttria is increased, the grain size becomes finer. The failure of composites shows the ductile to brittle fracture due to the presence of yttria particles*.

Keywords: Aluminum Metal Matrix Composite, yttria, hardness, tensile strength, microstructure, fractography.

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INTRODUCTION

Aluminum Metal Matrix Composites (Al MMCs) have solidified their position as a cornerstone across a spectrum of industries, spanning aerospace, sports, automotive, and defence sectors. This prominence is attributed to their exceptional strength-to-weight ratio and commendable resistance to corrosion and wear. Notably, the 6XXX series within the realm of Al alloys, featuring magnesium and silicon as primary alloying elements, emerges as a versatile candidate for applications demanding high-stress tolerance, such as trusses, bridges, and transportation components (1–3).

Bouaeshi et al. delved into the realm of aluminium microstructure and mechanical properties, specifically focusing on the impact of Y_2O_3 (yttria) addition through arc melting. The findings unveiled a fascinating phenomenon: an increase in yttria content resulted in a finer aluminium microstructure. Equally noteworthy was the substantial enhancement in hardness and resistance against wear observed in aluminium samples enriched with yttria (4–6).

Kim et al. further advanced the discourse by scrutinizing the dispersion characteristics of Y_2O_3 powders in molten aluminium. Their investigation revealed a pivotal threshold, with 2wt% of Y_2O_3 content ensuring uniform particle dispersion, while a higher content of 3wt% led to particle aggregation. At 2 wt% Y_2O_3 content, the mechanical properties were noticeably affected by the oxide content difference, with a 1.2-fold increase in hardness (up to 57HV) and a 1.55-fold increase in tensile strength (up to 80 MPa) compared to pure aluminium (7).

Neeraj Kumar Bhoi et al reported a significant improvement in density, micro and nano hardness and Young’s Modulus when the aluminium matrix was doped with yttria (0 to 5wt%). The composite exhibited higher density due to the strong interfacial bond between Y_2O_3 particles and aluminium. The homogeneous distribution of Y_2O_3 leads to efficient load transfer and the generation of dislocations which have contributed to the Orowan strengthening of the composite. The 5% yttria weighted composite showed an increase in microhardness, nano hardness and Young's module by 61.1%, 143.6% and 80.55% respectively (8).

An extensive investigation into the effects of different Y_2O_3 concentrations (3%, 6%, and 9vol%) on the mechanical and microstructural properties of AA6082 aluminium alloy was carried out by J. Ramesh Kumar et al. The samples were prepared through friction stir processing. The density of samples increased with the increase in Y_2O_3 volume. Hardness showed an enhancing nature as the content of Y_2O_3 increased in composites. This is because of the presence of uniformly distributed hard ceramic particles of Yttria which restrict the movement of dislocations and decrease in interparticle distance. Hardness was increased from 88HV to 140HV (9vol% Y_2O_3). Tensile strength increased with the addition of Y_2O_3 particle volume in composites, which was attributed to good interfacial bonding between uniformly distributed yttria particles and aluminium matrix and refinement of grain size. Maximum tensile strength showed by 9vol% Y_2O_3 sample, 320 MPa (9).

In this regard, the current research aims to contribute uniquely by investigating the effects of Y_2O_3 particles on the mechanical responses and microstructural properties of AA6061 alloy composites. Friction stir processing is a novel technique that is used to create these composites. This investigation aims to fill a significant void in the literature and add to the expanding reservoir of knowledge, especially with the underrepresented topic of composites of AA6061 alloy in existing publications.

EXPERIMENTAL DETAILS

Materials

In this current exploration, the choice of Al-6061 alloy for the specified application is strategic, driven by its exceptional strength-to-weight ratio (SWR), ductility, castability, and resistance to wear and corrosion. Table 1 provides a comprehensive breakdown of the composition of Al-6061 alloy, highlighting its adaptability and appropriateness for the intended use. The yttrium oxide or yttria is used as the reinforcement particle purchased from the Nano Research Lab, Jamshedpur.

