Synergistic Effects of Praseodymium and Antimony Additions on the Microstructural and Mechanical Properties of Al–15 Wt. % Mg_2Si Composites

Alif Fajar Putrawan[1], Shazarel Shamsudin[5], Hamidreza Ghandvar [4], Nor Akmal Fadil [1-2], Tuty Asma Abu Bakar [1-3]

[1]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor.

[2]Materials Research and Consultancy Group (MRCG), Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.

[3]Centre for Advanced Composite Materials, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.

[4]Department of Mechanical Engineering, School of Engineering, New Uzbekistan University, Movarounnahr Street 1, Mirzo Ulugbek District, Tashkent, 100000, Uzbekistan

[5]Advanced Manufacturing and Materials Centre (AMMC), Universiti Tun Hussein Onn Malaysia (UTHM), 86400, Parit Raja, Batu Pahat, Johor, Malaysia

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Abstract

Al Mg_2Si metal matrix composites (MMCs) are among the most promising materials for applications in the automotive industry, particularly for components such brake pads. These composites exhibit high strength, good wear resistance, excellent corrosion resistance, and low density. The incorporation of Mg_2Si particles can further enhance the properties of aluminium MMCs; however, coarse and dendritic of Mg_2Si phases are often formed during solidification due to the relatively low solidification rate. The sharp edges of primary Mg_2Si particles can act as stress concentrators, promoting crack initiation and reducing mechanical performance. To address this limitation, various modification techniques have been introduced, including alloying additions and post-processing treatments. Among the potential modifiers are praseodymium (Pr) antimony (Sb) have shown promising refinement effects. This study investigates the influence of simultaneous Pr and Sb additions on the microstructural evolution and mechanical characteristics of Al–15 wt. %Mg_2Si composites. Microstructural characterization was performed using optical microscopy and scanning electron microscopy (SEM) equipped with energy-dispersive X-ray spectroscopy (EDX), while tensile and hardness tests were conducted to evaluate the mechanical properties of the composites. The results indicate that the addition of 0.5 wt% Pr–Sb produced the highest tensile strength of 100 MPa, representing an improvement over the unmodified composite (93 MPa). In contrast, the composite containing 2.0 wt% Pr–Sb exhibited the highest average hardness value of 100.2 HV, compared with 75.3 HV for the unmodified composite, and showed the greatest Mg_2Si particle density per unit area. The improvement in mechanical properties was attributed to the refinement and more uniform distribution of Mg_2Si particles induced by the combined addition of Pr and Sb. Overall, the simultaneous addition of Pr and Sb effectively enhanced the microstructural and mechanical performance of Al-15 wt. % Mg_2Si composites.

Keywords: Al-Mg_2Si Composite, Metal Matrix Composites, Praseodymium, Antimony, Mg_2Si Refinement

1. Introduction

Aluminium is one of the most extensively utilised engineering materials because of its unique combination of properties, including low density, comparatively high melting and boiling temperatures, and excellent ductility (Davis, 2001). It also exhibits non-toxicity, non-magnetic, highly machinable, capable of retaining strength at very low temperatures, and easily recyclable. Owing to these characteristics and its natural abundance, aluminium is widely applied in industries such as automotive and aerospace manufacturing (Robles Hernandez et al., 2017), as well as in construction, kitchen utensils, electrical wiring, and food-processing equipment (Davis, 2001).

Aluminium exists in numerous alloy and composite forms, among which aluminium-silicon (Al–Si) alloys are particularly significant. The addition of silicon improves castability, minimises porosity, and enhances mechanical performance (Mathai et al., 2015), making Al–Si alloys highly suitable for advanced applications including aerospace systems and electric vehicles. The incorporation of other alloying elements can further improve the performance of Al–Si alloys, with magnesium being one of the most important additions. Magnesium reacts to form compounds such as Al–Mg_2Si, which contribute to higher mechanical strength (Dash & Chen, 2023)(Kumar et al., 2015). Al–Mg_2Si composites have recently attracted considerable attention as potential substitutes for conventional Al–Si alloys, particularly in automotive applications such as pistons and brake discs. Their attractiveness is mainly due to their lightweight characteristics and the superior physical properties associated with the dominant Mg_2Si intermetallic phase (Farhany et al., 2016).

Despite these advantages, Al–Mg_2Si composites commonly contain coarse primary Mg_2Si particles together with eutectic flake-like Mg_2Si structures, both of which negatively affect mechanical performance. The brittle behaviour and angular morphology of Mg_2Si particles create stress concentration regions, especially around sharp corners and edges, which can trigger crack formation either at grain boundaries or within the Mg_2Si phase itself. These cracks subsequently propagate through the aluminium matrix, leading to reduced strength and ductility (Ren et al., 2017).

