Influence of TiB_2 Particles on Modification of Mg_2Si Eutectic Phase in Al–Zn–Si–Mg–Cu Cast Alloys

Byung Joo Kim, Sung Su Jung, Yong Ho Park, and Young Cheol Lee

Abstract

In this study, the effect of TiB_2 particles on the modification of eutectic phase in Al–Zn–Si–Mg–Cu system alloys is investigated. The microstructure showed that an excellent effect can be achieved after the addition of TiB_2 particles. The morphology of eutectic Mg_2Si changed from large Chinese script to fine polygonal shape with a significant reduction in size. Modified eutectic Mg_2Si particles were investigated using an optical microscope and field emission scanning/transmission electron microscope, and it was confirmed that TiB_2 particles acted as nucleation sites for the eutectic Mg_2Si phase, and the grain size change of Al–Zn–Si–Mg–Cu alloy with increasing TiB_2 contents was analyzed by polarizing microscope. The mechanical properties were also improved by the modified of eutectic Mg_2Si phase. This manuscript also investigated the reason for the improvement in mechanical properties with the modification of the microstructures. Upon these results, a possible mechanism of eutectic Mg_2Si phase modification by the addition of TiB_2 particles is proposed.

Keywords

Aluminum alloys • Phase modification • Intermetallic compound • Mechanical properties

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Introduction

The transition of the intermetallic compound morphology in aluminum alloys, also called phase modification, is commonly used in industry to improve mechanical properties, especially ductility. Intermetallic compounds that form during solidification appear in various shapes and sizes, and there are three general morphologies, namely as needles, Chinese script and polyhedral or star-like crystals. Due to the edges or tips of these morphologies serious stress concentration is induced in the matrix, which leads to brittleness of the material. Conversely, the spherical or polygonal type does not concentrate the force and has minimal adverse effect on the elongation of the material. Thus, modification of intermetallic compounds is usually required to improve the mechanical properties of cast components.

Mg_2Si intermetallic compounds are used as core hardened phases in aluminum alloys containing Mg and Si (like as 6XXX) because of their high hardness (4500 MNm^{-2}), low density (1.99×103 kgm^{-3}), high elastic modulus (120 GPa), high melting temperature (1085 °C), and low coefficient of thermal expansion (7.5×10^{-6} K^{-1}) [1, 2]. The shape and size of intermetallic compounds have a great influence on the mechanical properties of aluminum alloy [3]. However, in general casting conditions, the final microstructure of Mg_2Si intermetallic compound became coarse with dendritic morphology. This morphology of the Mg_2Si phase is a weakness of the aluminum alloys. To solve this problem, many studies of the Mg_2Si phase modification have been carried out such as P [4, 5], Sr [6], Na [7] and TiB_2 [8, 9] addition. In our previously study, large amount of TiB_2 particles (about 1 wt% Ti contents) were shown to be very effective in modifying the shape of eutectic Mg_2Si intermetallic [8]. However, the effect of TiB_2 particles during solidification on the eutectic Mg_2Si crystal growth, and why a large amount of TiB_2 is needed to modify eutectic Mg_2Si, are unclear. The purpose of this study is to study the relationship of TiB_2 and Mg_2Si phases in Al–8Zn–6Si–4Mg–2Cu cast

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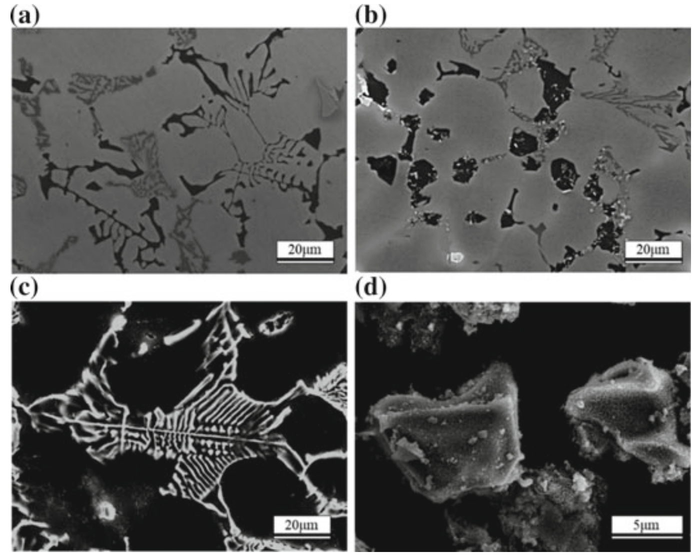

