Microstructure and mechanical properties of ultrasonically processed Al-7Si alloy / Y$_2$O$_3$ nanocomposite.

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Abstract
The present study aims to investigate the microstructure and mechanical properties of the A356 aluminum metal matrix composite reinforced with Y$_2$O$_3$ particles. The composite is synthesized by adding 1 and 2 vol.% of reinforcement via stir casting assisted by ultrasonic treatment (UT). Microstructural contemplates show improvement in the dispersion of nano Y$_2$O$_3$ particles and a decrease in the porosity level due to the ultrasound aided synthesis. The UT refines the size of the Y$_2$O$_3$ particles as well as helps to improve their dispersion. The secondary dendrite arm spacing of 2 vol.% Y$_2$O$_3$ reinforced samples with 5 min UT are found to be significantly reduced to 12 μm as compared to that of the as-cast A356 alloy. The addition of 2 vol.% of nanoY$_2$O$_3$ has significantly improved the hardness of the A356 alloy from 60 HV to 108 HV. A considerable increment in the YS and TS of the A356 alloy is observed with the increase in the amount of Y$_2$O$_3$ and found to further improve with UT. However, minimal reduction in ductility is observed with the addition of Y$_2$O$_3$ as well as ultrasonic treatment.

Keywords A356 alloy · Y$_2$O$_3$ · Ultrasonic treatment · Grain refinement · Mechanical properties

1 Introduction

Aluminum-based metal matrix composites (MMCs) are widely used in aerospace, automotive, mining structural, and military applications due to their low density to high strength ratio, wear resistance, high hardness, elevated temperature resistance, and greater stiffness compared to as-cast aluminum alloy [1–3]. To improve the mechanical properties of Al alloys, ceramic particulate reinforced composite systems were developed with the help of advanced processing techniques such as stir casting, ultrasonic-assisted casting, mechanical alloying, and severe plastic deformation, etc. Nevertheless, the ultrasonic-assisted casting method is reported as more efficient among the list since it can synthesize an interfacial clean and homogenized composite melt with added advantages of microstructural refinement and degasification [3]. A study by Raghu et al. [4] reported that ultrasonic-assisted casting is an efficient method to fabricate Aluminum/MgAl$_2$O$_4$ composites with clean interfaces. Another study by Nampoothiri et al. [5] revealed that ultrasonic treatment of A356/TiB$_2$ composite can induce α-aluminum matrix microstructure refinement. The microstructure revealed the transformation of the dendritic structure into fine globular structure along with modification of Si needles. It was evident that the ultrasonic treatment during the process of solidification is an effective method leading to the formation of globular structures.

Similarly, Jia et al. [6] reported on the formation of globular grain structures by UT in A356 samples. UT was reported to break up the dendritic structures and form globular grain structures, resulting in better mechanical properties. Xuan et al. [7] worked on reinforcing Al$_2$O$_3$ nanoparticles in A356 alloy and dispersed the reinforcement with ultrasonic cavitation processing. The microstructure was reported to refine into globular grain structures from dendritic grain structure on subjecting it to ultrasonic cavitation.

A recent study by R.K. Gupta et al. [8] states that ultrasonic treatment of Al-Cu alloy/Graphite composites can induce a particulate refinement and matrix microstructural refinements. Gupta reported that the combined effect
of particulate refinement and microstructural refinement resulted in doubled the tensile properties of composite material when compared to the Al matrix. Gupta added that post stir casting the ultrasonic treatment-induced ~80% porosity reduction compared to normal stir cast Al-Cu alloy / Gr composites. Gupta proposed that ultrasonic cavitation implosion-assisted particle refinement and degasification is the rationale for mechanical property enhancement.

A variety of studies were reported on the advantages of Al-Si alloys for their castability, corrosion, and wear resistance and it made Al-Si alloys an interesting matrix for metal matrix composite researches. A study by Radhika et al. [9] reported the tribological property enhancement of the LM25 matrix by the addition of SiO2 particles and Arunagiri et al. [10] reported the effect of AlB2 reinforcement on castability and wear behavior of LM25/ AlB2 composites. A recent study by Satish et al. [11] revealed that the T6 treatment of Al-7Si/ ZrSiO4 Composites can exhibit ~4 times better wear resistance compared to matrix alloy. Literature indicates that incorporation of Y2O3 hard ceramic particles by both severe plastic deformation and liquid metallurgy route to the Aluminum matrix can induce mechanical and tribological property enhancement [12–16]. Furthermore, the literature review suggests that the particle size reduction to the nano-regime can improve mechanical properties like yield strength (YS) and ultimate tensile strength (UTS) without affecting the matrix ductility. A study by Shian et al. [17] reported that the agglomeration of nanoparticles in its matrices can happen due to the high surface energy and subsequently it can reduce the mechanical property. But, Su et al. [18] reported that fabrication of Al2024/ nano-Al2O3 composites via mechanical stirring and ultrasonic vibration can improve dispersion of the particles and bonding with the matrix alloy. Yuan et al. [19] successfully produced A356 alloy/nano-SiCp composite using stir casting assisted by ultrasonic vibration and achieved uniform dispersion of nano-SiCp in A356 alloy matrix. Compared to A356 alloy, ultrasonic treated A356 alloy/2 wt.% nano-SiCp composite exhibited significant improvement in mechanical properties like YS, TS, and % El by 62%, 22%, and 24% respectively. Arpanet al. [20] made-up Al-WC nano-composites using UT with stirring. Significant improvement in the hardness and wear resistance of the UT composite samples was reported to be observed.

Studies reported by Li et al. [21] suggested that the post stir casting UT improves the particle dispersion in ex-situ A356/SiC nanocomposites and the mechanical properties also. Similarly, a study by Khandelwal et al. [22] pointed out that the ultrasonic-assisted casting resulted in noticeable enhancement in the dispersion of nanometric alumina particles in the Mg matrix and also refinement in both particle and grain size when compared to one without ultrasonic treatment. Recent studies by Nampoothiri et al. and Ramani et al. [5, 23–25] reported that the UT can refine particle size and grains and improve dispersion in Al/TiB2 in-situ composites with pure Al. A356 and Al-4.4Cu matrices. Murthy et al. [26] also mention that ultrasonic-assisted casting can improve particle dispersion and thereby mechanical and tribological property enhancement. Further, studies by researchers [27–29] also found that UT of aluminum melt such as A356 alloy, Sr modified A356 alloy can remove the dissolved gas inside the to reduce porosity.

