Production of Al-7Si-0.3Mg slurry for rheocasting via internal cooling of the melt below the liquidus temperature

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Abstract

Rheocasting is becoming the choice of the casting industry who looks up to semi-solid casting for high integrity structural parts. It is of great technological interest to identify simple methods to prepare slurries at reduced cost. Such a practice based on internal cooling of the melt was employed in the present work to produce Al-7Si-0.3Mg slurries for rheocasting. Al-7Si-0.3Mg melt was cooled internally by dissolving in it a solid block of the same alloy. The non-dendritic morphology in the water-quenched slurry samples seems to imply that dendritic solidification was suppressed once a critical level of initial-primary solidification was achieved.

Key words: semi-solid processing, aluminium alloys, microstructure, rheocasting

1. Introduction

Semi-solid metal casting has long been recognized as a high-volume, near-net shape manufacturing process for automotive castings [1–3]. Unlike conventional processes that use liquid alloy, semi-solid casting uses slurries with a non-dendritic solid fraction. Since the alloy to be cast is already partially solid, this innovative process offers minimum solidification shrinkage, shorter solidification time, reduced thermal fatigue of the die and laminar die filling and is thus capable of producing high integrity, heat treatable castings at die casting cycle times.

Semi-solid casting is performed in two major routes: thixocasting and rheocasting. In the former, non-dendritic feedstock prepared beforehand is reheated to the semi-solid temperature range and finally injected into a die, while molten alloy is treated into a slurry directly before casting in the rheocasting route [4]. High cost of non-dendritic feedstock and the inability to recycle its scrap have limited the widespread commercial use of the former. Rheocasting which uses slurry-on-demand tackles the cost issue and is becoming the choice of the casting industry who looks up to semi-solid casting for high integrity structural parts [5, 6].

Mechanical stirring is the first process employed to produce slurries for rheocasting [7, 8]. Low superheat casting produces a fine, equiaxed dendritic microstructure which will coarsen into non-dendritic material upon controlled cooling [9]. A number of rheocasting processes with attractive features have been developed in recent years [10–13]. However, the search for new and simple methods to prepare slurries at reduced cost is far from over [14–16]. Such a process to meet these expectations was reported very recently [17, 18]. This new process relies on internal cooling of the melt into the semi-solid range and is capable of producing high quality aluminium alloy slurries at reduced cost as it does not involve an additional isothermal holding step before casting. The present work was performed to identify the optimum internal cooling practice to produce Al-7Si-0.3Mg (A356) slurries for rheocasting. The effect of slurry temperature and stirring rate on slurry features were investigated.

2. Experimental procedures

The alloy used in this study is a commercial A356 alloy with 6.63 wt.% Si and 0.39 wt.% Mg. A356 ingot weighting 1 kg was melted in a carbon bonded silicon carbide crucible in an electric resistance furnace set at 700 ℃. Al-5Ti-1B and Al-10Sr master alloys were ad-

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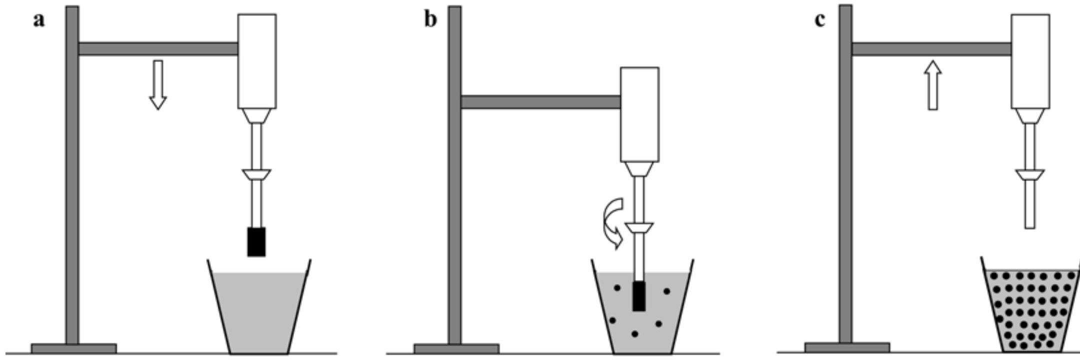

Fig. 1. Schematic illustration of the internal cooling practice employed in the present work: (a) solid block of the same alloy attached to a stainless steel rod, (b) the solid block dissolved in the melt with simultaneous stirring action, (c) the slurry thus produced.

