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The Effect of Direct Thermal Method, Temperature and Time on Microstructure of a Cast Aluminium Alloy

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The direct thermal method is used for the creation of globular microstructures suitable for semi-solid metal forming. In this paper both simulation and experimental results using direct thermal method are presented. ProCAST® software was used to estimate temperature distribution inside the aluminium billet. In validation work, molten aluminium A356 was poured into metallic copper tube moulds and cooled down to the semi-solid temperature before being quenched in water at room temperature. The effect of pouring temperatures of 630°C, 650°C, 665°C, 680°C and holding times of 45s and 60s on the microstructure of aluminium A356 alloy were investigated. The simulation results showed that the average temperature rate within the copper mould, from initial pouring temperature to just before quenching, was approximately 1°C/s. Examination of the solidified microstructures showed that the microstructure was more spherical when lower pouring temperatures and holding periods were used. From the micrographs it was found that the most globular and smallest structures were achieved at processing parameters of 630°C and 45s.

Keywords: Aluminium, A356, Direct Thermal Method, Pouring Temperature, Holding Time, Semi-Solid.

INTRODUCTION

Semi-solid metal processing has been commercially used for the casting of various sizes of components on an industrial scale. Commercial interests in semi-solid metal processing are mainly in the automotive, aerospace, ICT, plumbing and military supplier industries. This processing technique has become a common casting method for aluminium and magnesium alloys for producing high density and high strength products [1]. Some current research is also investigating ways to make this process feasible for semi-solid steel forming [2]. The effect of microstructure on fluidity which allows for semi-solid processing was discovered by Flemings and Spenser in Massachusetts Institute of Technology 40 years ago [3]. In the initial stage, Flemings and his co-workers discovered that the viscosity of the stirred material while in the semi-solid forming was much lower than the viscosity without stirring. It was also found that this lower viscosity was due to the generation of a spherical grained structure in the material from the stirred action during solidification. Interlocking network of dendrite grains in the unstirred material on the other hand generates a high viscosity fluid.

Semi-solid metal exhibits not only a shear rate thinning but also a time dependency. This fluid is therefore

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thixotropic in nature. This time dependency is mainly due to disagglomeration of particles clusters after increased shear rate processing or due to agglomeration of particles after reduced shear rate processing [3]. The particles have a natural affinity for each other and therefore agglomerate during periods of the shearing. However, particle bonds are re-melted during deformation as a result of shear stresses, which allows the material to flow with greater ease. The flow resistance of semi-solid metal is strongly depended upon processing history. The resulting microstructure (average grain size and shape and the distribution of grain size) in semi-solid metal state and the degree of particle agglomeration appear to be the most significant material characteristics contributing to this process history dependent flow behaviour.

Thermal treatment processing to obtain the required microstructure for semi-solid metal forming is the most commonly used commercial method to provide the required globular microstructure. In order to achieve this, the creation of many small nucleation sites is important. The higher the number of nuclei, the smaller is the average distance between nuclei and the smaller are the resultant grains.

The new-rheocasting process by UBE technology is one of the better known examples of this thermal method applied commercially. In order to generate more nuclei, the molten metal is chilled quickly from above the liquidus to below the liquidus and held for a short holding at a semi-solid metal temperature. This processes results in a very fine grained microstructure. In the new-rheocasting process, the semi-solid metal temperature is controlled with induction heating to maintain the desired fraction solid [4]. The treated semi-solid metal is then injected into the mould within the die casting machine. The success of the new-rheocasting process technique depends on the initial structure obtained in the material. There are few more techniques that use a similar principle in order to provide the required starting material. These include the swirled enthalpy equilibrium device [5], the continuous rheoconversion process [6], low superheat pouring with a shear field [7], and the direct thermal method [8].

In direct thermal method, liquid metal is poured into a thin cylindrical metallic mould that has low thermal mass and high conductivity [8]. Heat matching between molten metal and mould allow for pseudo-isothermal hold within the solidification range. This allows for the alloy to remain in a steady semi-solid state where the temperature is held between the solid and liquid phases of the alloy. This is achieved by the very low rate of heat loss to the environment through the mould, which is copper tubing with a metal base plate. The advantage of this technique is that the process uses the natural solidification principle and is low cost. The low superheat of the alloy is extracted into the mould such that the alloy rapidly cools into the semi-solid zone. The initial rapid cooling gives rise to a high rate of nucleation events in the alloy. After a short holding period this microstructure spherodises. In order to capture this microstructure, the mould is quenched into water at room temperature while the alloy is still within the semi-solid metal range.