Improving the mechanical performance of Al–Mg_2Si composites therefore require refinement and morphological modification of the Mg_2Si phase. Several post-processing approaches, including hot extrusion (Ghandvar et al., 2018) and equal channel angular pressing (ECAP) (Chegini et al., 2021), have been investigated for this purpose. In addition, different modifying elements such as strontium (Jiang et al., 2018) and bismuth (Nordin et al., 2013), antimony (Bo et al., 2010) has been studied to alter the microstructure of aluminium alloys (Hazmi et al., 2024). As example antimony has been reported to improve mechanical properties by reducing particle size. Rare-earth (RE) elements have also demonstrated significant potential in enhancing the microstructure and mechanical properties of these composites. Previous studies have mainly focused on elements such as Ce (Nordin et al., 2015), La (Liu et al., 2015), Y (Zhao et al., 2025), Er(Chang et al., 2024), Gd (Wang et al., 2020), and praseodymium (Pr) (Aziz et al., 2019). Pr has been shown to refine Mg_2Si particles and improve mechanical properties (Yi, 2014). However, only limited studies have examined the simultaneous use of Pr and Sb as modifying alloying elements in Al-15 wt. % Mg_2Si. Therefore, this study investigates the combined addition of praseodymium (Pr) and antimony (Sb), focusing on their effects on the microstructural and mechanical properties of Al–15 wt. %Mg_2Si composites.

2. Method

Pure industrial-grade Al (99.98% purity), Si (99.0%), and Mg (99.85%) were used to fabricate the Al–15wt.% Mg_2Si composite ingot. The melting was done using an electric resistance furnace. Melting starts with pure Al at 800 °C, then Si is added to dissolve in the pure Al. Reduce the temperature to 750 °C, then pure Mg was added, and the mixture was cast into a metal mould to make an Al-Mg_2Si composite. To make the Al-Mg_2Si composite with different Pr- Sb compositions, similar process like before which with pure Al was melted at 800°C, then Si was added to dissolve in the pure Al. The temperature was reduced to 750 °C, and at this temperature, Pr-Sb compositions (0.5, 1.0, 1.5, and 2.0 wt.%) were added to the molten metal. Afterwards, at the same temperature Mg was added and cast into a metal mould. The total weight of cast aluminium composite needed to be fabricated is 1125 g. Table 1 illustrates the weight of used raw materials to fabricate Al-15 wt. %Mg_2Si composites with different contents of (Pr-Sb).

Table 1

Types of material	Al	Mg	Si	Pr	Sb
0.0wt%Pr-Sb	956.25g	106.875g	61.875g	0g	0g
0.5wt%Pr-Sb	956.25g	106.875g	61.875g	2.8125g	2.8125g
1.0wt%Pr-Sb	956.25g	106.875g	61.875g	5.625g	5.625g
1.5wt%Pr-Sb	956.25g	106.875g	61.875g	8.4375g	8.4375g
2.0wt%Pr-sb	956.25g	106.875g	61.875g	11.25g	11.25g

Before microstructural examination, the samples were cleaned ultrasonically and sequentially ground using silicon carbide abrasive papers with grit sizes of 400, 600, 800, 1200, 2400, and 4000. The ground surfaces were subsequently polished using a 0.5 µm colloidal silica suspension to obtain a mirror-like finish. Initial microstructural observations were conducted using an optical microscope (Nikon-MICROPHOT-FXL) at a magnification of 200× to evaluate the

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morphology of the primary Mg_2Si particles in the composites. Parameters including average particle size, particle density, and aspect ratio were analysed using ImageJ software.

Further microstructural analysis was carried out using a variable-pressure scanning electron microscope (VP-SEM) equipped with Energy-Dispersive X-ray Spectroscopy (EDX). Observations were performed at magnifications of 250×, 500×, and 1000×. In addition, backscattered electron (BSE) imaging together with point and area mapping techniques was employed to study the elemental distribution and phase dispersion within the composites.

Tensile testing was conducted using an Instron 5569 universal testing machine with a constant crosshead speed of 1 mm/min. Three tensile specimens, each with a gauge length of 10 mm and a diameter of 3 mm, were prepared from the samples and tested under identical conditions. To improve the reliability and accuracy of the results, a minimum of two specimens were tested for each composition.

