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Eutectic Solidification in Near-eutectic Al-Si Casting Alloys

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Eutectic solidification in near-eutectic Al-13 wt pct Si casting alloys and the effect of trace addition of boron or strontium on it have been investigated using thermal analysis and microstructural characterization. In unmodified alloy, dual eutectic structure has been observed. The coarse eutectic (dendrite-like Al+ coarse Si flakes) is formed above the equilibrium temperature of eutectic (Al+Si) reaction (577°C). The coarse eutectic (CE) grains nucleate from the primary silicon particles formed earlier due to local enrichment of silicon solute and grow in a divorced mode between the dendritic Al phase and large silicon flakes. The fine eutectic (FE) grains nucleate later on other potential sites activated by melt undercooling and grow in coupled-growing mode with the silicon crystals as fine flakes. The formation of the FE grains is favored in the alloys containing boron because of a great number of potential nucleation sites being added from boron-containing particles. Addition of strontium to the alloys restrains completely the formation of primary silicon particles and hence limits the nucleation of the CE. This is because the eutectic point has moved far enough to make the alloy, at this composition (Al-13 wt pct Si), hypo-eutectic. Local cooling rate during solidification has an important influence on competition formation of these two eutectics.

KEY WORDS: Al-Si alloy; Eutectic; Solidification; Dual eutectic grains; Grain refinement

1. Introduction

With increasing requirements in reducing vehicle weight and improving fuel economy, Al-Si based casting alloys have been widely used in automobile[1–3]. Most Al-Si based casting alloys used in automobile containing 50–90 vol. pct eutectic and the eutectic reaction is the last major phase transformation during solidification. It is therefore expected that eutectic solidification has a significant effect on final microstructure, casting defects, and mechanical properties. In recent years, the understanding of eutectic solidification in Al-Si based casting alloys has drawn a great attention to many researchers. Makhlof and Guthy[4] reviewed the research works reported in past half century on crystallogphy of eutectic and mechanisms of eutectic reaction in Al-Si alloy. Shankar *et al.*[5] investigated the solidification of an unmodified Al-Si alloy and concluded that eutectic Si phase nucleates on the pre-formed β-(Al, Si, Fe) particles and eutectic Al then nucleates on the eutectic silicon. The β-(Al, Si, Fe) phase can nucleate in the solute field ahead of the growing aluminum dendrites even with trace quantity of Fe in the alloy. Dahle and co-workers[6–10] have reported their research works on eutectic solidification in hypoeutectic Al-Si alloys using electron backscatter diffraction (EBSD). They put forward three different possible eutectic nucleation and growth modes in the Al-Si system, depending on the solidification conditions: (a) nucleation on or adjacent to the mold wall and the solid front growth opposite to the thermal gradient, (b) nucleation and growth on the primary aluminum dendrites in unmodified alloy and (c) independent heterogeneous nucleation of eutectic grains in interdendritic regions in Sr-modified alloys. However,

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recent work reported by Dahle′s group[11] appears to be conflicting with their own proposed modes. In an investigation of the quenched macrostructures of commercial purity and high-purity Al-10 wt pct Si alloys, a large number of eutectic grains were observed in the commercial purity unmodified alloy, each growing with an asymmetrical grain shape and large interphase spacing[11]. In the high-purity unmodified alloy, however, very few eutectic grains nucleated and each grain grew with a flatter or spherical interface. The amount of primary dendrites in both commercial purity and high-purity Al-10 wt pct Si alloys was approximately the same. Dahle′s group[11–13] then thought that the nucleation of eutectic grains in the commercial alloy might occur adjacent to the primary aluminum dendrites and AlP particles in the melt could afford the nucleation sites of eutectic silicon required.