Simulation using finite element method to examine the heat distribution during solidification was carried out by Wang et al. [9]. This research work showed that the combination of simulation and experimental techniques were used to optimize the product design in order to avoid the casting defects. Publications in recent years have shown that the globular microstructure can be achieved by using direct thermal method [8]. The combination of accurate pouring temperature and holding time significantly affect the globular structure creation. It was suggested from previous research that a lower pouring temperature would create smaller primary and secondary phases within the microstructure [10, 11]. Finite element method was seen in their work as a useful tool to predict the heat distribution during solidification process. However the effect of these parameters on the resultant microstructure is still not fully understood due to the vast range of possible casting

conditions in terms of alloy, holding time, pouring temperature, mould materials and quenching medium used. This work focused on investigating the effect of pouring temperature and time on the microstructure of A356. In particular, simulation and experimental focused on a pouring temperature range of 630°C to 680°C and specific holding times of 45s and 60s.

SIMULATION AND EXPERIMENTAL

Simulation

The purpose of the simulation was to investigate the heat distribution inside the billet during solidification. The simulation results were used to estimate the temperature of the billets at various times during the holding period. The solidification process of the alloys was simulated using finite element analysis software ProCAST®. Standard heat transfer via Fourier modelled was used [9]. The Fourier heat conduction equation used is represented as follows:

$$\rho c \frac{dT}{dt} = \nabla(k\nabla T) + \dot{Q} \quad (1)$$

where T is the temperature, t is the time, ρ is density, c is specific heat, k is thermal conductivity, and $\dot{Q}$ is the internal power source. The calculations are based on Cartesian coordinates x, y, z of the part geometry such that equation (1) can be re-written as follows:

$$\rho c \frac{dT}{dt} = \frac{d}{dx}\left(k\frac{dT}{dx}\right) + \frac{d}{dy}\left(k\frac{dT}{dy}\right) + \frac{d}{dz}\left(k\frac{dT}{dz}\right) + \dot{Q} \quad (2)$$

The simulation work began with the development of the mould geometry which was of the same geometry as that used to produce the billets experimentally. These cylindrical billets were 25 mm in diameter and 75 mm in height. The model was transferred to the GEOMESH Environment software for the meshing process. The finite element mesh of the ingot consisted of 70,752 nodes and 396,795 tetrahedral elements.

Aluminium A356 was used for the ingot (billets) and copper for the mould. The initial conditions of the mould were set at 680°C for the ingot and 24°C for the mould. Other boundary conditions and thermo-physical properties which were used in the model are summarized in Table 1. The moulds were filled via pouring under gravity with the crucible lip position 25 mm above the copper mould during pouring.

TABLE 1. - Boundary conditions and thermo-physical properties of A356 used in the simulations.

Property	Value
Liquidus Temperature	616°C
Solidus Temperature	556°C
Pouring Temperature	680°C
Mould Temperature	24°C
Latent Heat	389kJ/kg
Conductivity	151W/mK
Density	2670 kg/m^3
Heat Transfer Coefficient	14.26kW/m^2 [12]

Experimental

A 1kg aluminium A356 ingot was placed in a graphite crucible and was heated to a temperature 720°C using induction furnace. Once the desired temperature of the melt was obtained, it was poured into a cylindrical copper mould of 1 mm wall thickness, 25 mm in diameter, and 75 mm in height.

The different pouring temperatures were set at 630°C, 650°C, 665°C and 680°C. After pouring, the molten metal was held in the mould for 45s or 60s, at semi-solid temperatures, before quenched into room temperature water. A billet with pouring temperature of 665°C was also allowed to solidify via natural solidification.

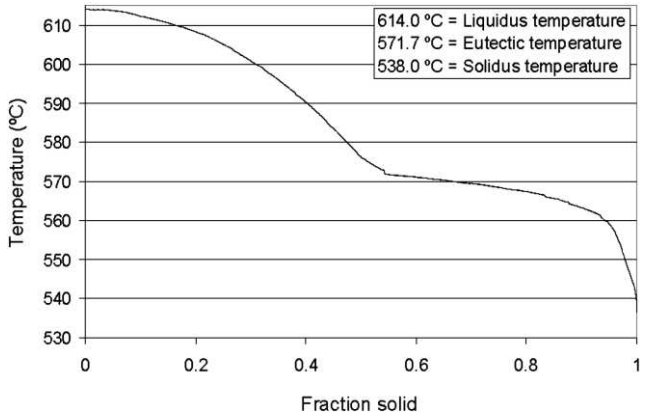

FIGURE 1. - A fraction solid vs temperature curve for A356 at a cooling rate 0.6°C/s [13].

