Original Article

Effects of important parameters in the production of Al-A356 alloy by semi-solid forming process

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A B S T R A C T

There are many routes to produce feedstock with globular microstructure. Cooling slope methods has been attracted as the result of its simplicity and also produces of the globular shape billets quicker than other methods. In this method molten metal is poured on a tilted slope that is cooled by water circulating underneath. Due to shear stress exerted to the slurry, it is solidified with globular microstructure. By simulation of semi-solid casting with cooling slope the effects of different pouring conditions on the microstructure of A356 aluminum alloy are investigated. The simulations are carried out by a CFD code called FLOW3D. The average diameter and shape factor of primary α-Al particles from experiments and the time duration of slurry presence on the slope, solid fraction of the slurry, strain rate and turbulence from the simulations were investigated. Comparing the results of simulations with experimental results showed that for having the best microstructure with higher sphericity and lowerest particle size, the residence time of slurry on the cooling slope be enough, while the shear stress and turbulence be as high as possible. Also, combination of the process parameters including pouring temperature, tilt angle and slope length should lead to adequate value of t, where solid fraction of slurry at the exit of slope is about 30–35%.

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1. Introduction

Manufacturing metal parts by semi-solid methods is increasing because of the various advantages of these methods. To manufacturing parts with complex geometry with high quality, high strength, and by consuming low energy, ingots with fine and globular microstructure are required [1]. The production of the helical gearbox cap [2] and the Centrifugal Pump Flange [3] was investigated with changing parameters (solid fraction of alloy, die temperature, applied pressure, punch velocity, and heat treatment conditions) by Kolahdooz et al.

All alloy systems can be used for semi-solid forming processes but to manufacture parts with high quality and low weight, aluminum alloys are attracting more attention [4]. There are various methods to produce ingots for thixoforming, such as strained induced metal activation (SIMA) [4], mechanical vibration [5] and mechanical stirring [6,7] and magneto-hydrodynamic (MHD) stirring [8]. One such method is cooling slope (CS) that needs low equipment and running costs [9–12]. Many researchers have been performed to investigate the influences of various process parameters such as

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pouring temperature, tilt angle and length of cooling slope on the ingots microstructure properties. Birol [13] showed that to achieve a good microstructure the length of cooling slope should increase with increasing the pouring temperature. He also showed that by holding the ingot at 570 °C for 5 min the globular microstructure is obtained. Kolahdooz et al. studied the influence of using the controlled atmosphere system in semi-solid casting [14]. The effect of porosity on microstructure and mechanical properties of Al2O3(p)/Al–A356 MMC is investigated by Damavandi et al. [15]. They showed that the amount of porosity and agglomeration of particles was high in metal matrix composite with handy injection of particles. While injection with inert gas, using heat treatment and Al/Al2O3 milling caused improved wettability and uniform distribution of particles in molten Al. Also, in the other work of these researchers [16], the effect of inert gas flow rate in injection Al2O3 (p) within molten Al–A356 is investigated on microstructure and mechanical properties of Al/Al2O3 MMC. Baseri et al. [17] have used a back-propagation algorithm to correlate fine a relationship between the process parameters (the pouring temperature, tilt angle of cooling slope and cooling length) to grain size. Afterward, they employed genetic algorithm to optimize the process parameters.

Difficulty of analyzing the cooling slope process due to its multiplicity of effective parameters and their interactions with each other proves the importance of the process simulation. Kund et al. [18] simulated the cooling slope semisolid casting of A356 alloy. At their work the influence of inlet velocity, pouring temperature, slope angle, and slope length on temperature distribution, velocity distribution and macro-segregation was investigated. Wang et al. [19], by simulating the cooling slope process, investigated the influence of inlet temperature and velocity, the cooling slope temperature and the mold temperature on the ingot temperature, solid fraction, solid particles distribution and size, and solute concentration.

In the present paper the influence of pouring temperature, slope angle and slope length on the primary α-Al plate size and sphericity is experimentally investigated. Then the simulation of the process with the same parameters is performed to analyze how changing the process variables affect the microstructure properties. The residence time of the slurry on the cooling slope, solid fraction, shear rate, and turbulence energy are considered as output variables of the simulations.

2. Experimental procedure

Commercial A356 alloy was used in this study (Table 1). As shown in Fig. 1, the liquidus temperature of the alloy is 615 °C, and its eutectic temperature is 570 °C. The ingot was melted in a furnace. Then the molten metal was poured on a 100 mm wide inclined copper plate cooled underneath by a water circulation. The cooling slope apparatus used in this study is shown in Fig. 2.

