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Abstract. Under a NASA (National Aeronautics and Space Agency)-ESA (European Space Agency) collaborative research project, MICAST (Microstructure formation in casting of technical alloys under a diffusive and magnetically controlled convection conditions), three Al-7wt% Si samples (MICAST-6, MICAST-7 and MICAST2-12) were directionally solidified at growth speeds varying from 10 to 50 μm s^{-1} aboard the International Space Station to determine the effect of mitigating convection on the primary dendrite array. The observed primary dendrite trunk diameters during steady-state growth of MICAST samples show a good agreement with predictions from a coarsening based model developed by the authors. The trunk diameters in the terrestrial-grown equivalent samples were larger than those predicted from the model. This suggest that thermosolutal convection increases the trunk diameter of primary dendrites, perhaps by increasing their tip radius due to compositional changes.

1. Introduction

During directional solidification (DS) of alloys in a positive thermal gradient (G_L) a mushy-zone consisting of array of primary dendrite arms and interdendritic liquids in between, develops between the melt above and the solid below. Analytical and numerical theories have been developed to describe various aspects of the dendrite network, e.g., cell to dendrite transition, dendrite tip radius and primary dendrite spacing [1-8] under diffusive growth conditions. Given that mechanical properties depend upon the dendrite spacing and distribution, numerous experiments have been carried out to measure primary spacing as a function of solute content (C_o,), growth speed (R), thermal gradient (G_L) and the physical properties of the alloy to compare with model predictions [9-27]. Invariably the discrepancy between the experimental observations and model predictions has been attributed to convection in the melt. Convection itself has been treated by a pseudo-analytical approach of defining an overall mushy-zone Rayleigh Number for the growth conditions [28-40], and correlating, for example, the increasing propensity for convection with observed reduction in mean spacing in terrestrial-grown samples as compared with those solidified in microgravity [30-33, 40]. While primary spacing has been extensively evaluated as the morphology parameter for the dendritic arrays, another feature, the primary dendrite trunk-dimeter [41-44] has remained relatively unexplored. The trunk-diameter responds to an abrupt speed change more quickly because it is more reflective of the dendrite tip radius as compared with the primary spacing which achieve the new steady-state value only after further DS for two to three mushy-zone length [45]. Here we present primary dendrite trunk diameter measurements from three Al-7Si alloy samples (MICAST6, MICAST-7 and MICAST2-12), which were directionally solidified on the Space Station at growth speeds varying from 5 to 50 μm s^{-1}. It is seen that the observed primary dendrite trunk-diameters during steady-state growth of MICAST samples are in a good agreement with predictions from a coarsening based model developed by some of the authors [44].

2. Experiments

Cylinders with a diameter of 7.8 mm and a length of ~25-cm were machined from [100] oriented terrestrially grown dendritic Al-7Si samples and inserted into alumina ampoules kept within the Sample Cartridge Assembly (SCA) inserts of the Low Gradient Furnace (LGF) for MICAST-6 and MICAST-7 and in the Specimen Quench Furnace (SQF) for MICAST2-12. The A-7Si cylinders were partially re-melted in space and directionally solidified by withdrawing the furnace with respect to the SCA; their unmelted solid portions at cold end acted as [100] oriented seed. Fig. 1 shows a schematic representation of the solidification processing conditions. The unmelted portion is left of T_E (eutectic isotherm) with the melted and directionally solidified portion on the right. The mushy-zone lengths at the onset of DS are indicated in the figure. For MICAST-6 the withdrawal speed was 5 μm s^1 for 3.75 cm, and then 50 μm s^{-1} for rest of the 11.2 cm long melt. For MICAST-7 it was 20 μm s^{-1} for 8.5 cm and then 10 μm s^{-1} for the rest 10.5 cm. For MICAST2-12 it was 40 μm s^{-1} along its entire 12 cm long melt column.

