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MAGNETIC RESONANCE IMAGING OF STRUCTURE AND CONVECTION IN SOLIDIFYING MUSHY LAYERS

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Summary We use Magnetic Resonance Imaging to study the structure and convection inside a solidifying mushy layer formed from a binary alloy cooled from above. We focus especially on systems in which defects known as chimneys are observed. We obtain high-resolution images and have direct access to a number of measurements (chimney behaviour, porosity, etc.). The mushy layer is seen to grow in a self-similar manner until internal convection begins, when the solid fraction increases in the lower part of the layer.

INTRODUCTION

Many modern technological components are cast from metallic alloys that are poured into a mould in a molten state then cooled and solidified to form the final product. During solidification, the constituents of the alloy become segregated: one or more of the constituents preferentially form the first solid to precipitate, which usually creates a matrix of crystals (often dendritic), while the other constituents are left behind in the melt between these crystals, where they solidify later, at lower temperatures. The two-phase region comprising the matrix of primary crystals and interstitial, residual melt is called a mushy layer. One of the common defects observed during this process is the formation of so-called freckles, channel segregates or chimneys [1]. Such defects can result in the component being discarded, at huge cost in terms of wasted production time and reprocessing of materials. This phenomenon is also observed in sea ice and may occur in magma chambers and in the Earth's core.

We aimed principally at determining the conditions under which the chimneys occur. Until now, experimental studies [2-5] have tried to describe what is happening inside the mushy layer during solidification by indirect means such as studying the evolution of the bulk liquid properties (such as concentration, volume, etc.) to deduce the mean evolution of the mush. Observations have also been made of the mushy layer / liquid interface to study the crystal matrix properties or the onset of appearance of the chimneys. Most studies have been made *a posteriori*, once the solidification stopped (for example, to obtain the local porosity, the mushy layer is cut in slices; or more sophisticated techniques are used such as X-rays). But this gives information only at one instant. In our work, using a Magnetic Resonance Imaging technique, we obtain direct observations and quantitative measurements inside the mushy layer during solidification.

EXPERIMENTAL SET UP

The experimental set up consists of a cylindrical tank of internal diameter 3.5cm and depth 18cm, filled with a mixture of sugar and water; typically a 20 %wt sugar solution (figure 1). We cool it from the top at -20C, well below the liquidus temperature. A mushy layer then develops with a solid phase made of pure ice. The liquid phase corresponds to a mixture of sucrose and water more concentrated in sucrose than initially in the bulk. As the liquid density increases with sugar concentration this system convects, which leads to the formation of the channels free of crystals, called chimneys.

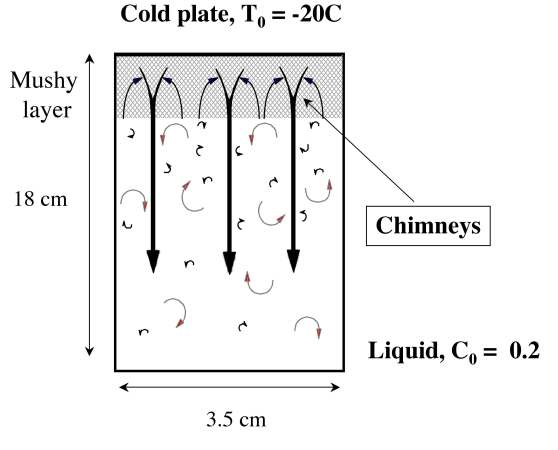

Figure 1. experimental set up.

The experimental set up is placed inside a magnet with a cooled jacket to insure thermal insulation. In contrast with previous experiments, we can obtain continuous data during solidification. The data consist of images of vertical and horizontal slices across the sample. The slices are typically 2mm thick with 4mm between two slices. The solid phase doesn't yield any MRI signal so the intensity of signal received for each pixel corresponds to the liquid fraction.

RESULTS

Structure

With the MRI technique, we obtain information on the structure of the mushy layer. First, with the highest resolution, which is about 100 μm, we distinguish the ice matrix platelet structure inside the mushy layer, as can be seen in the figure 2a in a horizontal slice. In the horizontal slices the chimneys appear as white disks (see figure 2a). From time and position sequences we can study the chimneys' size and distribution. We also observe that the chimneys do not penetrate the whole mushy layer. Using the vertical slices, we can follow the time evolution of particular chimneys with time. In figure 2b one can see such a vertical slice after 14h (6cm of growing mushy layer). We then observe that chimney appears to get a complex structure with a lot of branches.

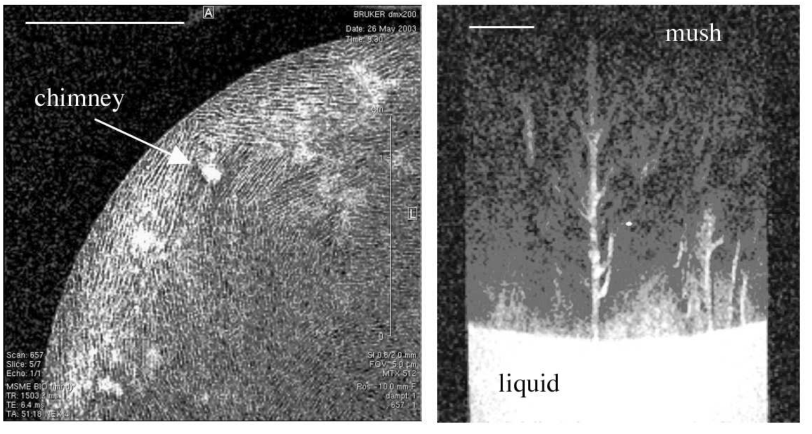

Figure 2. a) platelet structure of the ice matrix and chimneys observed in an horizontal slice.
b) branched chimney in a vertical slice. In both case the white line represents 1cm.

Local porosity

We also obtain more quantitative data such as the local porosity as a function of time. These data are obtained locally for the first time and allow comparison with theoretical models [6-9]. For example we can show that initially the vertical mean porosity (averaged across a horizontal slice) follows a similarity law. This is consistent with there being little or no convection inside the mushy layer. We show that this similarity law is valid until a certain critical Rayleigh number is exceeded, as predicted previously, and is correlated with the appearance of chimneys. Thus knowledge of the local porosity and its time evolution gives direct information on the convection inside the mushy layer.

CONCLUSIONS

Using a powerful Magnetic Resonance Imaging technique, we have obtained for the first time measurements of the evolution of structure within a solidifying mushy layer. Quantitative measurements such as local porosity have been made and are shown to provide direct information on the convection which occurs inside the mushy layer.

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