EFFECTS OF CONVECTION ON UNIDIRECTIONAL SOLIDIFICATION OF A Pb-Sn ALLOY

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Substantial convective mixing in the interdendritic liquid seems to take place in unidirectionally solidified Pb–40 wt.% Sn alloy over a range of growth conditions. The increase in temperature gradient (G) tends to shorten secondary arms and raise the area fraction of dendrites. The secondary dendrite arms appear to be unstable at $G = 13.8$ K/mm.

1. Introduction

Several investigations [1–8] in recent years have pointed out the possible influence of convection on the microstructure of unidirectionally solidified ingots. It is well known that convection in the bulk liquid can affect the morphology of cast structures, particularly when the solute is lighter [9,10]. Recent experiments on dendritic solidification under low-gravity condition [11] or with transparent model melts [12,13] have manifested that the fluid flow in the interdendritic channels also warrants attention, because it can cause a reduction in the primary dendrite arm spacing over that for the diffusion-limited case. Empirical criteria for the indication of significant convection are based, so far, on the clustering of the dendrites or on the distortion of the growth front [5,7].

The variation of primary spacing (λ) with the temperature gradient (G) and growth velocity (V) in the presence of convective mixing is not yet well documented. This paper reports the possible effects of fluid flow on the dendritic morphology in a unidirectionally solidified Pb–40 wt.% Sn alloy, where hydrodynamic instability is expected due to the divergence in densities between Pb and Sn.

2. Experimental

The Pb–40 wt.% Sn alloy was prepared by melting in an evacuated pyrex tube, and the melt was thoroughly shaken prior to solidification in situ. Portions of this alloy were remelted in evacuated pyrex tubes (specimen tubes) of 100 mm length and 6 mm inner diameter, and unidirectionally solidified in a gradient tubular furnace moving steadily upward. The gradient was achieved by placing a water cooling jacket in the lower half of the furnace tube.

Two solidification passes were performed on each specimen tube in a manner similar to Klaren et al. [2]. The temperature gradient at the dendrite tip in the liquid was determined in the first pass from the cooling curves of two thermocouples placed 20 mm apart in each specimen tube. During the second pass the samples were quenched in water at a predetermined stage of solidification to retain the microstructure.

The specimens were polished to 1 μm diamond and etched in a solution of HNO_3 : CH_3COOH : glycerol mixed in a ratio of 1 : 1 : 4. The transverse sections of the specimens were examined with a Versamet metallograph to determine the area fraction of dendrites (f_d). Solute composition in the quenched unetched specimens was measured by a Camscan 2DV scanning electron microscope fitted with a Link AN/25s EDAX system by using the software package ZAF-4/FLS.

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3. Results and discussion

Several theoretical analyses [14–16] of directional growth assuming diffusive solute transport, as well as related experiments [7] at high G/V (e.g., $G/V \geqslant 2.5\times10^6$ K/s for Pb–8 wt.% Au alloy [7]) show a nearly linear decrease in solute content in the interdendritic channel along the dendrite length, as shown schematically in fig. 1. In contrast, the present experiments performed at relatively low G/V ($\leqslant 0.5\times10^6$ K/s) with Pb–40 wt.% Sn alloy reveal that the interdendritic liquid is well enriched in solute content along most of the dendrite length, which is manifested by the marked positive deviation from linearity of the solute concentration profile (cf. fig. 1). Apparently, the enhanced intermixing in the interdendritic liquid region, as compared to the diffusion-limited case, evidences significant convective mass transfer in the present experiments, and it is conceivable that the lighter Sn-rich liquid flows up from the root to the tip of the dendrites.

In a recent study on chill based unidirectional solidification Sarazin and Hellawell [20] have pointed out that the convective flow in Pb–40 wt.% Sn alloy may not be a streamline one, and the convection seems to originate near the dendritic growth front. The mushy zones in unidirectional solidification experiments at constant growth velocity are, however, much shorter ($\approx$miscibility gap/G) [7,14] as compared to that of the chill based solidification. Hence, in the present experiments bulk liquid convection as well as the localized convection in the shallow mushy zone can apparently influence the microstructure.

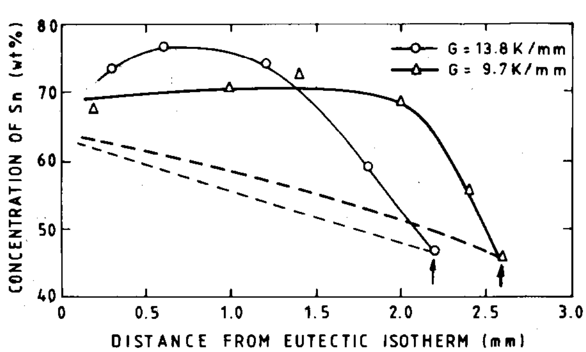

Fig. 1. Composition profile in the interdendritic liquid region of the Pb–40 wt.% Sn alloy grown at $V=3$ μm/s. The arrow heads point at tip positions. The dashed lines display schematically the concentration–distance curves in the diffusion-limited case.

