PRODUCTION OF LM4 FEEDSTOCK FOR THIXOFORMING USING COOLING SLOPE CASTING

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ABSTRACT: LM4 aluminium alloys are commonly used in automotive industry due to a combination of good fluidity and mechanical strength. In the present work, Cooling slope casting process was employed to produce A319 billets with near spherical morphology of primary Al-phase. To date, there are few studies that have investigated the association between the microstructural evolutions of alloy in a mould. The transformation of dendritic to non-dendritic microstructure is clearly obtained as the alloy filled the mould at the end of the cooling slope. A fundamental issue of mechanism of the microstructural transformation through nucleation and fragmentation was highlighted. The alloy was poured from the inclined plate of 200mm, 300mm and 400mm length at a pouring temperature of 647°C. The pouring was carried out on an inclined plate with tilt angle of 30°, 45° and 60°. Microstructures of specimens obtained using the optical microscope was examined to reveal the evolution of the microstructure. Grain size analysis of produced samples was carried out and the Vickers test was used to determine the hardness of the LM4 alloy. The results showed that the flow length of the melt and tilt angle affected the microstructure of α-Al. Hence, it was determined that by pouring at 45° for 400mm length would increase the nucleation and led to more breaking of dendrite arms, thus, improving the LM4 mechanical properties. In this study, the convection of melt at inclined cooling slope length played an important role on the formation of non-dendritic primary of α-Al particle.

KEYWORDS: *Cooling slope casting, Aluminium alloy, Microstructure evolution, Mechanical properties*

1.0 INTRODUCTION

For the last 40 years, semi-solid metal (SSM) processing or thixoforming is frequently described for the near-net-shaped method for metal and alloy especially for automotive industry to produce fuel efficient vehicles, resulting in the increased use of aluminium alloys [1-3]. Besides , thixoforming has many advantages such as prolonged die life due to the reduced thermal shock and its ability to reduce macrosegregation, porosity and forming forces during the shaping process. Furthermore, SSM processing enhances good mechanical properties while minimizes the usage of feedstock materials to reduce the cost of manufacturing process.

Non-dendrite microstructures consist of spheroids of solid phase in a liquid matrix which is an important characteristic in the SSM processing and plays a key role in feedstock production. Therefore, feedstock containing fine and homogenous globular solid particle distributed in a liquid matrix is an ideal feedstock that can behave thixotropically in semisolid state. Thixotropic behaviour is an important characteristic of the SSM alloy which can be handled as a solid while flowing like a liquid when it is sheared.

In recent years, there has been an increasing interest in producing non-dendrite microstructure feedstock for SSM processing. Each has its advantages and drawbacks. Various method have been developed to produce a non-dendrite microstructure such as magneto hydrodynamic (MHD), recrystallization and partial melting (RAP), stress-induced melt activation (SIMA) and cooling slope (CS) casting. Eventhough MHD is an ideal technique in producing the feedstock [4], it has led to extra cost in feedstock production to improve the nonuniformity of microstructure in the billet while the CS casting consumes very low cost processing of feedstock [5-6]. Therefore, CS castings offer the simplest , low cost equipment to cast the semisolid slurry for thixoforming [7-10].

There are three important parts of CS casting process; the furnace to melt the alloy, incline dplate with water underneath for the molten alloy to flow down and the mould that collects the solidified molten alloy at the end of the CS. Furthermore, CS casting also promotes a fine globular primary particles [11-13] and increases the nucleation rate of the α-Al by controlling the pouring temperature, tilt angle, flow length of the melt, mould temperature and mould material [14,15].

Aluminium alloys are widely used in automotive manufacturing industries, especially aluminium–silicon (Al-Si) alloys due to their good fluidity and mechanical strength. The mixture of a primary phase and eutectic phase in these alloys produced eutectic silicon and other intermetallic compound of Al-Si microstructure. The size, shape and particle distribution of Al-Si microstructure has given a significant effect on the mechanical properties of the alloy. Preferably, the fine and homogenous globular microstructure of the primary α-Al phase is bounded by a eutectic mixture layer that acts as a bond between the components of the primary phase and enables the primary phase to resist an applied force. Aluminium alloys have major advantages such as low density, high strength and excellent castability [16]. These alloys are particularly suitable for components such as cylinder heads, pistons and cylinder blocks. Although a lot of work has been carried out for the past 5 years using cooling slope casting, the number of alloys that have been selected for this processing are very limited.

