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The investigation of continuous nucleation and refinement of primary Si in Al–30Si mushy zone

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ABSTRACT

In this paper, the refinement performance of Al–P master alloy on mushy Al–30Si alloys was investigated and a new refining method was proposed. The results show that primary Si can be refined partially when the Al–P master alloy is added into mushy Al–30Si alloys, proving that the heterogeneous nucleation of primary Si is a continuous process even in liquid–solid state, which is also confirmed by EPMA results. On basis of these results, a new refining method named as continuous refining method has been proposed, i.e. continuously adding refiners at different temperatures during the cooling and solidifying stage of Al–30Si. Compared with the conventional refinement method by which the alloys are refined at high temperature, better refinement effect can be obtained in the new refinement method: the average size of primary Si is decreased to 30 μm, and the tensile strength increases by 19.6%. Moreover, the mechanism of the continuous refining method was also discussed.

1. Introduction

Aluminum alloy is one category of casting materials which is the second most widely applied after ferrous castings in tonnage terms, and among all aluminum alloys the hypereutectic Al–Si alloys are catching more and more attention as the appropriate material for pistons of gas engines due to their high wear resistance, low density, low coefficient of thermal expansion, high thermal stability, corrosion resistant and thermal conductivity, etc. [1–5]. These properties can be effectively improved by further increasing the silicon content of the alloys. However, the main limitation of hypereutectic Al–Si alloys is attributed to the presence of coarse, irregular and brittle primary Si that easily cracks exposing the soft aluminum matrix to extreme working conditions. So it is deservedly essential for primary Si to improve the morphology, decrease the size and uniformize the distribution. Recently the microstructure of hypereutectic Al–Si alloys can be refined by refiner addition [6–11], melt vibration [12–15], pulse treatment [16], etc., among which phosphorus-containing refiner addition is widely applied in practice. Among all phosphorus-containing refiners, the Al–P master alloy developed these years is able to overcome the shortcomings of other phosphorus-containing refiners (Cu–P master alloy or phosphate salt) such as environmental pollution and instable refinement efficiency, etc., and now has obtained a good application [11].

It is known that the refinement effect of Al–P master alloy is influenced by several melting parameters, such as temperature, holding time etc. Recently the conventional technique that adding refiner at high temperatures (100 °C above liquidus temperature) is widely applied [10]. By using this technique it is possible to achieve significant refinement effect. However, high temperature can increase suction gas and oxidation of the melted alloys [6], which are wasteful of raw-materials and energies. In this article, it is aimed to explore a new method to refine hypereutectic Al–Si alloys in the mushy zone particularly below the liquidus temperature to avoid the aforementioned problems, and the refinement mechanism is discussed. In addition, the continuous refining method, which means that the refiners are continuously added at different temperatures during the cooling and solidifying stage of Al–30Si alloys, is also proposed.

2. Experimental procedures

The Al–30Si alloy used in the experiments was prepared with commercial pure Al (99.7%, all compositions quoted in this article are in wt.% unless otherwise stated) and commercial pure crystalline Si (99.9%) in 25 kW medium-frequency induction furnace, and the Al–3.5P binary master alloy rod (the composition is given in Table 1.) was supplied by Shandong Al&Mg Melt Technology Co. Ltd. Different refinement experiments were all conducted in 5 kW electric resistant-heating furnace. The melt temperatures were controlled by the thermocouple in the resistant-heating furnace, and assisted by the K-model handset thermocouple, making sure that the error is controlled below ±5 °C. All the samples were poured into the same type of cast iron chill mold preheated at about 150 °C before pouring.

The Al–30Si alloys were re-melted in a clay-bonded graphite crucible using the electric resistant-heating furnace and held at 845 °C. The experimental parameters

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Table 1
The composition of Al–3.5P binary master alloy rod.[a].

	P	Other total	Al
Al–P master alloy rod	3.2–3.7	≤0.5	Bal.

[a] Supplied by Shandong Al&Mg Melt Technology Co. Ltd.

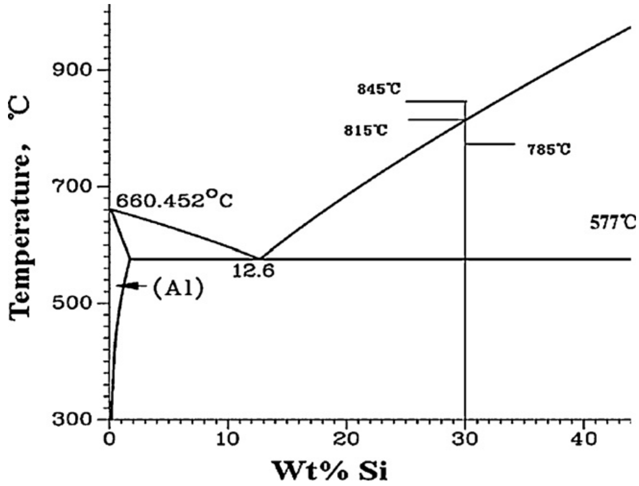

Fig. 1. Refinement temperatures based on Al–Si binary phase diagram.