Table 1: Chemical composition of AA6061 matrix material (wt.%)

Mg	**Si**	**Fe**	**Mn**	**Al**
0.8-1.2	0.4-0.8	0.7	0.15	Balance

Fabrication method

The current study focused on producing Metal Matrix Composites (MMC) using the stir casting process, which was selected for its versatility and adaptability. The experimentation encompassed varying proportions of reinforcement particles, contributing to the creation of a diverse set of samples.

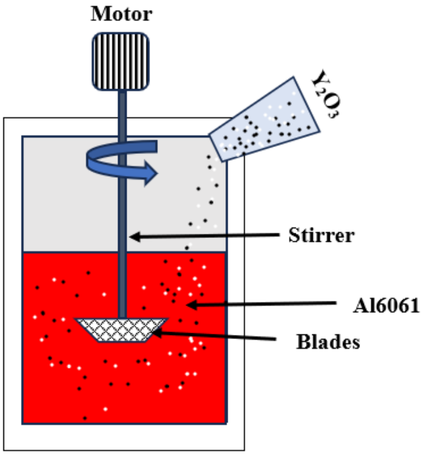

Fig. 1: Schematic diagram of stir casting process

Initially, the required amount of Al 6061 matrix material was added to the crucible of a computer-controlled stir-casting process at NIT, Kurukshetra. To ensure uniform melting of the matrix material, the furnace was heated to 750 °C, which is greater than Al 6061's melting point of 650 °C. The purpose of adding magnesium powder was to make the solid reinforcing materials and molten matrix more wettable (10,11). Upon completion of melting, a stirrer equipped with four flat blades was inserted into the crucible to a depth proportional to one-third of the melt's overall height from the base. The molten matrix was able to undergo vortex formation thanks to the stirring procedure, which was carried out at 500 rpm. A separate furnace was used to warm the reinforcement particles to 300 °C at the same time (12). A 2 lpm flow of inert gas (argon) was used to carefully inject the preheated reinforcing particles into the crucible after the vortex had been formed. After that, the melt was brought up to 630 °C, just above the solidus temperature but below the liquidus temperature. The regular distribution of particles was ensured by the enhanced viscosity caused by this swampy melt phase. The melt's fluidity was improved by increasing the furnace temperature to 680 °C after mixing (13). After thoroughly mixing the ingredients, the mixture was vacuum-poured into a mould that had been preheated. The mould was then let to firm into the appropriate shape. The stir-casting process is illustrated schematically in Figure 1.

RESULTS AND DISCUSSION

Density Measurement

A key aspect being studied in the painstaking effort to comprehend the produced composites is their density. A digital balance exhibiting an astonishing accuracy of ± 0.0001 g was used to undertake precise density measurements, utilizing the venerable principle of Archimedes. The samples that were used for these measurements were all sculpted to have dimensions of 5 mm × 5 mm × 5 mm. Y_2O_3 weightage percentage impacts the density of these surface composites, as seen in Figure 2, which uncovers an intriguing narrative. The produced composites have a discrepancy between their theoretical and experimental densities because of porosity. Increases in porosity were seen in samples with increasing Y_2O_3 level in the matrix. The increase in porosity, as previously observed in the literature, could be due to poor wettability and particle agglomeration (14).