Literatures reveals that smaller addition of nanoparticles can enhance the strength of matrix alloy without compromising ductility and also, UT assisted processing can improve particle and microstructural refinement, particle dispersion, and degasification. Furthermore, reports show that, though works have been reported on Al/Y2O3 composites preferably on micro composite or powder metallurgy nanocomposite systems, very limited exploratory works has been reported on an effective scalable method such as ultrasonic-assisted casting for fabrication of Al/Y2O3 nanocomposites. Studies added out that, aluminum alloys reinforced with Y2O3 via powder metallurgy methods can offer substantial property enhancement than other ex-situ composite systems. Though Al/Y2O3 nanocomposites have significant potential in the field of the transport industry, there are very little works has been reported in the scalable processing routes such as casting. Detailed analysis and understanding of structure-property correlation are essential for the selection and design of composite material for specific applications. This gives research opportunities for developing and/or optimizing a scalable liquid metallurgy process to fabricate Al/Y2O3 nanocomposites. Hence in the present study, an attempt has been made to understand the effect of post-stir casting UT of Al-7Si/Y2O3 composites on its microstructure and mechanical properties.

## 2 Experimental Procedure

Aluminum A356 cast alloy and yittia (Y2O3) powder (99% pure) were chosen as matrix alloy and reinforcement for the present study. The chemical composition of A356 cast alloy was determined using an optical emission spectroscope (Bruker, Q8 MAGELLAN) and presented in Table 1. The

### Table 1

| Element | Si  | Fe  | Cu  | Mg  | Mn  | Zn  | Ti  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Vol.%   | 6.5–7.5 | 0.20 | 0.20 | 0.25–0.45 | 0.10 | 0.10 | 0.20 | Balance |
average size of the Y$_2$O$_3$ powder was determined using an SEM (JEOL 6360 model). Fig. 1 and b show the micrograph of the Y$_2$O$_3$ particles confirming the presence of particles with an average size to be ~5 μm.

Approximately 750 g of A356 ingot was charged into the ceramic crucible and melted using a pit-type electrical resistance furnace at a temperature of 750 °C. The required quantity of Y$_2$O$_3$ powder (1 and 2 vol.%) was preheated to 400 °C to remove the volatile impurities. The preheated powders were subsequently added to A356 alloy melt by conventional stir casting method using a zircon coated 3 bladed mild steel stirrer and spatula. To prevent the particle settlement due to the density differences between molten matrix (ρ_{Al-melt} = 2.375 g.cc) and reinforcement (ρ_{Y2O3} = 5.01 g.cc), an uninterrupted continuous stirring at 600 rpm for 10 min, subsequently transferred into a cast-iron mold of 80 mm length and 20 mm diameter. Thus the prepared stir cast composites are henceforth designated as micro composites in this article.

The stir cast composites were re-melted to a temperature of 730 °C and the melt was subjected to UT for 5 min. A schematic representation of the UT setup is shown in Fig. 2. The working of the magneto restrictive transducer is shown in Fig. 2 and can be briefed as follows: the unit consists of two major parts namely an electromagnetic coil and a ferromagnetic material. Upon supply of the electrical power, the coils in the transducer create an electromagnetic field and the field thus generated induces an atomic level compression in the ferromagnetic material inside the transducer. The compressive stress developed in the ferromagnetic bar induces a compressive strain. The compressive stress developed in the ferromagnetic material can vary according to

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**Fig. 1** a) SEM image of the Y$_2$O$_3$ particles and b) particle size distribution.

**Fig. 2** Ultrasonic treatment setup.
the generated electromagnetic field. The cyclic variation in the electromagnetic field generated will vary the compressive strain developed in the ferromagnetic material and it can raise the vibrations [30]. The frequency and amplitudes of the generated vibratory waves can be engineered to the required regime of ultrasonic waves. The vibration generated can be mechanically amplified with the help of a concentrator and transferred to the melt with the help of a sonotrode. A circulating water line is provided to take away the heat generated during the process. In the present work, a magneto restrictive transducer from RELTEC, Russia is used to generate ultrasonic waves with a frequency of 20.4 kHz and a stainless steel (SS304) sonotrode of 40 mm diameter is used to transfer the generated ultrasonic waves at an intensity of 128 W/cm² to the melt. To prevent the temperature drop and wall-crystal formation effect, the sonotrode was coated with zircon and preheated to 730 °C before introduction into the melt. Immediately after completion of ultrasonic treatment, the sonotrode was removed and the molten composite was cast into the mould.

Samples for microstructural studies were sliced from the casting and were ground through 240 to 2000 grit papers, polished with alumina paste, and finally etched using Keller’s reagent. For etching, Keller’s reagent was wiped over the sample surface and allowed to react for 15 s. And thus etched samples were finally cleaned using the ultrasonic cleaner for about 30 s. Microstructural studies were carried out by using polarized light microscopy (Carl Zeiss Axiol Scope A1). Transmission Electron Microscopy (TEM) analysis were carried out using JEOL JEM 2100 operating at 200 Kv. The Secondary Dendrite Arm Spacing (SDAS) was measured by detailed analysis of optical microstructures of the samples using “Image J” image analyzing software.

