Microstructure Characterization and Tensile Properties of Al-15%Mg_2Si-xYSZ Hybrid Composite

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Abstract

Aluminum matrix composites (AMCs) are widely used in the automotive industry as engine cylinders, pistons, and brake discs. It is due to its ability that better mechanical performance and physical properties are exhibited. Recently, hypereutectic Al-Mg_2Si in-situ composite with a large amount of hard Mg_2Si particles has attracted considerable attention due to the beneficial features of Mg_2Si particles. However, there are some limitations in the application of this composite due to its low tensile and machinability properties. Therefore, the purpose of this study was to fabricate and characterize the microstructure and tensile properties of Al/(15Mg_2Si+xYSZ) hybrid composites by using an in-situ reinforcement, namely magnesium silicide (Mg_2Si), and ex-situ reinforcement, yttria-stabilized zirconia (YSZ). The effect of different YSZ concentrations (i.e., 3, 6, and 9 wt. %) on the size, shape, and distribution of Mg_2Si particles was analyzed accordingly. Microstructure characterization was carried out by using optical microscope (OM), scanning electron microscopy (SEM), and X-ray diffraction (XRD). The microstructure examinations showed that with increasing YSZ concentrations, the size of primary Mg_2Si particles was reduced from 74.4 µm (i.e., without YSZ) to 65.2 µm (with 9 wt. % YSZ addition). Similarly, the tensile properties were enhanced parallel to the increasing concentrations from 53.54 to 85.65 MPa with 6 wt. % of YSZ.

Keywords: Al-Mg_2Si; YSZ; hybrid composite; microstructure; tensile properties

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Introduction

Aluminum matrix composite (AMC) is a combination of aluminum alloy with other types of material in which two different constituent phases are formed to improve its mechanical properties. The strength of composite materials is highly dependent upon the composition, grain size, microstructure, and fabrication process [1]. Generally, stir casting is accepted as a particularly promising route and is currently practiced commercially due to its simplicity, flexibility, and applicability to large quantity production. An additional advantage is its role for the low cost of the final product [2]. Meanwhile, hybrid AMC is the second generation of composites that pose a potential in substituting single reinforced composites due to its improved properties [3]. According to authors' knowledge limited studies have been examined the microstructure and tensile properties of Al-Mg_2Si-YSZ hybrid composite. In this study, hybrid composite materials were fabricated by using two types of reinforcements produced from two different techniques, specifically the in-situ and ex-situ techniques. Mg_2Si was synthesized by the in-situ technique, whereas YSZ reinforcement was added by the ex-situ technique. Both techniques have been associated with their own advantages and disadvantages. The in-situ technique generally shows good wettability of the particles and matrix, which enhances the high-temperature properties. It can also form reinforcement of a finer size and produce a more uniform distribution of the particles [4]. Moreover, the formation of Mg_2Si particles during the in-situ technique incorporation influences the mechanical properties of the composite material [5]. Meanwhile, the addition of YSZ reinforcement may assist in improving the mechanical properties of the hybrid composite as these reinforcements have resulted in high melting point, high hardness, and mechanical properties. Besides, they act as the dispersion strengthening agents and hinder the dislocation motion, leading to an improved composite strength [5].

This paper discusses the results obtained in producing aluminum hybrid composites. It encompasses the characterization of hybrid MMCs by using SEM, whereby its observation allows a look into the distribution of YSZ and Mg_2Si reinforcements within the MMCs. Furthermore, the fracture mode of each sample can be determined by observing the fractured surface of tensile samples via SEM. Therefore, the important feature of this paper consists of studying the tensile properties of hybrid MMCs produced at different weight fractions of YSZ (i.e., 0, 3, 6 and 9 wt. %) by using the tensile test.