The microstructures of the transverse sections displayed in fig. 2 illustrate that the length of the secondary arms gradually diminishes and ultimately disappears with the increase in G. It may be postulated that the additional solute enrichment in the mushy zone (cf. fig. 1) caused by the interdendritic convective flow [8,11,17,18] possibly results in localized remelting (and detachment) of dendrites with concomitant decrease in resistance to fluid flow. The log λ versus log G plot for the present alloy displayed in fig. 3 shows a non-linear relationship, whereas theoretical analysis [19] as well as experiments [2,3] suggest a linear interrelationship for the diffusion-limited case. Mason et al. [3] have also indicated such a deviation from linearity for Pb–40 wt.% Sn alloy, when the growth velocity is $\leqslant 4.5$ μm/s. Thus, the negative deviation from linearity at higher G with relatively small value of V (e.g. in fig. 3, $V=3$ μm/s) may also be attributed to the enhanced convection in the interdendritic channels.

The area fraction of dendrites (f_d) is found to increase in the present experiments with the rise of G/V (cf. fig. 4). A similar trend has been reported for the same alloy [3] solidified at different growth velocities with $G=10.7$ K/mm, and for Pb–8 wt.% Au [7] grown at $G/V \leqslant 2.5\times10^6$ K/s (cf. fig. 4). The increase of f_d with G/V in the Pb–Sn alloy is more pronounced than that in the Pb–Au alloy (cf. fig. 4), which may be attributed to the hydrodynamic instability caused by the rejection of lighter solute Sn from the growing dendrites in the former alloy, whereas in the latter case Au being heavier than Pb does not contribute to such instability. It may be pointed out that the experiments carried out at still higher G/V [5,7] have shown a decrease of f_d with increasing G/V. In this case, the reduced permeability of the dendritic mesh at higher G/V is believed to inhibit the minimum liquid entrainment necessary for the convection to be effective; because the experiments in low-gravity condition [11] have already demonstrated that λ continually decreases with the rise in G/V. Nevertheless, it appears that the increase of f_d with G/V (cf. fig. 4) may indicate significant fluid flow in the interdendritic channels.

Fig. 2c evidences the absence of secondary arms in the transverse section just behind the eutectic iso-

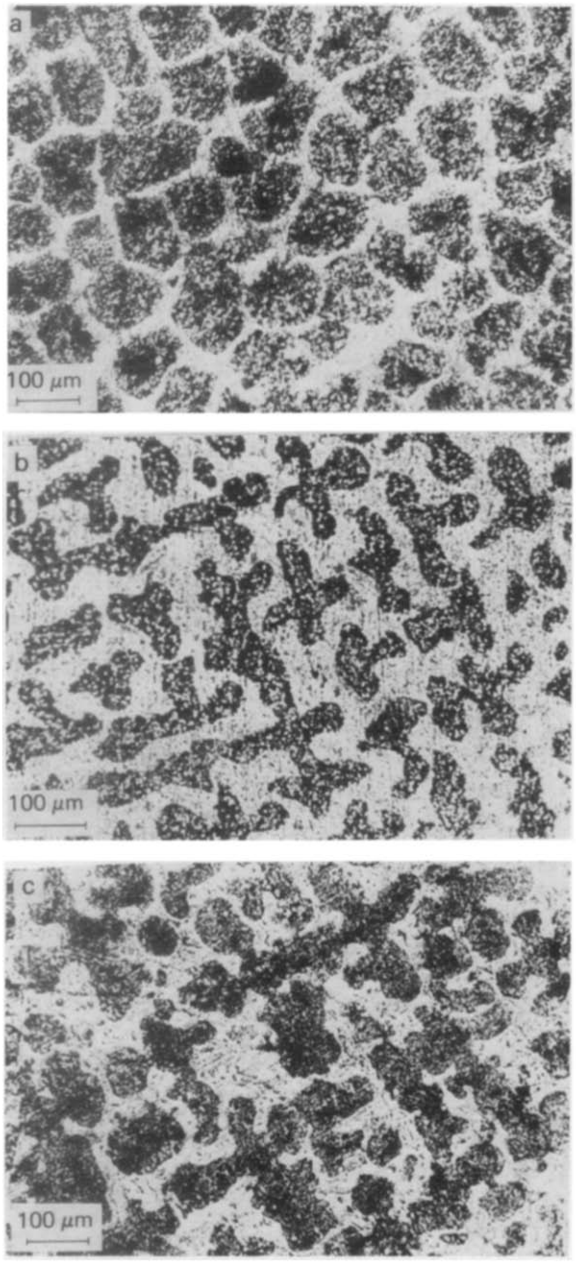

Fig. 2. Transverse sections of unidirectionally solidified Pb–40 wt.% Sn alloy grown at $V=3$ μm/s with (a) $G=5.3$ K/mm, (b) $G=9.7$ K/mm and (c) $G=13.8$ K/mm.