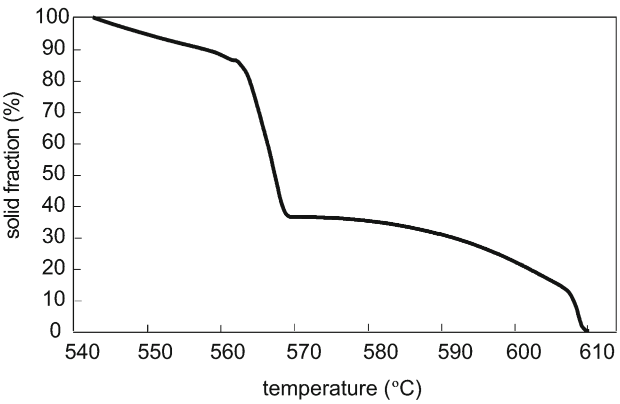

Fig. 2. Solid fraction vs. temperature curve of the A356 alloy obtained from heat flow vs. temperature data recorded during cooling from the molten state.

ded to the melt in accordance with the standard commercial practice. The crucible with the melt was then transferred to a second electric resistance furnace the temperature of which was set at 650 ℃. It was held in this furnace for at least 60 minutes to allow for temperature equilibration. The crucible was then withdrawn from the furnace and the melt was cooled internally (at approximately 1 ℃ s^{-1}) by dissolving in it a solid block of the same alloy prepared beforehand to facilitate partial solidification (Fig. 1). The alloy block was attached to a stainless steel rod which was stirred at 1100 rpm until it was completely dissolved in molten alloy. The stirring feature was intentionally omitted in one experiment. The temperature of the melt and the weight of the solid alloy block were adjusted so as to achieve the targeted slurry temperatures with the desired solid fraction. The slurry thus obtained was sampled with a 2 cm^3 stainless steel cup and was immediately quenched in water. In a seperate experiment, the melt was first cooled internally to obtain a slurry with some initial solid. This slurry was then allowed to cool at a rate of approximately 0.2 ℃ s^{-1} to facilitate further solidification under quiescent conditions before it was finally sampled and quenched in water. Another experiment involved slow cooling of the molten alloy without internal cooling. The water-quenched slurry samples were prepared with standard metallographic practices and were examined with an optical microscope.

Differential Scanning Calorimetry (DSC) was used to obtain the change in solid fraction with temperature (F_s vs. T) inside the semi-solid temperature range. The heat flow vs. temperature data recorded during solidification was used to obtain the F_s vs. T curve since the formation of the slurry relies on cooling an already molten alloy rather than partial melting of a solid feedstock in the rheo route.

3. Results and discussion

The practice employed in the present work relies on internal cooling of the melt into the semi-solid range to produce high quality slurries without an additional isothermal holding step. The temperature of the slurry is a key parameter as it dictates not only the solid fraction of the slurry but also the microstructural features of the final casting. The slurry temperature should be as low as, i.e. the solid fraction as high as, possible to take full advantage of semi-solid practice without impairing the die filling ability of the slurry. It is clear from Fig. 2 that slurry temperatures below 570 ℃ and above 605 ℃ are troublesome due to a sudden change in solid fraction with very small temperature fluctuations outside this range (as much as 0.09 $℃^{-1}$). Between 570 ℃ and 600 ℃, on the other hand, this change is very small, only as much as 0.002 $℃^{-1}$ at 580 ℃.