Materials and Methods

The starting material to fabricate MMCs were pure Al (99.5% purity), pure Mg (99.8% purity), pure Si (98.8% purity) and pure YSZ (>99% purity, 10-30 μm) supplied by Stanford Advanced Materials (CA 92630, USA). To prepare Al-15Mg_2Si in-situ composite ingot, pure Al and Si were melted in a graphic crucible using resistance furnace at 800 °C. Consequently, pure Mg was added into the melt once the temperature decreased to 750 °C and finally cast in a metal mould. In order to prepare the hybrid composite Al/ (Mg_2Si+YSZ), firstly, the YSZ particles were peroxided at 800 ℃ for 2 h to obtain a better wettability. The mass fractions of YSZ particle addition were set at 0, 3, 6, and 9 wt. % accordingly. Then, approximately 300 g of Al-15Mg_2Si composite ingot was melted in a graphite crucible in an electric resistance furnace.

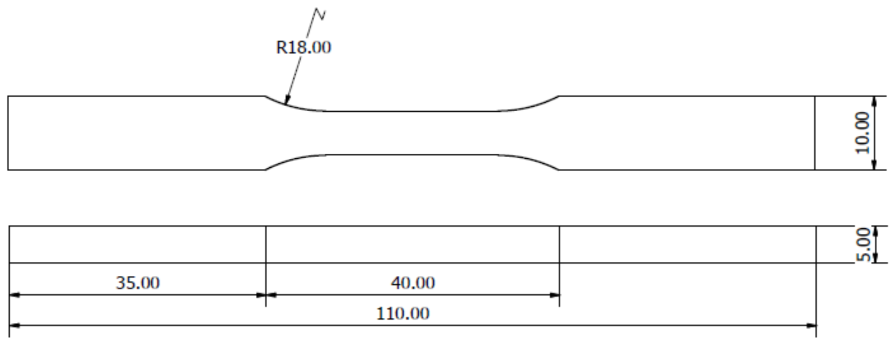

Figure 1. Drawing of the tensile sample (all dimensions are in mm)

Following this, the pre-heated YSZ particles were added into the Al-Si-Mg melts at 750 °C with stirring action, whereby the stirring condition for Al/(Mg_2Si+YSZ) composite fabrication was stirring speed of 500 r/min and stirring time of 15 min. Subsequently, after holding for 15 min, the composite melts were reheated to 720 °C and poured into a steel die to produce cylindrical samples with 30 mm diameter. The flat tensile test bars were extracted from the solidified samples using wirecut and prepared according to ASTM E8/E8M-13. The geometry of the tensile samples is shown in Fig.1. Subsequently, the tensile test was carried out by utilizing an Instron universal mechanical testing machine (5982) with load cell size of 400KN equipped with a strain gauge extensometer and at a constant crosshead speed of 1.0 mm/min at ambient temperature.

The metallographic specimens were polished via standard routines and examined by using OM and SEM (Philips XL40), as well as coupled with energy dispersive spectroscopy (EDS) to observe the features of the Mg_2Si phase and YSZ particles in the composites. The microstructure characteristics of the specimens were examined using SEM, whereas the mean size of Mg_2Si particles was analyzed by incorporating a quantitative analysis system (i-Solution image analyzer). Meanwhile, the phase constituents were analyzed by using XRD (PHILIPS binary diffractometer with Cu-kα radiation application).

Results and Discussion

Microstructural Characteristics

The optical micrograph was taken for different hybrid MMC samples using the same magnification to measure the particle size of the primary Mg_2Si. Figure 2 (a) shows large-sized Mg_2Si particulates within the Al-Mg_2Si composite, whereas other micrographs in Figures 2 (b) to 2 (d) reveal the Mg_2Si particles together in the presence of YSZ ex-situ reinforcement. In Figure 2, the size of Mg_2Si particle decreases with increasing volume fraction of ex-situ YSZ reinforcement. To clarify the decreasing size of Mg_2Si particles, an optical analysis was conducted to measure both particle sizes. The results after measurement are displayed in Table 1. According to previous research, the decreasing size of Mg_2Si particles alongside increasing volume fraction of ex-situ reinforcement is attributable to more nucleation sites present for the primary Mg_2Si particles. Essentially, it leads to the refinement of these particles' size, whereby reducing the size causes an increment in the number of nuclei during the initial stage of solidification; it is thus responsible for the grain refinement of the primary Mg_2Si particles [6].