Theoretical density (ρt) of the as-cast alloy and its composites was calculated using the rule of the mixtures and the density of the sample, M is mass in air, Mw is the mass of sample in water and ρw is the density of water. The density analysis was carried out by weighing cylindrical samples of (φ 15 x 20 mm) in both air and distilled water. Afterward, the density was estimated using Eq. (1)[31].

\[
ρ_m = \frac{M ρ_w}{M - M_w} \tag{1}
\]

where \(ρ_m\) is the density of the sample, M is mass in air, \(M_w\) is the mass of sample in water and \(ρ_w\) is the density of water. For the current experiment conditions, corresponding to a temperature of 30 °C, the density of water was selected as 0.99565 g/cm³[32]. Based on the density measurements, the % porosity (Po) was calculated using Eq. 2 [33].

\[
P_o = \left(1 - \frac{ρ_m}{ρ_t}\right) \times 100 \tag{2}
\]

3 Results and Discussion

3.1 Density Analysis

Hardness test was carried out using a Vickers hardness testing machine loaded with a diamond indenter carrying a load of 1 kg that to be applied on the sample for 15 s (as per ASTM E384 standards). An average of five readings is accounted for as the respective sample hardness. To study the room temperature tensile properties of the composites, the samples were machined as per ASTM E8M standard and the tensile specimens of 6 mm diameter and 30 mm gauge length was tested on a computerized test. Tensile testing was carried out using a computer-controlled universal testing machine (UTM, make: Instron 4467 USA) with dogbone samples of 30 mm gauge length and an initial strain rate of 0.01 mm/min. Three samples were tested for each composition and consistent results have been reported.

| S. No. | Sample                       | Theoretical density (g/cm³) | Experimental Density (g/cm³) |
|-------|------------------------------|-----------------------------|-------------------------------|
| 1     | A356 alloy                   | 2.713                       | 2.686 ± 0.0026               |
| 2     | A356/1 vol.% Y₂O₃ stir cast  | 2.736                       | 2.6911 ± 0.0026              |
| 3     | A356/2 vol.% Y₂O₃ stir cast  | 2.759                       | 2.6972 ± 0.0026              |
| 4     | A356/1 vol.% Y₂O₃ 5 min UT   | 2.736                       | 2.7102 ± 0.0026              |
| 5     | A356/2 vol.% Y₂O₃ 5 min UT   | 2.759                       | 2.7312 ± 0.0027              |

Table 2 Average size of SDAS and density of A356 alloy and its composites.
vol.% sample possesses a porosity level of 0.9%. The post stir casting UT reduced the percent porosity of 2 vol.% sample from 2.2 to 1.07%.

The porosity reduction by UT can be attributed to ultrasonic wave-induced degasification mainly by the non-linear effect of wave propagation through the molten metal [29]. The transmission of ultrasonic waves through melt generates pressure waves inside the liquid melt and associated cyclic compression and rarefaction events also. These events lead to the formation of numerous tiny cavitation bubbles inside the melt. The bubbles developed inside the melt can enhance the dissemination of dissolved gas to the bubble or accumulate over the surface of bubbles. On the progression of this event, the size increased bubbles float to the melt surface and explode to release the gases. In addition, there will be a formation of shockwaves due to the cavitation implosion phenomena. The shock waves thus generated can break the particle agglomerated and improve the dispersion and consequently the fluidity. In these manners, the UT can help to mitigate porosity levels.

### 3.2 Microstructural Analysis

Optical Micrographs of A356 cast alloy, A356/1 vol.% Y₂O₃ nanocomposite stir cast, A356/2 vol.% Y₂O₃ nanocomposite stir cast, A356/1 vol.% Y₂O₃ nanocomposite with 5 min UT, A356/2 vol.% Y₂O₃ nanocomposite with 5 min UT are respectively shown in Fig. 4(a-e). Fig. 4(f) shows the magnified view of a coarse dendritic structure of α-Aluminum and eutectic silicon phase. The magnified image of Fig. 4(a) shown in Fig. 4(f) reveals the presence of acicular needles of eutectic Si with an average size of ~29 μm. The microstructure analysis presented in Fig. 4 shows that the alloy, composite samples without and with UT exhibit a dendritic morphology. It reveals that the addition of Y₂O₃ particles and UT has a marginal effect on the dendrite morphology. However, the incorporation of particles and UT reduced the size of the dendrites in the composite samples. From the micrographs of the composite samples, it can be observed that the SDAS of samples with UT is significantly reduced compared to the samples without UT. The average value of measured SDAS of the A356 alloy and its composites is estimated and the as-cast A356 alloy has an SDAS of ~29 μm. However, it is observed that 1 vol.% and 2 vol.% of Y₂O₃ particles added samples have an average SDAS of 18.9 ± 1.8 μm and 17.3 ± 1.7 μm respectively. Nevertheless, the performance of UT on 1 and 2 vol.% composite samples resulted in an SDAS of about 15.8 μm and 12.7 μm respectively. Similar results have been explained by Jayakrishnan et al. [36] In their study on UT of A356/TiB₂ in-situ composites. The presence of Y₂O₃ particles inside melt can increase the events of nucleation by acting as nucleation sites to attribute the SDAS reduction. Further upon the ultrasonic treatment, the particles can be fragmented during the ultrasonic cavitation implosion and the shock waves generated during the implosion can make the surface of the particle beneficial for nucleation[37]. Thus the increased number density of Y₂O₃ particles and active nuclei particles can contribute to the further reduction of SDAS in the ultrasonically treated samples. In addition, the formation of agglomerates is evident from the micrographs (Fig. 4b and c) and the presence of agglomerates is marginal in UT samples shown in Fig. 4(d and e).

Figure 5a shows the SEM image of A356 alloy and Fig. 5(b and c) shows the SEM images of A356/1 and 2 vol.% Y₂O₃ stir cast composite without UT and Fig. 5(d and e) show SEM images of the A356/1 and 2 vol.% Y₂O₃ composite with 5 min UT. A small region is magnified and shown as an inset in Fig. 5d. It can be inferred from the SEM micrograph that, the Si needles in the A356/1 vol.-% composite (Fig. 5a)) exist in the acicular morphology with an average needle size of 12 ± 3.9 μm. The addition of 2 vol.% of Y₂O₃ particles via stir casting reduced the average eutectic Si needle size to 7.1 ± 2.4 μm and UT of 1 and 2 vol.% composites resulted in further reduction of eutectic Si size to 4.9 ± 2.8 and 4.4 ± 3 μm respectively. The presence of particles such as Y₂O₃ can act as pinning agents for the growth of Si needles and the number density enhancement by UT-assisted particle reduction can further restrict the Si growth. Fig. 5(d) reveals that the agglomerates of Y₂O₃ particles are broken and also the size of particles was...
significantly reduced from 5 μm to 500 nm due to UT. It can also be observed from Fig. 5(d) that, the nanoparticles are found to be spherical in shape.