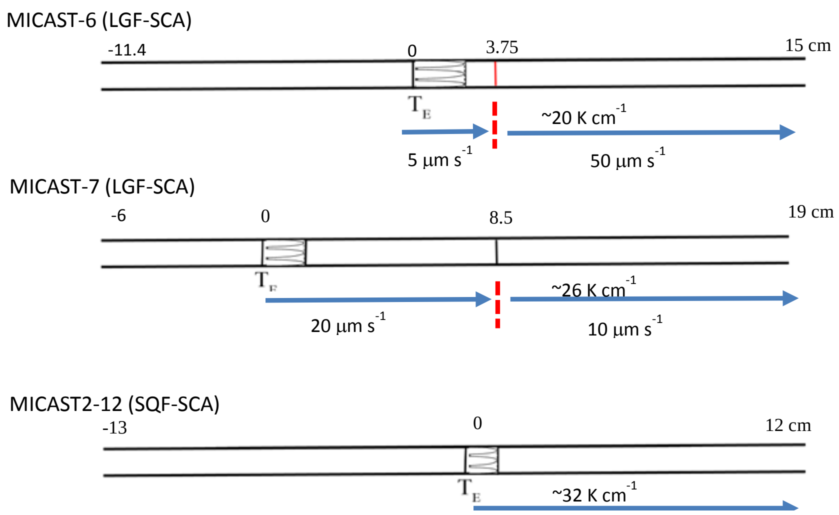


Figure 1. Solidification processing conditions of the MICAST samples. The unmelted portion is left-of eutectic temperature (T_E) with the melted and directionally solidified portion on the right. The mushy-zone lengths at the onset of directional solidification are indicated near T_E.

Temperatures along the sample length during DS were recorded by eleven thermocouples which were attached at regular intervals on the outer surface of the alumina ampoules along their length. Growth speeds and thermal gradients extracted from such thermal profiles are plotted in Fig. 2 for the MICAST-6, MICAST-7 and MICAST2-12 samples. Fig. 2(a), on the left, plots the thermal gradients at the liquidus (G_{TL}) (solid lines) and at the eutectic (G_{TE}) (dashed lines) temperature as a function of distance from the cold end of the samples. Fig. 2(b), on the right, plots the liquidus (V_{TL}) and eutectic (V_{TE}) isotherm velocities along the sample lengths. The thermal gradients were observed to vary during directional solidification. For example G_{TL} varied from 22 to 14 K cm^{-1} during growth of MICAST-6, from 26 to 24 K cm^{-1} for MICAST-7, and from 33 to 31 K cm^{-1} for MICAST2-12.

