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Theoretical Considerations for Thermal Control over Solid Fraction of Aluminum Alloy Slurry Prepared by Cup-Cast Method

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Currently, semi-solid metal (SSM) processing has been established as a common technique of manufacturing net-shape components. Among different techniques available for SSM processing, Cup-Cast method is a recently developed technique that produces semi-solid slurry with appropriate properties in the easiest way. In Cup-Cast method due to variation in the alloy and cup, solid fraction and heat transfer condition would change. Consequently, the process would be more robust if the suitable cup for specific alloy can be predicted. For this purpose a dimensionless number γ has been introduced to determine the fraction solid and its variations, and it also can apply to find the condition with homogeneous temperature in the cup. By calculating fraction solid variations as a function of the dimensionless number γ, suitable range of cup for experimental test can be predicted. [doi:10.2320/matertrans.MB200751]

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1. Introduction

Today's engineers can select among numerous techniques of manufacturing net-shape components using metals and their alloys. Majority of these techniques, in principle, could be classified into two conventional methods restricted to either solid or liquid state.[1,2] The liquid-state methods involve casting with a variety of modifications: gravity, high-pressure die casting, squeeze casting, etc. In contrast, the solid state techniques generally require multi-step operations after casting, such as homogenization of chemistry, hot working, cold working, forming, machining, or heat treatment. As a result, the properties of wrought components are predominantly superior to castings. The number of manufacturing steps and their complexity, however, significantly contributes to a higher cost of the final product.[4–6] The economy factor represents the downside of many non-conventional manufacturing techniques (*e.g.* powder metallurgy). Therefore, there is a continuous quest for a technology that reduces costs and at the same time improves properties. It is believed that the emerging technology of Semi-Solid processing might satisfy these requirements.[1–5]

According to review of the literature, conventional solidification of foundry alloys including Al-Si takes place along to the dendritic formation of the primary α-Al phase in the eutectic matrix. The alloy composition, temperature gradient within the melt, convection, rate of heat extraction, and the resulting constitutional super cooling are considered the most effective parameters on the morphology of the primary α-Al phase. Any change in these factors during solidification should alter the as-cast structure. For instance, the introduction of agitation (forced convection) into the solidifying melt changes the distribution of chemical composition. This factor could remove constitutional super cooling and promote dendrite-to-equiaxed transformation (the breakdown and globularization of the α-Al phase). The degeneration of the α-Al phase creates some opportunities that seems to be of commercial interest.[6–9]

Cup-Cast method –recently developed by the authors– is based on heat transfer and forced convection of melt- the direct result of pouring of low super heat melt into a metallic cup. In this method, embryos of solid particles might be created on the inner surface of the cup and evolve to nuclei. These nuclei might be separated from the cup's wall by flow of the melt and move to the other parts of the melt bearing low temperature and composition gradient. These circumstances bring about a non-dendritic growth.[7,10,11]

In cup-cast method an alloy, at low superheat with different conditions will be poured into a metallic cup that has gotten different diameter and thickness, which is necessary for rapid absorption of heat from the alloy at nucleation stage followed by a slow cooling to discourage dendritic growth. Figure 1(a) shows the schematic figure of cup-cast method, and 1(b) shows the photo of slurry-cut that was produced by this method.

In Cup-Cast method non-dendritic solid particles in a liquid matrix would be produced by the means of applying agitation caused by pouring from somewhat high position to a molten metal during solidification and also direct spheroidal growth. Because of that several factors such as turbulence and its duration, nucleation sites, and some other parameter – those have effect on agitation to molten metal or nucleation and growth– affect the slurry properties in Cup-Cast method. Figure 2 shows the micro-structure of Al-A356 slurry that was produced by Cup-Cast method as an example of effectiveness of this method.

Although Cup-Cast method was already considered a viable method in semi-solid processing, it is still under intensive development and a kind of critical breakthrough is expected. Therefore this article introduces dimensionless number γ, in Cup-Cast method, which allows a proper understanding of this modern method. In fact, the slurry prepared by Cup-Cast method is affected by some parameters such as, material and dimension of cup, temperature of melt, and cup's temperature. There is a need to know how to predict these factors, and as a result how to make cup design more efficient and effective. The dimensionless number γ provides the solution for this problem.