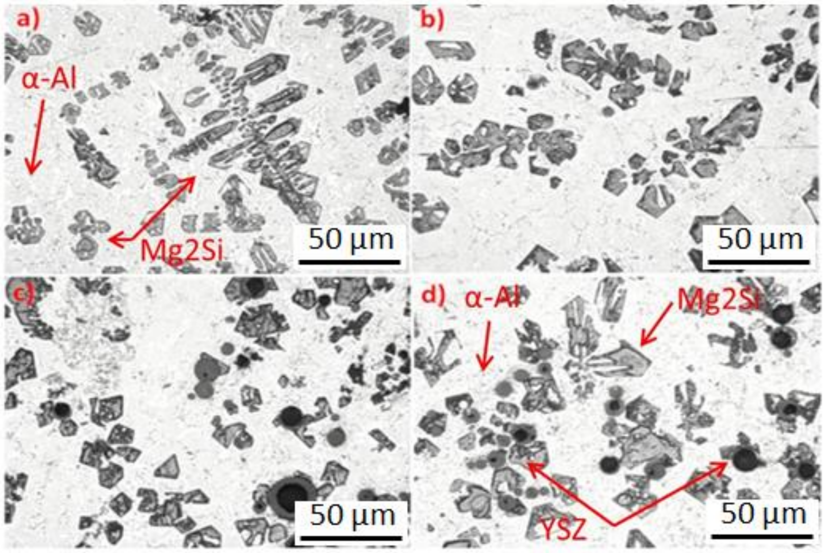

Figure 2. Optical micrographs of Al-Mg_2Si composite with a) 0wt. %, b) 3wt. %, c) 6wt. % and d) 9wt. % of YSZ

Table 1. Microstructure analysis of aluminum composite

Composite	**Al-15Mg_2Si**	**Al-15Mg_2Si-3wt. % YSZ**	**Al-15Mg_2Si-6wt. % YSZ**	**Al-15Mg_2Si-9wt. % YSZ**
Mg_2Si particle size (µm)	74.4	73.8	72.4	65.2

Phase analysis

Figure 3 shows the XRD patterns for Al-Mg2Si composite reinforced with different volume fractions of YSZ particles. Similar peaks were observed for both Al and Mg2Si phases accordingly, whereby the phase analysis confirmed the presence of in-situ Mg2Si phase formation in the composite material. Meanwhile, the addition of ex-situ particles in the composite materials resulted in the formation of three new peaks in the XRD pattern, which matched the YSZ compounds at 2θ of 30, 50, and 60 [7].