Fig. 1 Microstructure of the eutectic Mg_2Si phase of Al–8Zn–6Si–4Mg–2Cu alloy; **a** and **c** without Al–5Ti–1B master alloy; **b** and **d** with the Al–5Ti–1B master alloy at 1 wt% Ti content

alloys. The mechanism of change in the direction of Mg_2Si crystal growth during the solidification process is also discussed.

Experiments

Al–8Zn–6Si–4Mg–2Cu–*x*Ti (*x* = 0, 0.1, 0.5, 1 wt%) alloys were produced by gravity-casting. A 20 kHz high frequency furnace was used for melting the alloys. These alloys were prepared by adding pure Zn (99.99%), Mg (99.9%), Cu (99.997) ingot, Si (99.9%) crystalline and Al–5Ti–1B master alloy rods to aluminum molten (99.7%) held at 710 ± 5 °C. After adding the elements, the molten alloys were held for 10 min to assure alloying additions dissolution and melt homogenization. Cast for metallographic specimens were prepared using a cylinder mold (32 Dia. × 70 mm, FC25 cast iron) preheated to 250 °C. Microstructures were examined using a polarizing microscope, a FE-SEM, FIB and a 200 kV FE-TEM. Deep etching was carried out in 20% NaOH water solution to confirm the 3-dimensional morphology of the eutectic Mg_2Si phase. 2% Fluoboric acid water solution was used as etchant to electrolytic etching, and grain size measurement was according to ASTM E1382. The tensile test were carried out according to the ASTM E8 M using the universal testing machine.

Results

Figure 1a, b show the morphology of the eutectic Mg_2Si phase when Al–5Ti–1B master alloy was added to Al–8Zn–6Si–4Mg–2Cu alloy at 0, 1 wt%. Ti contents. Figure 1c, d shows the change of morphologies of eutectic Mg_2Si before and after modification by deep etching. In Fig. 1a, c, without Al–5Ti–1B addition, coarse Chinese script type eutectic Mg_2Si phase can be clearly observed. When Ti was added, eutectic Mg_2Si morphology changed to a polygonal shape, less than 10 μm in size (Fig. 1b, d). TiB_2 particles with bright contrast were also observed inside and outside the modified eutectic Mg_2Si in the same figure.

Optical microscope images of microstructure after electrolytic polishing of Al–Zn–6Si–4Mg–2Cu alloy with different Al–5Ti–1B addition amounts are shown in Fig. 3. It can be seen that the grains are clearly determined according to the different color contrast of grains. When 0.1 wt% of Ti was added, the grain size decreased from about 322–120 μm, and there was no further grain refinement, even when the Ti addition amount was increased to 1 wt%.

In the Al–8Zn–6Si–4Mg–2Cu alloy, the eutectic Mg_2Si phase was observed at the inner edge of the aluminum grain (Fig. 2b). As the amount of Ti was increased, more modified eutectic Mg_2Si phases were observed. Interestingly, polygonal shaped Mg_2Si phases were observed in the grain boundaries, as opposed to Chinese script type morphology (Fig. 2h).

Figure 3 shows the change of mechanical properties of aluminum alloy with different contents of Ti wt% [8]. As the content of Ti increases to 1 wt%, the mechanical properties also increase. Yield strength increased from 175–206 MPa and tensile strength increased from 195–253 MPa. The highest increase was the elongation, increasing from 0.63 to 1.05%.