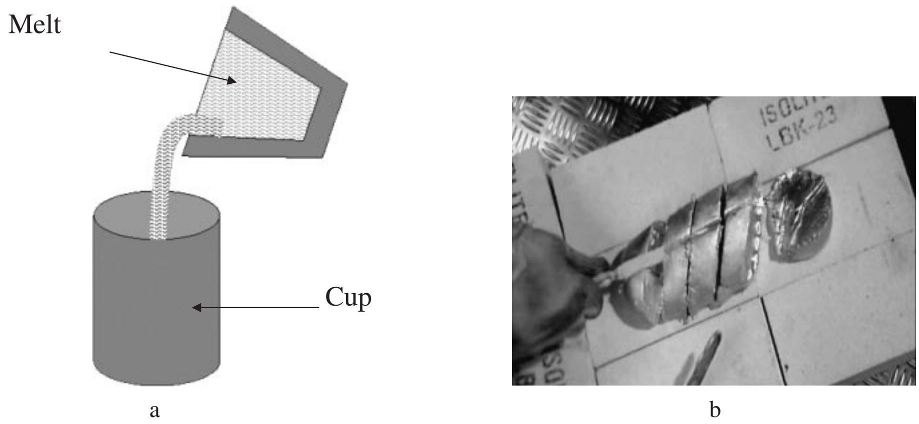


Fig. 1 a- Schematic Figure of Cup-Cast method, b-Slurry that was produced by Cup-Cast method.

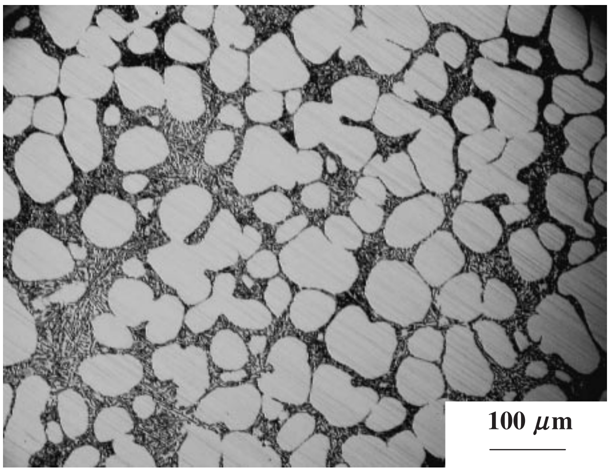


Fig. 2 Micro-Structure of Al-A356 Slurry that was produced by Cup-Cast method.

The ultimate goal in this research is considered to use γ in Cup-Cast method and calculating fraction solid as a function of γ in order to predict the suitable cup for specific alloy.

2. Heat Transfer Calculation

2.1 Dimensionless number γ

As it was mentioned in Cup-Cast method,[10,11] the melt will be poured into the cup and after meeting the following conditions the slurry would be prepared. There should be a sufficient rest time after pouring finished – that is necessary for achieving heat balance. Therefore, there would be a heat balance between cup and melt. As a result, cup and melt will reach to saturation point (equilibrium temperature between cup and melt).[10,11] Based on the temperature measurement[12] and some assumptions (such as, constant material properties, and no heat loss from the cup and melt to the air) dimensionless number γ, could be calculated as follow.

Initial heat of the melt and cup are given as

$$H_{ic} = (C_c T_c + H_f)\rho_c V_c \tag{1}$$

$$H_{im} = C_m T_m \rho_m V_m \tag{2}$$

Where the subscript c and m represent as casting (melt and slurry) and cup respectively, H_i represents initial heat and C is specific heat capacity. T is temperature, H_f is latent heat, ρ is density and V is volume.