The microstructure of the sample quenched from 620 ℃, just above the liquidus point, is shown in Fig. 3a. Fine α-Al dendrites and the interdendritic

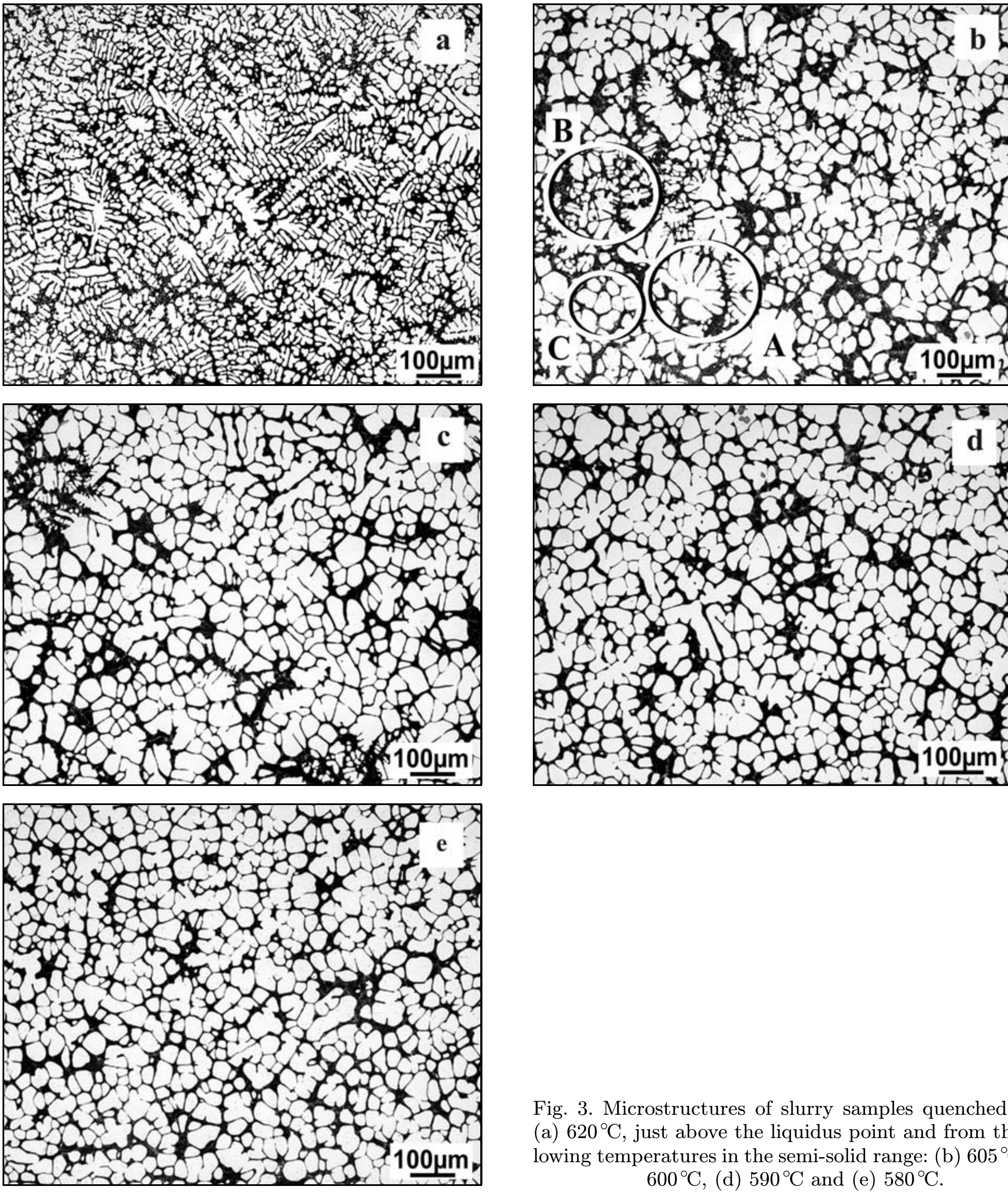

Fig. 3. Microstructures of slurry samples quenched from (a) 620 °C, just above the liquidus point and from the following temperatures in the semi-solid range: (b) 605 °C, (c) 600 °C, (d) 590 °C and (e) 580 °C.

