



Development and characterization of low-silicon cast aluminum alloys for thermal dissipation



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ABSTRACT

Two low-silicon quaternary aluminum alloys, Al-(0.5–1.5)Mg–1Fe–0.5Si and Al-(1.0–1.5)Si–1Fe–1Zn, are investigated for their potential to combine a high thermal conductivity with good castability and anodizability. By comparing to the physical and casting properties of the commercial ADC12 alloy, the developed alloys show 170–190% of thermal conductivities (160–180 W/m K), a similar medium-thick-wall fluidity, 60–85% of thin-wall fluidity, 100–130% of hot tearing susceptibility (HTS), and a comparable ultimate tensile strength. As Mg and Si, the major alloying elements, increase, the thermal conductivity decreases and the strength increases. The thin-wall fluidity and the HTS are both inversely proportional to the Mg content and directly proportional to the Si content. These opposite trends within the two alloy systems arise mainly from differences in the Al dendrite coherency and first intermetallic crystallization points, and in the crystallization behavior of β -AlFeSi phase. The lower viscosity and lower surface energy of the Al-(0.5–1.5)Mg–1Fe–0.5Si and Al-(1.0–1.5)Si–1Fe–1Zn alloys, respectively enhance their fluidity in thicker and thinner sections. A large fluidity sensitivity to the channel diameter of the aluminum alloys developed here is attributed to their higher melting points, lower latent heats, and higher formation tendency of oxide films and inclusions.

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1. Introduction

As the amount of heat generated in electric devices such as light-emitting diodes increases greatly with their output, efficient heat dissipation is important to improve their lifespan and operating characteristics [1,2]. Metal matrix composites, carbon/aluminum composites in particular, have received substantial attention as thermal management materials, because they can combine high thermal conductivity, low density, and a low thermal expansion coefficient [3,4]. However, the industrial application of these composites has so far been limited by manufacturing problems. Carbon/aluminum composites are generally manufactured by powder metallurgy or via liquid metal routes such as infiltration and stir casting. Powder metallurgy is advantageous in terms of the uniform distribution of filler materials it affords; however, it is only suitable for the mass production of small components [5,6]. Infiltration is the route most commonly adopted, but its industrial application has been limited by the high filler volume fractions that are required, as well as by the number and duration of the processing steps [7,8]. Stir casting on the other hand is the most easily

adopted route in conventional foundries but has still not been shown to provide satisfactory filler distributions [9,10].

Such being the case, light metal alloys with good thermal conductivities are currently being considered as potential heatsink materials [11–14]. At present, heatsinks are mainly produced with aluminum alloys using high-pressure die-casting (HPDC). This allows heatsinks with complex 3-dimensional shapes conducive to heat dissipation to be fabricated in a near-net-shape manner with high productivity and cost-effectiveness. However, aluminum, the most common heatsink material, has inherent disadvantages to be overcome. Although high purity aluminum possesses excellent thermal conductivity, it is extremely difficult to die-cast, requiring alloying elements to be added despite the associated loss in thermal conductivity. ADC12, a commercial Al–Si-base aluminum alloy, is currently the most commonly used alloy for heatsinks. However, the low thermal conductivity (less than 100 W/m K) and the poor anodizing characteristics of ADC12 are becoming problematic with the increasing power requirements of electric devices [2,15,16]. Although heat treatments (e.g. the T6 and T7 processes) may significantly improve the thermal conductivity of HPDC aluminum alloys, these cannot normally be adopted in industry because of the surface blistering and dimensional changes in the components that they induce [17]. Other commercial aluminum alloys also have some major

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issues to be applied; (1) inapplicable for high power electric device applications due to low thermal conductivity or (2) poor castability.

Therefore, a number of studies have recently been devoted to the development of low-alloy aluminum alloys that can be die-cast and exhibit a high thermal conductivity in the as-cast state. However, these previous studies concentrated chiefly on the thermal, mechanical, and casting characteristics of these alloys [11–14], while a systematic microstructural interpretation of these properties has so far been lacking.

In the present study, two low-Si quaternary aluminum alloys, Al-xMg-1Fe-0.5Si and Al-xSi-1Fe-1Zn, were investigated as promising candidates to provide both a high thermal conductivity and good castability and anodizability. The thermal conductivity of the alloys and properties relating to their castability such as fluidity, hot tearing susceptibility (HTS), and mechanical strength, were assessed as a function of the Mg and Si contents, and compared to those of ADC12. This study focuses on exploring the effect of Mg and Si contents on the solidification paths and the microstructural evolution of Al-xMg-1Fe-0.5Si and Al-xSi-1Fe-1Zn alloys. In addition, we discuss the castability of developed alloys based on the experimental results.