When the melt reach to equilibrium temperature, it contains solid, so that the heat of melt and cup at saturation point could be calculated as

$$H_c = \{C_c T_{eq} + (1 - f_s)H_f\}\rho_c V_c \tag{3}$$

$$H_m = C_m T_{eq} \rho_m V_m \tag{4}$$

The symbol f_s represents the solid fraction, and T_{eq} is temperature at equilibrium condition –when cup reach to its saturation temperature. According to the energy conservative law, the H_{ic} could be written as:

$$H_{ic} + H_{im} = H_c + H_m \tag{5}$$

By substituting the definition of H_{ic}, H_{im}, H_c, and H_m from eqs. (1) to (4) into eq. (5) and introducing γ (eq. (6)), equilibrium temperature between cup and melt as a function of γ and f_s will be determined as eq. (7).

$$\gamma = \left(\frac{\rho_m C_m}{\rho_c C_c}\right)\left(\frac{V_m}{V_c}\right) \tag{6}$$

$$T_{eq} = \frac{T_C + \gamma T_m + \left(\frac{H_f}{C_c}\right) f_s}{1 + \gamma} \tag{7}$$

Where γ is a function of the cup design (V_m/V_c) and material constant of melt. Regarding eq. (7), it is clear that if process conditions T_c, T_m, γ and solid fraction f_s as a function of T are given, the equilibrium temperature or the equilibrium solid fraction can be driven out.

2.2 Temperature-fraction solid (T-f_s) curve

Since the semi-solid alloy is held in the two-phase region for extended times in cup-cast method, the solid grains are round and their radii are much larger than the tip of the dendrite formed during solidification. Consequently, the curvature under-cooling can be neglected. Since the specific flow behavior of melt in Cup-Cast method makes the solute distribution in the liquid uniform, the constitutional super-cooling can also be neglected. Some diffusion will occur in the solid but the fraction solid can be estimated using complete thermodynamic equilibrium.

Figure 3 shows the fraction solid versus temperature curve

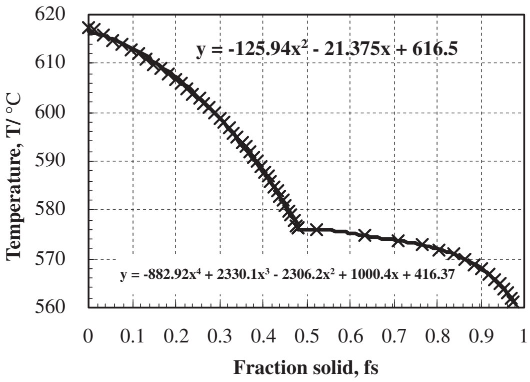


Fig. 3 Temperature as a function of fraction solid calculated by Thermo-Calc for Al-A356.

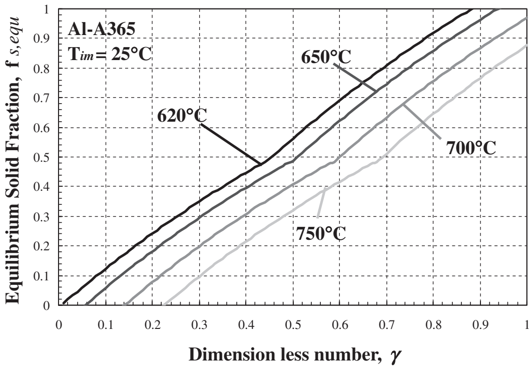


Fig. 4 Solid fraction as a function of dimensionless number γ, for different pouring temperature.

Table 1 Chemical composition of used Al-A356 alloy.

Si	Mg	Fe	Cu	Zn	Mn	Sn	Ni
7.12	0.45	0.11	0.007	0.007	0.006	0.006	0.003

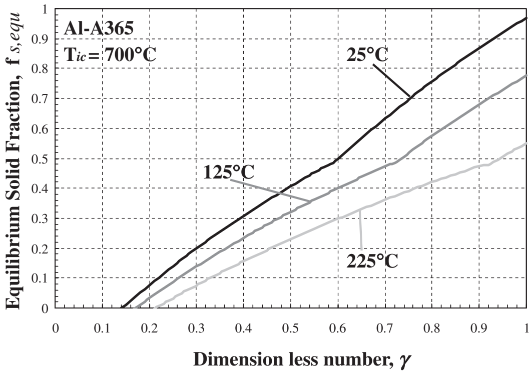


Fig. 5 Solid fraction as a function of dimensionless number γ, for different Cup temperature.