Jayakrishnan et al. [36] achieved a reduction in the size of TiB<sub>2</sub> particles from micron size to nano-size after 5 min of UT and the results of the present study correlate the same. In addition, the Y<sub>2</sub>O<sub>3</sub> particles in the inset of Fig. 5(d and e) are found to be present in both the eutectic Si phase and primary matrix phase, which confirms that the added nano Y<sub>2</sub>O<sub>3</sub> particles were trapped into the solid solution and are not rejected by the solid-liquid interface throughout solidification. The particles present in the eutectic Si phase restrict the grain growth generation and form a Y<sub>2</sub>O<sub>3</sub> rich eutectic domain along with eutectic silicon. A similar effect was reported by Bouaeshi et al. [37] in their reports on Y<sub>2</sub>O<sub>3</sub> addition of aluminum. Puga et al. [38] also supported the above mechanism in their study on the properties of AlSi<sub>9</sub>Cu<sub>3</sub> alloy. Khalifa et al. [39] explained the formation of the eutectic domain along with silicon and its effect. Yu Pan et al. [40] and Kewei Xie et al. [41] observed significant refinement in grain structure with the addition of TiC to Ti and Al nanoparticle to Al respectively.

No other harmful or unconventional intermetallic phases were observed from the SEM micrographs and it may be due to the thermodynamic stability of nano Y<sub>2</sub>O<sub>3</sub> particles. Rahul Gupta et al. [42] accounted the similar outcomes in their study on creep properties of ultrasonically processed in-situ Al<sub>3</sub>Zr-Al alloy composites. During the cavitation implosion, a localized temperature rise to about ~8000 °C and pressure rise to 2–3 MPa have occurred and this temperature can slowly dissolve the Y<sub>2</sub>O<sub>3</sub> particles to the melt and later can be precipitated [36]. During the course of particle precipitation, the shock waves of implosions can break the growth of the particles to form nanoparticles [5]. In addition, the cavitation implosion shock wave produces some “hammering” effect on particles to break to nano regime. Further, the UT acoustic streaming and cavitation non-linear effect
gives efficient stirring to distribute the particles throughout the matrix.

TEM bright-field micrograph of the $Y_2O_3$ particle (Fig. 6a) shows the size of the particle to be about 500 nm. Fig. 6a reveals the excellent bonding of the particles with the matrix and is free from interfacial reactions. EDS analysis (Fig. 6b) further confirms the presence of $Y_2O_3$ particles in the composite. The simulated and the observed Selected Area Diffraction (SAD) pattern of nano $Y_2O_3$ particles are shown in Fig. 6(c & d). The SAD pattern indexing also confirms the presence of $Y_2O_3$ particles, as the d-spacing is following the $Y_2O_3$ particles. Fig. 6e shows the magnified view of the area from the α-Al matrix and it shows the presence of string/worm-like structures in the image. The micrograph in Fig. 6(e) matches well with the standard morphology of dislocations reported in the literature [42] the presence of a large number of dislocations near the grain boundary. These dislocations will aid in significantly improving the mechanical properties of the matrix alloy. Further, direct observation and the threshold filtering analysis [43] done with the help of Image J software (Fig. 6(f)) confirmed the presence of the dislocation densities.

### 3.3 Hardness Measurement

Figure 7 shows the average hardness values for the monolithic alloy and composites. A356 alloy reinforced with 1 vol.% and 2 vol.% of $Y_2O_3$ particle without UT is about 75 HV and 95 HV receptively. Similarly, the average hardness values for the composites reinforced with 1 vol.% and 2 vol.% of nano$Y_2O_3$ particles (with UT) is about 85 HV and 108 HV respectively. It can be inferred that the addition of 2 vol.% of nano$Y_2O_3$ has significantly improved the hardness of the A356 alloy from 60 HV to 108 HV. It can be seen that the hardness sample increases with UT and the synergistic effect of $Y_2O_3$ particles and UT significantly increases the
hardness of A356 alloy by about 80%. The presence of high dislocation density in nanocomposites are evident from the TEM micrograph shown in Fig. 6(e) and the combined effect of porosity reduction, SDAS reduction, size reduction of Y₂O₃ particles to nano regime, and associated dislocation density formations and or enhancements can jointly contribute to the hardness increment. The presence of particles can enhance the hardness through dislocation bypass and interaction effects and also by load transfer effect.

3.4 Tensile Properties

The room temperature tensile behavior of A356/Y₂O₃ composites and monolithic alloy were compared in Fig. 8. It can be noted that the average yield strength (YS), tensile strength (TS), and elongation at break (% El) of 79 MPa, 138 MPa, and 4.94% respectively. 1 vol.% Y₂O₃ particles added composites exhibited an increase in YS and UTS to 86 MPa and 138 MPa respectively as shown in Fig. 8. Further, 2 vol.%
Addition of Y_2O_3 particles resulted in a significant improvement in YS to 101 MPa and UTS 150 MPa. The YS and UTS are found to be improved by 27% and 13% respectively when compared to the matrix alloy. The samples with 1 vol.% of nano Y_2O_3 resulted in tensile properties of 97.6 MPa YS, 148 MPa TS, and elongation of 3.6%.

The tensile properties of the samples reinforced with 2 vol.% nano Y_2O_3 particle added composite with 5 min UT exhibited a YS of 109 MPa and UTS 167 MPa with % of improvement by 27% and 26% respectively. The ultrasonic cavitation treatment significantly enhanced the YS and UTS of the composite. It can be observed that the UT improves the % of elongation and the elongation of 1 vol.% nano Y_2O_3 particle added composite with UT is higher than that of 2 vol.% nano Y_2O_3 particle added composite with UT. Generally, composites reinforced with micrometer-sized ceramic particles will reduce the ductility of the matrix due to their stress raiser effect, whereas the nano Y_2O_3 particle reinforced composites improved the tensile properties by retaining the ductility. Similar results were reported by Yuan et al. [34] for A356 alloy/nano SiC particles reinforced composites prepared by UT.