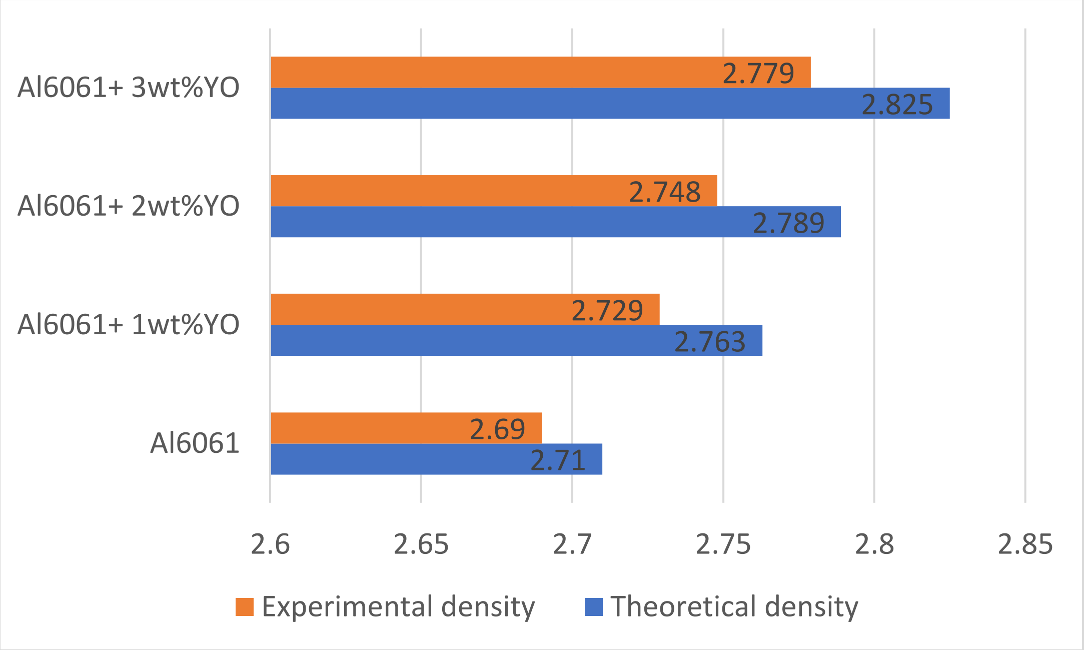

Fig. 2: Comparison of Experimental and Theoretical Density

Microstructural Analysis

As illustrated in Figure 3, the SEM images vividly portray the dendritic structure inherent in the prepared composites, each exhibiting distinctive characteristics contingent upon the varied content of reinforcements. Observation reveals a remarkably consistent dispersion of yttria particles within the matrix, devoid of any discernible particle agglomeration. This dispersion phenomenon is attributed to the introduction of Mg into the melt during composite fabrication, which initiates the formation of a transient interfacial layer between the matrix and the reinforcements. This interfacial layer significantly enhances wettability.

To make sure the yttria particles are well distributed and properly wetted, this interfacial layer lowers the surface tension of the liquid matrix, which allows the particles to encase themselves in a structure similar to the matrix alloy. Detailed examination via SEM imaging underscores the impact of yttria addition on matrix grain size, with a clear inverse relationship observed: as the mass fraction of yttria increases, grain size decreases proportionally. This reduction in grain size is further compounded by the presence of reinforcements at grain boundaries, which exert a pinning effect, impeding grain growth and resulting in smaller, finer grains within the matrix (15).

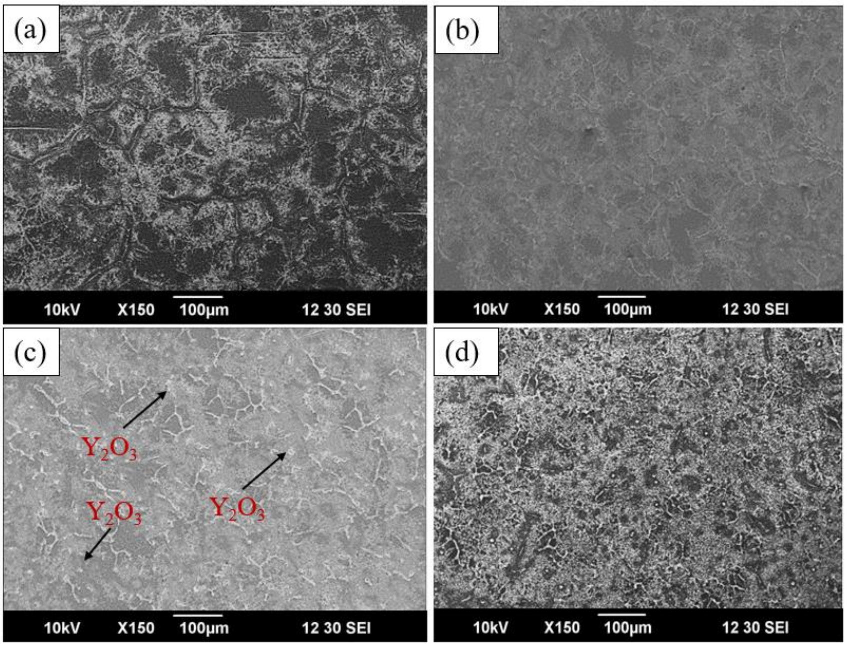

Fig. 3: SEM graphics of specimens (a) Al6061 (b) Al6061 + 1wt%YO (c) Al6061 + 2wt%YO (d) Al6061 + 3wt%YO