from Al-A356 alloy with the composition shown in Table 1, which was calculated by commercial software package Thermo-Calc. Aluminum-rich phase (primary α-Al phase) forms below the liquidus temperature of 617°C. The eutectic phase forms at eutectic start temperature (T_{eu}) 576°C, where the fraction solid is about 0.48. Figure 3 presents also the change in solid fraction by temperature change, when the temperature is higher than T_{eu}, the curve is steep and a small temperature variation results in a correspondingly small fraction solid variation. However when the temperature is lower than T_{eu}, the curve is relatively flat and a small temperature change can result in a large fraction solid variation.

From Fig. 3, equilibrium temperature as a function of solid fraction can be obtain as eq. (8)

$$T \geq 576^{\circ}\text{C} \quad (f_s \leq 0.48)$$
$$T = -125.94 f_s^2 - 21.375 f_s + 616.50 \tag{8a}$$
$$T \leq 576^{\circ}\text{C} \quad (f_s \geq 0.48)$$
$$T = -882.92 f_s^4 + 2330.1 f_s^3 - 2306.2 f_s^2 + 1000.4 f_s + 416.37 \tag{8b}$$

2.3 Fraction solid as a function of γ

Equation (7) together with eq. (8) yields the equilibrium fraction solid as a function of the dimensionless number γ for different conditions.

Curves of fraction solid versus dimensionless number γ, for different pouring temperatures of melt into the cup with initial temperature of 25°C, are shown in Fig. 4. As it might be expected in each pouring temperature, by increase in γ, equilibrium fraction solid will increase, and in certain γ the more pouring temperature of melt the less the fraction solid will be. The effect of different cup temperatures on the fraction solid of slurry at different γ is shown in Fig. 5. The fraction solid variations in different cup's temperatures increase by increasing γ. It means by increase in γ, the effect of cup temperature on solid fraction during semi-solid processing will increase. As a result it likely to provide a more robust process; It is also clear, at certain γ, by increase in cup temperature, solid fraction will decrease.

3. Experimental Procedure

The Al-A356 alloy with the chemical composition —as shown in Table 1— was melted at the electrical resistance furnace in the graphite crucible in 680°C. In previous work of the authors, effect of different experimental condition (such as pouring height and duration, pouring temperature and cup's temperature) was considered. The optimum condition was set by micro-structural investigation. Under optimum conditions those were set previously, the melt was poured into the cups at room temperature.

For simplification the process and investigation effect of γ, simple cylinder shape was chosen for cup. This process would be applied on different cup with various dimension, and materials that were shown in Table 2. The temperature was measured in the center, near the wall of cup and outside of the cup's wall at three different heights —shown schematically in Fig. 6— by 0.1 mm thickness positive Chromel wire and negative Alumel wire thermocouples. The temperature was recorded during pouring melt and during rest time, it was recorded 20 times per second in order to achieve an exact temperature profile.

Table 2 List of different cups those were used in this research.

Material of cup	γ	Dimension	
		Diameter (D/mm)	Thickness (X/mm)
Copper $\rho = 8780\,kg.m^{-3}$ $c = 425\,J.kg^{-1}.K^{-1}$	0.186	64.0	2.6
	0.213	54.0	2.5
	0.216	64.0	3.0
	0.258	54.0	3.0
	0.270	44.8	2.6
	0.308	63.9	4.2
	0.314	44.8	3.0
	0.411	48.8	4.2
	0.466	53.8	5.2
Steel $\rho = 7758\,kg.m^{-3}$ $c = 553\,J.kg^{-1}.K^{-1}$	0.178	68.8	2.0
	0.225	68.8	2.5
	0.244	53.3	2.1
	0.271	68.8	3.0
	0.275	38.5	1.7
	0.293	53.3	2.5
	0.319	68.8	3.5
	0.344	38.5	2.1
	0.355	53.3	3.0
Cast Iron $\rho = 7170\,kg.m^{-3}$ $c = 563\,J.kg^{-1}.K^{-1}$	0.217	54.0	2.0
	0.343	54.0	3.1
	0.450	54.0	4.0