Hardness measurements were carried out using a Matsuzawa DVK-2 Vickers Hardness Tester. The test parameters included an indentation load of 50 N, a constant loading speed, and a dwell time of approximately 30 seconds. Eight indentations were made at different locations on each sample, with a minimum spacing of 2 mm between indentations. The average hardness value was then determined from the obtained readings.

3. Results

3.1 Microstructure Characterization

Figure 1(a)–(e) shows the optical micrographs of cast Al–15 wt%Mg_2Si composites containing different Pr–Sb additions of 0, 0.5, 1.0, 1.5, and 2.0 wt.%. As shown in Figure 1(a), the microstructure consists mainly of whitish-grey particles, α-aluminium matrix, and primary Mg_2Si particles distributed within a fibrous eutectic Mg_2Si matrix, commonly referred to as secondary Mg_2Si. The morphology of the primary Mg_2Si particles in the unmodified Al–Mg_2Si composite agrees with previous studies, where coarse dendritic structures with central cavities are typically observed. Figures 1(a)–(e) demonstrate the changes in microstructure with increasing Pr–Sb content from 0 to 2.0 wt.%. In the unmodified sample, the primary Mg_2Si particles remained coarse and dendritic. With the addition of 0.5 wt.% Pr–Sb, these particles became finer and more spherical, with fewer sharp edges, as shown in Figure 1(b), resulting in a more homogeneous distribution throughout the matrix. However, when the Pr–Sb content increased to 1.0 wt.%, over-modification was observed, causing the average size of the primary Mg_2Si particles to increase and leading to particle coarsening, as illustrated in Figure 1(c). Figure 1(d) show more coarsening. This coarsening of primary Mg_2Si had an adverse effect on the mechanical performance of the composite, with properties declining as particle size increased.

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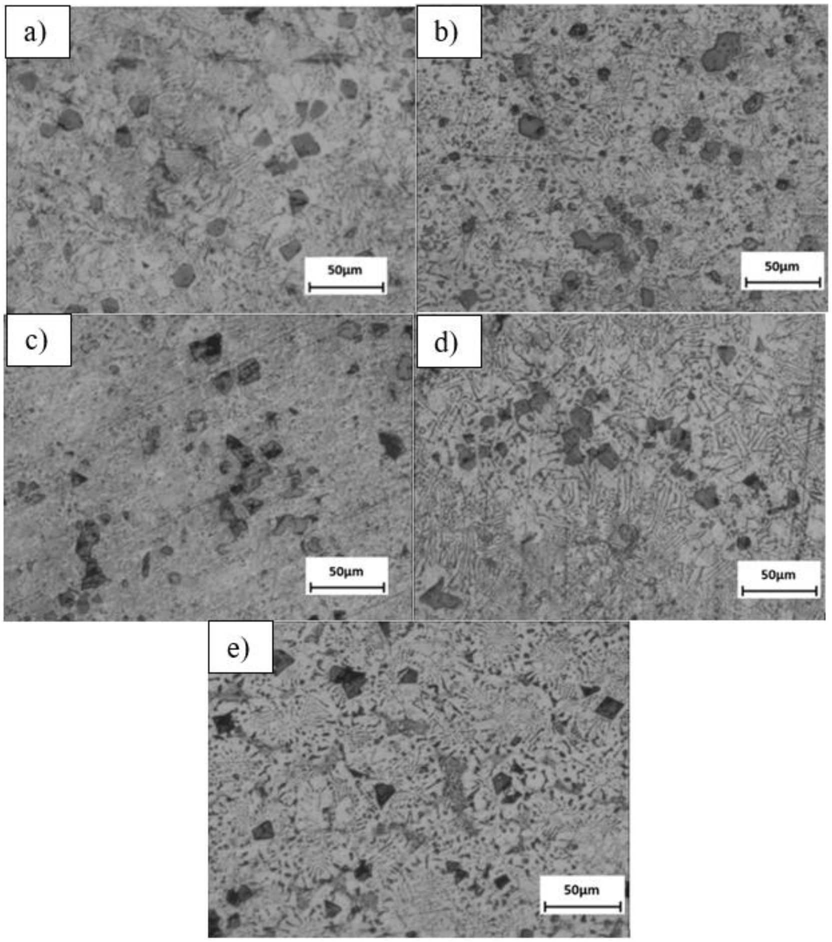


Figure 1. Optical Microscope of Al-15 wt.% Mg_2Si with different (Pr-Sb) wt% : (a) 0 wt.%, (b) 0.5 wt.%, (c) 1.0 wt.%, (d) 1.5 wt.%, and (e) 2.0 wt.%.