Significant improvement in the mechanical properties is due to the existence of uniformly dispersed nano Y_2O_3 particles and is probably contributed to the various strengthening mechanisms. The dominant mechanisms were observed in the present study. The large difference in Coefficient of Thermal Expansion (CTE) between the reinforcement Y_2O_3 (8.1 × 10^{-6}/K) and matrix (25 × 10^{-6}/K) may lead to the development of stresses during cooling resulting in the formation of a large number of dislocations around the particles as shown in Fig. 5e.

Orowan strengthening mechanism is one of the dominant strengthening effects and mainly depends on the reinforcement particle size, bond strength with the matrix, and interparticle spacing. Under tensile load, the softer matrix alloy deforms more plastically compared to the harder nano Y_2O_3 particles. During plastic deformation of the composite samples, closely spaced nano Y_2O_3 particles will become a barrier to the dislocation motion thus hindering their motion. As a consequence, dislocations will bend and form a loop in the region of Y_2O_3 particles. Consecutive dislocation incessantly forms a loop in the region of Y_2O_3 which brings on back stress and obstructs the dislocation movement further.

In this manner, the Y_2O_3 nanoparticle facilitates the strengthening of the A356 alloy matrix. Compared to the stir cast composites (without UT), inter-particle spacing in the nanocomposites (with UT) will be very less and thus offers more resistance to the dislocation movement and thus further strengthening the matrix. According to Hall–Petch theory, the fine grains with more grain boundaries will significantly improve the strength of the matrix [44]. In the present study, the combined effect of Orowan looping, CTE mismatch, load transfer effect, and SDAS refinement can contribute to mechanical property enhancement. The effect of each phenomenon can be quantified using Eqs. 3–8. For the calculation purpose, the Hall-Petch term is calculated using SDAS data since a study by Ehsan et al. [45] reported that, for Al-Si hypoeutectic alloys, secondary arm spacing fits better than grain size.

The theoretical yield strength (σ_y) of A356/Y_2O_3 composites can be written as:

\[
\sigma_y = \sigma_m + \frac{k}{\sqrt{d}} + \sqrt{\sigma_{oro}^2 + \sigma_{CTE}^2 + \sigma_{Geo}^2 + \sigma_{Load}^2}
\]  

(3)
where, \( k \) is the Hall-Petch constant, \( d \) grain size or SDAS, \( \sigma_m \) is the matrix yield strength, \( \sigma_{Oro} \) is the Orowan strengthening, \( \sigma_{CTE} \) is the contribution from stress developed by CTE mismatch between particles and matrix, \( \sigma_{Geo} \) is the stress contribution due to strain gradient associated with geometrically necessary distributions required to accommodate plastic deformation mismatch between matrix and reinforcement particles and \( \sigma_{Load} \) is the influence of load transfer effect between particles and matrix [36].

The Orowan strengthening can be calculated as [24]:

\[
\sigma_{Oro} = \frac{2mgGb \ln \left( \frac{\phi}{2b} \right)}{[(1.18)4\pi(\lambda - \phi)]}
\]  
(4)

where \( m \) is Taylor’s factor, \( G \) is the shear modulus, \( b \) is the Burgers vector, \( \phi \) is the particle size and \( \lambda \) is the planar interparticle separation,\( \phi/\sqrt{V_p} \), where \( V_p \) is the volume fraction of particles.

The strength contribution from CTE mismatch can be calculated as [36]:

\[
\sigma_{CTE} = \eta Gb \rho^{1/2}
\]  
(5)

where \( \eta = 1 \), and \( \rho \) is the dislocation density,

\[
\rho = \frac{12\Delta\alpha\Delta T V_p}{b\phi(1 - V_p)}
\]  
(6)

Where, \( \Delta\alpha \) is the difference in coefficient of thermal expansion of matrix alloy and reinforcement \( \Delta T \Delta T \) is the difference in testing and processing temperature.

The strength increments by geometrically necessary dislocations are [36].

\[
\sigma_{Geo} = \beta G \sqrt{\frac{V_p \in b}{\phi}} \sigma_{Geo} = \beta G \sqrt{\left( \frac{V_p \in b}{\phi} \right)}
\]  
(7)

Where \( \beta \) is a geometric factor with a numerical value of 0.2 and \( \epsilon \) is the plastic strain of the matrix.

| Table 3 Parameters for theoretical modeling of yield strength. |
|---------------------------------|
| Parameters | Value | Reference |
|-----------------|--------|-----------|
| \( V_p \) | 0.01, 0.02 | Present study |
| \( b \) | 0.286 nm | [36] |
| \( G \) | 27 Gpa | |
| \( \alpha \) of Al | 25X10^{-6} K^{-1} | |
| \( \alpha \) of \( Y_2O_3 \) | 8.1X10^{-6} K^{-1} | |
| \( \Delta T \) | 730 °C | |
| \( \epsilon \) | 0.1 | |
| \( s \) | 1 | |
| \( m \) | 3.1 | |

Table 4 Theoretical and experimental tensile strength data.

| Sl.NO | Sample | Theoretical Yield Strength (MPa) | Experimental Yield Strength (MPa) |
|-------|--------|---------------------------------|-----------------------------------|
| 1     | A356/1 vol.% \( Y_2O_3 \) | 91.255 | 86.2 |
| 2     | A356/2 vol.% \( Y_2O_3 \) | 93.527 | 101.2 |
| 3     | A356/1 vol.% \( Y_2O_3 \)-UT | 108.98 | 97.6 |
| 4     | A356/2 vol.% \( Y_2O_3 \)-UT | 117.59 | 109.2 |

And the contribution of load transfer effect is calculated as [36],

\[
\sigma_{Load} = 0.5s\sigma_m V_p \sigma_{Load} = 0.5s\sigma_m V_p
\]  
(8)

Where \( s \) is the aspect ratio of particles.