The semi-solid temperature range of A356 alloy is quoted with different solidus and liquidus temperatures depending on the source of reference. In one previous work this range was reported as 538°C to 614°C. Figure 1 shows the fraction solid vs temperature curve of A356 at 0.6°C/s cooling rate [13]. This fraction solid curve was used to estimate the amount of solid before quenching.

The samples were sectioned 5 mm from the bottom of the cast billets and mounted in Bakelite and microstructure analysis was performed by optical microscope after etching the surface of the polished moulded samples with Keller's reagent. A Reichert light optical inverted microscope with Me F2 universal camera connected to a PC was used for image capture. Microstructures were examined with Buhler Omnimet Enterprise software.

RESULTS AND DISCUSSION

Simulation Results

The temperature profile within the billet from 2.5s to 61 s after pouring is shown in Figure 2. The simulation results show that the mould was fully filled with molten metal 2.5s after pouring, see Figure 2 (a). In the initial solidification stage, the temperature started to drop first in the lower region of the mould as shown in Figure 2 (b).

In the simulation, when the pouring process completed, the bottom part showed lower temperature than the upper part of the mould. This is may be due to the fact that the bottom part of the mould is farthest away from the hot metal that just transferred from the crucible and also has a longer period of time in contact with the mould walls compared to the melt within the upper regions of the mould.

This temperature difference between the top and bottom regions became evident after 21s pouring time (Figure 2 (c)). The effects of pouring temperature on heat distribution were also observed by other in previous work [14].

The temperature continued to drop until 61s with a drop rate of 3°C/s in the simulation and the average temperature drop during the previous experimental findings was 1°C/s [12]. This is come to the agreement that the simulation results were close to the previous experimental result, supporting the accuracy of simulation result.

From the simulation, after 45s and 60s, the temperatures were approximately 638°C and 622°C respectively. The equivalent recorded temperatures from the experimental work conducted were 635°C and 620°C at 45s and 60s respectively. By correlating with Figure 1, these results could then be used to estimate the fractions solid of the billets before quenching.

In direct thermal method, the temperature cycle was influenced by the material and wall thickness of the mould [12]. The temperature drops within a copper were higher than a steel mould as steel has the higher volumetric heat capacity. Furthermore, the greater selection of a wall thickness is needed for a steel mould.

Experimental Results

Effects of Pouring Temperature

The billet produced with 665°C pouring temperature and with natural solidification to room temperature produced a dendritic microstructure, see Figure 3, as would be expected under this conventional type of solidification. Even though the molten metal was poured into the copper mould, without

a controlled period for holding within the semi-solid temperature region, a ripened type of dendritic microstructure was produced. The microstructure of the billets with different pouring temperatures and holding times are presented in Figure 4 and Figure 5. The lower pouring temperatures would be expected to have a significant effect not just for the finer grain size but also the morphology of the grain [11]. As per previous findings, the lower pouring temperatures were found to produce more globular and finer microstructures [15]. The primary phase microstructures were also found within this work to be more spherical when produced at lower pouring temperatures as shown in Figure 4 (a).

Lower pouring temperatures lead to higher cooling rates from above the liquidus to below the liquidus as less superheat has to be extracted. Furthermore, when the cooling rate is higher, the undercooling of the alloy becomes larger. A raise in undercooling increases the amount of nucleation which ultimately results in a smaller grain size from this larger crystallization driving force [16].

