The Effects of Cooling Slope on the Semi-solid Microstructures of Al4.8Si2.8Cu0.5Mg Aluminium Alloy

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ABSTRACT

Thixoforming process is a metal forming process in the semi-solid condition to produce near net shaped products. The key requirement of the thixoforming process is the production of feedstock materials that consists of solid spheroids in the liquid matrix, rather than dendrites. The solid spheroidal structure could not be generated if the gravity cast alloy that consists of the dendritic structure is directly subjected to partial remelting. Cooling slope casting process is one of the simplest and cheapest methods that can be utilised to produce the non-dendritic structure. In the present study, the effects of cooling slope casting process on the microstructure of Al4.8Si2.8Cu0.5Mg aluminium alloy were investigated. The alloy was melted at a superheated temperature of 700 °C before cooled down to the selected pouring temperature (650 °C) and subsequently poured onto a stainless steel plate with the cooling length of 400 mm. The plate was tilted at 60° from horizontal and was cooled with water circulation underneath to promote the nucleation of fine α–Al particles. Finally, the poured molten metal was collected in a 150 °C preheated cylindrical stainless steel mould. The alloy billet that consists non-dendritic α-grains with a shape factor of 0.74±0.13 and an average primary particle size of 31.94±6.76 µm was successfully produced from gravity cast alloy with a dendritic microstructure by cooling slope casting process. After partial remelting at 575 °C, the non-dendritic structure has changed into fine solid

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spheroidal α-Al grains with a shape factor of 0.84±0.06 and an average primary particle size, approximately 35.92±9.13 µm. These solid spheroidal structures surrounded by a liquid matrix may be offer thixotropic behaviour and suitable for thixoforming applications.

Keywords: *Cooling slope; Semi-solid; Thixoforming; Microstructure; Aluminium alloy.*

Introduction

Semi-solid metal processing (SSMP) is a near net shape forming process for metals in the semi-solid state i.e. between the solidus and liquidus [1]. The concept of SSMP actually originates from a coincidence experiment of hot tearing in steels casting. Sn-15Pb was used as a model system to evaluate the viscosity of the partially solidified alloy. The melt was stirred vigorously using a Couette viscometer. However, the viscometer gives an unexpected outcome where the shear stress increased very slowly as the temperature was decreased below the liquidus [2]. Afterwards, a comprehensive research was carried out and it was found that the alloy behaves like a solid if it is allowed to stand, but it will flow like a liquid when sheared [3]. This non-Newtonian behaviour is recognized as thixotropy and then was found beneficial for the thixoforming process.

Thixoforming is one branch of SSMP which involves the preparation of feedstock material with nondendritic structure, followed by the heating of the feedstock material to the appropriate semi-solid temperature and finally forming the feedstock material in a die [4]. This process offers the combination of several advantages of casting and forging such as the ability to produce components with high geometric and surface quality, low shrinkage porosity and uniform fine microstructure, which is heat treatable in order to improve the alloy strength. The most important requirement of thixoforming process is the generation of the solid spheroidal grains in a liquid matrix. This structure could be generated when the alloys with non-dendritic structure are partially remelted at its semi-solid temperature [5, 6, 7].

To date, there are many processing techniques utilised to alter the alloy structure from dendrite to non-dendritic form [1, 2, 8]. Cooling slope, CS casting process is one of the simple and low-cost technique to generate such a structure whereby molten metal is poured onto a tilted metal plate [9]. Although there are many experimental works on the effects of CS on the microstructure of aluminium alloys, they were focused only on a few of commercial aluminium alloys, for example, A356, A357 and A319 and the investigations on new formulation aluminium alloys have been only sparsely reported. In this study, experimental work was conducted to investigate the effects of CS casting on the semi-solid microstructure of Al4.8Si2.8Cu0.5Mg aluminium alloy.

