Effect of As-Cast Microstructure on Precipitation Behavior and Thermal Conductivity of Al-Si-Mg Alloys

Saif Haider Kayani, Kwangjun Euh, Jung-Moo Lee, Young-Hee Cho
Department of Aluminum, Advanced Metallic Division, Korea Institute of Materials Science, Changwon 51508, Republic of Korea
*Corresponding address: e-mail: saifkayani@kims.re.kr

Abstract: This study examines the precipitation evolution during T5 heat treatment of an Al–7Si–0.35Mg alloy component with varying thicknesses. We employ a step mold casting technique to develop an Al–7Si–0.35Mg alloy component with cavity thickness ranging from 4-40 mm. Our experimental investigations unveil varying solidification times (from 5.0 to 152.2 sec) and cooling rates (ranging from 2 to 50 K/s) due to the step mold casting. The thermal conductivity of component sections increase from 174.1 to 178.9 W/mK as the cooling rate surged to 50 K/s. Microstructure analysis of 50 K/s alloy reveals a large number density of coarse Mg-Si-rich pre-precipitates near dendritic cell boundaries, alongside fine GPII and β″ pre-precipitates within the cell interior. The pre-precipitation behavior in 50 K/s alloy is attributed to the retention in the mold until thick sections fully solidify, leading to low solute supersaturation and higher conductivity. Contrarily, 2 K/s alloy exhibits the formation of fine dot-like β″ and a few coarse Mg-Si-rich pre-precipitates along the cell boundaries. This alloy demonstrates superior age-hardening behavior and its low thermal conductivity increases during aging. This increment is associated with a small lattice misfit between precipitates and matrix in the as-cast state, inducing significant lattice distortion which lowers the thermal conductivity. Upon peak aging, these distortions are replaced by dislocations at the precipitate-matrix interface due to large lattice misfits. Finally, we offer an insight into how the solidification microstructure affects T5 treatment considering hardness and conductivity synergy.

Keywords: Al–Si–Mg alloy; Cooling rate; Pre-precipitation; Age-hardening; Thermal conductivity

1 Introduction

The automotive industry is driven by the need for lighter, stronger, and more environmentally friendly vehicles due to increased CO_2 emissions and fuel costs. To meet these demands, manufacturers utilize structural components made of lightweight alloys like Al–Si–Mg, known for their high-strength-to-weight ratio and excellent castability. However, these components face challenges during operation due to large temperature variations, often leading to non-uniform temperature distribution caused by uneven thicknesses [1].

Artificial aging, particularly the T5 treatment, presents a promising solution to enhance the thermal conductivity of Al–Si–Mg alloys and achieve uniform temperature distribution. Unlike the T6 treatment, which incurs high costs and distortion issues, T5 treatment after casting is preferred. Understanding the casting parameters' influence on microstructure is crucial for successful T5 treatment implementation, as it directly impacts age-hardening, primarily achieved through precipitation nucleation and growth [2].

Pre-precipitation, occurring during casting under specific solidification conditions, can deplete mobile solute atoms and vacancies, hindering subsequent strengthening precipitate formation during aging. This phenomenon is more pronounced in thick sections experiencing slower cooling rates. Recent studies have shown that water quenching during casting enhances solute supersaturation, while slow cooling promotes pre-precipitation, affecting the alloy's age-hardening capability [3].

Although strengthening mechanisms typically lower thermal conductivity by impeding heat carrier movement, recent findings present conflicting results, suggesting precipitation-induced increases in thermal conductivity [4]. The coherency of precipitates formed during aging, influenced by pre-precipitation, remains unexplored. Therefore, analyzing the effect of as-cast microstructure on thermal conductivity and age-hardening behavior is imperative. This study investigates the impact of as-cast microstructure on precipitation evolution during T5 treatment in an Al–7Si–0.35Mg alloy, evaluating age-hardenability, thermal and electrical conductivity. Ultimately, a trade-off relationship between hardness and conductivity is established, elucidating the influence of as-cast microstructure on alloy aging behavior.