Therefore, in this paper, LM6 aluminium alloys was chosen in order to investigate the effect of pouring temperature and cooling slope length on the microstructure and mechanical properties of the alloy. The mechanical testing was carried out to the selected samples in order to determine the mechanical properties of the alloy.

2.0 METHOD

The chemical composition of LM4 aluminium alloy used in this work is given in Table 1. Figure 1 shows a CS casting apparatus consists of stainless steel slope plate, stainless steel mould and furnace with graphite crucible. The melt was poured on the top of the CS and collected in a mould before being allowed to solidify at room temperature. The pouring temperature and superheat temperature of this experiment was selected based on the differential scanning calorimetry (DSC) test in Figure. 2. The DSC curve of LM4 aluminium alloy showed a liquidus temperature of 647°C and solidus temperature was 536°C. Based on the DSC curve, pouring temperature was set close to the liquidus temperature at 647°C to ensure rapid cooling to increase the grain growth.

Table 1: Chemical composition of LM4 aluminium alloy.

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
5.31	0.27	3.11	0.01	0.13	0.01	0.01	0.02	0.06	BAL

To begin this process, LM4 aluminium alloy was cut into small pieces approximately 4mm thickness each using the band saw machine (BOMAR STG 280 DG). For this experiment, the LM4 aluminium alloys were then superheated using the furnace at 700°C in a graphite crucible and allowed to cool to the selected pouring temperature (647°C) before being poured into inclined plate made of stainless steel. Moreover, the Furnace also comes with easy handling holder for melt pouring process and temperature controller. Three parameters were considered in the CS casting process namely pouring

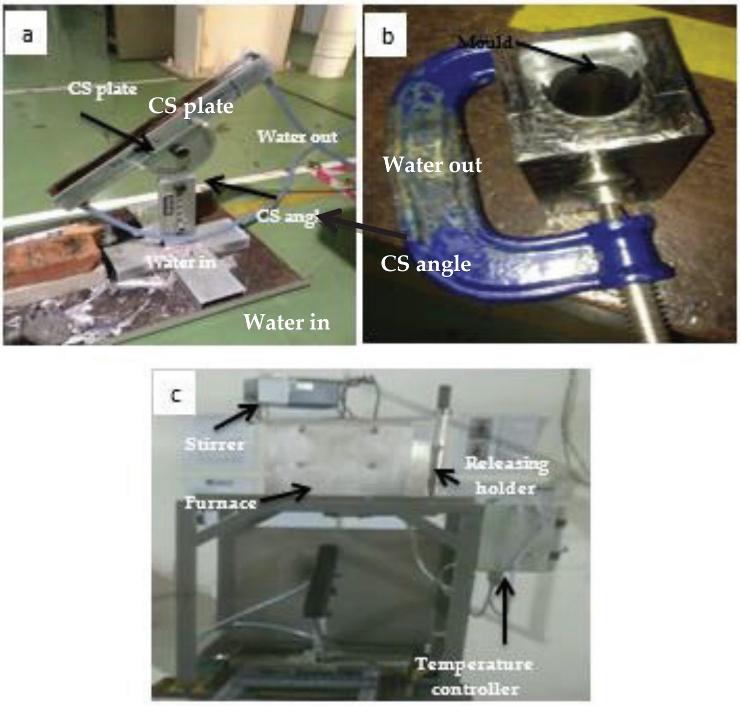

Figure 1: Cooling slope casting apparatus; (a)Cooling slope (CS), (b)Stainless steel mould, (c)Furnace.

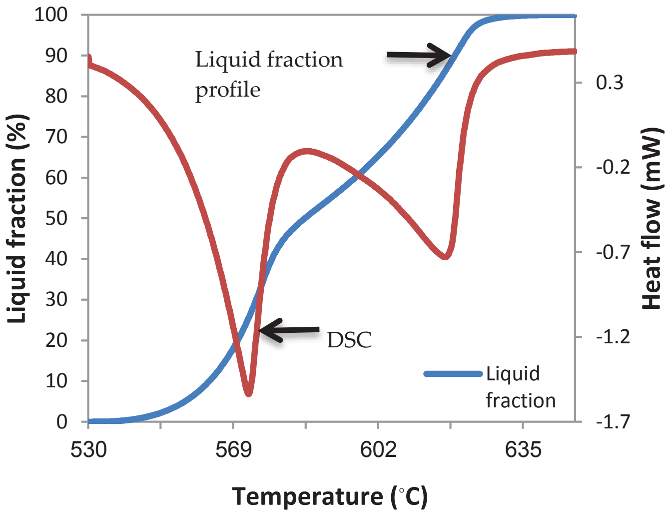

Figure 2: Differential scanning calorimetry (DSC) heating flow and liquid fraction curves for LM4 alloy.