Materials and Methods

The starting material of Al4.8Si2.8Cu0.5Mg aluminium alloy was produced by gravity casting process. The chemical composition of the alloy was determined by using the spark emission spectrometer machine and listed in Table 1. A Netzsch-STA (TG-DSC) 449 F3 simultaneous thermogravimeter was used to analyse the liquidus, solidus and liquid fraction profile of the alloy. The alloy was superheated at 700 °C in a silicon carbide crucible using an electric resistance furnace. Argon gas was flowed at 2.5 *l*/min in the crucible to prevent the alloy from oxidation. The molten alloy was then allowed to cool to the selected pouring temperature i.e. 650 °C before pouring onto 400 mm long CS stainless steel plate. The CS plate was inclined at 60° with respect to the horizontal plane and was cooled with water circulation underneath to promote the nucleation of fine α–Al particles. The casting experiment was conducted using CS apparatus equipped with a resistance furnace as shown in Figure 1. A preheated (at 150 °C) cylindrical stainless steel mould with a height of 120 mm and diameter of 26 mm was used to collect the poured molten metal.

The ingot obtained from CS casting was sectioned to a 100 mm length before partially remelted at 575 °C. The partial remelting process was carried out with a high-frequency induction heating system (30 to 80 kHz, 30 kW). The measurement was taken to achieve rapid heating at 70 °C/min to prevent undesirable grain growth. A K-type thermocouple was used to monitor the temperature of the alloy ingot during the partial remelting process. The alloy ingot immediately water quenched when reaching the partial remelting temperature in order to freeze the semi-solid microstructure.

The microstructural observations were conducted utilising an optical microscope (Olympus brand) and analysed by ImageJ software in order to measure the size and shape of grains. The alloy samples were ground by using 120, 400, 800 and finally, 1200 grit silicon carbide abrasive paper before polished with a Leco Microid diamond paste compound (6 µm, 3 µm and finally 1 µm). All samples were etched with Keller's solution for 15 seconds.

Table 1: Chemical composition of Al4.8Si2.8Cu0.5Mg aluminium alloy

Element	Si	Cu	Mg	Fe	Mn	Al
(wt. %)	4.78	2.76	0.48	0.45	0.14	balance

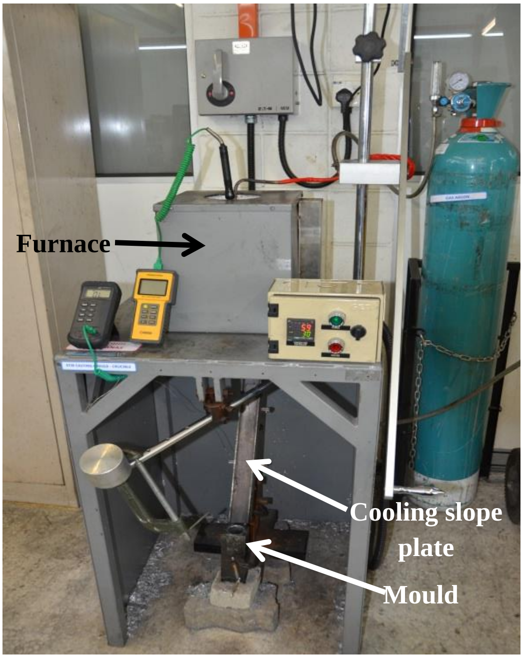

Figure 1: Cooling slope casting apparatus

Results and Discussions

Figure 2 shows the microstructures of Al4.8Si2.8Cu0.5Mg aluminium alloy ingots before (as-cast) and after the CS process. The Al4.8Si2.8Cu0.5Mg aluminium alloy used in this study was produced using gravity casting technique. Figure 2(a) shows that the as-cast microstructure comprises dendritic and interdendritic eutectic structure. The coarse dendritic structure was obtained when the molten alloy directly cast into the preheated mould. The main requirement in thixoforming is a generation of the alloy billets with non-dendritic grain structure. Figure 2(b) shows the change in the microstructural features after the CS casting. The solid α-Al was transformed completely from dendritic to the non-dendritic structure when the as-cast alloy ingot was poured onto the CS at 650 °C of pouring temperature and 400 mm cooling length. The formation of fine non-dendritic microstructure occurred due to the nucleation of recrystallized primary grains when the melt was poured over a CS plate that was cooled by water circulation underneath [10, 11].