network of the Al-Si eutectic structure, typical of hypoeutectic aluminium alloys, are readily identified. A series of slurries were produced by cooling the molten alloy into the semi-solid temperature range. The effect of slurry temperature on microstructural features of the water-quenched slurry samples is shown in Fig. 3b–e. The slurry sample quenched from 605 ℃, where the fraction of solid is nearly 17 %, reveals a largely degenerated dendritic structure of the primary α-Al phase. There are occasional α-Al dendrites (marked "A" in Fig. 3b) and small dendritic clusters (marked "B" in Fig. 3b) dispersed in between α-Al rosettes (marked "C" in Fig. 3b). With features almost identical to those in Fig. 3a, fine dendritic clusters in Fig. 3b are believed to have formed via the undercooling of the liquid fraction of the slurry sample upon quenching. However, the fraction of the liquid phase, estimated from Fig. 2 to be nearly 83 % liquid at a semi-solid temperature of 605 ℃, is far greater than the volume fraction of the fine dendritic clusters in Fig. 3b. It is thus claimed that solidification of the remaining liquid phase has been through the growth of the α-Al rosettes which have formed during internal cooling before quenching.

The dendritic features become less frequent; dendritic clusters almost vanish; α-Al rosettes are refined and the globularity of the primary phase increases with decreasing slurry temperatures (Fig. 3c–e). Finally, the microstructure of the slurry sample quenched from a semi-solid temperature of 580 ℃, with an estimated solid fraction of 35 %, is predominantly globular. The average size of the α-Al globules is approximately 50 microns, relatively smaller than the globule size obtained with this alloy in the thixo route [19]. While the primary phase morphology is well established to change from globular to dendritic with increasing cooling rates, the non-dendritic morphology in the water-quenched slurry samples seems to imply that dendritic solidification is suppressed once a critical level of initial-primary solidification is achieved.

Figure 4 shows a series of slurry samples quenched after internal cooling to 605 ℃, to an estimated solid fraction of 17 %, with and without simultaneous stirring. The sample processed without stirring is predominantly dendritic, implying that gradual internal cooling alone does not suffice to suppress dendritic solidification. The dendritic structure is only partially replaced by α-Al rosettes when stirring is employed at 550 rpm while almost the entire sample is non--dendritic when the stirring rate is doubled (1100 rpm). Stirring not only improves the primary solidification features but also extends the lifetime of the slurry before full solidification. Slurries processed with stirring at 1100 rpm retained their "slurry" features for nearly 3 times longer with respect to those processed without stirring.

In a separate experiment, the molten alloy was first cooled internally to just below the liquidus point (609 ℃), to a rather low fraction of solid (7 %). The slurry thus obtained was then allowed to cool gradually in a quiescent state at 0.2 ℃ s^{-1}. Samples were water-quenched at the start and in the course of cooling to find out about the evolution of the initial primary solid with time when stirring was absent. The micrograph in Fig. 5a, of the slurry sample quenched in water right after internal cooling with stirring, is typical of those quenched at low solid fractions, with fine dendritic clusters dispersed between α-Al rosettes. The dendritic clusters seem to be replaced gradually by α-Al rosettes which become increasingly coarser during subsequent cooling at 0.2 ℃ s^{-1}. After about 3 minutes, when the slurry cools to approximately 580 ℃, the predominant feature is α-Al globules (Fig. 5d). While these features are very similar to those achieved in slurries processed with stirring, the microstructure from quiescent cooling is strikingly coarser. The average globule size (approximately 100 microns) is nearly twice that of the slurry sample cooled to nearly the same temperature with stirring.