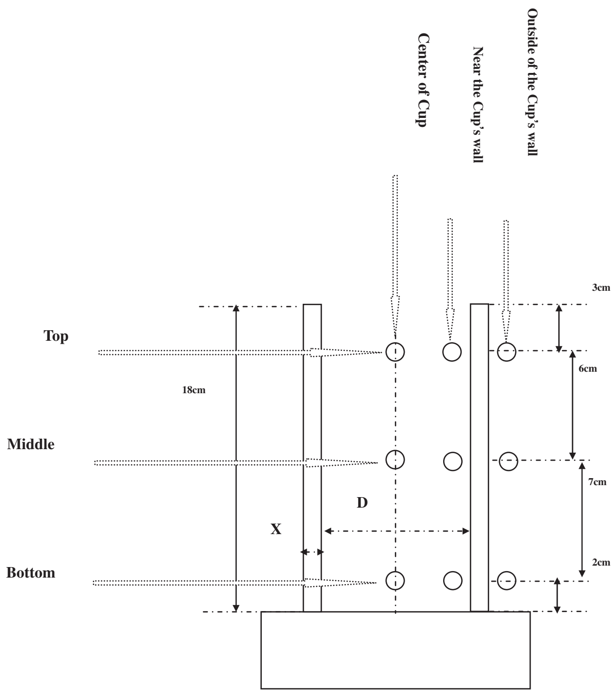


Fig. 6 Schematic of 9 points of measuring temperature.

4. Result and Discussion

4.1 Temperature measurement

As shown in Fig. 7 (that is a typical temperature measurement profile in this investigation), the temperature climbed to its maximum rapidly in the center of the cup after pouring

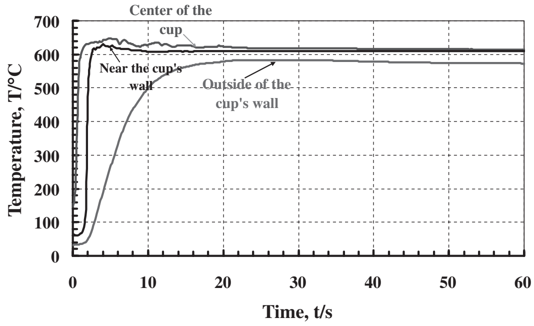


Fig. 7 Temperature profile at different points of the cup in the middle height during Cup-Cast method.

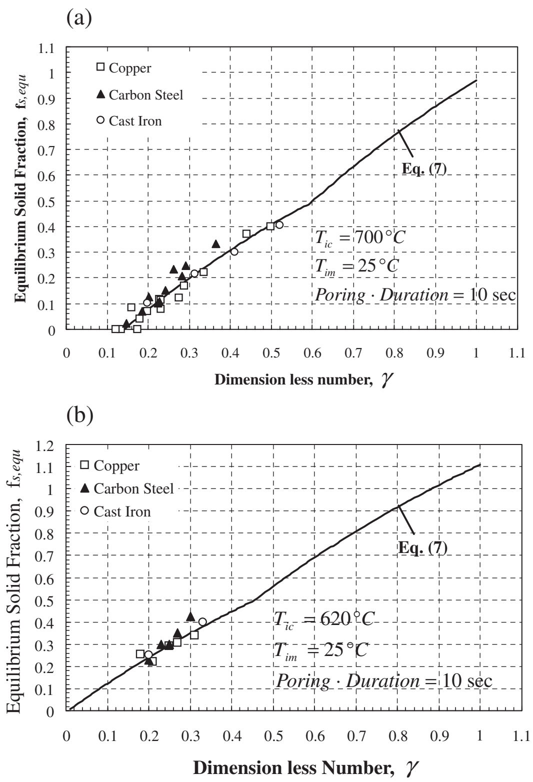


Fig. 8 Comparison of experiment result of solid fraction with calculated one, a- pouring temperature 700°C, b- pouring temperature 620°C.