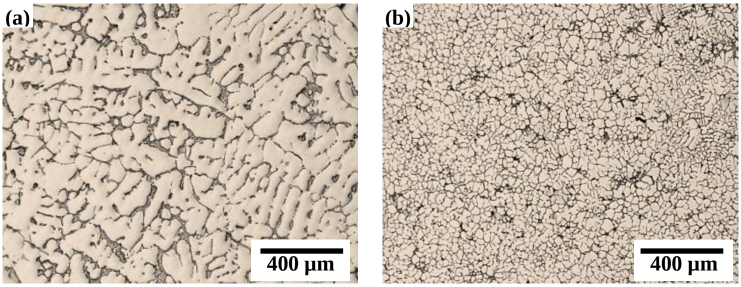

Figure 2: Optical microstructures (20X magnification) of Al4.8Si2.8Cu0.5Mg alloy (a) as-cast and (b) after the CS casting at a pouring temperature of 650 °C and cooling length of 400 mm

In the thixoforming process, the sensitivity of liquid fraction to temperature changes is one of the important parameters that should be considered. The liquid fraction of the as-cast Al4.8Si2.8Cu0.5Mg alloy as a function of temperature was estimated from thermal analysis by DSC. The DSC heating curve, together with its corresponding liquid distribution, of the as-cast Al4.8Si2.8Cu0.5Mg, is shown in Figure 3. Note that liquid formation tends to be controllable if the amount of eutectic in the structure occurs between 0.3 and 0.5 fraction liquid [12]. According to the liquid fraction curve, 0.3 and 0.5 fraction liquid correspond to 569 °C and 600 °C, respectively. In order to melt the entire eutectic structure, the partial remelting process should be accomplished above the highest "knee" point as presented on the liquid fraction curve [13]. Therefore, 575 °C was chosen as suitable partial remelting temperature for Al4.8Si2.8Cu0.5Mg alloy correspond to 0.35 fraction liquid.

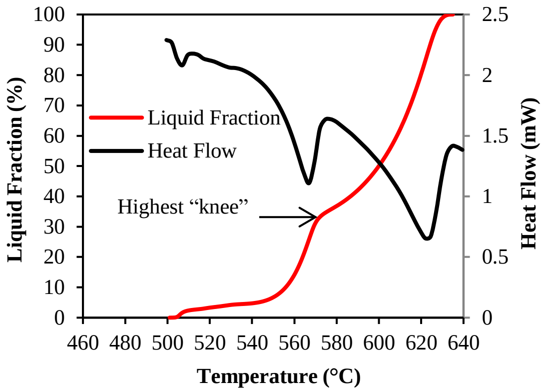

Figure 3: DSC heating flow and liquid fraction curves for Al4.8Si2.8Cu0.5Mg alloy

Figures 4 shows Al4.8Si2.8Cu0.5Mg microstructures subjected to partial remelting at 575 °C using an induction heating coil. For successful semi-solid processing, the feedstock materials with solid spheroidal structure in a liquid matrix should be generated when the alloy billet is partially remelted at semi-solid temperature [14, 15]. However, Figure 4(a) shows that the solid spheroidal structure could not be generated if the gravity cast alloy with dendritic structure is directly subjected to partial remelting. The semi-solid microstructure with fine and near-spherical morphology as shown in Figure 4(b) was successfully produced when the CS casting sample with non-dendritic microstructures was subjected to partial remelting. These near-spherical solid grains surrounded by liquid matrix has resulted with materials behaving thixotropically that is suitable for SSMP applications.