Shapes like Fig. 1a are brittle to mechanical load, because the stress is easily concentrated at the tip. This stress concentration is reduced as the shape of the intermetallic

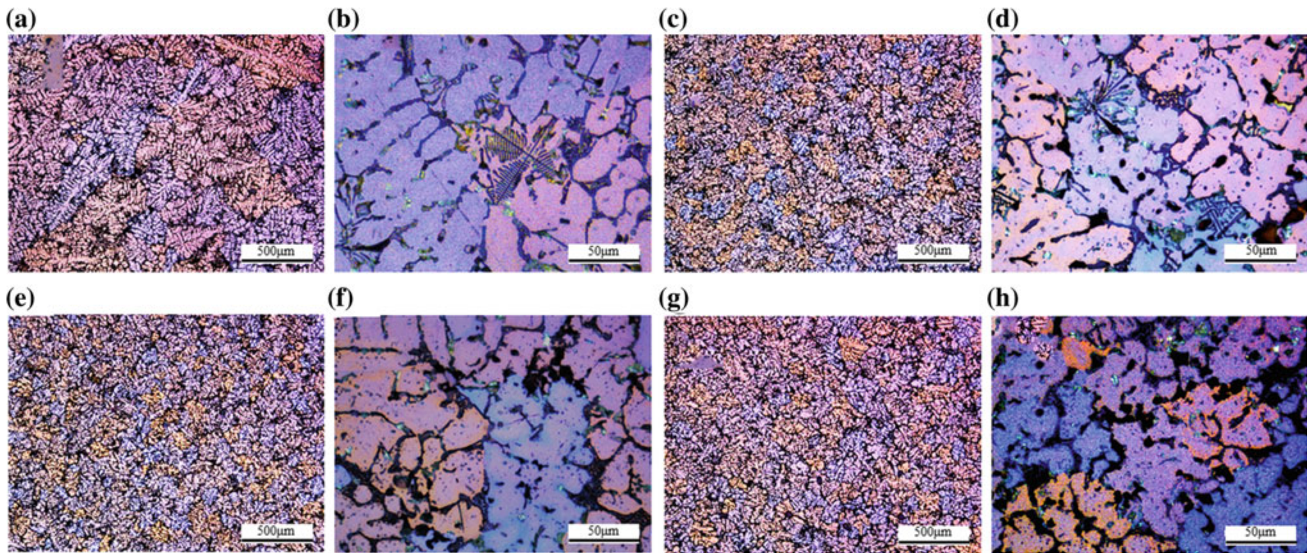

Fig. 2 Optical microscope images of the Al–8Zn–6Si–4Mg–2Cu alloys after electrolytic polishing; **a**, **b** no Ti, **c**, **d** 0.1 wt% Ti, **e**, **f** 0.5 wt% Ti, **g**, **h** 1 wt% Ti

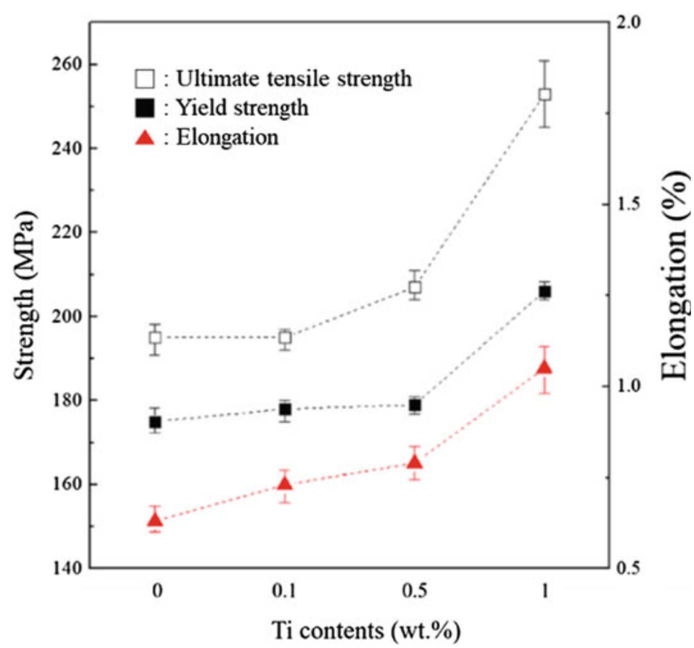

Fig. 3 Mechanical properties of Al–8Zn–6Si–4Mg–2Cu alloys with different Ti contents [8]

