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Microgravity studies of solidification patterns in model transparent alloys onboard the International Space Station

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We review recent *in situ* solidification experiments using nonfaceted model transparent alloys in science-in-microgravity facilities onboard the International Space Station (ISS), namely the Transparent Alloys (TA) apparatus and the Directional Solidification Insert of the DEvice for the study of Critical Liquids and Crystallization (DECLIC-DSI). These directional-solidification devices use innovative optical videomicroscopy imaging techniques to observe the spatiotemporal dynamics of solidification patterns in real time in large samples. In contrast to laboratory conditions on ground, microgravity guarantees the absence or a reduction of convective motion in the liquid, thus ensuring a purely diffusion-controlled growth of the crystalline solid(s). This makes it possible to perform a direct theoretical analysis of the formation process of solidification microstructures with comparisons to quantitative numerical simulations. Important questions that concern multiphase growth patterns in eutectic and peritectic alloys on the one hand and single-phased, cellular and dendritic structures on the other hand have been addressed, and unprecedented results have been obtained. Complex self-organizing phenomena during steady-state and transient coupled growth in eutectics and peritectics, interfacial-anisotropy effects in cellular arrays, and promising insights into the columnar-to-equiaxed transition are highlighted.

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INTRODUCTION

Solidification microstructures in alloys largely determine the properties of materials, and their characterization is of utmost interest in industrial research. It is common practice to identify those microstructures *ex situ* under the microscope and to measure their morphological features with full knowledge of the chemical nature of individual compounds and the physical properties of the mixture. Most often, however, information is lacking on the actual solidification path during the cooling process, and a clear interpretation of how the distribution of the microstructures in the bulk solid occurred cannot be achieved. The central question—how, upon cooling, a heterogeneous crystalline solid forms from a homogeneous liquid mixture—is actually strikingly complex when considered on a fundamental level^{1–3}. Frozen-in or as-cast microstructures form out of equilibrium. They arise from self-organizing processes during growth at the advancing interface between the solid and the liquid. Some characteristic lengths and their approximate scaling with microscopic properties and control parameters can be derived theoretically. A scaling analysis is however insufficient: spatiotemporal phenomena during solidification depend on boundary conditions, initial conditions, and the whole history of the process⁴. Theoretical challenges are primarily associated with steady-state shapes and patterns, their morphological stability against symmetry breaking, and the formation of long-lived stacking defects within basically periodic arrangements. In addition, this dynamics can be influenced by instrumental characteristics and by the crystalline structure of the growing solid—being a single- or a polycrystal or made of crystals of

different phases—via the so-called interfacial anisotropy. Such challenging issues call for fundamental research based on *in situ* experimental diagnostics, using systematic protocols guided by the general concepts of the nonlinear physics applied to solidification phenomena⁵.

In this review, we will report on recent observations made during microgravity solidification experiments using model transparent alloys. Focus is placed on unprecedented results obtained with two devices installed onboard the International Space Station (ISS), namely, the Transparent Alloys (TA) apparatus of the European Space Agency (ESA)⁶ and the Directional Solidification Insert of the DEvice for the study of Critical Liquids and Crystallization (DECLIC-DSI) developed by the French National Center for Space Studies (CNES)⁷ in close collaboration with NASA. Two distinctive features and strengths of this scientific research are worth underlining. First, considering the long characteristic times of the targeted phenomena, the ISS is the only facility that provides a stable reduced-gravity environment for experimental campaigns that typically require several weeks. Access is thus given to dynamic phenomena that are difficult to reproduce in a laboratory due, in particular, to the interaction of the solidification with convective motion in the liquid. High-quality experiments in essentially diffusion-controlled crystal growth conditions are key to a direct comparison with numerical simulations and an unequivocal identification of the relevant physical and geometrical parameters. Second, transparent alloys that freeze like metals⁸ have been used for many decades as model systems for *in situ* experimental studies of solidification patterns^{9–12}. The shape of the solid growing from the liquid mixture can then be followed in

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