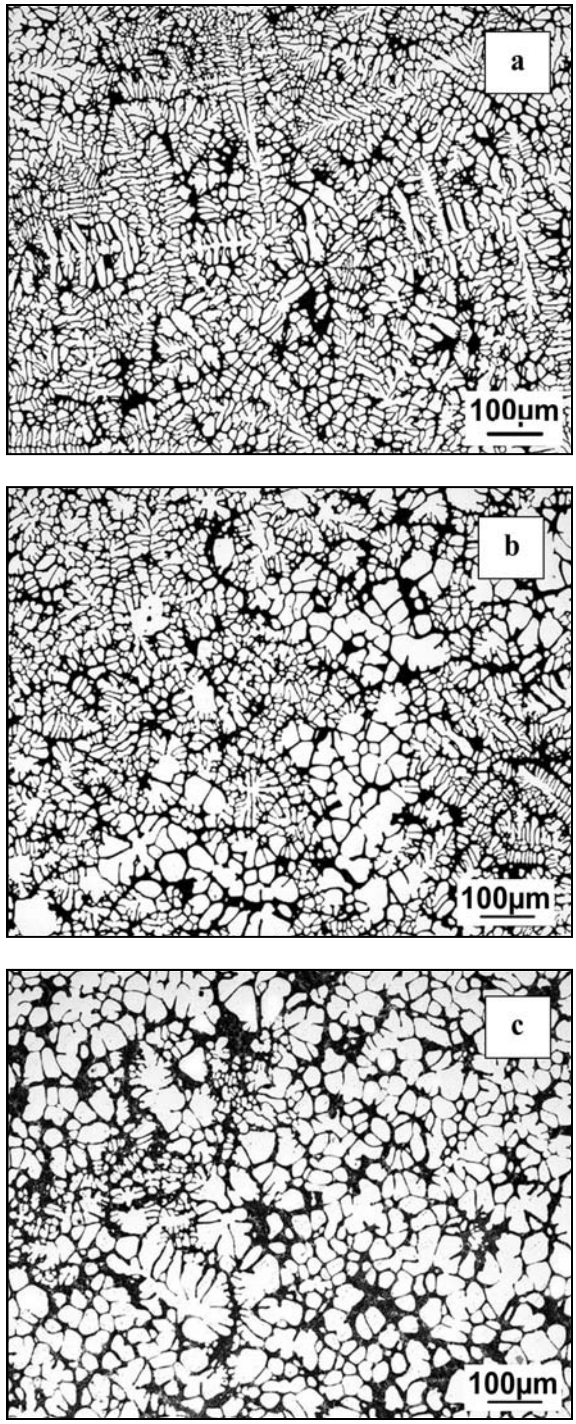

Fig. 4. Microstructures of slurry samples quenched from 605 ℃: (a) without stirring, (b) with stirring at 550 rpm and (c) at 1100 rpm.

The last experiment involved cooling of the molten alloy into the semi-solid temperature range on its own at 0.2 ℃ s^{-1} without the benefit of internal cooling and of simultaneous stirring. Samples were taken from the slurry and water-quenched starting shortly after the melt cooled to just below the liquidus point,