SEM images of Al-15% Mg_2Si with different (Pr-Sb) wt.% are shown in Figure 2 a) to e). Very similar with light microscope results, Figure 2a) is coarse shape because no (Pr-Sb), Figure 2(b) indicates that incorporating 0.5 wt.% (Pr-Sb) into the Al-15 wt% Mg_2Si composite produced the smallest primary Mg_2Si particle size among all (Pr- Sb) concentrations. The original polyhedral Mg_2Si particles transformed into a more polygonal shape, which may help reduce stress concentrations at sharp edges. Figure 2c),d),e) Shows coarsening effect from over-modificaiton.

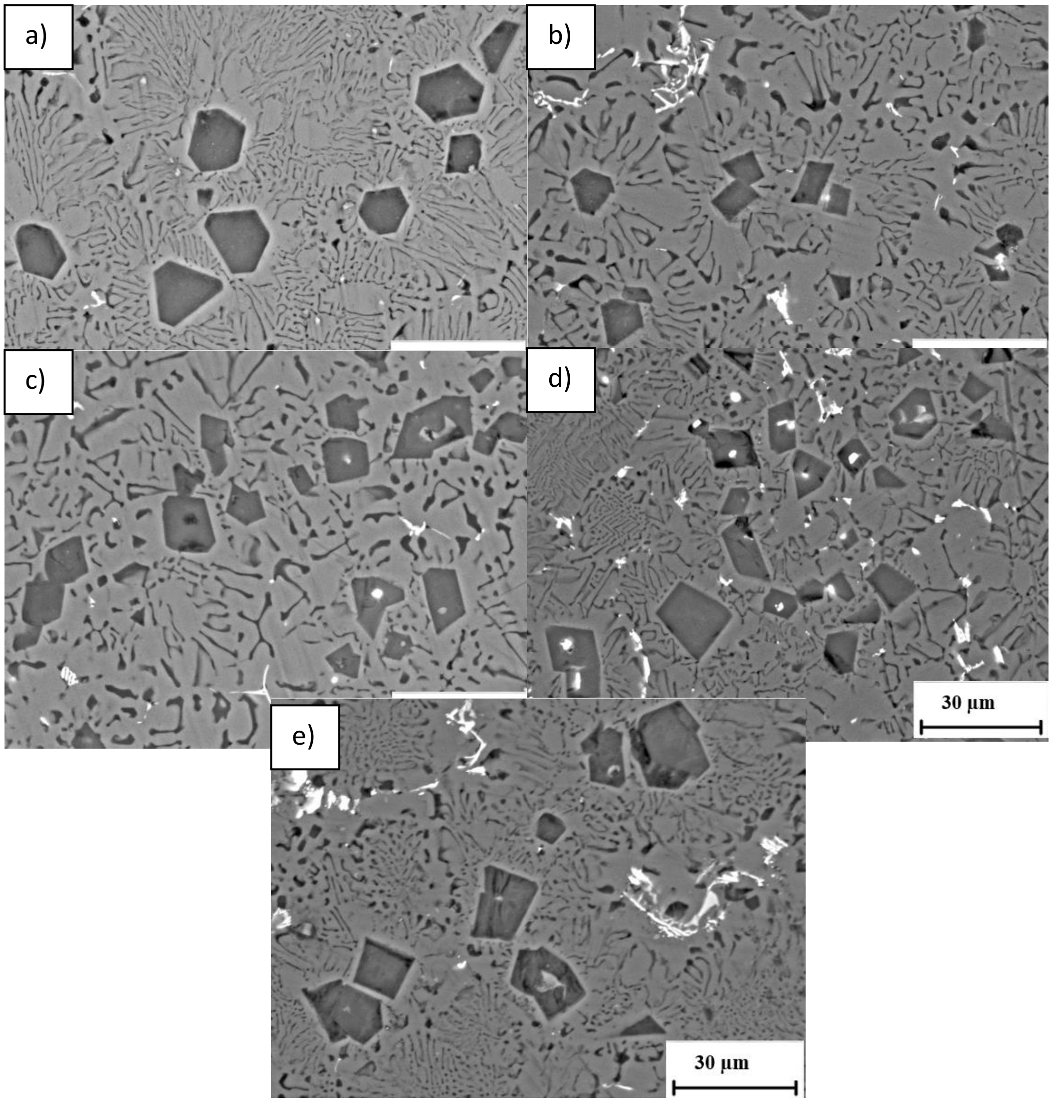
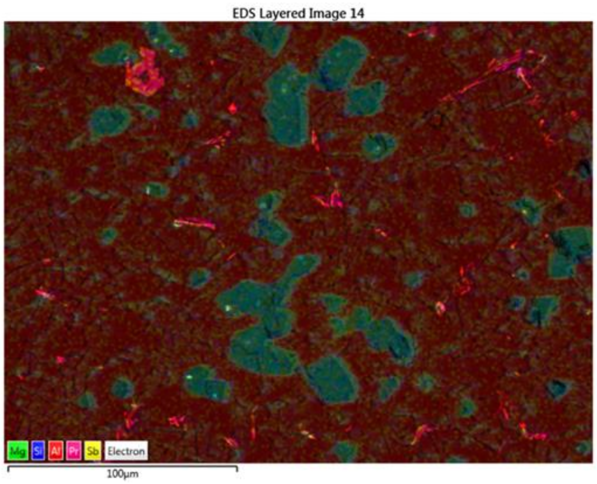