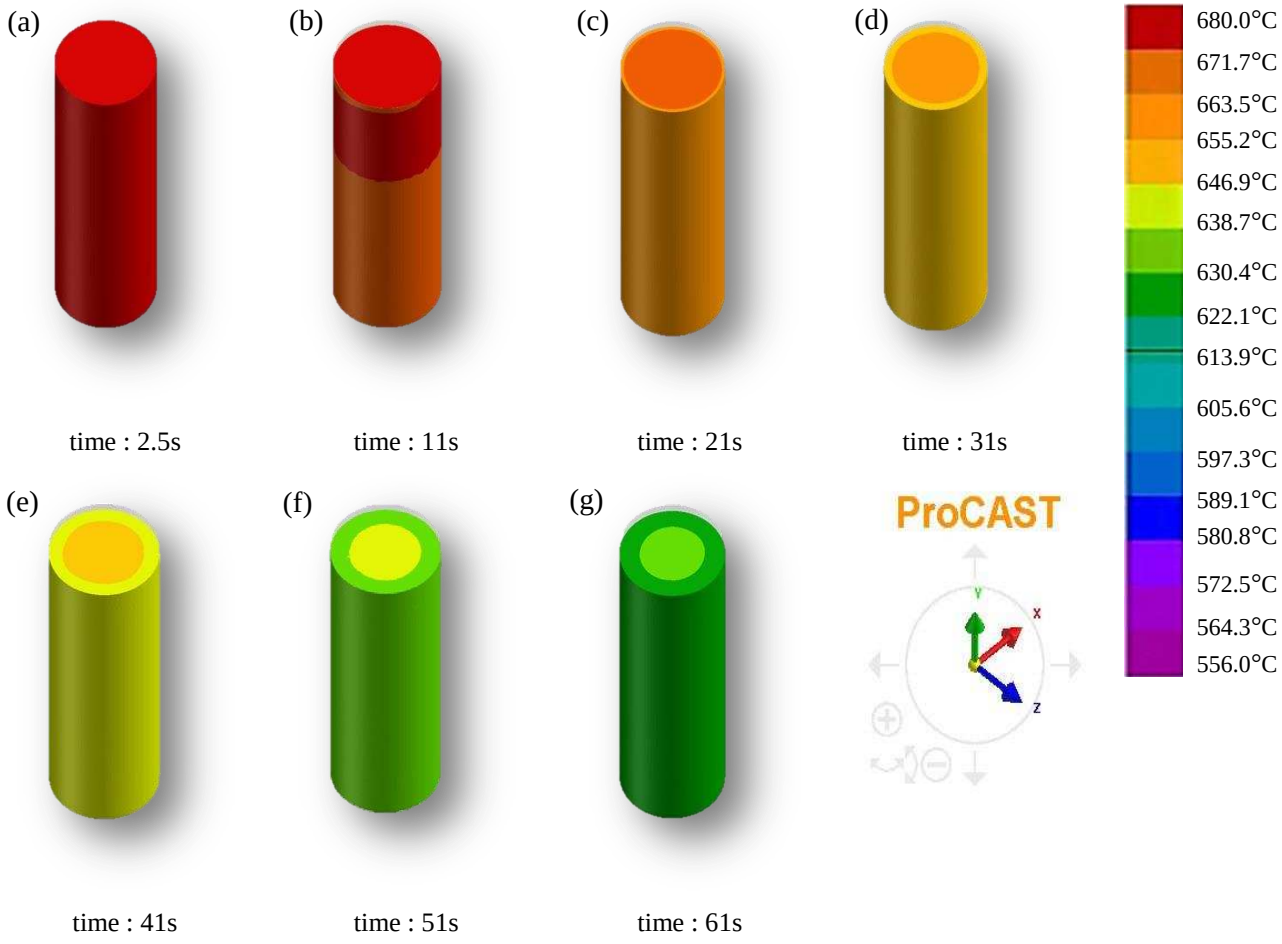

FIGURE 2. - Temperature distributions within aluminium billet from (a) 2.5s to (g) 61s after pouring.

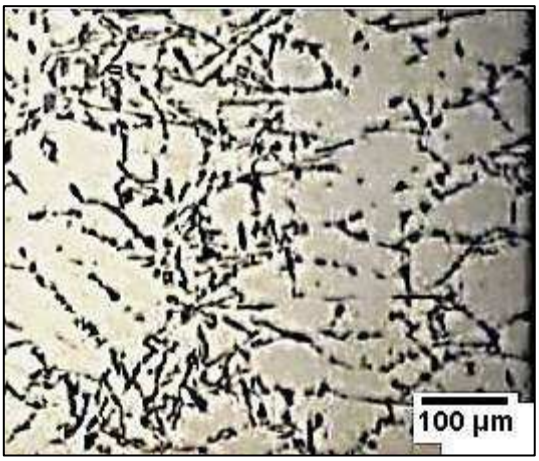

FIGURE 3. - Dendritic microstructure formed within billet after solidification from pouring temperature of 665°C under air cooling.

Effects of Holding Time

The role of holding time was to ensure an adequate fraction solid before quenching. A longer holding time for a specific constant pouring temperature produced larger primary phase grains. Figure 5 shows the microstructures for the samples produced with 630°C, 650°C and 680°C pouring temperatures and with 60s holding time. These have larger grain sizes compared with the microstructures of the samples shown in Figure 4 produced with 45s holding time.