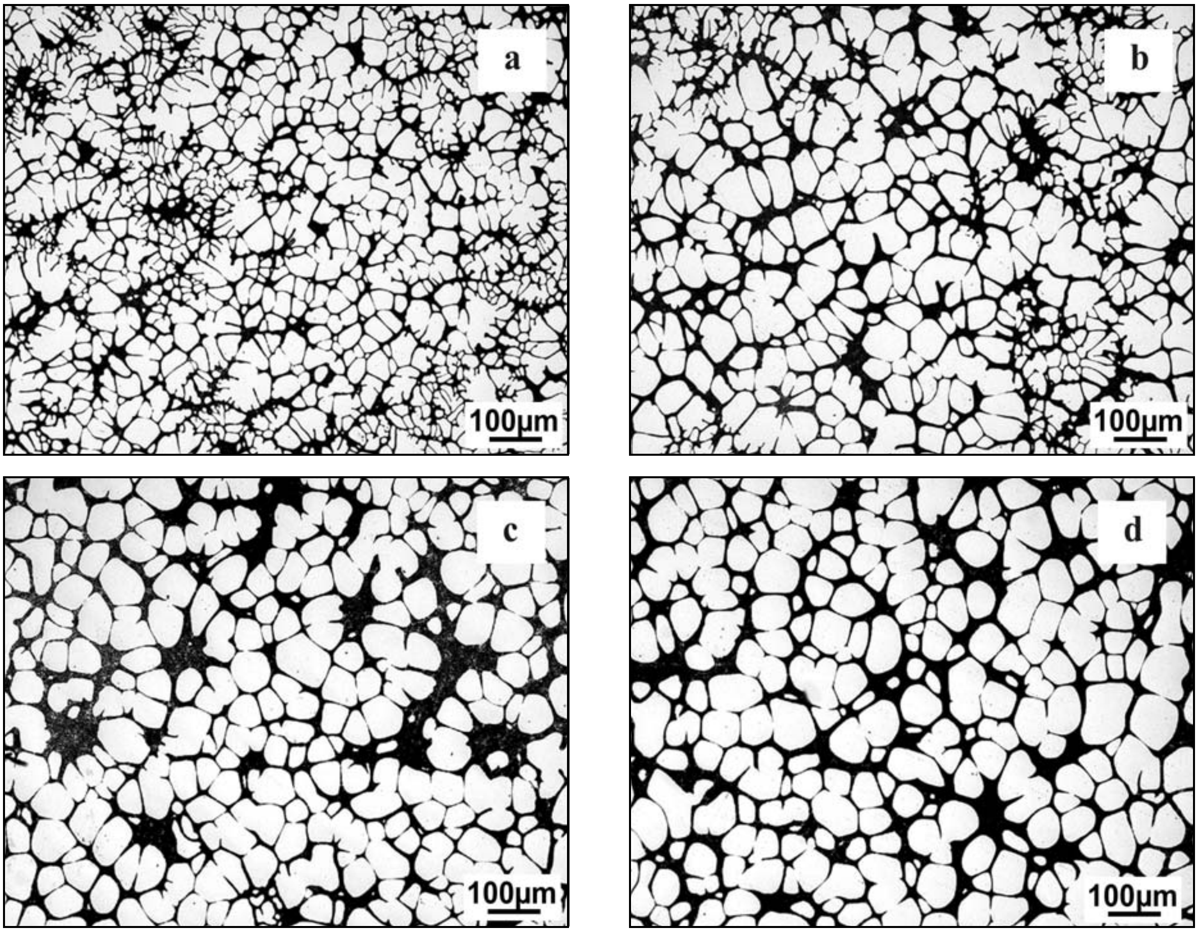

Fig. 5. Microstructures of slurry samples water-quenched: (a) right after the melt is internally cooled with stirring to 609 ℃ and (b) 1, (c) 2 and (d) 3 minutes after the start of quiescent state cooling at 0.2 ℃ s^{-1}.

to 609 ℃ and 1, 2 and 3 minutes later. The dendritic features are retained for the entire duration of the experiment (Fig. 6). No evidence for a globular structure is available even after 3 minutes of cooling shortly before the fluidity of the slurry is fully impaired. In contrast to the case of internal cooling with stirring where the solidification occurs throughout the entire volume of the melt, solidification proceeds from the crucible walls towards the centre. A comparison of the micrographs in Figs. 3 and 6 demonstrates clearly the impact of internal cooling and simultaneous stirring. Even a small volume fraction of initial solidification under stirring improves the features in a striking fashion (Fig. 5).

The internal cooling practice employed in the present work involves gradual cooling of the melt into the semi-solid range with a simultaneous stirring action. Heterogeneous nucleation is believed to occur continuously and uniformly throughout the entire volume of the melt during internal cooling with a small undercooling. Temperature and solute fields around the primary α-Al particles are much more uniform due to the melt convection provided by the stirring of the solid alloy block. Stirring also helps to reduce constitutional undercooling, leading to similar growth rates in all directions and is thus instrumental in allowing the slurry to cool uniformly and fast, promoting bulk nucleation. All these factors help to avoid dendritic growth and the primary particles finally become globular. The decrease in size, i.e. the increase in number of α-Al globules at lower slurry temperatures implies continuous nucleation during cooling across the semi-solid temperature range. Nucleation occurs over a wider temperature range when gradual cooling is extended to achieve lower slurry temperatures. The impact of heterogeneous nucleation throughout the melt and of forced convection on the primary solidification features is evident in the present work and confirms earlier reports [13, 16]. A globular microstructure is possible even when much of the primary solidification occurs in a quiescent state provided that a critical population of heterogeneous nuclei is first made available throughout the entire volume of the melt. While this allows for handling of the slurry at the casting station and is thus very welcome, one has to tolerate relatively coarser globules in the final casting in this case.