Table 2: CS casting parameters.

Melting temperature (°C)	Pouring temperature (°C)	CS angle (°)	CS length (mm)
660	647	45	200
660	647	45	300
660	647	45	400
660	647	60	200
660	647	60	300
660	647	60	400

A thin layer of boron nitride as shown in Figure 3(a) was sprayed onto the CS plate to prevent the adhesion between the molten alloy and CS plate. Moreover, F318 wax shown in Figure 3(b) was also sprayed on the mould surface to improve the melt flow. A K-type thermocouple was placed inside the furnace to ensure the temperature of the molten alloy was according to the selected pouring temperature. After the feedstocks solidified, it was cut into small pieces of 25mm thickness before being ground, polished and etched using Keller's reagent for morphology investigation using the Axioskop 2 MAT optical microscope. Then, the average grain size and roundness of the grains were measured using Image-J software (Java-based image processing programed). Finally, hardness test was conducted using the Mitutoyo Hardness Testing Machine (MicroWiZhard) to study the surface hardness of LM4 alloy. In total, 10 readings of Vickers measurements were taken in order to get reliable data.

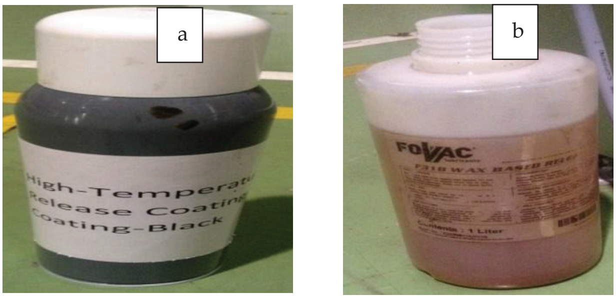

Figure 3 (a) High-temperature release coating (boron nitride) (b) F318 wax.

3.0 RESULT AND DISCUSSION

3.1 Microstructural evolution

Figure 4 shows the as-cast microstructure of LM4 aluminium alloy that was directly poured into the mould after being superheated at 647°C. The non-dendritic microstructure shows an irregular shape distributed homogenously in the sample. Figure 5 shows a CS casting feedstock after being casted on the cooling slope plate. The surface of the CS feedstock was smooth and no porosity was detected on that sample because the argon gas reduced the hydrogen attack during the feedstock melting process. Figure 6 shows the microstructures of the CS casting with different tilt angle and cooling slope lengths. Surprisingly, the microstructures were different from the conventionally casting feedstock. Even though the grain of the α-Al did not yield homogenous fine globular microstructure, the dendritic microstructure had fully transformed to the non-dendritic microstructure due to the effect of the CS casting.

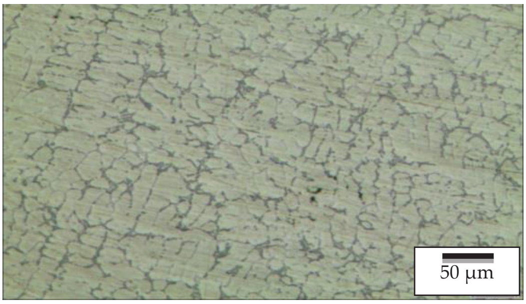

Figure 4: Microstructure of the as-cast alloy.

Figure 5: Cooling slope casting feedstock.

The relationships between the lengths of melt flow and the tilt angle of CS had significant effect to the formation of primary α-Al grain. For the cooling slope length of 200mm and 400mm and tilt angle of 30° and 45° respectively, the optical micrograph of the CS casting feedstocks showed a homogeneous distribution of solid globules in the liquid matrix. However, in the feedstock that casted at cooling slope length of 200mm with tilt angle of 45° and 60° respectively, it shows the coalescence grain formed in the sample. In addition, the slope length of 300mm and 400 mm with tilt angle of 30°, 45° and 60° gave the same result, as the coalescence grain was formed in the sample. Hence, the low cooling rate reduced the transformation of dendrite to non-dendrite microstructures. Moreover, the microstructure for CS casting feedstock at tilt angle of 60° for 400mm needed longer contact time to fully transform the microstructure to