Formation of globular microstructure was influenced by fraction solid [17]. The sample with a 630°C pouring temperature was quenched at 570°C, equivalent to 0.65 fraction solid. The corresponding microstructure is shown in Figure 5 (a). For the sample with 650°C pouring temperature, with microstructure shown in Figure 5 (b), was quenched at 590°C (0.4 fraction solid). The microstructure was less globular compare with the sample produced with a pouring temperature of 630°C. This was confirms that size of primary grains was affected with a low fraction solid used [17].

The sample with 680°C pouring temperature was quenched at 620°C (Figure 5 (c)). This sample was therefore still in the liquid condition upon quenching. The microstructure results from this sample showed a primary phase which was too large and irregular compared to what would typically be required for semi-solid metal forming.

In order to understand the relationship between pouring temperature and viscosity, the microstructure of the respective billets should be related to the material fluidity. Viscosity is an important indicator of the material capability to fill the die cavity during casting. Lower viscosity produced better movement of the material and allows the semi-solid metal to move into the complex geometries such as thin die cavity sections.

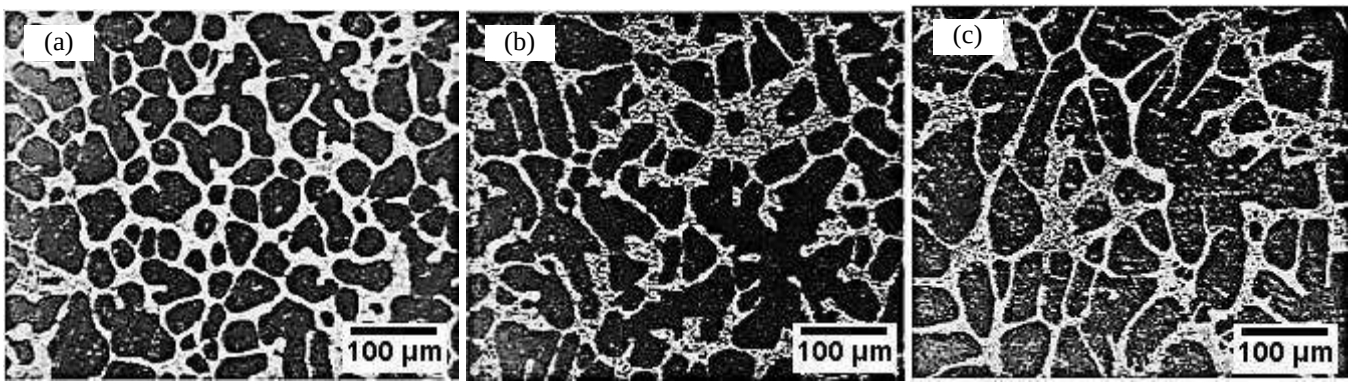

FIGURE 4. - Microstructures from a 45s holding time and with pouring temperatures of (a) 630°C, (b) 650°C and (c) 680°C.

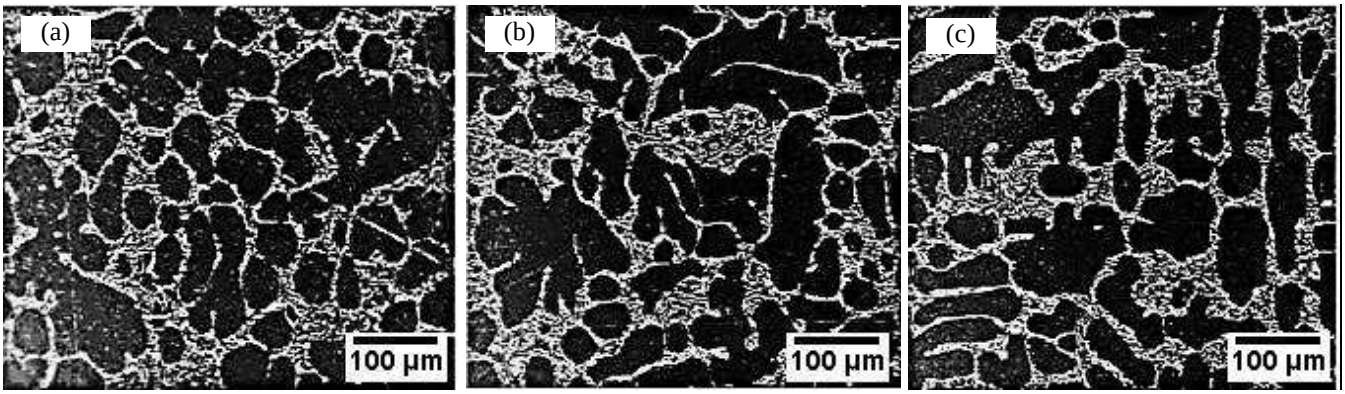

FIGURE 5. - Microstructures from a 60s holding time and with pouring temperatures of (a) 630°C, (b) 650°C and (c) 680°C.