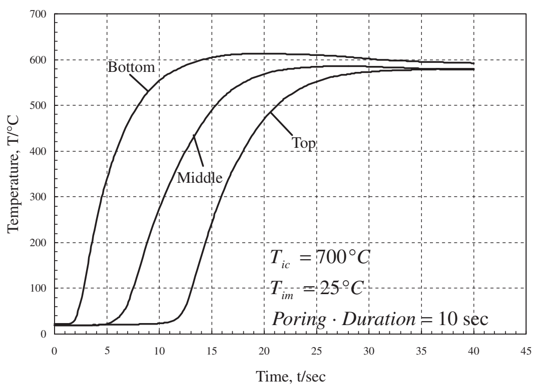
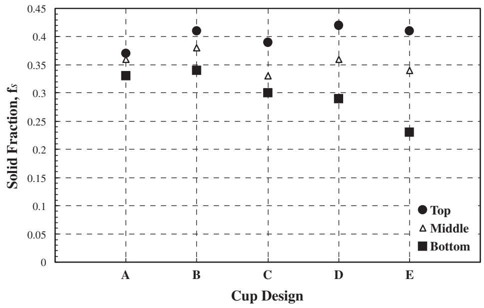


Fig. 9 Typical temperature profile of outside of cup's wall at different height of cup.

Cup No.	Diameter, D/mm	Thickness	Height, h/mm	γ
A	53.3	2.3	53	0.243
B	53.3	2.3	80	0.244
C	53.3	2.3	107	0.243
D	53.3	2.3	130	0.244
E	53.3	2.3	160	0.245

(a)

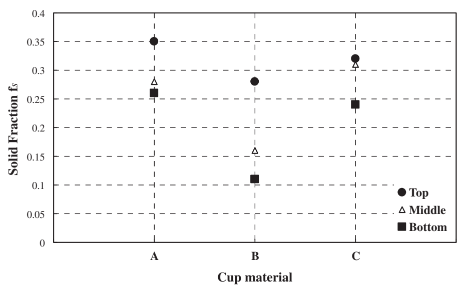


(b)

Fig. 10 a- dimension of used cup in detail, b- Solid fraction variation in cups with different height.

Cup No.	Diameter, D/mm	Thickness	Height, h/mm	γ	Cup material
A	54	3	180	0.29	Carbon steel
B	54	3	180	0.27	Copper
C	54	3	180	0.31	Cast Iron

(a)



(b)

Fig. 11 a- dimension of used cup in detail, b- Solid fraction variation in cup's material.

start as thermocouple was located at melt's stream; then decreased gradually to its optimum temperature. Optimum temperature is the temperature in which heat transfer between cup and melt become linear steady state heat transfer.[12] That is necessary for making low gradient temperature melt in Cup-Cast method. Regarding at near the cup's wall, the temperature increase was delayed, when the melt's flow during turbulence reached to the point –where thermocouple was set–the temperature increased up to the same temperature as the center of the cup. There would be just a trivial difference between the temperature of the melt at the center of the cup and near the cup's wall, so that is shown semi-uniform temperature distribution in the cup. In this section, one of the contributions of temperature measurement is introduced.

As heat transfer from melt to cup, temperature of the melt would decrease gradually but uniformly at the semi-solid state (between liquidus "617°C" and Solidus "560°C" line). The temperature of cup will rise up till it reaches to its saturation point. Cup's saturation point occurs when temperature of the melt at center of the melt and near the cup's wall reach to their optimum temperature. On the other hand when heat transfer between cup and melt become linear steady state, cup's saturation point occurs.[12]

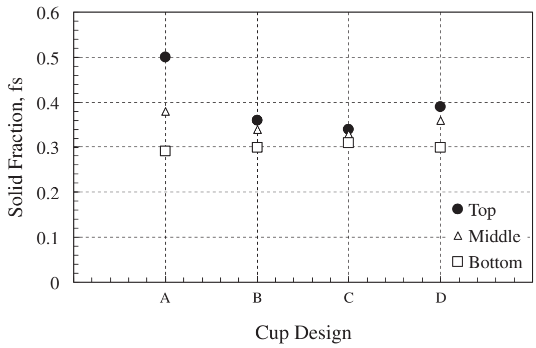


Fig. 12 Solid fraction variation in different design of cup.