compound becomes smaller and rounder. As the added TiB_2 particles, the eutectic phase of Chinese script shape changes to polygonal shape. As the Ti content was added by 1 wt%, Most of the eutectic phases were modified, which greatly increased the mechanical properties.

Figure 4 shows a cross-section of the modified eutectic Mg_2Si phase measured by TEM/EDS. Al, Mg, Si, Ti and B elements were detected by EDS. It confirms that a phase containing Ti, B is observed inside of the modified Mg_2Si. Analysis of the crystal orientation of Mg_2Si and TiB_2 by HR-TEM is shown.

Discussion

As shown in Fig. 1, the eutectic Mg_2Si phase was modified by the addition of Al–5Ti–1B master alloys. In previous studies, it was reported that TiB_2 particles in the Al–5Ti–1B master alloy modified the eutectic Mg_2Si phase [8]. Figure 2b, d show that the eutectic Mg_2Si phase was observed at the inner edge of the aluminum grains. Figure 5 shows the solidification mechanism of the eutectic Mg_2Si phase in the Al–8Zn–6Si–4Mg–2Cu alloy. Figure 5a shows the

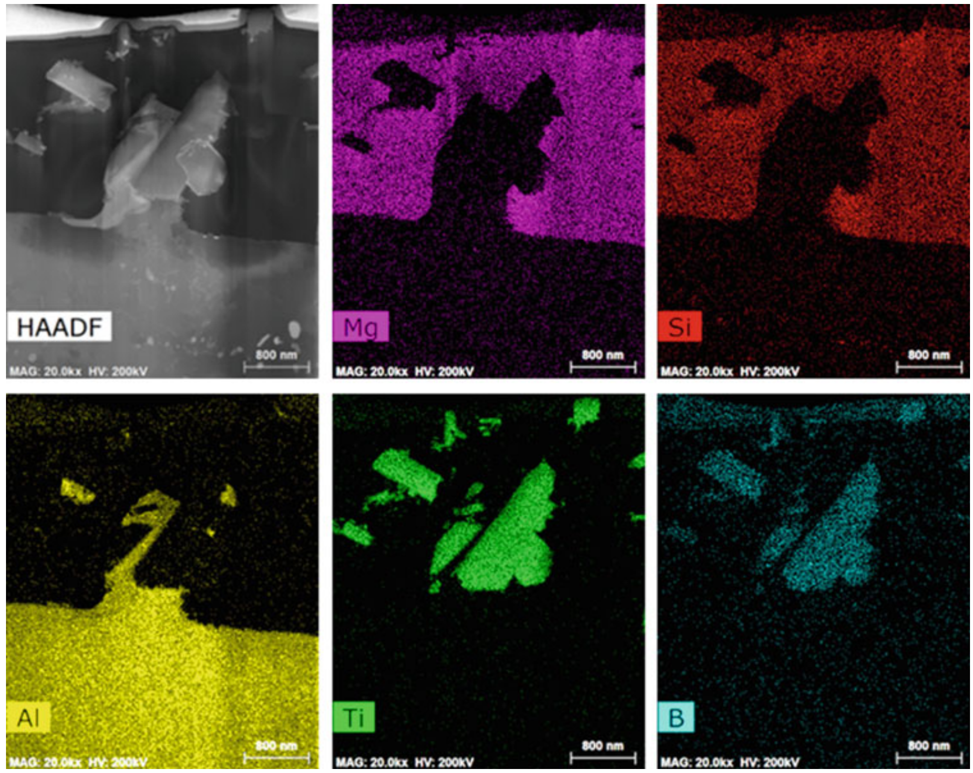

Fig. 4 TEM/EDS analysis data of modified eutectic Mg_2Si phase

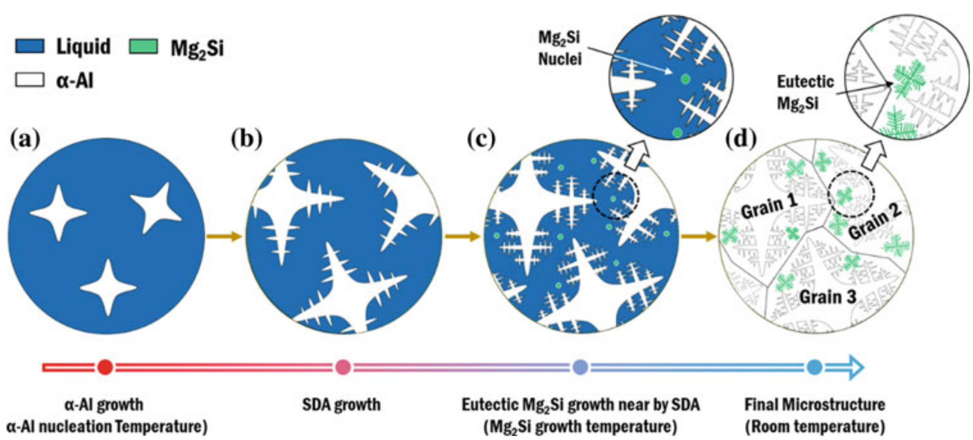

Fig. 5 Schematic illustrations presenting the stages in microstructural evolution during solidification of eutectic Mg_2Si with no TiB_2 particles

