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On the interest of microgravity experimentation for studying convective effects during the directional solidification of metal alloys

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ABSTRACT

Under terrestrial conditions, solidification processes are often affected by gravity effects, which can significantly influence the final characteristics of the grown solid. The low-gravity environment of space offers a unique and efficient way to eliminate these effects, providing valuable benchmark data for the validation of models and numerical simulations. Moreover, a comparative study of solidification experiments on earth and in low-gravity conditions can significantly enlighten gravity effects. The aim of this paper is to give a survey of solidification experiments conducted in low-gravity environment on metal alloys, with advanced post-mortem analysis and eventually by in situ and real-time characterization.

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1. Introduction

Structural material properties are directly related to their solidification microstructures, so that a precise control of the growth process is crucial in engineering [1]. Depending on the applied processing parameters and on the material physical parameters, a wide variety of solidified microstructures are observed in casting, in welding, and in other solidification processes. The most common structure is dendrite, which can be either equiaxed, when solidification occurs in nearly isothermal conditions like in the case of a snowflake, or columnar in the presence of a temperature gradient. Depending on the application, one type of grain structure is preferred and thus favored, e.g., equiaxed grains in car engines and columnar grains in turbine blades. These patterns can be described by suitable length scales such as dendritic primary spacing and tip radius. In pure diffusive transport regime, characteristic laws have been proposed to relate those shape characteristics to processing conditions. However, for most real solidification processes, and especially at low growth rate, gravity effects such as natural convection, sedimentation/buoyancy, mechanical effects and change in hydrostatic pressure cannot be neglected and significantly affect morphological instability [2]. The coupling between gravity effects and solidification has been the subject of a great deal of experimental, theoretical and numerical works since the birth of microgravity experimentation in the early eighties. The main conclusion of all these studies is that gravity is the major source of various disturbing effects, which can significantly modify or mask important physical mechanisms on Earth ($1g$). A review of some effects induced by gravity on the solidification process and investigated by mean of synchrotron X-ray radiography at the ESRF (European

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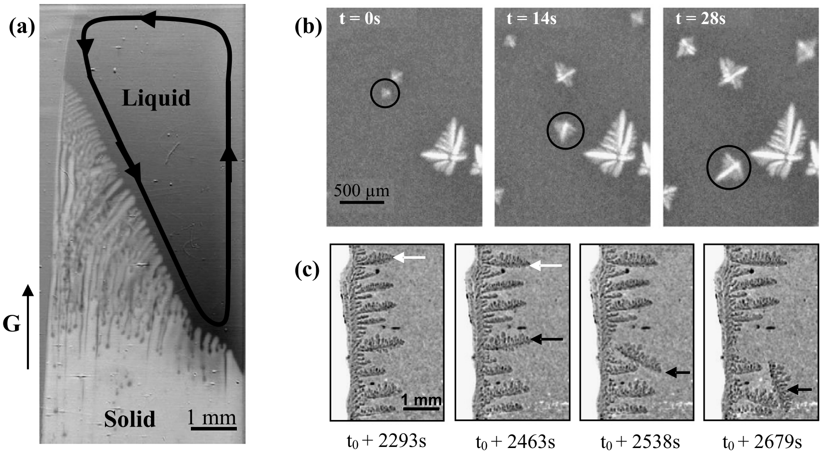

Fig. 1. In situ observation of gravity effects during direction solidification. (a) Deformation of the solid–liquid interface due to a convection loop forming during directional solidification of Al–4wt.%Cu (cooling rate = 0.3 K/min, temperature gradient = 35.5 K/cm). (b) Sequence of radiographs recorded during Al–10wt.%Cu equiaxed solidification showing the sedimentation of equiaxed grains. (c) Radiographs showing the bending and the fragmentation of secondary arms during the development of a columnar dendrite of Al–7wt.%Si (cooling rate = 0.5 K/min, temperature gradient = 15 K/cm).

Synchrotron Radiation Facility) in thin aluminum-based alloys is presented elsewhere [2], namely convection effects on the solid–liquid interface during the initial transient of solidification [3] (Fig. 1a), the sedimentation or floatation of equiaxed grains (Fig. 1b), and its effect on the columnar-to-equiaxed transition [4,5], and finally the cumulative mechanical moments induced by gravity on the dendrite during solidification [6,7], leading to the bending of the secondary arm of the dendrite (Fig. 1c).

Numerous experiments in microgravity conditions have shown that microgravity (μ*g*) environment is a unique and efficient way to eliminate buoyancy and convection to provide benchmark data for the validation of models and numerical simulations. For these reasons, materials science and more particularly solidification of metal alloys has been a prominent topic of research in the microgravity field, since the early stages of microgravity experimentation. In a microgravity environment, transport phenomena are essentially diffusive and buoyancy forces vanish, which highly simplifies the experiment's analysis and allow a more direct and precise comparison with theoretical models [8]. Let us mention here the outstanding experiment IDGE (Isothermal Dendritic Growth Experiment), performed in low-earth orbit by M.E. Glicksman and co-workers [9–13]. The IDGE was developed specifically to test dendritic growth theories by performing measurements with succinonitrile (SCN) and pivalic acid (PVA) under strictly diffusion-controlled conditions. The IDGE instrument was flown three times aboard the space shuttle Columbia, as part of NASA's missions, from 1994 to 1997 [12]. This series of experiments (hundreds of repeated experiments of steady-state dendritic growth) provided the first solid evidence that dendritic growth is indeed governed by heat diffusion from the solid–liquid interface. However, experiments also showed that Ivantsov's solution describing the diffusion process for a paraboloid crystal tip requires some modifications. The tip velocity and tip radius data were measured as functions of the initial undercooling and Glicksman's analysis indicated that, at least for pure SCN, the average scaling factor $\sigma^* \sim 0.02$ is a value that is independent of both undercooling and gravitational environment. The robustness of the interfacial scaling law, namely $VR^2 = \text{constant}$, where V is the velocity of the tip and R is the curvature radius at the tip, appears to be independent of the gravity environment, with a slight dependence on undercooling.

In addition, comparative studies of solidification experiments in 1*g* and μ*g* can also enlighten the effects of gravity. A demonstrative example of such a study on this topic is the work performed by M.D. Dupouy, D. Camel and J.-J. Favier in the early 1990s by post-mortem analysis of Al–Cu samples solidified during the D1 – Spacelab mission [14–16]. Low-concentration (1wt%) hypo- and hyper-eutectic alloys (26wt% and 40wt%) were directionally solidified under a temperature gradient of 25 K/cm. The influence of gravity on the structural transitions (dendritic/eutectic and cell-dendrite transitions), the difference between the space and ground samples primary spacing and the dendritic array morphology were thoroughly analyzed, showing a strong impact of the transport mode in the melt. In particular, the primary arm spacing was found five times larger in space than on Earth [14–16].

The results presented in this article are a selection of microgravity solidification experiments carried out by our team onboard two platforms (American shuttle and sounding rocket) on aluminum-based alloys. For each experiment, we first briefly describe the scientific objectives, the apparatus and the experimental procedure. Then we present the most significant results obtained in the framework of the experiments conducted in gravity-reduced conditions, and the effects of gravity-free conditions will be enlightened. We omitted in this review the recent experiments performed on the International Space Station on transparent alloys [17,18] or on Al–Si alloys [19,20], whose detailed analysis is still ongoing and would deserve a longer paper.

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