2 Experimental procedure

An Al-7Si-0.35Mg alloy was prepared by melting the raw materials in an electric resistance furnace. The melt underwent degassing with Ar gas for 10 minutes using a rotary impeller, followed by stabilization at 710 °C for 15 minutes. The melt was then poured into a pre-heated permanent steel step mold, featuring four steps with varying cavity thicknesses. After solidification, the component was extracted and water-quenched to room temperature. Cooling rates were determined using a tapered cooling method with K-type thermocouples. The microstructure was analyzed using optical, SEM, and TEM. Age-hardenability was assessed through matrix hardness and conductivity measurements, while thermal conductivity was determined using a light flash apparatus.

3 Result and discussion

The cooling curves indicated varying durations to reach the extraction temperature of 350 °C, notably 152.2 and 5.0 sec for steps 1 and 4, respectively, suggesting retention at high temperatures before water quenching, potentially affecting microstructure. Optical micrographs revealed primary α-Al dendritic cells with eutectic Si and intermetallic phases, with finer Si phases and smaller secondary dendrite arm spacing at higher cooling rates. Backscattered electron images identified β-AlFeSi intermetallic, with high-resolution scans revealing small pre-precipitates in slower-cooled alloy and needle-like pre-precipitates in faster-cooled alloy. TEM analysis confirmed fine pre-precipitates β″ and solute clusters in slower-cooled alloy and GP zones and β phases in faster-cooled alloy. As a result, faster-cooled sections showed higher conductivity in as-cast state compared to slower-cooled sections. Matrix hardness and electrical conductivity increased with aging time, with slower-cooled sections showing higher response. After aging, thermal conductivity increased, except for a slight decrease in faster-cooled specimens. TEM analysis revealed evolution of precipitates during aging, with slower-cooled alloy exhibiting finer precipitates and faster-cooled alloy experiencing rapid coarsening due to pre-precipitates.

Contrary to literature, our study shows that a fast cooling rate of 50 K/s results in higher thermal and electrical conductivities in as-cast state. This is attributed to coarse pre-precipitation, particularly near dendritic cell arms, due to retention in mold at high temperature. In contrast, slower cooling at 2 K/s promotes fine dot-like β″ phase and needle-like pre-precipitation near cell boundaries.

These differences in pre-precipitate distribution affect conductivity. For instance, coherent interfaces between β″ pre-precipitates and the matrix, observed at slower-cooled specimen in as-cast state, cause lattice distortions, impeding electron and phonon movement and resulting in low conductivity.

Aging causes a loss of coherency between precipitates and the matrix, leading to misfit strain and dislocation loop formation. The interspacing among solute clusters and precipitates exceed the mean free path of electrons (~100 nm) for beneficial conductivity effects [5]. However, the high density of pre-precipitation in the 50 K/s alloy limits precipitation coarsening and impedes conductivity enhancement during aging. Our results show that achieving synergy between hardness and conductivity is easier at slower cooling rates (2-16 K/s) due to finer pre-precipitates. In contrast, the presence of coarse pre-precipitation at 50 K/s hampers this balance. Overall, pre-precipitation not only reduces solute supersaturation but also limits conductivity and age-hardenability in Al–Si–Mg alloys.

4 Conclusion

This study highlights the significant impact of as-cast microstructure on the age-hardenability and thermal conductivity of Al–Si–Mg alloys. The faster cooling rate of 50 K/s resulted in higher conductivity in the as-cast state due to the formation of pre-precipitates, albeit at the expense of inferior age-hardening response compared to the slower cooling rate of 2 K/s. The superior age-hardening response and thermal conductivity improvement in the 2 K/s alloy after peak aging were attributed to the formation of cuboidal β″, stable β, and cubic Si precipitates, which replaced lattice distortions with misfit dislocations. This suggests that alloys solidified at slower cooling rates achieve a better balance between age-hardenability and conductivity, offering valuable insights for optimizing the properties of Al–Si–Mg alloy.

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