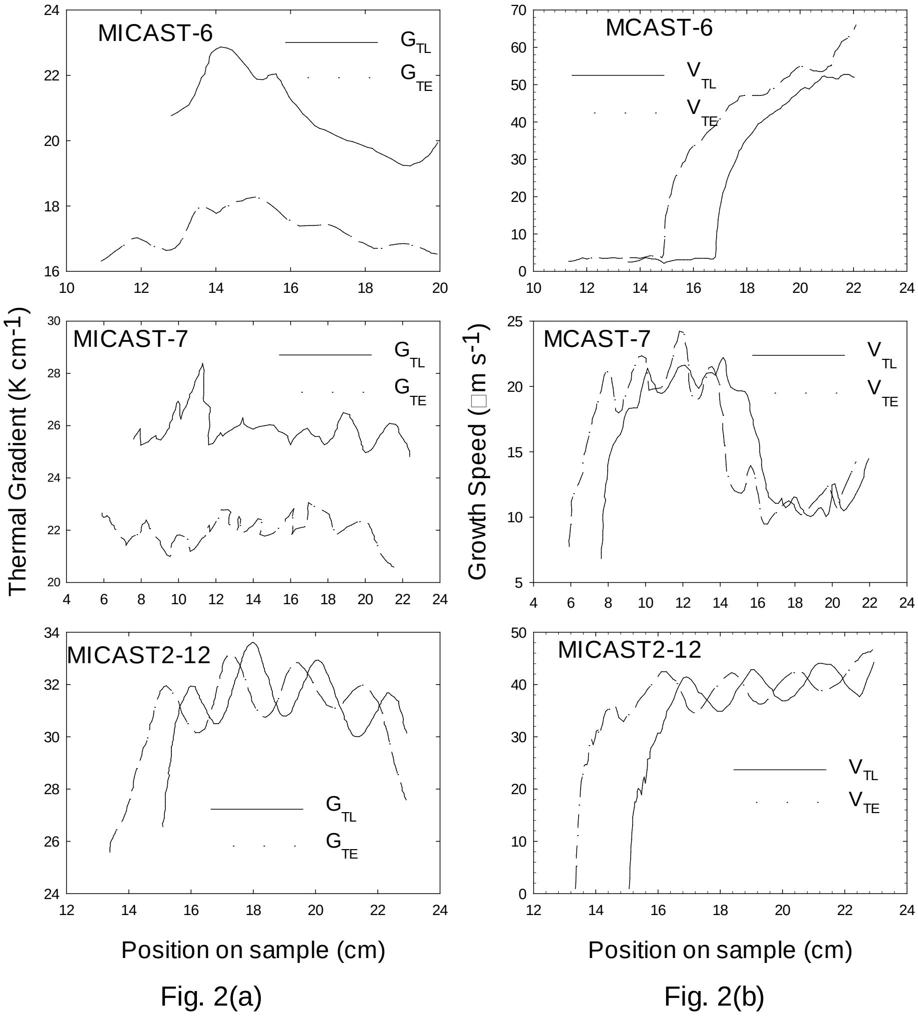
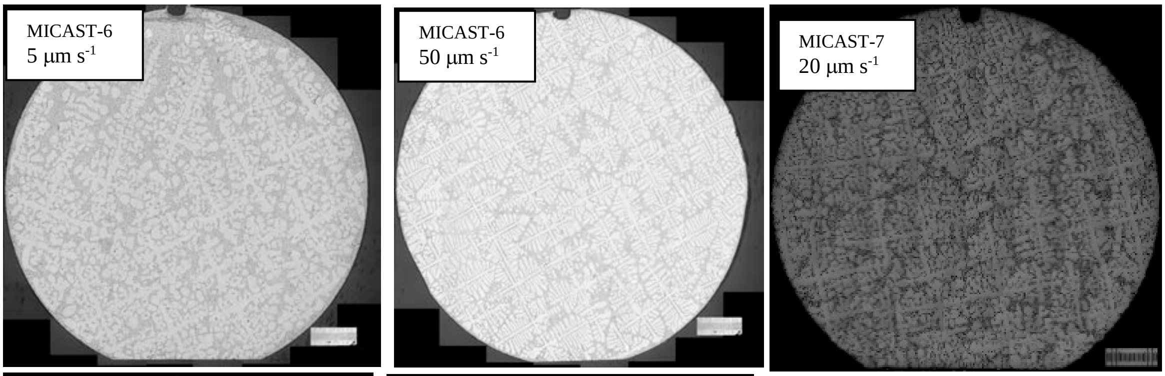


Figure 2. Thermal gradients at liquidus (G_{TL}) and at eutectic (G_{TE}) (Figs. 2(a) on the left), and velocities of liquidus (V_{TL}) and eutectic (V_{TE}) isotherms (Figs. 2(b) on the right) as a function of distance from the sample bottom during directional solidification of MICAST-6, MICAST-7 and MICAST2-12 samples.

3. Results

Fig.3 shows typical transverse microstructures along the lengths of the MICAST samples. Trunk diameters of primary dendrites on several such cross-sections along the length of the three MICAST samples were measured in the manner describes in Ref. 44. Figure 4 shows the variation in the primary dendrite-trunk diameter along the length of the three samples. Circles are average primary dendrite trunk diameter and error bars are the ± standard deviation; the dotted lines are predictions from a model proposed by the authors [44]. Recall that for the MICAST-6 samples there was a step increase in the growth speed from 5 to 50 μm s^{-1} at the distance of 3.75 cm (Fig. 1(a)) and for the MICAST-7 sample an abrupt decrease from 20 to 10 μm s^{-1} at 8.5 cm (Fig. 1(b)). The entire 12 cm long melted portion of MICAST2-12 sample was grown at 30 μm s^{-1} (Fig. 1(c)). The trunk-diameters respond to the speed changes almost immediately. Also, the predictions from the simple coarsening-based trunk-diameter model [44] are in a good agreement with the experimental observations during the transient and the steady-state DS.



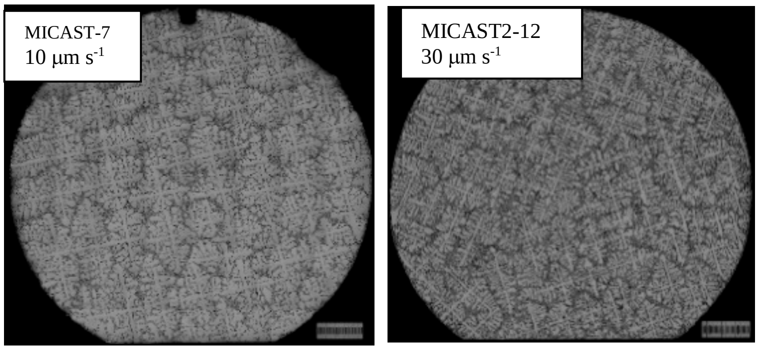


Figure 3. Primary dendrites on transverse sections of directionally solidified MICAST-6, MICAST-7 and MICAST2-12 samples. Markers correspond to 1-mm.

