INTERFACE PATTERN SELECTION CRITERION FOR CELLULAR STRUCTURES IN DIRECTIONAL SOLIDIFICATION

R. Trivedi, Principal Investigator, Department of Materials Science and Engineering, Iowa State University, Ames, IA 50011. Phone: 5515-294-5869; FAX 515-294-4291; trivedi@ameslab.gov
S. N. Tewari, Co-Investigator, Chemical Engineering Department, Cleveland State University, Cleveland, OH, 44115,
D. Kurtze, Department of Physics, North Dakota State University, Fargo, ND, 58105.

INTRODUCTION

The aim of this investigation is to establish key scientific concepts that govern the selection of cellular and dendritic patterns during the directional solidification of alloys. We shall first address scientific concepts that are crucial in the selection of interface patterns. Next, the results of ground-based experimental studies in the Al-4.0 wt % Cu system will be described. Both experimental studies and theoretical calculations will be presented to establish the need for microgravity experiments.

The formation of cellular and dendritic patterns is important in many disciplines of science. Since the growth conditions in directional solidification can be precisely controlled and measured, it provides a powerful technique to study the underlying principles that govern the formation of ordered, disordered or chaotic patterns. The formation of a cellular or a dendritic structure is accompanied by microsegregation of solute, which results in a nonhomogeneous material. This nonhomogeneity in composition not only influences mechanical properties, but it can also generate stresses or lead to the formation of a new stable or metastable phase in intercellular region that can significantly alter the properties of the material. Thus the reliability of products made by solidification techniques such as casting and welding largely depends upon our ability to control solute segregation patterns so as to minimize stresses or to avoid the formation of undesirable phases in the intercellular region.

In the cellular structure, different cells in an array are strongly coupled so that the cellular pattern evolution is controlled by complex interactions between thermal diffusion, solute diffusion and capillarity effects. These interactions give infinity of solutions, and the system selects only a narrow band of solutions. The aim of this investigation is to obtain benchmark data that will allow us to quantitatively establish the physics of the pattern selection process. A sequence of directional solidification experiments has been proposed to quantitatively establish the fundamental principles that govern cell/dendrite microstructure selection. As the solidification velocity is increased, or the temperature gradient decreased, the interface undergoes several transitions: planar to small amplitude cells, to deep cells, and finally to dendrites. These changes in microstructures occur at low velocities where thermosolutal convection is dominant. Since reliable theoretical models are not yet possible which can quantitatively incorporate fluid flow in the selection criterion, microgravity experiments on cellular and dendritic growth are proposed to obtain benchmark data that can be quantitatively analyzed to establish the fundamental principles that govern the selection of specific microstructure and its length scales.

GROUND-BASED EXPERIMENTS

Previous ground-based study established that the conditions under which cellular and dendritic microstructures form are precisely where convection effects are dominant in bulk samples. We have performed ground-based experiments investigating the potential of several methods to reduce convection in terrestrial experiments. The methods studied include use of magnetic fields (axial and transverse) and the use of very small diameter samples of metallic alloys.

In order to see if the application of a magnetic field can suppress convection, directional solidification experiments were carried out in presence of axial and radial magnetic fields. It was observed that the application of a transverse magnetic field does not reduce the extent of solutal mixing due to convection. In addition, the transverse magnetic field introduces an anisotropy in the fluid flow that distorts the cellular mushy zone morphology. Thus, another technique was developed to reduce convection. In this technique, A series of experiments has been carried out in the Al-4wt% Cu alloy system using thin tubes of diameters varying from 6.0 mm down to 0.4 mm. A bundle of thin samples of varying diameters was placed inside the 6 mm diameter tube, and all samples were directionally solidified simultaneously in a single experiment. As a result, the thermal profile and the translation rate imposed on the samples were identical except for the degree of convection which depends on the tube diameter. Since convection effects are gradually reduced as the sample size is decreased, quantitative evaluation of convection effects on microstructural development can be obtained. The results of this series of experiments are illustrated in Fig. 1 which shows microstructures as a function of both the sample size and growth velocities at a given temperature gradient G=10 K/mm.