nucleation and growth of primary aluminum dendrite. Figure 5b shows the growth of secondary dendrite arms (SDA) due to growth and coarsening of aluminum dendrites. Segregation of the solute element (Mg, Si) occurs during the growth of aluminum grains. In SDA where Mg and Si elements are segregated, the Mg_2Si nuclei form due to the compositional supercooling. Therefore, nuclei of eutectic Mg_2Si generate around the SDA and grow into Chinese script morphology (Fig. 5d). While the eutectic Mg_2Si phase grows near the SDA, the α-Al also grows and these two phases come into contact during solidification. Segregation of solvent elements (Al) occurs around the growing eutectic Mg_2Si phase, the edge of Chinese script morphology has a low potential for the contacted α-Al. For this reason, α-Al will easily engulf the eutectic Mg_2Si, and as a result, the eutectic Mg_2Si phase solidifies at the edge of the grain as shown in Figs. 2b, d, and 5d.

The solidification path of the Al–8Zn–6Si–4Mg–2Cu alloy has been reported to proceed in the order of α-Al → Mg_2Si → Si → $Al_5Cu_8Si_6Mg_2$ [8]. The particle pushing of TiB_2 particles by α-Al is known in many research [10, 11]. Particularly, the agglomerated TiB_2 particles have a high potential at the interface with the growing aluminum, and they are easily pushed by the growing aluminum [11]. TiB_2 particles also act as good nucleation sites on Mg_2Si because the crystal arrangement at the interface between the