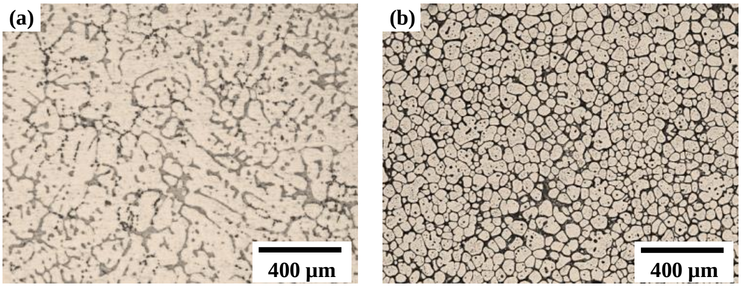

Figure 4: Optical microstructures (20X magnification) of Al4.8Si2.8Cu0.5Mg alloy subjected to partial remelting at 575 °C in an as-cast sample (a) and in a sample previously poured onto a CS with a cooling length of 400 mm and 650 °C of pouring temperature (b)

The average shape factor (SF) of solid grains was calculated using the formula of $4\pi A/P^2$; where A is represents the area and P represents the parameter of the grain (shape factor is defined as circularity of a grain and the circularity of a perfect sphere is equal to 1). While the average size of solid grains was calculated using the formula of $[\sum 2(A/\pi)^{1/2}]/N$; where N is the total number of counted grains [5, 7, 16, 17]. Figure 5 shows the variations in the SF and globule size of α-Al grains after CS casting and subsequently partial remelting in a semi-solid state. The analysis indicates that when the molten alloy was poured onto the surface of stainless steel plate at pouring temperature of 650 °C and cooling length of 400 mm, the fully dendritic microstructure of primary α–Al particles have completely transformed into very fine non-dendritic structure with SF of 0.74 ± 0.13 and an average primary particle size of 31.94 ± 6.76 µm. After partially remelted at 575 °C, the non-dendritic structure of CS casting sample changed into individual spheroidal grains with surrounded by a liquid phase. During partial remelting, the primary particles getting nearer to a spherical shape due to the spheroidisation process with the

SF of 0.84 ± 0.06. The reheating process also contributes to the coarsening of primary α–Al particles into coarser average grain size, approximately 35.92 ± 9.13 μm.

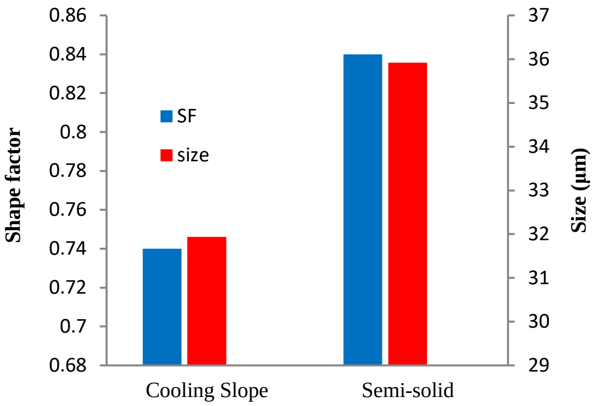

Figure 5: Variations in the SF and globule size of α-Al particles after CS casting and subsequently partial remelting in a semi-solid state.

Conclusion

Cooling slope casting process was used to prepare the feedstock material of Al4.8Si2.8Cu0.5Mg aluminium alloy with non-dendritic microstructures. The solid α-Al was altered totally from the fully dendritic to the non-dendritic structure when the as-cast alloy ingot was poured onto the CS at 650 °C of pouring temperature and 400 mm cooling length. Subsequently, the fine and near-spherical morphology of solid α-Al grains in a eutectic matrix with SF of 0.84 ± 0.06 and an average primary particle size, approximately 35.92 ± 9.13 μm were successfully produced after partially remelted at 575 °C. The formation of the solid metal spheroids in a liquid matrix has resulted in a material having a thixotropic behaviour, which is suitable for thixoforming applications.

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