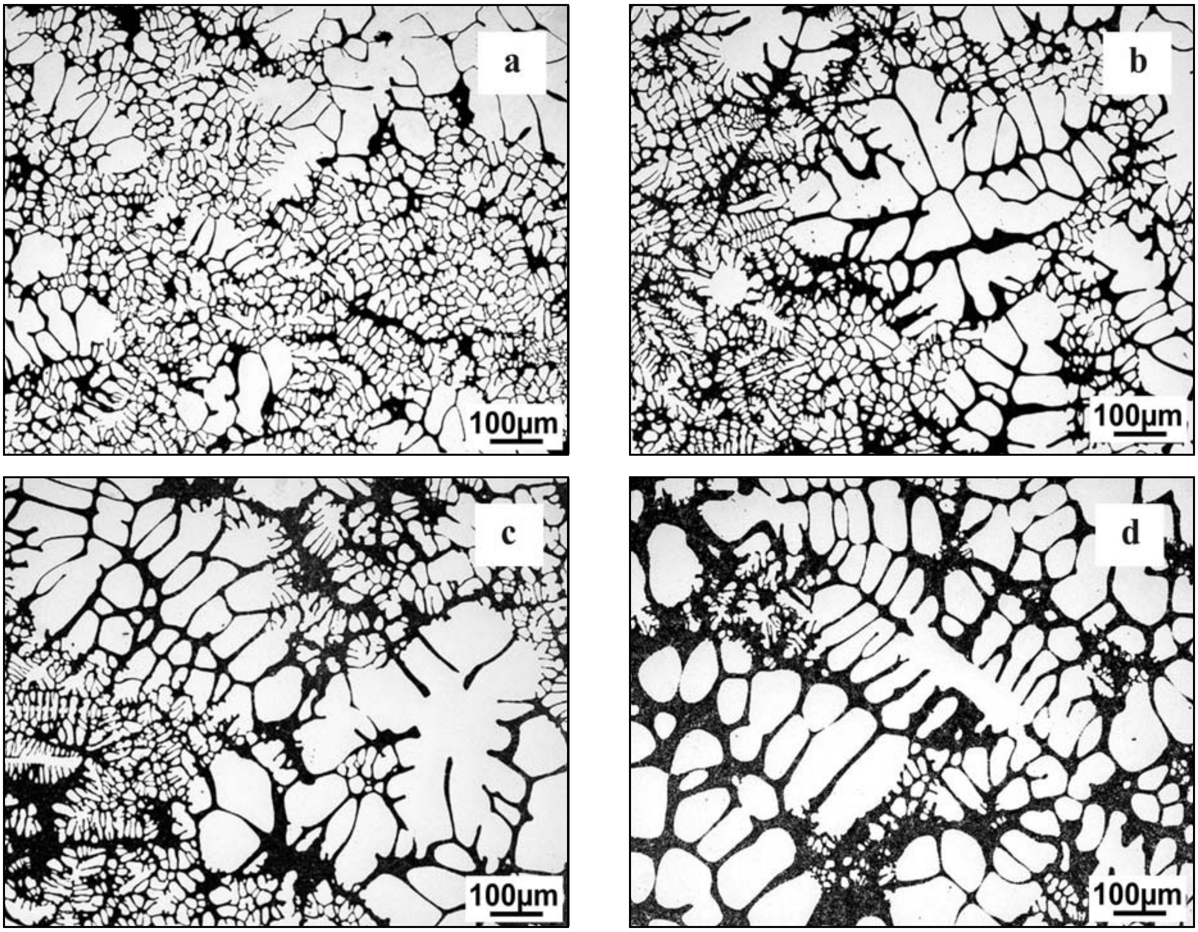

Fig. 6. Microstructures of slurry samples water-quenched: (a) right after the melt cools on its own in a quiescent state to 609 ℃ and (b) 1, (c) 2 and (d) 3 minutes later.

4. Summary

A356 alloy melt is cooled internally by dissolving in it a solid block of the same alloy. Nucleation is promoted throughout the entire volume of the melt during internal cooling. Temperature and solute fields around the primary α-Al particles are uniform due to the melt convection provided by stirring of the solid alloy block. Stirring also helps to reduce constitutional undercooling, leading to similar growth rates in all directions. Dendritic growth is thus prohibited and the primary particles become globular. While the primary phase morphology is well established to change from globular to dendritic with increasing cooling rates, the non-dendritic morphology in the water-quenched slurry samples seems to imply that dendritic solidification is suppressed once a critical level of initial-primary solidification is achieved.

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