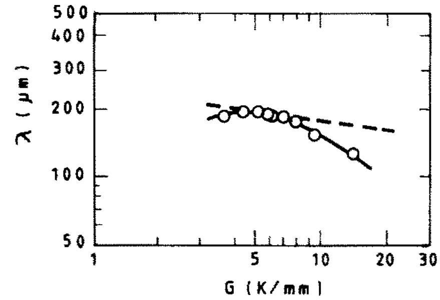

Fig. 3. Plot of log λ against log G for the present alloy grown at 3 μm/s. The dashed line represents the diffusion-limited case, as obtained from linear extrapolation of the data of Mason et al. [3].

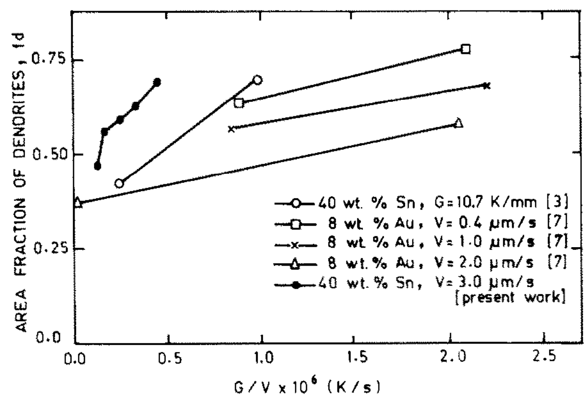

Fig. 4. Plot of f_d against G/V for different Pb-based alloys.

therm of the sample grown at $G=13.8$ K/mm. However, the longitudinal section of the same sample displays short secondary arms on that part of the dendrites which protrudes into the liquid (cf. fig. 5). It is plausible that these secondary arms are unstable under the prevailing growth condition. Although such a phenomenon has not yet been reported in metallic systems, in situ experiments with the ice–water system [21] have already identified unstable secondary arms.

4. Conclusions

(1) Solute composition profiles in unidirectionally solidified Pb–40 wt.% Sn alloy evidence significant convection in the interdendritic liquid region over a range of growth conditions.

(2) The secondary arms seem to shorten and ultimately disappear with increasing temperature gra-

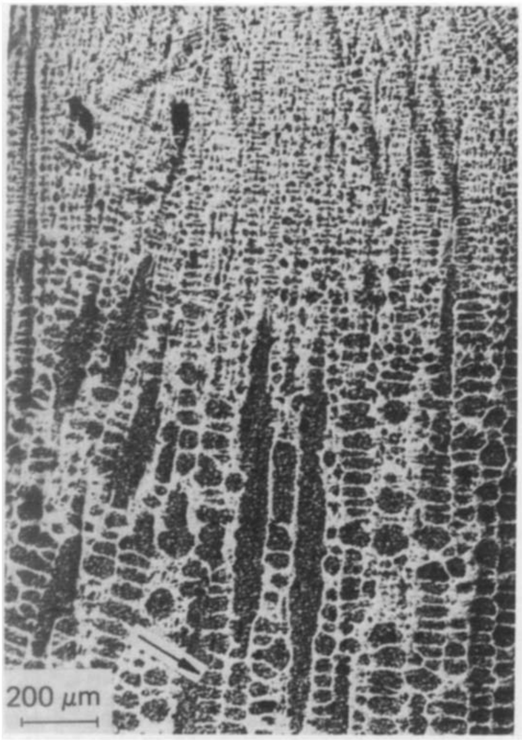

Fig. 5. Longitudinal microstructure showing macroscopic interface of Pb–40 wt.% Sn alloy grown at $G=13.8$ K/mm and $V=3$ μm/s. The arrow head displays the secondary arm on a primary dendrite protruding into the liquid.

dient more rapidly than the diffusion-limited case, which may be attributed to the convection.

(3) The increase in area fraction of dendrites with G/V may also indicate significant fluid flow in the interdendritic channels.

(4) The secondary arms on the dendrites appear to be unstable at $G=13.8$ K/mm.

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