The values of parameters used that for theoretical calculations of yield strength of A356/\( Y_2O_3 \) composites are given in Table 3.

The theoretically calculated and experimental tensile data is consolidated in Table 4 for ready references.

It can be inferred from Table 4 that, the yield strength of composite without UT has anomaly with theoretical values than the monolithic alloy and UT composites. This anomalous behavior in composites without UT can be attributed to inhomogeneity in the samples. On the other hand, the experimental YS of other composites is closely matching with the theoretical value. However, the small error in the theoretically calculated YS and experimentally measured YS can be rationalized by the unavoidable errors in machine compliance corrections, leftover porosities, and small variations in elastic constants of the samples.

Fig. 9 Comparison of strengthening contributions.
The percentage contribution from each strengthening model is analyzed and plotted in Fig. 9. It reveals that the Hall-Petch mode is the main strengthening mechanism when the particle size is in the micron regime and is followed by CTE mismatch strengthening. However, as the particle size is reduced to 500 nm, the strengthening contribution from CTE mismatch and Hall-Petch strengthening become nearly equal. The contribution of Orowan strengthening and geometrically necessary dislocations also considerably increased when the particle size is reduced to 500 nm. It can be inferred from Fig. 9 that, in A356/Y₂O₃ micron composites, grain boundary strengthening is the primary mechanism and in nanocomposites, CTE mismatch is the activated mode of strengthening.

Fractography examinations of tensile-tested samples (for both stir cast and UST) have been carried out to understand the effect of the Y₂O₃ particles in the fracture mechanism of the A356/Y₂O₃ composite samples. Fig. 10a and Fig. 10(b-e) show the SEM micrographs of A356 alloy and Y₂O₃ particle added composites respectively after the tensile test. SEM image of the A356 alloy Fig. 10a shows a ductile fracture, whereas the composites show a cleavage fracture. From the surface morphology of stir cast samples and UT samples (Fig. 10b-e), it can be observed that there...
are sufficient tear ridges on the fracture surface, demonstrating the quasi-cleavage fracture as the main fracture mechanism. Apart from this, the UT samples show the presence of tiny dimples on the fracture surface leading to increased ductility as compared to the stir cast samples. Good interfacial bonding between the Y2O3 particles and the A356 alloy prompts effective load transfer from the Y2O3 particles to the A356 alloy. This in turn reduces the crack propagation leading to a major improvement in the tensile properties of the composites with a reduction in ductility [46–50].

The present study infers that post stir casting ultrasonic treatment of Al/Y2O3 micron composite is a novel and facile method to synthesize Al/Y2O3 nanocomposites. This process can refine micro-sized Y2O3 particles into nano regimes such as 500 nm and disperse the particles through the matrix. This process is scalable to mass production too. As a limitation of the present study, the authors propose that, since ceramic particles below 100 nm can significantly improve the mechanical properties with the addition of less volume fraction of particles, further studies are required to extend Y2O3 size refinement to the prescribed regime below 100 nm.

4 Conclusions

From the present study, it can be inferred that the post stir casting UT can reduce the particle size from micron to nano regime. The addition of Y2O3 particles in both sizes is found to induce a significant reduction in SDAS. However, more reduction can be observed in A356/2 vol.% of Y2O3 nanocomposites. Increased particle number density and ultrasonic-assisted activation of nuclei particles are suggested as the rationale for the SDAS refinement of nanocomposite samples. However, a detailed study is required to understand the effect of Y2O3 and UT on dendritic modification and SDAS refinement.

The ultrasonic treatment of stir cast composite is effective in melt degasification and associated improvement in the density of cast product. The combined effect of reinforcement particle refinement, SDAS refinement, and degasification contributed significantly towards the mechanical properties of composites. The theoretical model-based analysis on strengthening mechanism revealed that in A356/Y2O3 micron composites, grain boundary strengthening is the governing one, and while the particle size is reduced to 500 nm, CTE mismatch strengthening becomes the predominant mechanism.

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Data Availability Not applicable.

Declarations

Ethics Approval and Consent to Participate Not applicable.
Consent for Publication Not applicable.
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References

1. Thandalam SK, Ramanathan S, Sundarraj S (2015) Synthesis, microstructural and mechanical properties of ex situ zircon particles (ZrSiO4) reinforced Metal Matrix Composites (MMCs): a review. J Mater Res Technol 4:333–347. https://doi.org/10.1016/j.jmrt.2015.03.003
2. Meti VKV, Shirur S, Nampoothiri J, Ravi KR, Siddhalingeshwar IG (2018) Synthesis, Characterization and Mechanical Properties of AA7075 Based MMCs Reinforced with TiB2 Particles Processed Through Ultrasound Assisted In-Situ Casting Technique. Trans Indian Inst Metals 71:841–848. https://doi.org/10.1007/s12666-017-1216-5
3. Xu H, Jian X, Meek TT, Han Q (2004) Degassing of molten aluminum A356 alloy using ultrasonic vibration. Mater Lett 58:3669–3673. https://doi.org/10.1016/j.matlet.2004.02.055
4. Raghav R, Nampoothiri J, Satish Kumar T (2018) In-situ Generation of MgAl2O4 particles in Al-Mg alloy using H3BO3 addition for grain refinement under ultrasonic treatment. Meas J Int Meas Confed 129:389–394. https://doi.org/10.1016/j.measurement.2018.07.056
5. Nampoothiri J, Raj B, Ravi KR (2015) Role of Ultrasonic Treatment on Microstructural Evolution in A356/TiB2 In-Situ Composite. Trans Indian Inst Metals 68:1101–1106. https://doi.org/10.1007/s12666-015-0653-2
6. Jia S, Zhang D, Xuan Y, Nastac L (2016) An experimental and modeling investigation of aluminum-based alloys and nanocomposites processed by ultrasonic cavitation processing. Appl Acoust 103:226–231. https://doi.org/10.1016/j.apacoust.2015.07.016
7. Xuan Y, Nastac L (2018) The role of ultrasonic cavitation in refining the microstructure of aluminum based nanocomposites during the solidification process. Ultrasonics 83:94–102. https://doi.org/10.1016/j.ultras.2017.06.023
8. Gupta RK, Nampoothiri J, Dhamodharan S, Ravi KR, Udhayabanu V, Peshwe DR (2020) Ultrasonic assisted synthesis of Al–Cu/2 vol% Grp composite and its characterization. J Alloys Compd 845:156087. https://doi.org/10.1016/j.jallcom.2020.156087
9. Radhika N, Raghv R (2017) Investigation on Mechanical Properties and Analysis of Dry Sliding Wear Behavior of Al LM13/AlN Metal Matrix Composite Based on Taguchi’s Technique. J Tribol 139:041602. https://doi.org/10.1115/1.4035155
10. Arunagiri KS, Radhika N (2016) Studies on adhesive wear characteristics of heat treated aluminium LM25/AlB2 composites. Tribol Ind 38:277–285