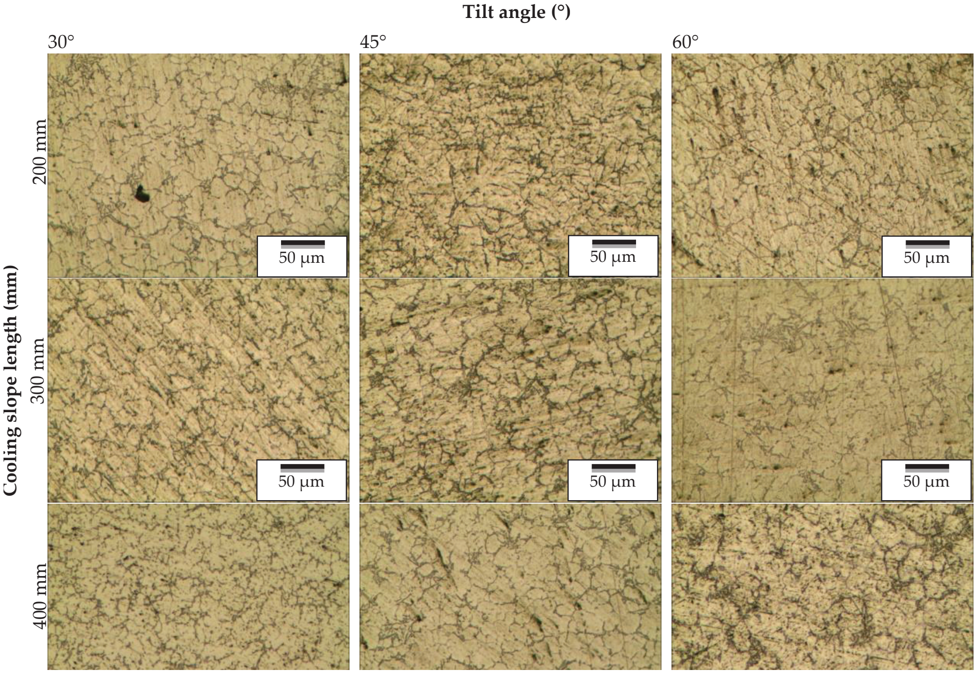

Figure 6: Microstructures of CS casting LM4 feedstock at pouring temperature of 647°C.

Conventionally, the slope has been seen as a copious source of nuclei, however it clearly plays an important role in the spheroidization process as well [17]. The α-Al crystal nucleates and grows on the slope wall and afterward isolates out due to melt flow. These nuclei are detached from the slope wall as a result of applying shear stress and melt flow. Copious nucleation in the flowing melt is attributed to the instant heat extraction that allow dendrite arm breaking, which allows more nucleation sites to become active and successive formation of higher number of nuclei.

The impact of tilt angle and cooling slope length that influence the grain nucleation is very important during feedstock production. A significant discussion on the subject has been presented by Mohammed et al. (2013). They identified that the nucleation mechanism have three characteristics which are dendrite arm fragmentation, dendrite arm root remelting, and growth control mechanisms [18]. In order to produce new grain, the dendrite arm must be fractured. By adopting the shearing forces during the melt flow on the CS slope, large disorientation was introduced on the plasticity behaviour of dendrite arm. This way helped the development of grain in the alloy. The dendrites arm disorientation led the dendrite arms to detach themselves by melting off and yielding new grain.

Kirkwood et al. (2010) explained in order to obtain a nearly spheroidal microstructure (equiaxed grains), the dendritic arm must undergo the detachment process through the remelting process of dendritic arm on main dendrite during the shearing forces created by the melt flow [19]. Lin et al. (2010) also stated that to fragmentise the dendrite arm, stirring method (also known as shearing) could be used to produce a spheroidal microstructure [20].

Based on morphology screening from Figure 6, only CS microstructures obtained using tilt angle of 30° and 45° and the slope length of 200mm and 400mm respectively, were selected for image analysis due to the primary phase morphology transformed. By changing the length of melt flow and tilt angle, the nucleus distribution became more homogenous and the α-Al nucleation number increased due to a more uniform cooling. When the microstructures were examined in this direction, it was observed that the dendrite structure had changed to the desired non-dendritic rosette structure due to the shear stress. Even though the whole pouring process only took a few seconds, the contact time between the melt and CS increased with the increase of melt flow length and tilt angle. Therefore, the contact time should be enough to avoid the melt solidified on the CS in order to generate the non-dendritic microstructures.