The two important phases in the microstructure of A356 are the primary aluminium phase which solidifies first and the secondary aluminium-silicon phase which solidifies second, shown in Figure 6. In general, a microstructure with more globular primary grains and more liquid phase, seen as secondary upon solidification, will have higher fluidity.

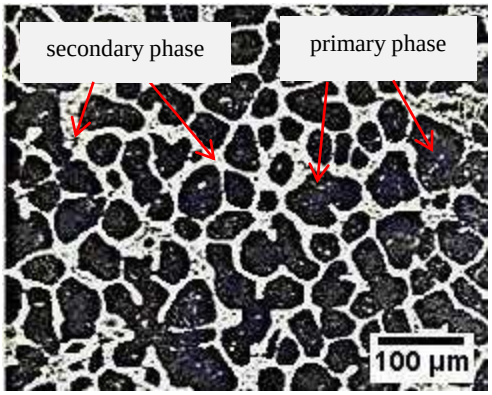

FIGURE 6. - Microstructure of the sample produced with a 45s holding time and a pouring temperature of 630°C.

Pouring temperature is one of the important parameters that affect the evolution of the primary phase during solidification [18]. Low pouring temperature is a key factor that establishes higher temperature gradients within the semi-solid metal which encourage the formation of a multitude of nuclei and subsequently a more globular microstructure upon holding within the semi-solid state.

Relationship between the pouring temperature and microstructure formation is determined by the under cooling temperature. The undercooling is the difference between the equilibrium temperature and temperature which the material cools, before the start of solidification [19]. The undercooling is influenced by the solidification rates which depend on the type of a mould material, mould thickness etc. The formation of a microstructure which evolves within material depends on the degree of undercooling. During solidification process, as the undercooling temperature and time increase, the melt potential nucleation decreases resulting in a coarse-grained structure deformation. Higher cooling rate is therefore associated with a finer grain size and a globular microstructure. The higher pouring temperature lead to a higher cooling rate as it need more time to cool from the liquidus to solidus temperature. For this reason, dendritic microstructure occurs.

The formation of a globular microstructure in these experiments was influenced by the volume fraction of solid. In semi-solid metal processing, the volume of the fraction solid play the important rules in determined the successful of the process. The fraction solid which is used in semi-solid processing is normally in the range of 0.30 to 0.7 depending on the type of the material used [20]. During rapid solidification, the nuclei start to deform from the liquid condition. The nuclei evolved and impinged to each other within the material and later produced a dendritic

microstructure as in typical solidification process. During this process (from the liquid to dendritic microstructure formation), the fraction solid which occurs inside the material is increase as it approaching the solidus temperature. The formation of the nuclei which is small at this stage, become larger due to the increment of fraction solid volume. The quenching technique which was applied in this period, captured a finer globular shape microstructure. For this reason, the proper selection of a holding time in direct thermal method is crucial to allow the formation of a desire microstructure feature due to the fraction solid effect.

CONCLUSION

The simulation of the heat distribution inside the billet and direct thermal method experiment was successfully carried out. The simulation provided useful information about solidification temperature and time prediction before quenching. The copper mould was only fully filled 2.5s after pouring. The A356 billet temperature decreased at approximately 1°C/s from the initial pouring temperature. The experimental work showed a fine spherical microstructure can be achieved with the correct selection of pouring temperature and holding time. A lower pouring temperature contained more primary particles which were also more globular than those formed from higher pouring temperatures. The spherical microstructures were dominant at the lower pouring temperature (630°C) regardless the holding time either 60s or 45s. The longer holding time produced larger primary phase particles which were also less globular. The results of this work showed that the best pouring temperature and time for the A356 alloy were at 630°C and 45s respectively. In direct thermal method, the combination of proper pouring temperature and holding time are necessary in order to produce the microstructure required for semi-solid metal forming.

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