In all experiments the pressure and temperature of water was 1 bar and 18 °C, respectively. The steel mold had a diameter of 55 mm and height of 140 mm with a draft angle of 3° for easy removal of the solidified ingot. The plate was coated with a thin layer of zirconium oxide to prevent adhesion between the molten metal and the plate. After solidification the samples were sectioned horizontally from the top, middle and bottom section of the ingots. Metallographic specimens were polished and etched by a 0.5% HF aqueous solution, then examined with an optical microscope. The metallographic images were taken from the wall zone, mid-radius zone and center zone (Fig. 3).

To determine the area (A) and perimeter (P) of the primary solid phase, all images were analyzed by image analyzer software (MATERIAL PLUS 4.1). The particle diameter (dave) and shape factor (SF) are determined according to Eqs. (1) and (2).

\[
d_{ave} = \frac{\sum^{N}_{i} \sqrt{4A_{i}/\pi}}{N}
\]

\[
SF = \frac{1}{\sum^{N}_{i}(4\pi A_{i}/N)}
\]

Ideal value of 1 for the shape factor shows that the particle is completely spheroid.

The thermophysical properties and model data used for simulations are given in Table 2. All simulations are done in 2 stages. First stage that the molten metal is poured on the cooling slope had done at 5.5 s. In the second stage, pouring process is stopped and the slurry after crossing on an inclined plate is poured into the mold and solidified. This stage had done at 60 s. To apply the cooling effect of environment, air considered as the second phase. To apply the cooling effect of cooling slope, it is assumed that the copper plate is a heat source with negative magnitude.

Fig. 4 shows the boundary conditions that intended for two different blocks. The first block is set for the cooling slope and the mold. In this block, all boundaries are selected the outflow type that means all of them are open boundaries except the upper boundary that is selected symmetry type. The symmetry boundary means that there is not any heat flux or any other flux. The second block was considered in order to pour the melt. Some settings such as speed, pressure and melt temperature must be set in this block. So the boundary mode that should be selected for this block is the specific velocity.

3. Results and discussion

3.1. Influence of pouring temperature

To investigate the influence of pouring temperature on the microstructure, the molten metal with the temperature of 680, 650, and 625 °C is poured on the slope with tilt angle of 50° and length of 500 mm. After sectioning the ingot the metallurgical images obtained from three zones are studied. Fig. 5 shows the microstructure obtained from conventional casting and semisolid casting.

| Table 1 – Chemical composition of A356 aluminum alloy. |
|---|---|---|---|---|---|---|---|
| Al | Si | Mg | Fe | Ti | Cu | Mn | Other |
| 92.14 | 7.10 | 0.33 | 0.17 | 0.10 | 0.06 | 0.03 | <0.08 |
It is obvious that by the use of cooling slope, the shape of primary $\alpha$-Al turns from dendritic to globular. Figs. 6 and 7 show the particle diameter and shape factor at different pouring temperature.

In all samples microstructure at center zone has bigger particle size and more sphericity. It is also shown that with decreasing pouring temperature, particle size increases and particle diameter increases. To explain these changes in microstructure, some simulations are performed in according to experiments. Results of the simulations show that the residence time of the slurry on the cooling slope or flowing time ($t_f$) for different pouring temperature varies from 1.3 s to 1.6 s. Fig. 8 shows the shear rate exerted to the slurry at the early moments of contacting the slurry to the slope at pouring temperature of 625 °C. At the moment of contacting, the shear rate is about 150–200 s$^{-1}$, but it continue to decrease to
Fig. 3 – Three zones of cross section.

Fig. 4 – Boundary condition that set for simulation.

