CELL SHAPES IN DIRECTIONAL SOLIDIFICATION : A GLOBAL STUDY

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Summary We experimentally characterize the *whole* shape of growth cells in directional solidification, from their tip to their grooves, and in a large *domain* of control parameter. For this a library of cell shapes is determined and fitted to a class of definite shape functions. This first global characterization of cell geometry in both the real space and the control parameter space provides a firm ground for testing or improving theories or simulations of directional growth in the cellular to near dendritic regime.

INTRODUCTION

Far from eutectic composition, nearly pure alloys solidifying in a thermal gradient undergo, above a critical pulling velocity, a morphological instability which makes a planar front restabilize onto a non-linear growth solution: a cellular array (Fig.1). The shape of these cells is important in many different issues. It first monitors micro-segregation with important consequences on the resulting properties of the solid material. It also conditions the subsequent instabilities that may develop on each cell (sidebranching, tip-splitting) or on the cell array (2λ-O modes, cell elimination) [1,2]. It finally stands as a relevant test of models or simulations and thus, as a valuable challenge for improving our understanding of directional growth or our ability in adressing more complex regimes.

However, despite long-standing efforts, only a partial understanding or determination of cell shapes have been achieved. For instance, although different models have been developed for treating cell tips or cell grooves [1,3], one still lacks a global model capable of handling the *whole* cell shape. Also, on the experimental side, attention has been devoted to the characterization of the local geometry at cell tip or of the asymptotic features in cell grooves [1], but no global observation or treatment of the cell geometry taken as a *whole* has been achieved to date.

The present study is devoted to determine the global shape of cells displayed in the directional solidification of an alloy and to characterize its evolution with the control parameters. For this, we experimentally scan a large range of thermal gradient G, pulling velocity V and cell spacing L. We then characterize the geometry of this family of cell shapes by fitting each of them to a class of non-linear functions. This class is chosen so that its parameters are geometrically meaningful and display coherent variations with the control parameters (L,V,G). We thus obtain the first global characterization of cell shape both in the real space and in the control parameter space. This provides a firm ground for testing or improving models or simulations of directional growth in the cellular regime.

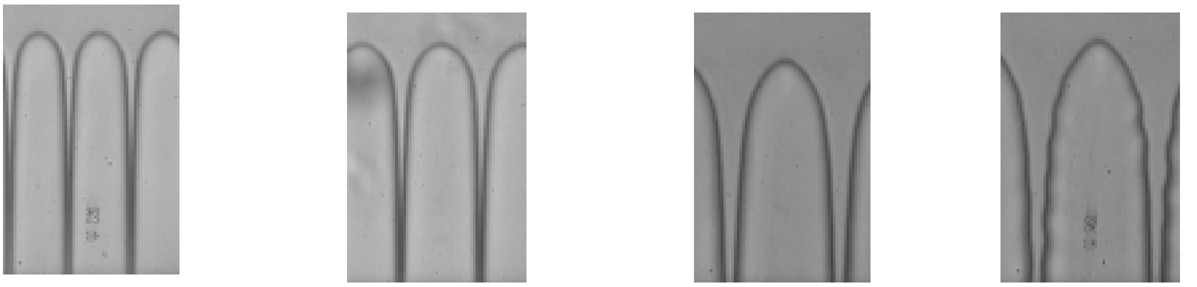

Fig 1 : Snapshots of cell shapes in the cellular or near dendritic regime. The width of each picture is about 180 μm.

EXPERIMENTAL CONFIGURATION AND RESULTS

The experiment is driven in thin samples so as to avoid buoyancy effects. The solidified material is an impure transparent plastic crystal (succinonitrile) which behavior may be considered similar to that of a dilute metal alloy. The experimental range extends from the cellular to the near-dendritic regime of solidification. Control parameters are the thermal gradient G ($50<G<140$ K/cm), the pulling velocity V ($8<V<24$ μm/s) and the local cell spacing L ($50<L<200$ μm). Due to an hysteretic behavior of the system, L has been proven to be a real independent control parameter that could be monitored experimentally [4]. Observations are made by using a microscope with a large frontal distance and the experimental pictures are treated by image processing.