11. Kumar TS, Shalini S, Priyadarshini GS (2021) Effect of T6 Treatment on Wear Behavior of Al-7Tsi/ ZrSiO4 Composites. Silicon 13:1051–1058. https://doi.org/10.1007/s12633-020-00492-4

12. Hassan SF (2011) Effect of primary processing techniques on the microstructure and mechanical properties of nano-Y2O3 reinforced magnesium nanocomposites. Mater Sci Eng A 528:5484–5490. https://doi.org/10.1016/j.msea.2011.03.063

13. Ponappa K, Aravindan S, Rao PV (2013) Influence of Y2O3 particles on mechanical properties of magnesium and magnesium alloy (AZ91D). J Compos Mater 47:1231–1239. https://doi.org/10.1177/0021993114546501

14. Polly P, Chandra Sekhar K, Ravisankar B, Kumaran S (2014) Densification of mechanically alloyed Al5083·5 wt% Y2O3 nanocomposite by equal channel angular pressing. Appl Mech Mater 592–594:963–967. https://doi.org/10.4028/www.scientific.net/AMM.592-594.963

15. Mahdi FM, Annaz A-U (2015) Effect of Ytria Content up to 15 wt% on Mechanical Properties of Al- Y2O3 Composites Prepared Via Squeeze Casting and Powder Metallurgy Routes. Sualimani. J Eng Sci 2:55–64. https://doi.org/10.17685/jes.100024

16. Mattil MR, Shakoor A, Matti PR, Mohamed AMA (2019) Microstructure and compressive behavior of Al– Y2O3 nanocomposites prepared by microwave-assisted mechanical alloying. Metals (Basel) 9:414. https://doi.org/10.3390/m metals9040414

17. Jia S, Xuan Y, Nastac L, Allison PG, Rushing TW (2016) Microstructure, mechanical properties and fracture behavior of 6061 aluminium alloy-based nanocomposite castings fabricated by ultrasonic processing. Int J Cast Met Res 29:286–289. https://doi.org/10.1080/13640464.2016.1181232

18. Su H, Gao WL, Zhang H, Liu HB, Lu J, Lu Z (2012) Study on preparation of large sized nanoparticle reinforced aluminium matrix composite by solid-liquid mixed casting process. Mater Sci Technol 28:178–183. https://doi.org/10.1179/1743284711Y.0000000009

19. Yuan D, Hu K, Li S, Wu S, Qi G (2018) Preparation and properties of nano-SiCp/Al5356 composites synthesised with a new process. Mater Sci Technol (United Kingdom) 34:1415–1424. https://doi.org/10.1080/02670836.2018.1458479

20. Pal A, Poria S, Sutrathdar G, Sahoo P (2018) Tribological behavior of Al-WC nano-composites fabricated by ultrasonic cavitation assisted stir-cast method. Mater Res Express 5:036521. https://doi.org/10.1088/2053-1591/aab577

21. Yang Y, Lan J, Li X (2004) Study on bulk aluminium matrix nano-composite fabricated by ultrasonic dispersion of nano-sized SiC particles in molten aluminum alloy. Mater Sci Eng A 380:378–383. https://doi.org/10.1016/j.msea.2004.03.073

22. Khandelwal A, Mani K, Srivastava N, Gupta R, Chaudhari GP (2017) Mechanical behavior of AZ31/Al2O3 magnesium alloy nanocomposites prepared using ultrasound assisted stir casting. Compos Part B Eng 123:64–73. https://doi.org/10.1016/j.compositesb.2017.05.007

23. Nampoothiri J, Raj B, Ravi KR (2015) Effect of Ultrasonic Treatment on Microstructural and Mechanical Property of In Situ Al/ TiB2 Particulate Composites. Mater Sci Forum 830–831:463–466. https://doi.org/10.4028/www.scientific.net/MSF.830-831.463

24. Nampoothiri J, Balasundar I, Raghu T, Ravi KR (2019) Structural and Mechanical Behavior of Al–4.4Cu/TiB2 In-Situ Nanocomposites Fabricated by Post-In-Situ Reaction Ultrasonic Processing Metall Mater Trans B Process Metall Mater Process Sci. https://doi.org/10.1007/s11663-019-01713-x

25. Ramani S, Wins KLD, Nampoothiri J, Ravi KR, Ebenezer Jacob Dhas DS (2021) Effect of post-reaction ultrasonic treatment on synthesis, microstructural evolution and mechanical behaviour of Al 4043/TiB2 in situ nanocomposites. Arab J Sci Eng 46:7521–7531. https://doi.org/10.1007/s13369-021-05468-z

26. Murthy NV, Reddy AP, Selvaraj N, Rao CSP (2016) Preparation of SiC based Aluminium metal matrix nanocomposites by high intensity ultrasonic cavitation process and evaluation of mechanical and tribological properties. IOP Conf Ser Mater Sci Eng 199:012106. https://doi.org/10.1088/1757-899X/199/1/012106

27. Han QY (2014) Ultrasonic degassing of aluminum alloys. Mater Sci Forum 783–786:155–160. https://doi.org/10.4028/www.scientific.net/MSF.783-786.155

