Experimental Studies of the Interactive Dynamics of Parallel Shear Flow and Directional Solidification

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It is recognized that flow in the melt can have a profound influence on the interface dynamics and hence the quality of the solidified materials. In particular, flow affects the heat and mass transfer, and causes spatial and temporal variations in the flow and melt composition. This results in a crystal with nonuniform physical properties. Flow can be generated by buoyancy, expansion or contraction upon phase change, and thermo-soluto capillary effects. In general, these flows cannot be avoided and can have an adverse effect on the stability of the crystal structures. This motivates the crystal growth experiment in a microgravity environment, where buoyancy-driven convection is significantly suppressed. However, transient accelerations (g-jitter) caused by the acceleration of the spacecraft can affect the melt, while convection generated from the effects other than buoyancy remain important.

Rather than bemoan the presence of convection as a source of interfacial instability, Hurle in the 1960's suggested that flow in the melt, either forced or natural convection, might be used to stabilize the interface. Delves considered the imposition of both a parabolic velocity profile and a Blasius boundary layer flow over the interface. He concluded that fast stirring could stabilize the interface to perturbations whose wave vector is in the direction of the fluid velocity. Forth and Wheeler considered the effect of the asymptotic suction boundary layer profile. They showed that the effect of the shear flow was to generate traveling waves parallel to the flow with a speed proportional to the Reynolds number. There have been a few quantitative, experimental works reporting on the coupling effect of fluid flow and morphological instabilities. Huang studied plane Couette flow over cells and dendrites. It was found that this flow could greatly enhance the planar stability and even induce the cell-planar transition. A rotating impeller was buried inside the sample cell, driven by an outside rotating magnet, in order to generate the flow. However, it appears that this was not a well-controlled flow and may also have been unsteady.

Numerous experiments have been done by other researchers to conduct morphological studies with transparent organic compound growing in a Hele-Shaw cell. The Hele-Shaw cell was used to provide a 2-dimensional solidification chamber which made *in situ* observations and measurements possible. Some analytical results on the effect of flow on morphological stability are also based on this configuration. In the present experimental study, we want to study how a forced parallel shear flow in a Hele-Shaw cell interacts with the directionally solidified crystal interface. The Hele-Shaw cell consists of two parallel quartz glass plates separated by a thin gap. Each plate is ground to less than 1/4 wavelength per inch optical flatness. The bottom plate is covered with an aluminium reflective coating, which serves as a front-surface mirror. The top plate has two groups of holes through which liquid alloy can be added or removed. A parallel shear flow is formed by adding liquid into the cell through the holes on one side and removing it through the holes on the other side. The direction of the flow can be reversed by interchanging the inlet and outlet holes.

The directional solidification system is based on a horizontal Bridgman furnace. The Hele-Shaw cell sits on top of the heater/cooler pair and can travel back and forth in the towing direction. The temperature distribution inside the cell is detected by an embedded Iron-Constantan thermocouple with an accuracy of 0.1 °C. The thermocouple is placed next to the incoming flow. The transparent organic alloy SCN (succinonitrile)-1.0 Wt% acetone was used as the specimen material. In one set of experiments, the flow was started when the planar interface just became unstable (early-flow); in another set, the cellular interface was fully developed when flow was started (late-flow). The experiments were adjusted so that no heat source or sink effect was brought in by the flow. The experiment process was observed in-situ under an interference microscope.

The comparison between the results of the no-flow experiments and the early-flow experiments showed that the parallel shear flow has a strong stabilizing effect on the planar interface by damping the existing, initial perturbations. In the late-flow experiments, the flow also showed a stabilizing effect on the cellular interface by slightly reducing the exponential growth rate of cells. Furthermore, the left-right symmetry of the cellular structure was broken by the parallel flow with cells tilting toward the incoming flow direction. The tilting angle increased with the velocity ratio (the ratio of flow speed to towing speed). Secondary dendrites were found to appear only on the downstream side of the cells. The wavelengths of the initial perturbations and of the cellular interface were insensitive to the imposed flow.

The physical mechanism explaining these observations is a version of that discussed by Dantzig and Chao using a parallel shear flow model. Since the forced parallel flow does not affect the thermal transport, it influences the interface morphology by altering the solute transport. When the parallel shear flow is applied at an interface with small amplitudes (<0.010 mm in the experiment), the flow field is minimally altered by the shallow cells and is still locally parallel to the interface. This local parallel flow dramatically enhances the lateral solute transport. Therefore the early parallel flow stabilizes the interface by smoothing out the lateral solute inhomogeneity at the interface. However, when the parallel shear flow is applied at the deep cellular interface, the flow field is distorted by the periodic curved interface and is no longer locally parallel to it. Flow has a stronger compressing effect on the upstream side of cells than the downstream side, which leads to an asymmetry in the concentration field with a thinner solutal boundary layer and greater concentration gradient G_C at the upstream side. Since G_C has a destabilizing effect on the interface, the upstream side of cell has a higher normal growth rate than the downstream side and as a result the cell tilts toward the incoming flow direction. It is proposed that it is the coupling effect between the interfacial morphology and the imposed parallel shear flow that leads to different crystal structures.