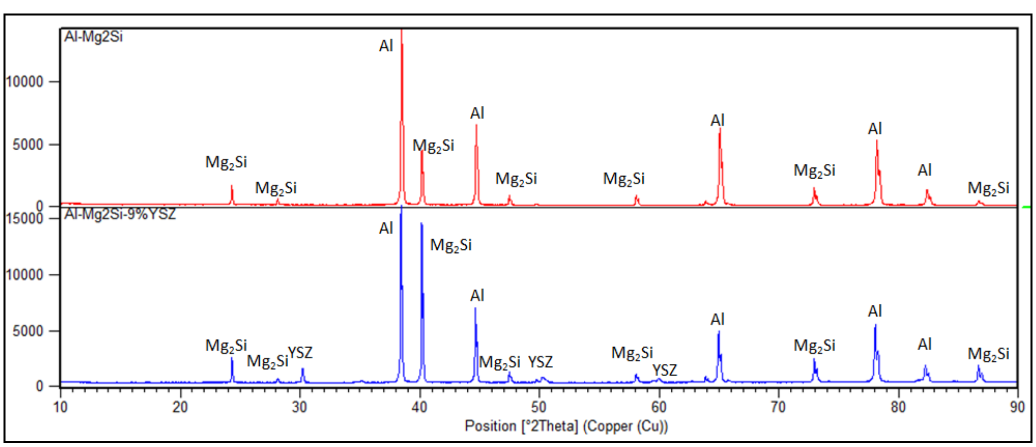

Figure 3. XRD patterns for Al-Mg_2Si composite reinforced with 0wt. % YSZ and 9wt. % YSZ

Tensile Properties

Figure 4 shows the SEM micrograph of Al-Mg2Si composite materials with three different reinforcement volume fractions. The grey area in the micrographs represents the aluminum matrix, whereby the white particles are YSZ particles and the black areas are Mg2Si particles. The YSZ particles are nearly round in shape and almost uniformly distributed in all hybrid composite samples. However, Figure 4 (d) shows some agglomerations of the reinforcement particles in the tensile fracture surface of the aluminum hybrid composite in the presence of 9 wt. % of YSZ. This feature is caused by manual mixing of YSZ powder in the molten Al-Mg2Si composite during the stir casting process [1]. Apart from that, such agglomeration of particles may also be formed due to the high processing temperature [8]. The agglomerated YSZ particles have introduced interfacial defects and resulted in low bonding strength between the reinforcement and matrix interfaces.

The agglomeration behaves like bigger particles and acts as the sites of stress concentration when a load or tension is applied to the composite and the stress transfer between the particles is inefficient [6]. This can be attributed to the low value of tension for the aluminum hybrid composite in the presence of hard YSZ particles. Figure 5 shows the typical stress-strain curve of the fabricated composites. According to Fig.5 and Table 2, it is seen that smaller UTS values belongs to Al-Mg2Si composite, which corresponds to the coarse and large particles of the primary Mg2Si particles. In contrast, better tensile properties were obtained in the hybrid composite reinforced with 3 wt. % and 6 wt. % of YSZ particles, thereby indicating that the loads were successfully and efficiently transferred from the matrix material to the reinforcement particles. Additionally, Figure 5 shows greater UTS values with the addition of 6 wt. % of YSZ composite compared to 3 wt. % due to an increased number of volume fractions, leading to a higher number of stress concentrating points [9].

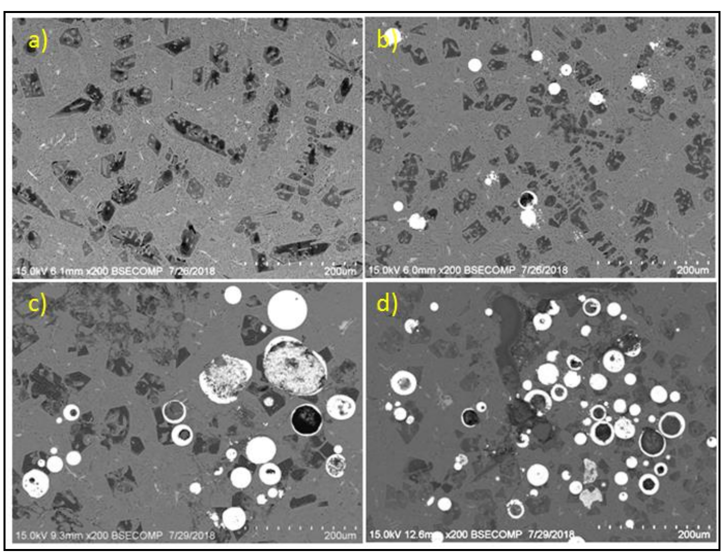

Figure 4. SEM micrographs of Al-Mg_2Si composite with; a) 0wt. %, b) 3wt. %, c) 6wt. % and d) 9wt. % of YSZ