The choice of the family of fitting functions has been guided by the following requirements: i) the fit parameters must be geometrically significant, ii) their number is restricted to the minimum in order that their variation from shape to shape be relevant, iii) the geometry near the cell tips must be parabolic., iv) the shape must involve asymptots in the grooves. This led us to chose a family of fitting functions involving two free parameters only, each being physically relevant to the description of either the tip region or the grooves. Taking the z-coordinate parallel to thermal gradient and pointing towards the liquid zone, and the second coordinate x in the sample plane, the generating function of the chosen family may be written : $\underline{z} = - b/(2a)\ \mathrm{atanh}(\underline{x}^2)$, where atanh is the inverse hyperbolic tangent and where z and x have been rendered non dimensional : $\underline{z} = z/b$ and $\underline{x} = x/b$. Parameter a corresponds physically to the tip curvature radius ρ, whereas 2b stands for the effective cell width at the bottom of the cell image. Each shape of the cell library could be finely fitted this way as a *whole*, i.e. from the tip to the grooves. Evolution of their geometry is displayed in figure 2, together with the variation of tip-undercooling, i.e. of tip position, with the control parameters.

Interestingly, it is found that the parameters a and b vary very smoothly with the control parameters (L,V,G) with no discontinuity or slope breaking, even at the onset of sidebranching. This makes the fit parameters (a,b) easily linked to the control parameters by power laws : $a= 0.097\ L^{3/4}V^{-1/4}G^{1/2}$ and b = 0.43 L, where the units of a, b and L are μm and where V and G are expressed in μm/s and in K/cm.

The absence of shape transition at the occurrence of sidebranching confirms that sidebranching does not refer to a change of branch of solution [4]. The variation of parameter a with cell spacing ($a \approx L^{3/4}$) deviates from the pure geometrical similarity expected at zero Péclet number. Its variation with velocity ($a \approx V^{-1/4}$) also significantly differs from the well-known relationship $\rho^2 V$ = constant that is well documented in free growth [6] and which is actually expected in directional growth at infinite Péclet number.

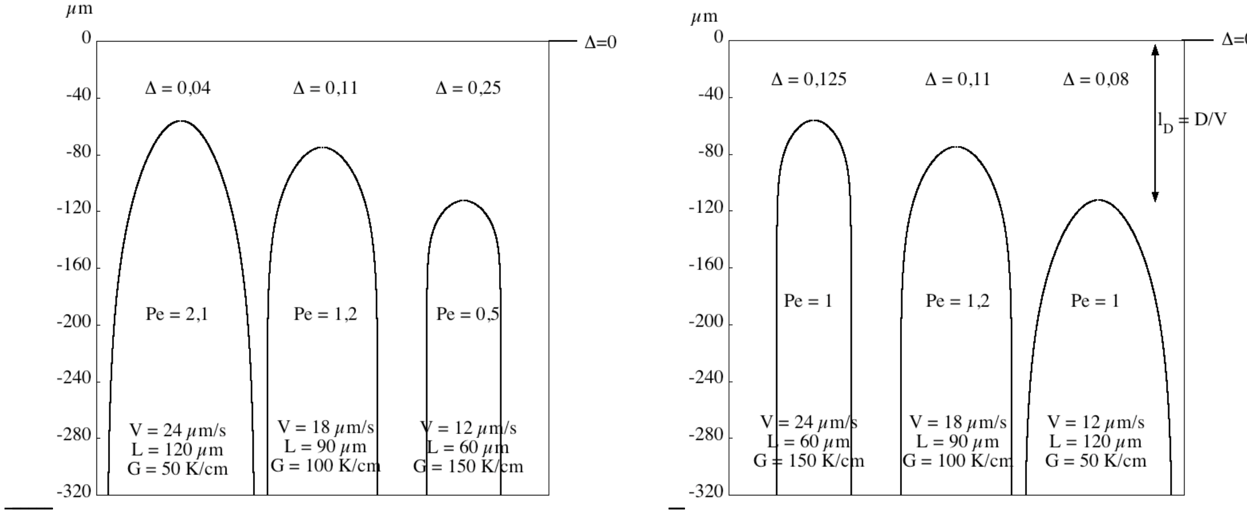

Fig 2 : Examples of cell geometries ranging from large sharp shapes to thin rounded shapes. Lines correspond to the shapes recovered by the fitted function with adequate parameters. The position of cell tips have been set so as to correspond to the undercooling relationship determined in [5], The Péclet number and the solutal diffusivity are denoted Pe=LV/D and D respectively.

CONCLUSION

We have achieved the first characterization of the *whole* geometry of cells in directional solidification both in the real space and in the control parameter space. This determination would worth be recovered by simulation or theories, not only on a given cell, but also on the whole cell library, so as to improve our understanding of directional growth. In addition, applying theoretical or numerical stability analysis to these cell profiles would help us better clarify cell stability, in particular regarding sidebranching.

References

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