Mechanical Analysis

The ductility, microhardness, and tensile strength of AMCs are greatly influenced by the presence of hard yttria particles and the subsequent formation of voids surrounding these particles. The combination of hard yttria particles with a less hard yet ductile matrix results in an increase in hardness through many methods. The higher stiffness and hardness of yttria particles compared to the matrix material impede dislocation movement, with these individual hard reinforcements acting as hindrances within the matrix. The introduction of small yet potent hard reinforcements into the matrix can hinder dislocation motion, provided these reinforcements surpass the strength of the base material (16). As a result, the composite exhibits an increase in both tensile strength and hardness, as illustrated in Figure 4 (17).

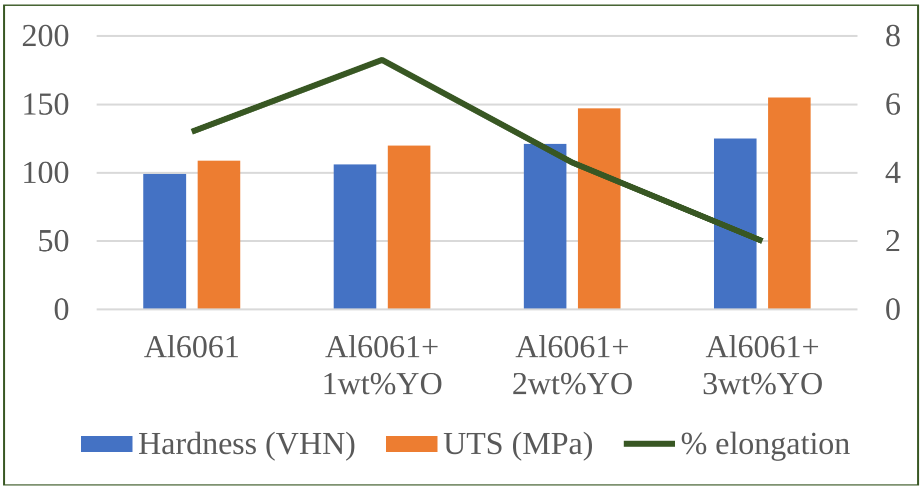

Fig. 4: Variation of Hardness, UTS and elongation with the Y_2O_3 particles

Incorporating reinforced particles also helps to increase hardness by making the matrix material's grain size finer. As the yttria particle content rises, the microstructure is refined because the inclusion of hard particles in the matrix creates favourable heterogeneous nucleation sites for the matrix grains (18). The number of hard yttria particles has a direct impact on the ultimate tensile strength (UTS), as demonstrated in Figure 4. The Orowan mechanism states that the presence of uniformly dispersed, high-weightage, fine, and stable particles acts as barriers to the movement of dislocations, leading to increased strength (19).

As can be seen in Figure 4, the elongation of the samples was also proportional to the yttria particle concentration. One possible explanation is that yttria causes strain hardening when deformed, which in turn reduces ductility (8). The composites' decreased ductility is attributed in part to the presence of porosities, which are especially noticeable at the interface between the AA6061 matrix and the yttria particles.

Fractography

The pivotal determinant of fracture mode in Aluminum Matrix Composites (AMCs) lies in the strength of the particle−matrix interfacial bonding. This critical parameter significantly influences the deformation process, dictating whether particle fracture or decohesion between the aluminium matrix and yttria particles will occur during mechanical stress (20,21). When the interfacial bonding strength is robust, particle fracture takes precedence in the deformation mechanism. Conversely, weaker bonding leads to decohesion between the 2w aluminium matrix and yttria particles before particle fracture ensues.