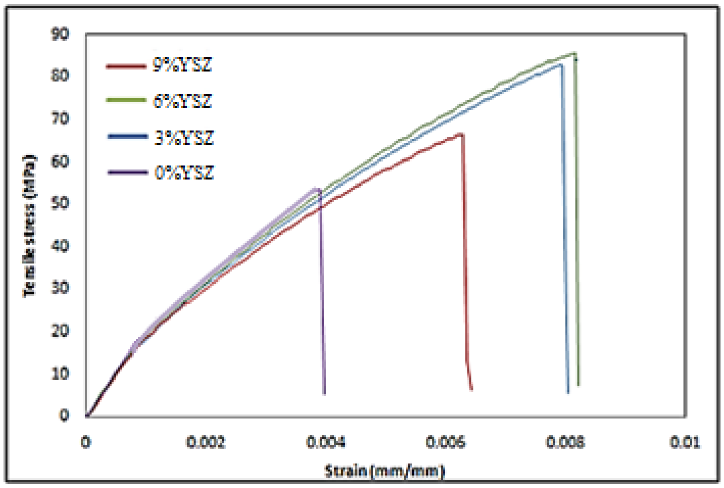

Figure 5. Stress-strain engineering curve of composite materials

Table 2. Experiment Tensile Test

Composite	**Al-15Mg2Si**	**Al-15Mg2Si-3wt.% YSZ**	**Al-15Mg2Si-6wt.% YSZ**	**Al-15Mg2Si-9wt.% YSZ**
UTS (MPa)	53.54	83.27	85.65	66.48

Figure 6 shows the fracture surface samples from the tensile test in which Figures 6(a) to 6(d) show the presence of crack on the Mg2Si particles.

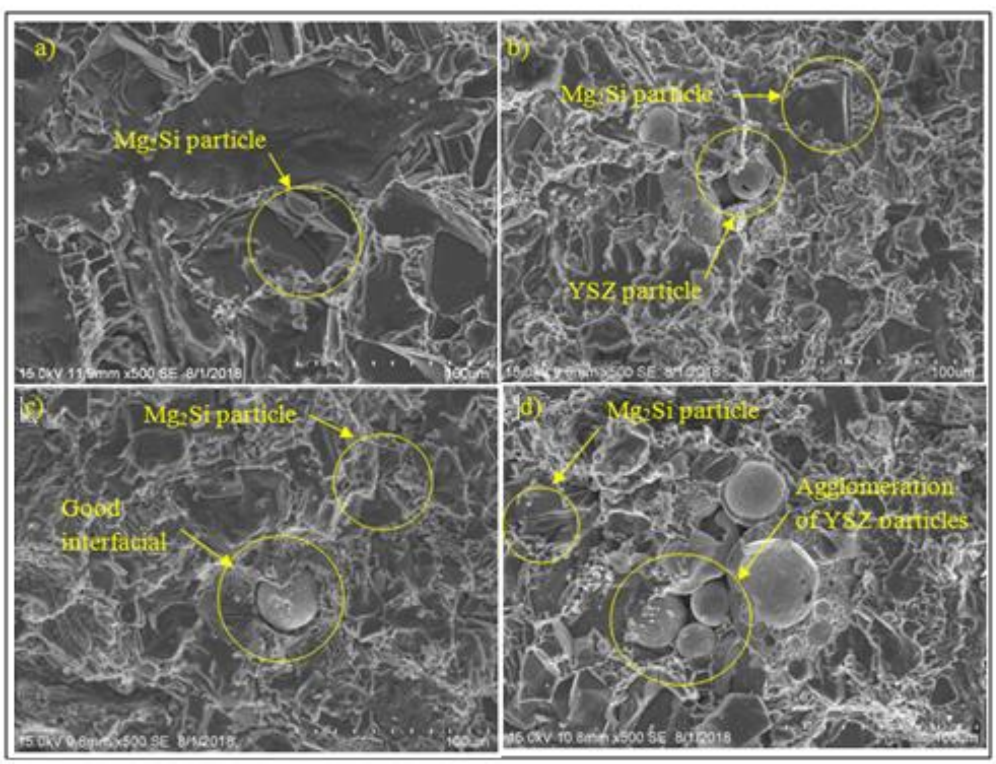

Figure 6. SEM micrographs of tensile fracture surface of Al-Mg_2Si composite with; a) 0wt. %, b) 3wt. %, c) 6wt. % and d) 9wt. % of YSZ