Furthermore, the intermetallic compound formations were also produced during the CS casting process. The intermetallic compounds had significant effect to the mechanical properties of alloy produced. The iron-rich intermetallic compound was the most unwanted because it caused brittleness to the alloy. The iron-rich also reduced the tensile strength and ductility of alloy. Moreover Rincon et al. (2009) also stated that the formation of Al_2Cu also contributed to the brittle behaviour in aluminium alloys [21].

3.2 Mechanical properties

Figure 7 shows the average grain size for tilt angle of 30° with melt flow length of 200mm was smaller than the average grain size for tilt angle of 45° with melt flow length of 400mm. Surprisingly, the shape factor of tilt angle of 45° and the length of melt flow of 400mm were smaller than tilt angle of 30° with melt flow length of 200mm. The grains were completely globular when the shape factor is equal to 1.

The hardness of the as-cast and as-CS (30◦/200mm and 45◦/400mm) in this work is shown in Figure 8. The hardness of the as-cast sample of LM4 was 65.8±4.98 HV, whereas the hardness of LM4 for 30◦/200mm was 89.3±4.95HV and the hardness of as-CS 45◦/400mm was 100.8±2.94HV higher than the as-cast and as-CS 30◦/200mm.

An increase in the hardness of the sample produced by cooling slope casting was due to the progressive growth of the primary α-Al phase in the alloy [22-23]. Generally, small grain size would provide higher strength to the alloys, however, an increase of sphericity, 1, led to a drop of elastic modulus whereas a decrease in sphericity would increase the cohesion and internal friction angle. Moreover, small particle size would increase the hardness of alloy known as the Hall-Petch relationship. However, inverse Hall-Petch effect could also occur below a critical grain-size where the hardness of the alloy could be decreased with the decreasing of grain size. Burapa et al. (2010) asserted that the relationship of the mechanical properties is directly proportional to the shape factor of the primary α-Al alloy [24]. Therefore, the mechanical properties could be affected by the grain size of the primary α-Al alloy and the shape factor in the sample.

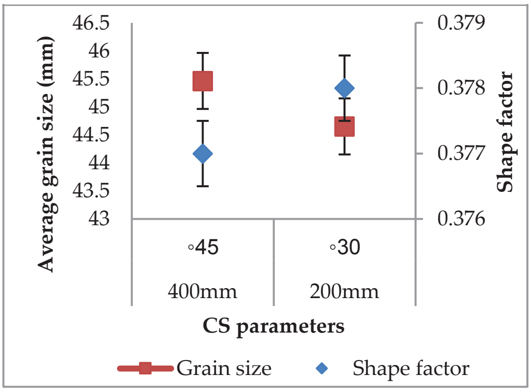

Figure 7: Grain size and shape factor for LM4.

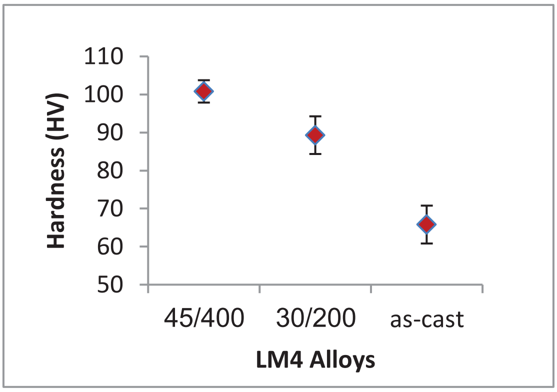

Figure 8: The hardness of LM4 samples.

Besides, the intermetallic compounds of the alloy had a significant effect on the mechanical properties of the LM4 alloy. Base elements in the aluminium alloy material were aluminium and silicon, however, copper, chromium, magnesium and iron were also present to enhance the strength and corrosion resistant. Silicon element offered better castability due to its low shrinkage and high fluidity. The Mg2Si element played an important role in order to refine the size and sphericity of α-Al particles. However, among all these compounds, the iron-rich metallic compound is the most unwanted because it causes brittleness ,thus. reduced the strength and ductility of the aluminium alloy

4.0 CONCLUSION

The dendritic microstructure of conventionally cast alloy has been successfully changed to a fine and non-dendritic structure after successfully cast by CS casting technique. Through the shearing process during melt flow on the CS, the dendrites are broken into fine particles by the CS casting in order to obtain the thixotropic behaviour of the non-dendrite feedstock. The deformation promotes the morphological transition from dendrite to fine and homogenous globular structure. It is found that cooling slope length of 400mm with tilt angle of 45° is an optimum length of melt flow and tilt angle in which maximum sphericity is obtained at a pouring temperature of 647°C.

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