4.2 Comparison of calculation and experimental result

By measuring the temperature at different 6 points of the melt, equilibrium temperature between cup and melt was obtained. Solid fraction can be calculated by applying average of these temperatures into the eq. (8). For each cup with different material, solid fraction was calculated at the center and near to the cup's wall in the middle of the cup. These obtained results were compared with the result of eq. (7) as shown in Fig. 8(a) for 700°C pouring temperature and in Fig. 8(b) for 620°C pouring temperature. As it was depicted in Fig. 8, there is a good agreement between the results of experiment and the heat balance equation (eq. (7)). It means at each pouring condition (different pouring temperature and different cup's temperature) solid fraction as function of dimension less number γ can be calculated.

4.3 Effect of dimensionless number γ

As it was mentioned in previous section (Fig. 7), there is a saturation time for cup (as order of 20 s). When cup temperature reaches to its saturation point, heat transfer between cup and melt is govern by linear steady state heat transfer condition.[12] By solving these equations and also from experimental temperature measurement, it is clear at optimum dimension of cup there is uniform temperature distribution in melt.[12] This uniform temperature distribution – one of the main concept in Cup-Cast method – is important in growth condition of solid particles and solid fraction variation at different point of cup.

If melt poured very fast (as order of 0.1 s) or very slowly (as order of 1000 s), because of the time that need for heat transfer between cup and melt, temperature distribution in

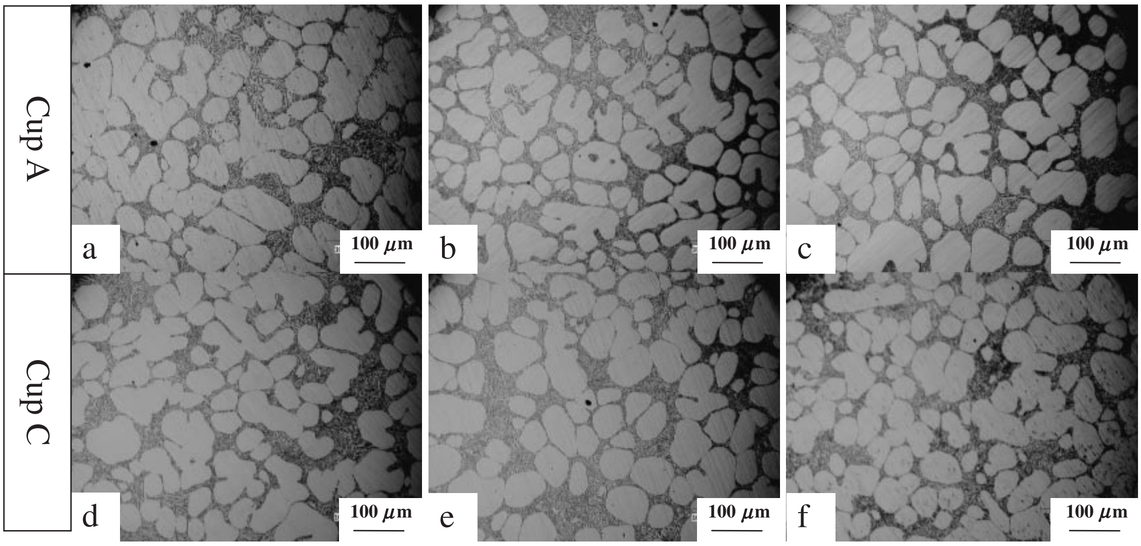


Fig. 13 Microstructure of slurry produced by Cup-Cast method with two different design cup A and C, at different height, a-Cup A bottom, b-Cup A middle, c-Cup A top, d-Cup C bottom, e-Cup C middle, f-Cup C top.

cup's wall at different height would be same. In experiment because of other effect of melt's flow, pouring duration was set as 10 s. In this pouring condition because of melt's flow and filling time, there is delay time in melt and cup contact at different height of cup that result temperature gradient in cup. Which means bottom of the cup will reach to its saturation temperature sooner than top of the cup. Figure 9 that is a typical temperature measurement profile at outside of the cup's wall for different height shows temperature gradient in cup for pouring duration 20 s. This temperature gradient between bottom of the cup and its top will affect heat transfer condition in the cup and temperature gradient in melt at different height of the cup.