Figure 2. SEM image of Al-15% Mg_2Si with different (Pr-Sb) wt.% : (a) 0 wt.%, (b) 0.5 wt.%, (c) 1.0 wt.%, (d) 1.5 wt.%, and (e) 2.0 wt.%.

3.2 Statistics and Data Analysis

Figure 3 presents the EDS point and elemental mapping. The primary Mg_2Si appears as dark-green polygonal particles embedded within the red α-aluminium matrix. The white particle is identified as Pr, shown in light red in the area mapping. BSE elemental mapping in Figure 3 shows that Pr and Sb are distributed homogeneously alongside the Mg_2Si particles, with the white phase identified as Pr on the Mg_2Si particles. EDS results suggest that the incorporation of Al, Pr, and Sb in the primary Mg_2Si led to the formation of this new phase.



	Wt%	σ
Al	80.1	0.1
Mg	11.1	0.0
Si	8.2	0.0
Pr	0.4	0.0
Sb	0.2	0.0

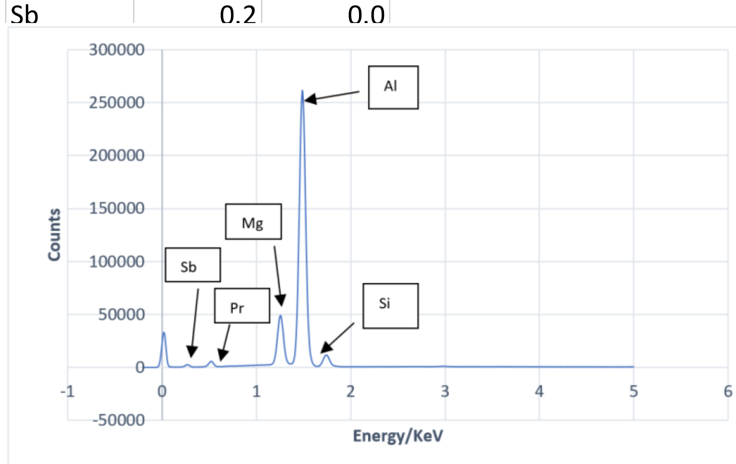


Figure 3. EDS analysis of Al-15% Mg_2Si with Pr-Sb

3.3 Size Analyses

Figure 4 shows the addition of 0.5 wt.% Pr–Sb significantly decreased the average particle size of primary Mg_2Si from 12 µm to 8 µm, representing a reduction of approximately 38%, which was the greatest refinement observed among all Pr–Sb concentrations. However, when the Pr–Sb content was increased to 1.0, 1.5, and 2.0 wt.%, the average particle size became larger, which may be attributed to over-modification and subsequent particle coarsening. Figure 4 also shows. The addition of Pr–Sb also affected the aspect ratio of the Al 15 wt%. Mg_2Si composite. The unmodified alloy exhibited an aspect ratio of 0.79, while the lowest value of 0.69 was recorded for the composite containing 0.5 wt.% Pr–Sb, corresponding to a reduction of 12.66%. This decrease indicates significant morphological refinement, where the primary Mg_2Si particles changed from coarse dendritic shapes into finer and more spherical forms.

Lastly particle density was likewise influenced by the combined addition of Pr and Sb. The unmodified composite had a particle density of 375 particles/mm². This value increased with the addition of Pr–Sb and reached a maximum of 767 particles/mm² at 0.5 wt.%. Beyond this concentration, the particle density gradually decreased with further Pr–Sb addition, eventually reaching 392 particles/mm² at 2.0 wt.% Pr–Sb.