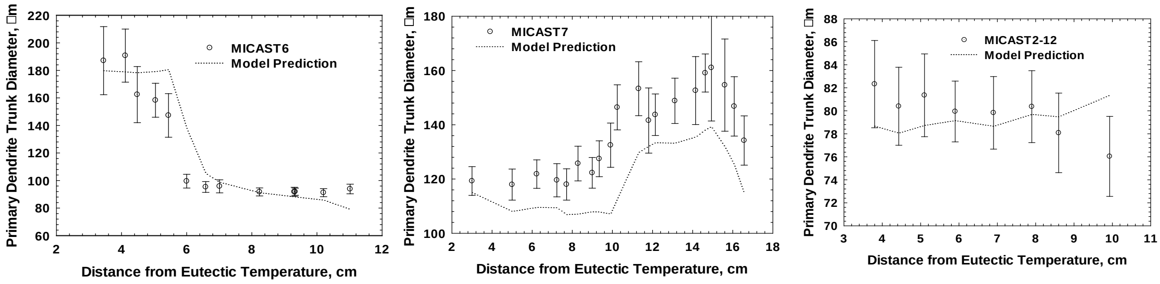


Figure 4. Primary dendrite trunk diameters along the DS length of MICAST-6, MICAST-7 and MICAST2-12 samples. Symbols are average values and error bars are ± one standard deviation; the dotted lines are predictions from a model proposed by the authors [44].

If we include data only from the steady-stare DS portion of the MICAST samples, the agreement appears to be even better (Fig. 5). For each growth speed the trunk-diameter measurements from only those transverse sections were pooled together which met the following conditions, (i) at least, 2-mushy zone lengths of directional solidification has occurred at one growth speed, (ii) at least, 2-mushy zone lengths of solid exists below T_E, and, also at least 2-mushy zone lengths of liquid exists above T_E. Fig.5 shows that predictions from the model (the dotted line) are in a very good agreement with the observed trunk diameters (symbols and ± standard deviation).

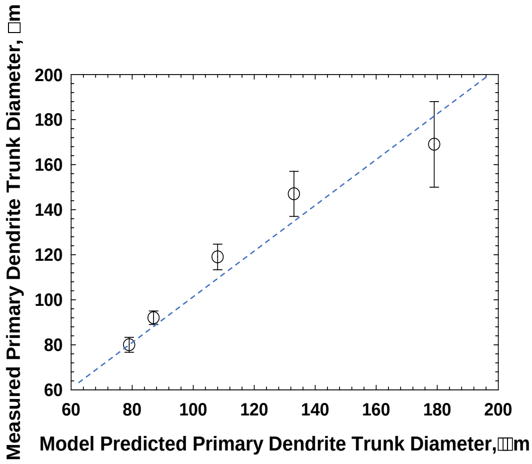


Figure 5. Comparison of the experimentally observed primary trunk diameters during steady-state directional solidification conditions in the MICAST-6, MOCAST-7, and MICAST2-12 samples with those predicted from a model proposed by the authors [44].

4. Discussion and Conclusion

Following additional observations were made during this study, details of which are not included in this paper because of the lack of space. The MICAST samples grown at 10, 20, 30 and 50 μm s^{-1} did not show the radial macrosegregation which invariably occurs during terrestrial DS of Al-7Si alloy [46] and is attributed to the “steepling” type thermosolutal convection [28-32, 46]. This strongly suggests that the three MICAST samples were indeed directionally solidified under convection-free diffusive transport conditions. We have also seen that primary dendrite trunk diameters in the Al-7Si samples, which were directionally solidified terrestrially under approximately similar growth conditions as the low-g processed MICAST samples, are larger than those predicted from the model. These observations strongly suggest that the thermosolutal convection during directional solidification not only reduces the spacing between primary dendrites [30-33] it also increases their trunk diameter as compared with growth under diffusive transport conditions, perhaps by increasing their tip radius.

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