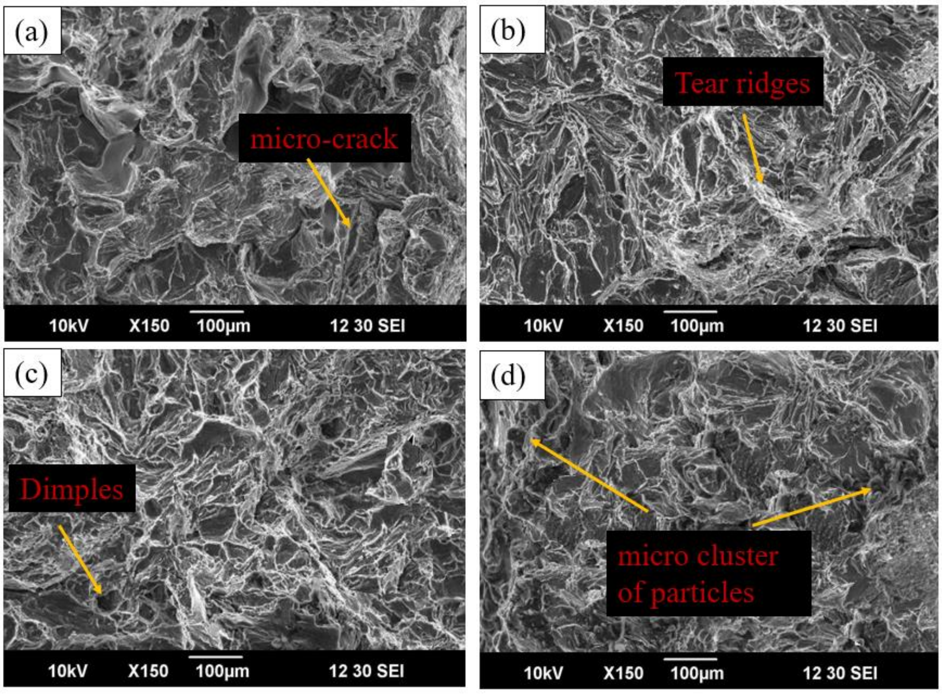

Fig. 5: Fractography images of composite samples (a) Al6061 (b) Al6061 + 1wt%YO (c) Al6061 + 2wt%YO (d) Al6061 + 3wt%YO

Figures 5(a, b, c) vividly illustrate the particle fracture mode in AMCs characterized by strong interfacial bonds. Dimples in the aluminium matrix provide a visual representation of how strong the connection is in this combination. When cracks first begin to form, they are slowed down by the presence of the reinforced particles, which are hard and brittle. After that, the crack travels through the matrix and particles, and eventually, the frwe

cture happens. The fact that the matrix and reinforcement cooperate until the last crack forms is indicative of a strong interfacial connection. However, as shown in Figure 5(d), the composite does in fact contain particle agglomeration. The weakening of the interface bonding between the matrix and reinforcement was caused by the particle clustering. Therefore, reduced tensile strength is the consequence of an easier debonding process caused by a weaker interfacial bond.

CONCLUSION

The fabrication of AA6061−yttria composites was successfully done using the stir casting technique. The mechanical properties like hardness, tensile strength and elongation percentage have been tested under atmospheric conditions. Based on the results of the experiments following conclusion has been derived.

1. Scanning electron microscopy analysis shows that when the yttria particle content in the composite increases, the composite's failure behaviour changes from ductile to brittle.

2. The mechanical qualities, specifically hardness and tensile strength are improved as the yttria particle content in the composite increases, but this improvement comes at the cost of reduced ductility. The addition of 1wt%YO, 2wt%YO, and 3wt%YO to the composites resulted in hardness improvements of 7%, 22%, and 26% correspondingly.

3. The addition of 1wt%, 2wt%, and 3wt% yttria particles to the basic material results in improvements in the tensile strengths of the composite by 10%, 34.86%, and 42.2% respectively. However, the elongation decreases when the amount of yttria is increased, which is attributed to the rise in porosity.

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