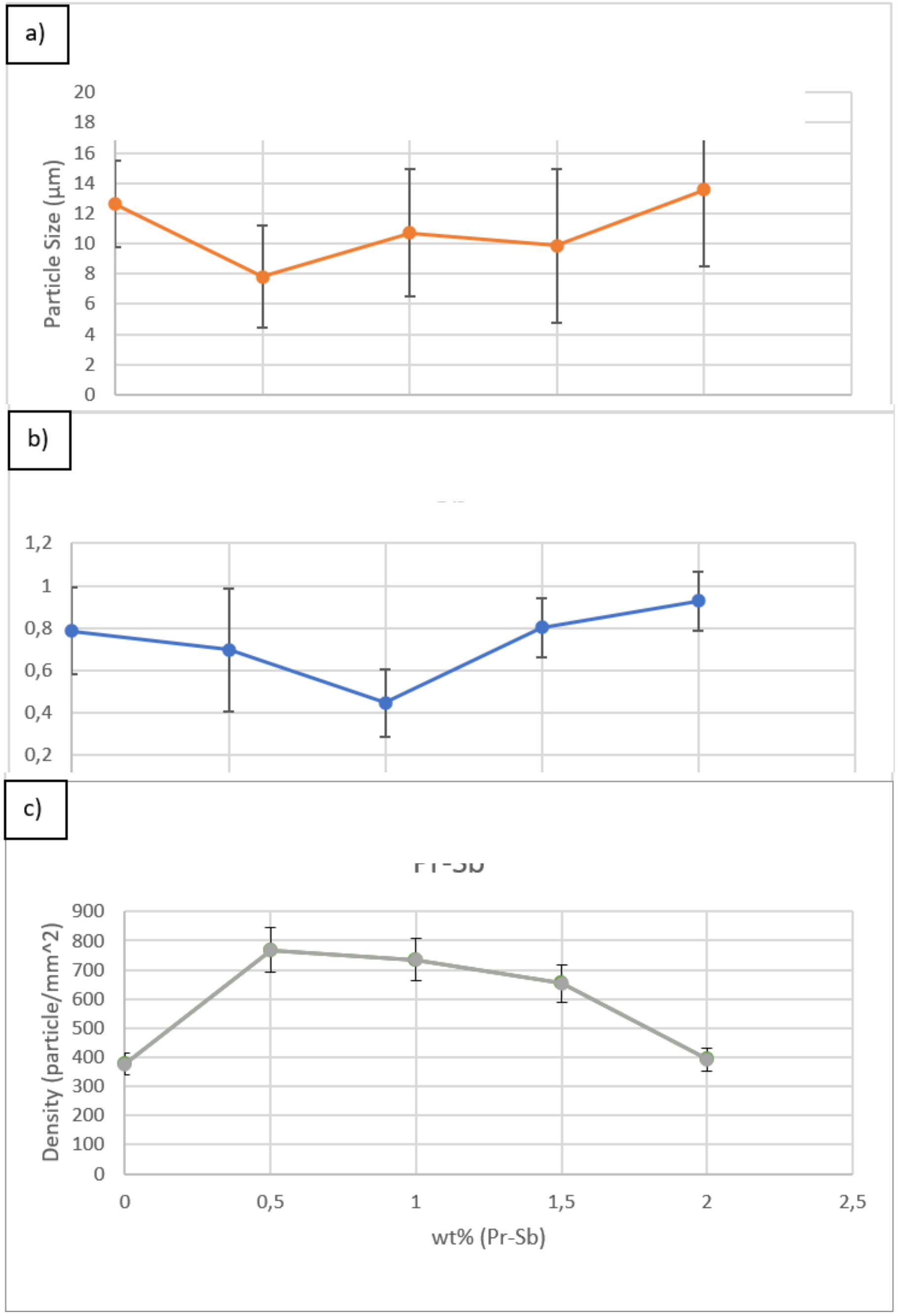


Figure 4. Effects of Pr-Sb of different percentages on Al-15 wt. % Mg_2Si on its a) particle size b) aspect ratio c) particle density

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3.4 Tensile Properties

It is shown in Figure 5 shows that generally using Pr and Sb as a modifier increases tensile strength. Without any addition of modifier, the UTS is 93 MPa. Then it improves until it reaches 0.5 wt.% (Pr-Sb) into the Al-15 wt% Mg_2Si alloy which has 100 MPa. The addition of (Pr-Sb) to the Al-15 wt.% Mg_2Si alloy resulted in a notable enhancement in mechanical performance, yielding approximately a 7.53 % increase in ultimate tensile strength (UTS). The elongation however somewhat decreases from 4.5 % to 3.8 % from 0 wt% Pr-Sb to 0.5 wt% Pr-Sb.