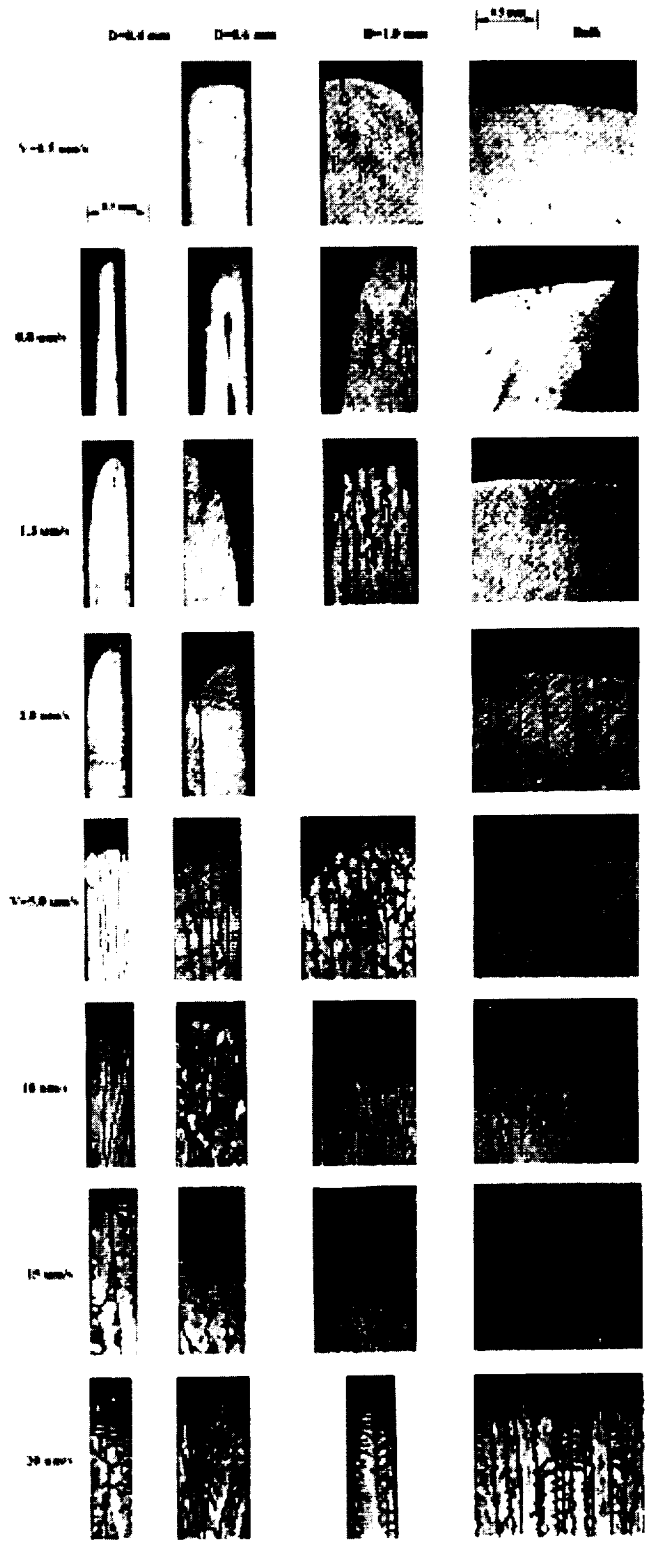

Figure 1. A matrix of microstructures with varying velocity and sample diameters in Al-4.0 wt % alloys.

Reducing the sample diameter (decreasing the extent of convection) results in the following:

- The tip temperature decreases.
- The primary arm spacing increases.
- Planar-to-cellular and cellular-to-dendritic transitions occur at lower growth speeds.

Microsegregation profiles across the cells obtained by electron-microprobe, Fig. 2, show that the solutal profile changed significantly until the diameter of the sample was reduced to 1 mm. Below this value there was no noticeable change. This suggests that diffusive growth conditions in Al-4.0 wt % Cu are approached only when the sample diameter is less than 1 mm. However, for this sample size, only very few cells were present and the constraint of the wall did not allow them to reach the steady-state configuration. A Steady state was approached only when a single cell was present at the center of a thin tube. In this case, no selection occurs and no information on the selection criterion can be obtained.

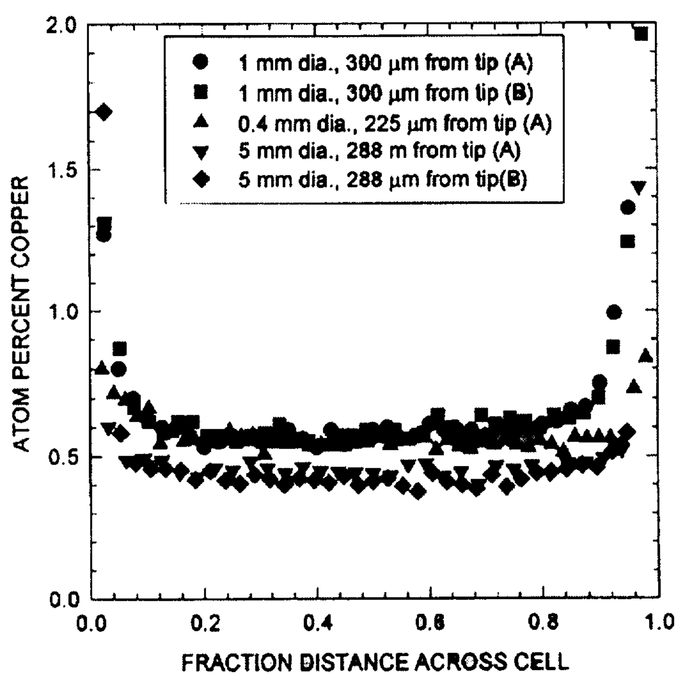

Figure 2. Microsegregation profile across cells for samples of different diameters that were directionally solidified in a single experiment.