were listed in Table 2. Part of the melt was poured into the iron chill mold and Sample-1 was obtained without any additions. Then, Sample-2 was obtained as follows: 1% the Al–P master alloy was added into the melt at the temperature of 845 °C, and after stirred by graphite rod, the melt was poured into the mold. Sample-3 was obtained in the same way as Sample-2 but at 785 °C based on Al–Si binary phase diagram in Fig. 1 and the DSC curve of Al–30Si in Fig. 2.

The processing parameters for the comparison between conventional and continuous methods were given in Table 3. The Al–30Si alloys were re-melted in the electric resistance-heating furnace at 845 °C. Sample-4 was obtained 20 min after the addition of 1% Al–P master alloy into the melt. However, Sample-5 was obtained after adding 0.4%, 0.3% and 0.3% of the Al–P master alloys at 845 °C, 815 °C, and 785 °C, respectively, without holding time. (The three temperature points were obtained through cooling in the air, and the cooling rate was about 2 °C/s.)

Metallographic specimens were all cut from the same position of the casting samples, then mechanically ground and polished using standard routines. The microstructures of primary Si in the investigated Al–30Si alloys were characterized using field emission scanning electron microscope (FESEM) (model SU-70, Japan) and analyzed using electron probe micro-analyzer (EPMA) (model JXA-8840, Japan).

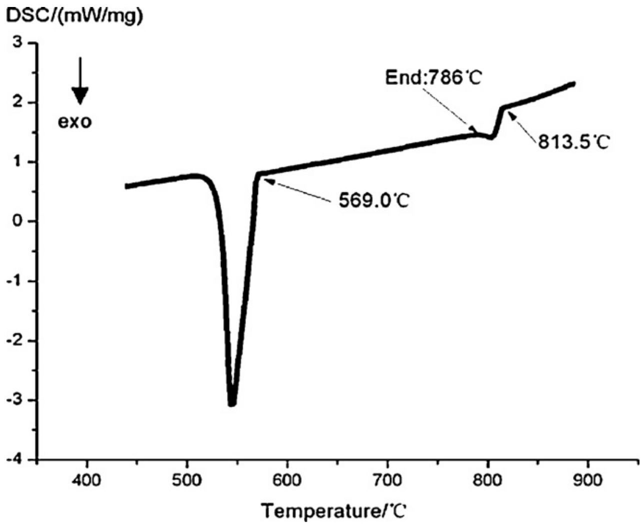

Fig. 2. DSC results for Al–30Si alloys.

3. Results

3.1. *Refining performance of Al–P master alloy on mushy Al–30Si alloys*

Fig. 3 shows that the microstructures of Al–30Si alloys under different refining conditions: as seen in Fig. 3(a), primary Si in unrefined Al–30Si alloys exhibits plate-like appearance and the size could reach 400 μm even more; the Sample-2 was obtained under the conventional refining condition (refined at 845 °C with 1% Al–P master alloy). An overwhelming number of primary Si is refined to approximately 50 μm and the morphology evolves from plate-like to blocky shape as shown in Fig. 3(b). Fig. 3(c) presents the microstructure of Al–30Si alloy refined at 785 °C. It is found that when 1% Al–P is added into the melt at 785 °C, part of primary Si phases are refined to approximately 30 μm, while most of primary Si are still in a large size and irregular morphology whose average grain size is about 180 μm, indicating that primary Si is not sufficiently refined under this condition. Fig. 4 shows the difference between the refining effects at the temperature 785 °C and 845 °C which are revealed by the average primary Si grain sizes and its volume fractions.

Table 2
The processing parameters in different refinement experiments.

Alloys designation	Processing parameters				
	845 °C	815 °C	785 °C	Holding time	Pouring temperature
Al–30Si					
Sample-1	–	–	–	–	845 °C
Sample-2	1% Al–P	–	–	–	845 °C
Sample-3	–	–	1% Al–P	–	785 °C

Table 3
The comparison of processing parameters between conventional and continuous methods.

Alloys designation	Processing parameters				
	845 °C	815 °C	785 °C	Holding time	Pouring temperature
Al–30Si					
Sample-4	1% Al–P	–	–	20 min	845 °C
Sample-5[a]	0.4% Al–P	0.3% Al–P	0.3% Al–P	–	785 °C

[a] The three melt temperature points in Sample-5 were obtained through cooling in the air.