In addition to hypoeutectic alloys, a great deal work has also been carried out on near-eutectic Al-Si casting alloys[14–21], due to its excellent castability and low raw materials cost compared with hypoeutectic Al-Si casting alloys such as A356 and 319 alloys *etc.* In near-eutectic Al-Si casting alloys, amount of primary phase (angular/blocky primary silicon particles or α-Al dendrites) is very small and eutectic structure is thus absolutely dominant. High strength and fracture elongation could be produced by adopting modification of eutectic Si and refinement of dendrites and eutectic grains combined with proper heat treatment for near eutectic Al-Si alloys[22–28]. It is interesting to note that in unmodified condition the dendritic Al phase, primary blocky silicon phase, and eutectic silicon and aluminum phase can all present in the near-eutectic alloy[22–25]. The reason for this coexistence is not understood. Adding strontium and boron significantly reduces the amount of primary blocky silicon phase and produces very fine eutectic grains[26–28], which is not in good accordance with the point of view of Dahle′s on eutectic solidification of hypoeutectic Al-Si alloys[11–13]. These indicate that the eutectic solidification in Al-Si alloys and the influence of the trace elements addition on it have not been well established. In this paper, the influence of addition of boron or strontium on eutectic solidification is discussed in detail and also a new eutectic solidification mode is presented.

2. Experimental

2.1 Experimental alloys

The base alloy used in the experiments, with a nominal composition of Al-13 wt pct Si, was prepared at a temperature of 760°C in an electrical resistance furnace, using Al-12.3 wt pct Si master alloy and crystalline silicon particles (commercial purity, 99.5 wt pct Si). After holding for 30 min, a flux was introduced at 730°C to ensure low hydrogen content. For alloys with boron and strontium addition, Al-10 wt pct Sr or Al-3 wt pct B master alloys were added to the degassed melts at about 730°C. After addition, the melt was held for at least 20 or 10 min for strontium or boron dissolution prior to sampling, respectively. Five experimental alloys including base alloy, one level of strontium and three levels of boron additions, were made in this work.

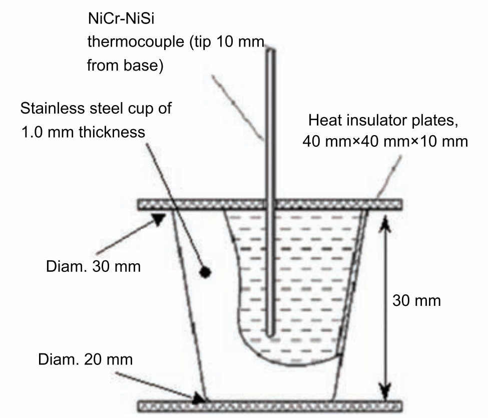

Fig. 1 A schematic (cut-away and exploded for clarity) of the experimental set-up for thermal analysis

2.2 Thermal analysis

The method to measure the cooling curves during solidification follows the literature [7] and [8]. Thermal analysis was performed in a tapered stainless steel cup, as shown in Fig. 1, which was coated with a thin layer of ZnO. In testing, the cups were preheated to the same temperature as the melt. Samples were taken by submerging the stainless steel cups into the melts at 720°C. Two samples were taken each time, one with and the other without a K-type thermocouple. During solidification, the cooling curve from the thermocouple in one of the two cups was monitored. The other one without a thermocouple was quenched into water immediately when eutectic arrest platform went just about 10 s as monitored in the cooling curves. In the Sr-modified alloy, the sample was quenched into water when the eutectic reaction was approximately 40% completed. The average cooling rate of the liquid prior to solidification is about 2.0 K/s measured. The thermocouples were calibrated using the high-purity aluminum, with ±0.5°C accuracy. Three characteristic temperatures of eutectic reaction were measured from the cooling curves according to the method of Tamminen[29]. These temperatures are the nucleation temperature, $T_{\rm N}$, defined as the first noticeable change on the derivative of the cooling curve, the minimum temperature prior to recalescence, $T_{\rm M}$, and the growth temperature, $T_{\rm G}$, defined as the maximum reaction temperature reached after recalescence.

2.3 Metallographic analysis

Quenched samples were sectioned in half along the

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