The findings indicated that the loads were able to transfer from the aluminum matrix to the Mg2Si reinforcement during the tensile test. Figure 6(b) specifically shows the YSZ particle crack, suggestive of the load is sufficient to fracture the ex-situ reinforcement, whereas Figure 6(c) reveals good interfacial bonding between the aluminum matrix and YSZ reinforcement. These features yielded significantly higher value of ultimate tensile strength compared to other composite materials reinforced with different volume fractions of YSZ particles. Moreover, the presence of YSZ particles agglomeration is shown in Figure 6(d), displaying these sites and their action as the stress concentration area and that the crack was assumed to occur within the YSZ particles.

Conclusion

A combination of two types of reinforcements, namely Mg_2Si and YSZ, successfully produced hybrid composite materials with good tensile properties. However, some of the materials were unable to act as anticipated, which was due to the limitations in fabricating the aluminum hybrid composites. A particular challenge encountered during their production was the stir casting technique. Therefore, several factors require improvements to ensure the production of superior composite properties, such as sustaining the YSZ feeding rate and maintaining the stirring speed to ensure the continuous formation of the vortex within the melt. Low stirring speed will cause an uneven distribution of particles, whereas a high feeding rate will cause the congestion of YSZ to settle into the melt. These scenarios will cause YSZ agglomeration to occur eventually. Additionally, the tensile properties of the composite may be improved by conducting heat treatment, resulting from homogenized microstructure and better particle distribution.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards

References

[1] Das, D. K., Mishra, P. C., Singh, S. & Thakur, R. K (2014). Properties of ceramic-reinforced aluminum matrix composites - a review. International Journal of Mechanical and Materials Engineering. 9(1) 12
[2] Annigeri, U. K., & Veeresh Kumar, G. B. (2017). Method of stir casting of Aluminum metal matrix Composites: A review. Materials Today: Proceedings. 4(2) pp 1140–1146.
[3] Singh, J. & Chauhan. A (2016). Characterization of hybrid aluminum matrix composites for advanced applications - A review. J. Mater. Res. Technol. 5(2) 159–169
[4] Ghandvar, H., Idris, M. H., Ahmad, N., & Emamy, M. (2018). Effect of gadolinium addition on microstructural evolution and solidification characteristics of Al-15%Mg_2Si in-situ composite. Mater. Charact. 135 57–70
[5] Srinivas, V. & Singh, V (2012). Development of in situ as cast Al-Mg2Si particulate composite: Microstructure refinement and modification studies. T Indian I Metals. 65(6) 759–764
[6] Guo, C., Zhou, L. & Lv, J (2013). Effects of expandable graphite and modified ammonium polyphosphate on the flame-retardant and mechanical properties of wood flour-polypropylene composites. Polym Polym Compos. 21(7) 449–456
[7] Gafur, M. A., Sarker, M. S. R., Alam, M. Z. & Qadir, M. R (2017). Effect of 3 mol% Yttria Stabilized Zirconia Addition on Structural and Mechanical Properties of Alumina-Zirconia Composites. Mater Sci. 8(7) 584–602
[8] Vani, V. V. & Chak, S. K (2018). The effect of process parameters in Aluminum Metal Matrix Composites with Powder Metallurgy, 7
[9] Chawla, N. & Shen, Y. L (2001). Mechanical behavior of particle reinforced metal matrix composites. Adv Eng Mater. 3(6) 357–370