Figure 5 shows that after adding more Pr-Sb modifier, a decline in ultimate tensile strength (UTS) was observed and when the Al-15 wt.% Mg_2Si alloy was reinforced with 2.0 wt% % (Pr-Sb), the elongation of the Al-15 wt. % Mg_2Si–2.0 wt.% (Pr-Sb) composite decreased from 4.5 % to 1.8%, while its UTS dropped from 100 MPa to 44 MPa.

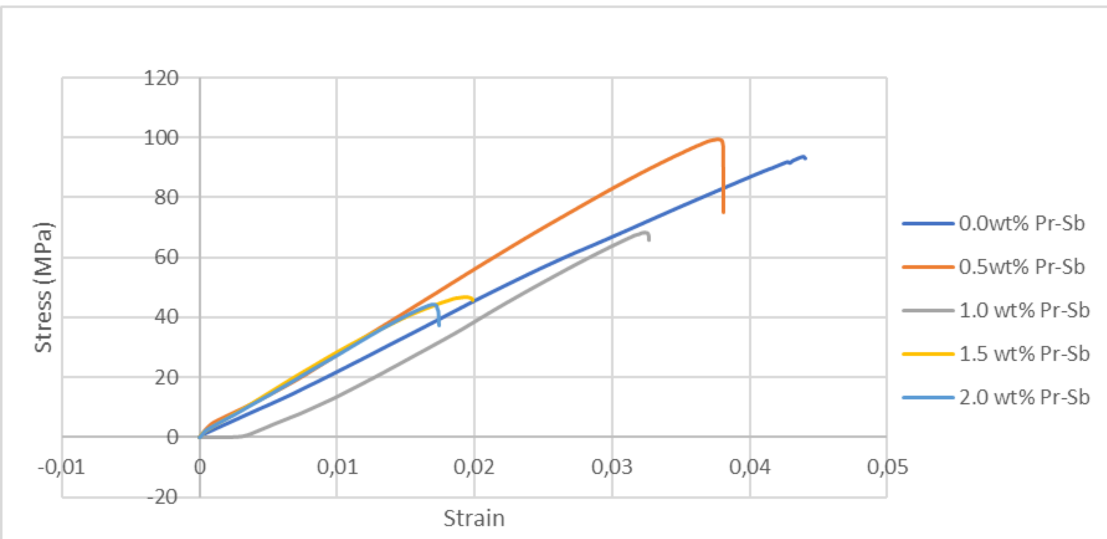

Figure 5. Stress-Strain Curve of Al-15 wt.% Mg_2Si composites modified with different content of (Pr-Sb)

As shown in Figure 2, Pr-containing intermetallic compounds act as obstacles to dislocation motion, thereby improving ductility at optimal levels. However, when the concentration of (Pr-Sb) is excessive, a substantial amount of brittle Pr intermetallic compounds (IMCs) forms, reducing the composite's ductility. Additionally, the increased Sb content promotes the formation of the rigid and brittle Mg_3Sb_2 phase along grain boundaries, which weakens the interfacial bonding with Mg_2Si and diminishes the plastic deformability of the (Pr-Sb)-modified composite (Sun et al., 2022)

3.5 Hardness Property

Figure 6 shows that with Pr-Sb addition hardness is affected. The hardness of the unmodified Al-15 wt% Mg_2Si increased generally as more wt% of Pr and Sb is added which rises from 75.3 Hv to 100.2 Hv with the incorporation of 2.0 wt.% (Pr-Sb), representing an approximate 21.10% improvement.