2. Experimental

2.1. Alloy design

In order to achieve a high thermal conductivity along with good castability and anodizability, two low-Si quaternary aluminum alloys were designed as follows. Firstly, Mg and Si were chosen as the major alloying elements by comparing the effects of different elements on the electrical resistivity [18], energy release on solidification [19], and viscosity [18,20] of aluminum as shown in Table 1. The energy released upon solidification was obtained by summing the latent heat and the

additional heat caused by superheating by 100 °C. The superheating energy was calculated using the specific heat of each element based on the simple rule of mixtures. In this context, the more favorable mixtures have a low electrical resistivity and viscosity and a high energy release on solidification. That is, as the electrical resistivity decreases, the thermal conductivity tends to increase, and as the energy release on solidification increases and the viscosity decreases, the castability tends to improve due to an increase in the melt fluidity. Thereby, the properties marked with an asterisk in Table 1 are expected to be favorable in terms of the resulting thermal conductivity and castability, and only two elements, Mg and Si, satisfy all the criteria considered here. Secondly, Fe was included to prevent the casting from sticking to the mold. Lastly, Si and Zn were added to the Mg- and Si-containing alloy systems, respectively, to enhance their fluidity and mechanical strength.

Table 2 lists the chemical composition of the two low-Si quaternary aluminum alloy systems, Al-xMg-Fe-Si (Alloy series 1) and Al-xSi-Fe-Zn (Alloy series 2) along with their predictive thermal conductivity. The total alloying level was kept at 2–3.5% for an optimal balance between thermal conductivity and castability. The concentration of the major alloy, Mg or Si, was varied from 0.5% to 1.5% to systematically investigate the effect on the thermal conductivity and castability of the alloys. These properties may respectively be deteriorated by too much or too little alloying. In particular, because Si particles have a negative impact on anodizability, the level of Si was kept below 1.5%, which is the maximum Si content of commercial wrought Al alloys known to have a good anodizability. An Fe content of 1% was chosen, similar to that of the ADC12 alloy. In the Al-xMg-Fe-Si alloys, 0.5% Si was included to increase the energy release on solidification. In the Al-xSi-Fe-Zn system, because Si has been reported to be less effective in strengthening the Al matrix than Mg [18], this was compensated by adding 1% Zn. Table 1 shows that Zn is the alloying element that leads to the lowest resistivity increment. The thermal conductivities of developed alloys were predicted from the data in Table 1 using the rule of mixtures and the Wiedemann–Franz law, to characterize the effect of the alloying elements on the thermal conductivity of the alloys.

2.2. Evaluation and analysis

Fluidity tests were carried out using two kinds of BN-coated steel molds, viz. a spiral (Fig. 1a) and a multi channel mold (Fig. 1b). The spiral mold fluidity tests were carried out under gravity casting conditions. The spiral cavity had a cross section of $4 \times 10 \text{ mm}^2$ with a maximum running length of 1200 mm ending in a vent. The mold preheating and melt superheating temperatures were 200 °C and 100 °C

Table 1
Effects of alloying elements on the electrical resistivity [18], energy release on solidification [19], and viscosity of aluminum [18,20] (calculations were performed for a ΔT of 100 °C). The properties, which are expected to be favorable in terms of thermal conductivity and castability, are marked with an asterisk (*).

Element	Resistivity		Energy release for solidification			Viscosity variation of Al with alloying	
	Maximum solubility in Al (wt%)	Resistivity increment of Al per wt% ($\mu\Omega\text{cm}$)	Latent heat, H of pure elements (kJ/kg)	Specific heat, c' of pure elements (kJ/K kg)	$H + c' \Delta T$ increment of Al per wt% (kJ/kg)		
							In solution
Cr	0.77	4.00	0.180	402	0.66	-0.3	(+)
Cu	5.65	0.34*	0.030	205	0.45	-2.5	(+)
Fe	0.05*	2.56	0.058	272	0.78	-1.5	(+)
Li	4.00	3.31	0.680	422	4.46	3.7*	
Mg	14.90	0.54*	0.220	362	1.34	0.0*	(-)*
Mn	1.82	2.94	0.340	268	0.70	-1.6	(+)
Ni	0.05*	0.81*	0.061	292	0.56	-1.5	(+)
Si	1.65	1.02*	0.088	1804	0.93	14.0*	(-)*
Ti	1.00	2.88	0.120	366	0.68	-0.6	(+)
V	0.50	3.58	0.280	329	0.62	-1.1	
Zn	82.80	0.09*	0.023	111	0.48	-3.4	(0)*
Zr	0.28	1.74	0.044	212	0.37	-2.5	

Table 2
Chemical compositions of the developed low-silicon cast aluminum alloys, Al-xMg-Fe-Si (Alloy series 1) and Al-xSi-Fe-Zn (Alloy series 2) (values shown in wt%).

Alloy	Major element		Anti-die-sticking element	Supplementary element		Base element	Thermal conductivity (W/m K)
	Mg	Si	Fe	Zn	Si		
1							
1-1	0.5	-	1.0	-	0.5	98.0	186
1-2	1.0	-	1.0	-	0.5	97.5	175
1-3	1.5	-	1.0	-	0.5	97.0	160
2							
2-1	-	1.0	1.0	1.0	-	97.0	171
2-2	-	1.2	1.0	1.0	-	96.8	163
2-3	-	1.5	1.0	1.0	-	96.5	153

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