This temperature difference and solid fraction variation will be changed by changing the dimension and material of the cup because of heat transfer concept.

Figure 10 shows the effect of cup dimension (height of the cup) on the solid fraction variation by using carbon steel cup with different height. Figure 10(a) shows dimension of the used cup in detail and Fig. 10(b) is the solid fraction variation from top to the bottom of the cup for different height of the cup. Cup's material also affects the solid fraction variation that was shown clearly in from Fig. 11 (Fig. 11(a) dimension of cups in detail and Fig. 11(b) solid fraction variation).

To confirm if dimensionless number γ, is the only parameter that govern the slurry properties which produced by Cup-Cast method, temperature was measured at different height of Carbon steel cup with different design. Bottom and top Thickness of the cup were changed while the dimensionless number γ stands at the same value; the detail of these cups' dimension is mentioned in appendix B. As it was shown in Fig. 12 by changing the cup's design solid fraction variation at different height of the cup will be changed.

Figure 13 represents the microstructure of slurry that was produced by Cup-Cast method at different height of the cup (Bottom, Middle, and Top). For better understanding the effect of Cup design on the slurry properties the microstructure of slurry of Cup A (that is normal Cup with same thickness) was compared with Cup C (that has got the best design among them because of less solid fraction varieties) in Fig. 13(a)–(f). Figure 13 clearly shows that by changing the cup design and less variety in solid fraction, that is because of more uniform temperature distribution among the cup, more uniform and spheroidal solid particles in slurry could be achieved.

5. Conclusion

Cup-Cast method is one of the most convenient methods for semi-solid casting that was just developed by the authors. It would be useful in this method suitable cup for specific alloy and condition can be predicted. These issues contribute to have less experimental observation for getting the desired condition. To this effort, dimensionless number γ has been used to determine the fraction solid and fraction solid variation. Firstly, the fraction solid was calculated as a function of γ. Secondly, by measuring the temperature and investigating the solid fraction variation effect of different parameter could be investigated. But there are some other parameters those govern semi-solid slurry properties in Cup-Cast method because of changing in heat and mass transfer in the melt which is one of the main principles of this method. Changing the dimension of the cup, cup's material and cup's design would be changed the solid fraction variation in the melt and slurry properties.

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Appendix A:

Nomenclature

		Value for Al-A356 in cup-cast method
H_i	Initial heat	
H	Heat at saturation point	
V	Volume	
H_f	Latent heat	$398\,kJ.kg^{-1}$
ρ	Density	Melt $= 2710\,kg.m^{-3}$
C	Specific heat capacity	Melt $= 963\,J.kg^{-1}\,K^{-1}$
f_s	Solid fraction	
D	Diameter of cylindrical cup	
h	Height of cylindrical cup	180 mm
t	Thickness of cylindrical cup	
γ	Ratio of heat capacity	constant
T_{eq}	Temperature at heat saturation	
Subscript c	Casting (melt and slurry)	
Subscript m	Mould (cup)	
	Initial temperature	25°C

Appendix B:

This figure shows the schematically of cup design with different thickness. And below table contain dimension of four carbon steel different cups was used in this investigation.

Cup No.	Diameter, D/mm	Thickness		Height, h/mm	Angle, θ/deg	γ
		Bottom, t/mm	Top, t/mm			
A	53.3	2.3	2.3	130	0	0.244
B	53.3	2.65	2.25	130	0.18	0.244
C	53.3	2.95	1.95	130	0.44	0.242
D	53.3	3.45	1.65	130	0.79	0.245