Experimental studies were carried out for different velocities and temperature gradient values to establish the conditions under which planar to cellular and cellular to dendritic transitions occur. These transitions were found to depend upon the diameter of the tube, or upon the presence of convection. Figures 3a shows the transition conditions in large samples, whereas Fig. 3b is for small diameter samples in which diffusive growth occurs. It is seen that convection effects stabilize, or require higher velocity, for both the planar to cellular and cellular to dendritic transitions. These results in thin samples will allow us to precisely characterize experimental parameters under microgravity conditions.

These ground-based experimental studies clearly demonstrated the presence of significant convection in bulk samples. Although this experimental method permits access of the diffusive regime, this technique cannot be used to characterize microstructures for which the microstructural length scale is of the order of the sample diameter. Since sample diameters of 1mm or less is required for diffusive growth, only a single cell can form. There is no selection for the formation of a single cell, so that it is not possible to obtain diffusive growth terrestrially in bulk alloy samples that are large enough to establish the selection criterion or to obtain statistically meaningful distribution of spacing of cell/dendrite arrays.

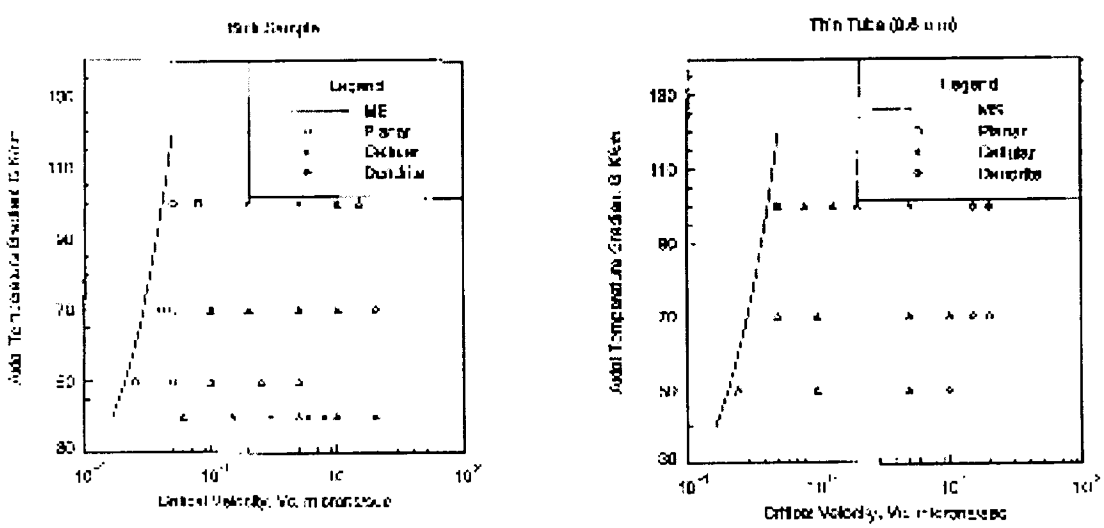

Fig. 3. Microstructures as a function of G and V. (a) Experiments in 6.0 mm tube in which significant convection is present. (b)) Experiments in 0.6 mm diameter tube in which diffusive growth conditions are present.

NUMERICAL STUDIES

In order to establish the effects of sample diameter on convection within the sample, we have developed a detailed numerical model of convection for the vertical Bridgman growth technique. A model was developed for the vertically upward solidification of a binary liquid of initial composition C_0 (in % solute) inside a two dimensional rectangular cavity. The vertical walls are rigid solid walls that represent the three-zone thermal assembly and are impervious to mass flux. The three-zone assembly consists of an isothermal cold zone wall at temperature T_c, an isothermal hot zone wall at temperature T_H, and a no-flux adiabatic zone between them. The system of coupled nonlinear equations written in coordinate frame fixed with the uniformly moving solid-liquid interface includes Boussinesq approximated Navier-Stokes equations, and the heat and solute transport equations. These equations are completely described by thermal and solutal Rayleigh numbers, the ratio of vertical to horizontal temperature gradients, the Peclet number based on growth rate, the partition coefficient, the Prandtl number, the Lewis number and the aspect ratio. Numerical calculation were carried out for conditions characteristic of solidification of Al-4.0% Cu at a growth rate of 1 μm/s in tubes of inner diameter 0.6 mm - 6 mm. These calculations show that the convective velocity is orders of magnitude larger than the diffusive velocity for samples of diameter larger than 6 mm. One needs to use sample diameter smaller than 1 mm to obtain conditions for which the convective velocity is smaller than the diffusive velocity in the Al-4.0 wt % Cu system. These calculations are in agreement with our experiments in thin samples, and both these studies clearly establish the dominant role of convection in sample diameters larger than 1 mm. The use of smaller than 1 mm diameter under terrestrial condition show that one would require microgravity level of 10^{-4} g to directionally solidify 1 cm diameter samples under diffusive conditions.

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