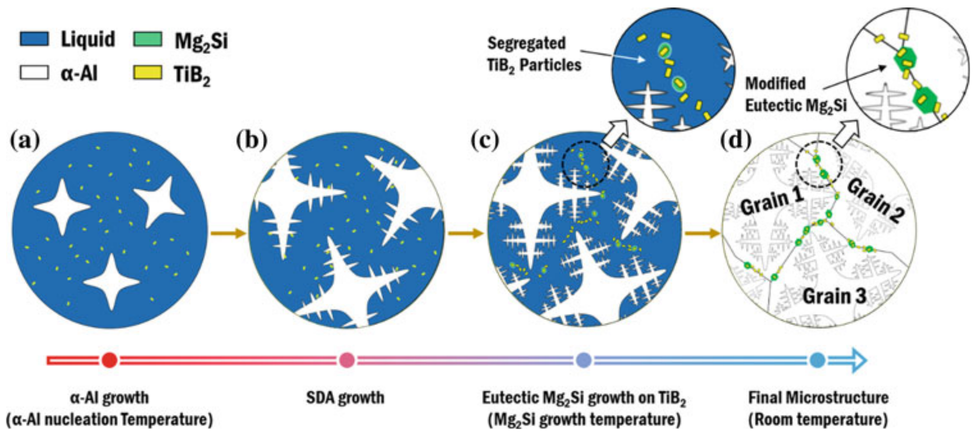

Fig. 6 Schematic illustrations presenting the stages in microstructural evolution during solidification of eutectic Mg_2Si with TiB_2 particles

(001) of TiB_2 and the (200) of Mg_2Si is similar [9]. In previously studies, and in Figs. 1 and 2 of this work, the modified eutectic Mg_2Si located at grain boundaries and the TiB_2 particles present in and around it suggest the following mechanism: TiB_2 particles were pushed into grain boundaries during the growth of the α-Al grain, and the TiB_2 particles agglomerated in the grain boundaries acted as nucleation sites for eutectic Mg_2Si. Figure 6 shows the solidification mechanism of the eutectic Mg_2Si phase of the Al–8Zn–6Si–4Mg–2Cu alloy with enough TiB_2 particles added. Figure 6a shows the nucleation and growth of primary aluminum as shown in Fig. 5a. As solidification progresses, the agglomerated TiB_2 particles are easily pushed out while the aluminum SDA is growing, because they have a high potential for aluminum (Fig. 6b). At the temperature where the magnesium phase forms, the eutectic Mg_2Si phase nucleate easily from the TiB_2 particles as shown in Fig. 6c. It means that the eutectic Mg_2Si phase nucleates on the TiB_2 substrates and grows in polygonal shape. During the growth of the eutectic Mg_2Si phase with TiB_2 particles, aluminum also grows and these two phases come into contact. Unlike the Chinese script eutectic Mg_2Si, the polygonal eutectic Mg_2Si and the agglomerated TiB_2 particles have a high potential for α-Al and are easily pushed into the grain boundaries. As shown in Figs. 2f, g and 6d, modified Mg_2Si and TiB_2 particles are located in the aluminum grain boundaries.

Another discussion point is the effect of grain refinement with TiB_2 addition on the morphology of eutectic Mg_2Si phase. Al-5Ti-1B master alloy is known as a good grain refiner for aluminum alloys. In this work, Al–5Ti–1B master alloy of 0.1, 0.5, 1 wt% Ti contents were added. With 0.1 wt % Ti addition, the grain size was greatly decreased from 322 to 122 μm. However, further refinement was not observed with addition of 0.5, 1 wt% Ti contents. As shown in Fig. 2b, d, the morphology and position of eutectic Mg_2Si did not change due to the grain refinement. From these results, it can be concluded that grain refinement does not affect the solidification mechanism of eutectic Mg_2Si.

Conclusion

1. The eutectic Mg_2Si phase of Al–8Zn–6Si–4Mg–2Cu alloy was modified by adding 1 wt% content of Al–5Ti–1B alloy. TiB_2 particles were observed inside the modified eutectic Mg_2Si phase. The good match of crystal growing orientation between TiB_2 and Mg_2Si was confirmed by TEM analysis. It was confirmed that TiB_2 particles cause modification of eutectic Mg_2Si.
2. The Chinese script type eutectic Mg_2Si was observed at the inner edge of the α-Al grains. Mg_2Si phase of polygonal shape, modified by addition of TiB_2, was observed at grain boundaries. It is believed that heterogeneous nucleation of eutectic Mg_2Si phase take place on the TiB_2 particles and they are pushed into grain boundaries during the growing process. When 1 wt% Ti content of Al–5Ti–1B was added to Al–8Zn–6Si–4Mg–2Cu alloy, there were enough TiB_2 particles to modify most of the eutectic Mg_2Si phase.

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