28. Kandemir S (2017) Microstructure and mechanical properties of A357/SiC nanocomposites fabricated by ultrasonic cavitation-based dispersion of ball-milled nanoparticles. J Compos Mater 51:395–404. https://doi.org/10.1177/0021998316644850

29. Nampoothiri J, Balasundar I, Raj B, Murty BS, Ravi KR (2018) Porosity alleviation and mechanical property improvement of strutium modified A356 alloy by ultrasonic treatment. Mater Sci Eng A 724:586–593. https://doi.org/10.1016/j.msea.2018.03.069

30. Ashish A, Rajagopal P, Balasubramaniam K, Kumar A, Purnachandra Rao B, Jayakumar T (2015) Development of Magnetostriiction Based Ultrasonic Transducer For In-situ High Temperature Inspection. Nde-2015 1:1–6

31. Spierings AB, Schneider M, Eggenberger R (2011) Comparison of density measurement techniques for additive manufactured metal parts. Rapid Prototyp J 17:380–386. https://doi.org/10.1108/1743284711Y.000000009

32. Williams ML (1996) CRC Handbook of Chemistry and Physics, 76th edition. Occup Environ Med 53:504–504. https://doi.org/10.1016/j.occupde.2011.08.105

33. Ali M (2020) Review of stir casting technique and technical challenges for ceramic reinforcement particulate and aluminium matrix composites. Epa - J Silic Based Compos Mater 72:198–204. https://doi.org/10.14382/epitoanyag-jscbm.2020.32

34. Ravi KR, Pillai RM, Amananatha KR, Pai BC, Chakraborty M (2008) Fluidity of aluminum alloys and composites: A review. J Alloys Comp 456:201–210. https://doi.org/10.1016/j.jallcom.2007.02.038

35. Nampoothiri J, Harini RS, Nayak SK, Raj B, Ravi KR (2016) Post in-situ reaction ultrasonic treatment for generation of Al–4.4Cu/ TiB2 nanocomposite: A route to enhance the strength of metal matrix nanocomposites. J Alloys Comp 638:370–378. https://doi.org/10.1016/j.matchemall.2016.05.067

36. Bouaoue WB, Li DY (2007) Effects of Y2O3 addition on microstructure, mechanical properties, electrochemical behavior, and resistance to corrosive wear of aluminum. Tribol Int 40:188–199. https://doi.org/10.1016/j.triboint.2005.09.030

37. Puga H, Costa S, Barbosa J, Ribeiro S, Prokic M (2011) Influence of ultrasonic melt treatment on microstructure and mechanical properties of AlSi5Cu2 alloy. J Mater Process Technol 211:1729–1735. https://doi.org/10.1016/j.matchemall.2011.05.012

38. Khalid Rafi H, Janaki Ram GD, Phanikumar G, Prasad Rao K (2010) Microstructure and Properties of Friction Surface Stainless Steel and Tool Steel Coatings. Mater Sci Forum 638–642:864–869. https://doi.org/10.4028/www.scientific.net/MSF.638-642.864

39. Pan Y, Li W, Lu X et al (2020) Microstructure and tribological properties of titanium matrix composites reinforced with in situ synthesized TiC particles. Mater Charact 170:110633. https://doi.org/10.1016/j.matchemall.2020.110633
41. Xie K, Nie J, Ma X, Liu X (2020) Increasing the ductility of heat-resistant AlNp/Al composites by submicron Al2O3 particles. Mater Charact 170:110672. https://doi.org/10.1016/j.matchar.2020.110672
42. Gupta R, Daniel BSS (2020) Impression creep behaviour of ultrasonically processed in-situ Al, Zr-Al alloy composite in as-cast condition. Mater Charact 169:110594. https://doi.org/10.1016/j.matchar.2020.110594
43. Kim K, Lee J, Kim H, Lee Z (2014) Quantitative Evaluation of Dislocation Density in Epitaxial GaAs Layer on Si Using Transmission Electron Microscopy. Appl Microsc 44:74–78. https://doi.org/10.9729/am.2014.44.2.74
44. Yang C, Liu Z, Zheng Q, Cao Y, Dai X, Sun L, Zhao J, Xing J, Han Q (2018) Ultrasound assisted in-situ casting technique for synthesizing small-sized blocky Al3Ti particles reinforced A356 matrix composites with improved mechanical properties. J Alloys Compd 747:580–590. https://doi.org/10.1016/j.jallcom.2018.02.010
45. Ghassemali E, Riesta M, Bogdanoff T, Kumar BS, Seifeddie S (2017) Hall-Petch equation in a hypoeutectic Al-Si cast alloy: Grain size vs. secondary dendrite arm spacing. Procedia Eng 207:19–24. https://doi.org/10.1016/j.proeng.2017.10.731
46. Radhika N, Thirumalini S, Jojith R (2019) Development and Properties of Centrifugally Cast Silicon Nitride Reinforced Functionally Graded Copper Matrix Composite. Silicon 11:2103–2116. https://doi.org/10.1007/s12633-018-0030-y
47. Radhika N, Sam M, Thirumalini S (2019) Experimental studies on mechanical and wear behaviour of TiC reinforced Cu-Sn-Ni functionally graded composite. Tribol Ind 41:537–547. https://doi.org/10.24874/ti.2019.41.04.07
48. Radhika N, Sasikumar J, Arulmozhivarman J (2020) Tribomechanical Behaviour of Ti-Based Particulate Reinforced As-Cast and Heat Treated A359 Composites. Silicon 12:2769–2782. https://doi.org/10.1007/s12633-019-00370-8
49. Jojith R, Radhika N (2020) Investigation of Mechanical and Tribological Behaviour of Heat-Treated Functionally Graded Al-7Si/B4C Composite. Silicon 12:2073–2085. https://doi.org/10.1007/s12633-019-00294-3
50. Kandasamy S, Rathinasamy P, Nagarajan N, Karumalai D, Thangamuthu M, Palaniappan M (2021) Assessment of erosion rate on AA7075 based surface hybrid composites fabricated through friction stir processing by taguchi optimization approach. J Adhes Sci Technol 1–22. https://doi.org/10.1080/01694243.2021.1929018

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