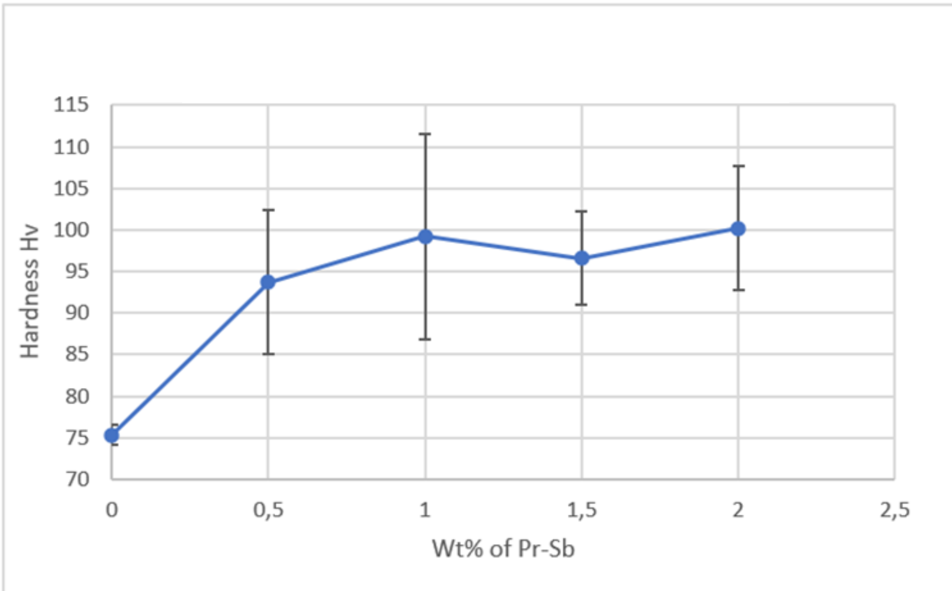

Figure 6. Hardness of Al-15wt.% Mg_2Si composites with different (Pr-Sb) additions

4. Discussion

After previous studies have demonstrated that the combined addition of Sb and rare-earth elements produces a synergistic effect, enhancing the refinement and morphological modification of primary Mg_2Si. The mechanism of how rare earth refine the Mg_2Si Particles is by inhibiting growth by segregating at the solid-liquid interface (Ghandvar et al., 2020). Based on the Gibbs–Curie–Wulff theorem and the competition mechanism, the equilibrium morphology of these particles is governed by the minimisation of total surface energy (Sun et al., 2022). The Sb element mechanism to modify the morphology is done changing in the surface anisotropy of some crystal facets (Nordin et al., 2013).

This reduction of density may be attributed to the excessive formation of Pr-rich intermetallic compounds. Additionally, reactions between Mg and Sb produced the Mg-Sb (Mg_3Sb_2) phase, while Al and Pr formed Al_3Pr. At high temperatures, these intermetallic compounds serve as effective heterogeneous nucleation sites for the formation of primary Mg_2Si. Their presence

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promotes a higher nucleation density and smaller particle sizes in the initial Mg_2Si phase (Sun et al., 2022).

This enhancement of tensile strength is attributed to the refinement of primary Mg_2Si particles, as smaller particles increase the number of grain boundaries, thereby improving the composite's tensile strength. According to dislocation theory, larger crystal sizes in the Al-15% Mg_2Si alloy promote dislocation accumulation and movement along the lattice. The inclusion of (Pr-Sb) suppresses crystallite coarsening and reduces primary Mg_2Si particle size, increasing grain boundary density and hindering dislocation motion (Nordin et al., 2013). Consequently, adding 1.0 wt.% (Pr-Sb) additions to the Al-15% Mg_2Si alloy enhance both strength and ductility through microstructural refinement and dislocation pinning mechanisms. This reduction in UTS can be attributed to excessive modification resulting from the high (Pr-Sb) content.

This increase in hardness is attributed to the formation of Pr intermetallic compounds, whose quantity rises with higher Pr content. These Pr-containing intermetallics possess inherently hard characteristics, contributing to the overall enhancement of the composite's hardness (Nordin et al., 2013).

Conclusion

Addition of Pr-Sb has effect on the morphology of Al-Mg_2Si composite. With the most optimal 0.5 wt.% (Pr-Sb) is added to the Al-15%Mg_2Si composite; it led to a distinct morphological transformation of the primary Mg_2Si phase, changing from large, irregular dendritic structures to smaller, more spherical particles. This minor (Pr-Sb) addition effectively refined and modified the coarse dendritic morphology observed in the unmodified Al- 15%Mg_2Si composite, producing particles with smoother contours and fewer sharp edges. Consequently, the density, particle size, and aspect ratio were all affected, with density increasing from 375 to 767 particles/mm^2, particle size decreasing from 12 µm to 8 µm, and the aspect ratio reducing from 0.79 to 0.69. The addition of only 0.5 wt.% Pr-Sb to the in-situ Al-15%Mg_2Si composite significantly enhanced its mechanical properties. The highest increase of tensile strength which is at 0.5 wt% Pr-Sb The tensile strength increased by approximately 7.53%, rising from 93 MPa to 100 MPa. However, elongation decreases from 4.5% to 3.8%. Furthermore, the formation of Pr-containing intermetallic compounds increased hardness, elevating it from 75.3 HV from 0.0wt% Pr-Sb to 100.2 HV at 2.0 wt% Pr-Sb.

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