**Table 2 – Thermophysical properties of A356 aluminum alloy.**

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat capacity of Al-A356</td>
<td>J kg⁻¹ K⁻¹</td>
<td>1082</td>
</tr>
<tr>
<td>Thermal conductivity of solid of Al-A356</td>
<td>W m⁻¹ K⁻¹</td>
<td>60</td>
</tr>
<tr>
<td>Thermal conductivity of liquid of Al-A356</td>
<td>W m⁻¹ K⁻¹</td>
<td>160</td>
</tr>
<tr>
<td>Density of Al-A356</td>
<td>kg m⁻³</td>
<td>2495</td>
</tr>
<tr>
<td>Viscosity of Al-A356</td>
<td>kg m⁻¹ s⁻¹</td>
<td>1.13 × 10⁻³</td>
</tr>
<tr>
<td>Latent heat of fusion (of Al-A356)</td>
<td>J kg⁻¹</td>
<td>397,700</td>
</tr>
<tr>
<td>Thermal conductivity of copper</td>
<td>W m⁻¹ K⁻¹</td>
<td>330</td>
</tr>
<tr>
<td>Specific heat capacity of copper</td>
<td>J kg⁻¹ K⁻¹</td>
<td>380</td>
</tr>
<tr>
<td>Density of copper</td>
<td>kg m⁻³</td>
<td>8900</td>
</tr>
<tr>
<td>Density of air</td>
<td>kg m⁻³</td>
<td>1.2</td>
</tr>
</tbody>
</table>

about 60–100 s⁻¹. Simulations at pouring temperature of 650 and 680 °C show that pouring temperature does not affect the shear rate.

Fig. 9 shows the solid fraction ($f_s$) of slurry on the slope with pouring temperature of 625 °C. At $t=2$ s the solid fraction of the slurry at the end of the slope is 0.36 and at $t=5$ s is 0.31. This difference is due to increasing the temperature of cooling slope and decreasing its cooling rate because of contacting the hot slurry. Solid fraction of the slurry at the end of slope at $t=2$ s and $t=5$ s are shown at Fig. 10. At high pouring temperature low fraction of slurry solidifies on the slope and solidification mostly occurs into the mold. At low pouring temperature solidification rate of slurry is so much that there is not enough time for solid particles to spheroidize.
As mentioned above with increasing the pouring temperature, the solidification rate on the cooling slope decreases and most of the slurry solidify into the mold. The results of the simulations also show that even at the end of 65.5 s of simulation, the slurry into the mold is not completely solidified. Fig. 11 shows the evolution of solid fraction at three zones of mold section with respect of time. As seen in this figure solidification begins from mold wall. High solidification rate at wall zone leads to small particles of α-Al phase. With approaching the center of the mold, due to decrease in heat transfer and increase in solidification rate particle diameter is increased. At this zone when the solid particles collide with each other with an appropriate contact angle, coalescence of the particles occurs and form bigger particles. This phenomenon is called agglomeration. The heat transfer rate also affects the
Fig. 9 – The solid fraction ($f_s$) of slurry on the slope with pouring temperature of 625 °C.

Fig. 10 – Solid fraction of the slurry at the end of slope.

Fig. 11 – Evolution of solid fraction at three zones of mold section.

Fig. 12 – Microstructure properties of the ingots with pouring temperature of 650 °C, slope length of 400 mm.

Fig. 13 – Shear rate and $t_f$ at various tilt angles with pouring temperature of 650 °C, slope length of 400 mm.

particles shape factor, as in the situation of very slow and uniform heat transfer the $\alpha$-Al phase solidify with globular shape, even without any shear stress [2]. Because of these reasons the microstructure at center zone has bigger particle diameter and more sphericity.

3.2. Influence of tilt angle

To investigate the influence of cooling slope's tilt angle on the microstructure, some experiments have been performed with pouring temperature of 650 °C, slope length of 400 mm at different tilt angle. Microstructure properties of the ingots are given in Fig. 12.

Simulation of the process with these parameters is done and influence of changing the tilt angle on shear rate, $t_f$, and solid fraction is studied. The results of simulation shown in Figs. 13 and 14 show that with increasing tilt angle, $t_f$ is decreased that means the time duration of exerting shear stress to the slurry and solid fraction of the slurry is decreased.

At tilt angle of 30° the shear rate is not enough to spheroidize the particles and at tilt angles of 50° and 60° $t_f$ and solid fraction is not enough. In this situation the best microstructure is obtained with tilt angle of 40° that leads to appropriate combination of $t_f$, solid fraction, and shear rate.
To better understand how tilt angle affects the microstructure, experiments have been performed with slope length of 600 mm and with tilt angle of 40°, 50°, and 60°. The results of the experiments demonstrated in Fig. 15 show that the best microstructure is obtained with tilt angle of 60°. The results of simulation including $t_f$, solid fraction at $t = 2s$ ($f_s(2)$) and $t = 5s$ ($f_s(5)$) are shown in Figs. 16 and 17. It should be noted that at tilt angle of $40^\circ$, $t_f$ is more than 2 s, the value of $f_s(2)$ given in the figures is the solid fraction of the slurry fraction reached to end of the slope.

With slope length of 600 mm it is also observed that with increasing the tilt angle shear rate is increased. Increasing the slope length leads to increase in cooling effect of the slope and so increase in solid fraction of the slurry at the end of slope. In this case at low tilt angle, relatively high volume of the slurry solidify on the slope and stuck to the copper plate (Fig. 18), so it is not practically possible to pour slurry continuously with this parameters. Appropriate combination time duration of exerting shear stress, cooling effect of slope, and magnitude of shear rate occur with tilt angle of 60°. Comparing this case with the case of slope length of 400 mm (that best microstructure was with tilt angle of 40°) shows that both have approximately the same $t_f$, but more shear rate at tilt angle of 60° leads to better microstructure.

Almost in all experiments it is observed that decreasing the particle diameter is in conjunction with increasing the shape factor. To have fine primary $\alpha$-Al particles, copious nucleation should occur on the cooling slope. These nuclei should be detached from surface of the slope and flow into the slurry without remelting. To improve the shape factor of the particles it is also necessary to have turbulent flow of slurry on the slope. Temperature and solute concentration gradient is the reason of forming dendrites. High turbulence of the flow leads to decrease in temperature gradient and solute concentration gradient into the slurry. Furthermore, at low turbulence agglomeration is possible. To determine the turbulence of the flow, a parameter called turbulent energy of the slurry at various tilt angles was measured. The results are shown in Fig. 19. Increasing the tilt angle leads to increasing the turbulent energy and shear rate that causes the nuclei formed on the cooling slope detach easier from the surface of the slope flow into the slurry. It also prevents the occurrence of agglomeration. So the particle diameter is decreased. In addition, decreasing the temperature gradient and solute concentration gradient of the slurry due to increasing turbulence and increasing the shear rate due to increasing the tilt angle lead to increasing the shape factor.
3.3. Influence of the cooling slope length

To investigate the influence of cooling slope length experiments have been done at pouring temperature of 650°C and tilt angle of 40° with various slope length. Particle diameter and shape factor obtained from cross-sectional images are given in Fig. 20.

Figs. 21 and 22 show the results of simulation based on these experiments. Since the cooling slope has the same tilt angle in all experiments, so the amount of shear rate is also equal. As mentioned above, increasing the slope length causes increasing of $t_f$ which means increasing the time duration of exerting shear stress to the slurry and also increasing cooling effect of slope. At tilt angle of 40° best microstructure is obtained with slope length of 400 mm. At slope length of 300 mm low value of $t_f$ and solid fraction of slurry entering
the mold causes forming of solid particles with relatively big size and low sphericity. In this case due to relatively high temperature many of the particles solidified on the cooling slope agglomerate and form bigger particles. In addition, in this condition the majority of slurry solidifies with dendritic structure that causes decreasing the shape factor. When slope length is more than 400 mm, due to inadequate value of turbulence and shear rate at tilt angle of 40° agglomeration occurs and bigger particles are formed. But at tilt angle of 50°, since turbulence and shear rate is more, the best microstructure is obtained with longer slope length. The results of experiments with tilt angle of 50° are shown in Fig. 23. The results of simulations according to these experiments are shown in Figs. 24 and 25.

Investigating the influences of parameters effective on the microstructure of the ingots obtained by semi-solid casting on cooling slope, it can be concluded that a conditions is needed to have a microstructure of α-Al phase with minimum particle size and maximum sphericity. At this condition the time duration of exerting the shear rate and also cooling rate should be adequate, while shear rate and turbulence should be as much as possible.

4. Conclusions

The residence time of the slurry on the cooling slope ($t_\text{j}$) is one of the most important parameters that affect on the microstructure properties. The parameter of $t_\text{j}$ should be selected in the optimum value. Actually if this parameter selected at high value, agglomeration will be caused, and if it is selected at low value, inadequate spheroidization will be caused. The result showed that, the higher tilt angle leads to higher shear rate and, therefore, turbulent energy will be increased. At the result of this phenomenon, the better microstructure will be obtained. Also, the results illustrated that the combination of the process parameters including pouring temperature, tilt angle and slope length should lead to adequate value of $t_\text{j}$. The best result obtained while solid fraction of slurry at the end of the cooling slope is around 30–35%. The higher shear rate and turbulence energy is existed in this solid fraction and at the end of slope.

Conflicts of interest

The authors declare no conflicts of interest.
REFERENCES