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Influence of gravity level on Columnar-to-Equiaxed Transition during directional solidification of Al − 20 wt.% Cu alloys

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ABSTRACT

Solidification experiments on refined and non-refined Al–Cu alloys were carried out on Earth and during two parabolic flights to investigate the influence of gravity level upon solidification dynamics. In situ and real-time monitoring of the microstructure formation was characterized by using an X-ray radiography device based on a microfocus X-ray source. This paper presents for the first time direct observation of metal alloy directional solidification under varying gravity level. By a comparative study between the experiments, the influence of gravity on fragmentation and dendrite fragments transport was enlightened. In addition, a spectacular transition from a columnar to a fully equiaxed microstructure was revealed when there is a sharp increase of gravity level. It was shown that this phenomenon is a consequence of a sudden increase of the liquid undercooling ahead of the columnar front accompanying the change in hydrostatic pressure.

1. Introduction

In casting processes, the final microstructure in the ingot and thus the accompanying macrosegregation are the result of the competition between the growth of columnar and equiaxed grains. In general, the ingot can be divided into an outer columnar microstructure (where the growth is preferentially oriented perpendicular to the mold walls) and an inner region (where equiaxed grains are growing in all space directions). The transition from a columnar microstructure to an equiaxed microstructure (CET) is induced by a coupled decrease of the temperature gradient at the solid–liquid interface and an increase of the solidification rate, both depending on the rate of heat removal at the chill. It is well known that the equiaxed microstructure leads to a material with more isotropic macroscopic mechanical properties and a more homogeneous composition field than columnar microstructure. As a consequence, it is critical for industrial applications to precisely control the formation of the microstructures. This requires a clear understanding of the successive steps that take place during CET [1]. Firstly the columnar growth (dynamics of microstructure formation and selection of solidification patterns [2]), then the transition itself (origin of nuclei ahead of the columnar front in non-refined [3] and refined alloys [4], interaction between growing equiaxed grains and columnar front leading to the CET [5–11]) and eventually the equiaxed growth (density, size, and shape of equiaxed grains) [12–14], grain transportation [15] and effective front propagation [16,17].

Furthermore, the influence of gravity on CET has been clearly recognized, but the complete mechanism by which it operates is still a pending question. Firstly, gravity induces natural convection in the melt, which dramatically modifies heat and solute fluxes ahead of the solidification front, and therefore can strongly affect the liquid undercooling (i.e. the conditions for the occurrence of the transition) [18]. Moreover, for non-refined alloys, fragmentation process in the mushy zone is the most potent mechanism for the formation of an equiaxed microstructure. However, the origin of the fragmentation is still a controversial topic. Thermal remelting [3,19] and dissolution [20–25] are generally invoked to cause dendrite fragmentation. However, comparison between experiments in terrestrial and microgravity conditions in Al − 20 wt.% Cu shows that fluid flow can have a significant impact on the fragmentation process [26]. This is confirmed by solidification with

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forced convection generated by magnetic fields, either permanent [27] or alternating [28], or a forced convection loop [19]. So far, it is difficult to accurately determine the relative contributions of the solute transport in the mushy zone, which may accelerate the dissolution mechanism of secondary arm necks [3,21,23], and of mechanical effects such as the addition of a torque on the secondary arms [29–32]. In refined alloys, equiaxed grains nucleate on refiners acting as preferential sites for heterogeneous nucleation and fragmentation can usually be neglected as origin of new grains. However, transport of inoculant particles by fluid flow during the columnar growth might affect the CET, in particular during casting [33]. Secondly, after the nucleation of equiaxed grains ahead of the columnar front, the dominant effects associated to gravity is the grains transportation by fluid flow and the action of buoyancy force. Indeed, depending on the respective densities of the grains and the surrounding liquid, grains can either sediment and interact with the columnar front [14,34], or being transported away in the bulk liquid [15,26]. Thirdly, gravity is at the origin of mechanical effects, which can induce the bending of secondary arms when the latter are long enough. Indeed, the bending phenomenon precedes the dendrite fragmentation in several cases [30,32]. Finally, a less common issue related to gravity is the hydrostatic pressure in the melt, despite his well-known impact on human body during space travel. Hydrostatic pressure applied during solidification significantly reduces the formation of porosities by enabling the liquid to fill empty spaces. On the contrary, in microgravity conditions, hydrostatic pressure vanishes and the liquid shape is only determined by the surface tension and the wetting behavior of the melt on solid surfaces. Hence, the loss of hydrostatic pressure in the melt can cause shrinkage and the formation of voids along the sample during microgravity experiments [35]. Therefore, a deeper understanding of gravity effects in solidification microstructure is of great importance for scientists and industrials alike.

In the present study, we report series of directional solidification experiments on refined and non-refined Al − 20 wt.% Cu alloys performed in terrestrial laboratory and during two parabolic flights. The motivation was to enlighten the influence of gravity level, as well as variation of gravity level, on the formation and selection of solidification microstructure. This work is part of the CETSOL (Columnar-to-Equiaxed Transition in Solidification Processes) and XRMON (In situ X-ray monitoring of advanced metallurgical processes under microgravity and terrestrial conditions) projects, funded by the European Space Agency (ESA). Most phenomena occurring during CET in metallic alloys, and the different open issues mentioned previously, are in essence dynamical and intricately interact with each other. As a consequence, it is of major interest to be able to investigate the time evolution and dynamical selection of the dendritic columnar and equiaxed microstructures. Hence, X-ray radiography, which allows direct observation of solidification processes in metallic alloys [36], was utilized during all experiments and in particular during the parabolic flight campaigns.

2. Experiments

2.1. XRMON-PFF facility

To deepen our understanding of the influence of gravity level, as well as variations of gravity level, on the Columnar-to-Equiaxed Transition, solidification experiments were planned on Earth, with a constant gravity level, and during two parabolic flights, with time-varying gravity level. For that purpose, a solidification furnace with an X-ray radiography system, entitled XRMON-PFF (Parabolic Flight Facility), was specifically built by SSC (Swedish Space Corporation) to be fitted in the Airbus A300 Zero-G operated by Novespace (www.novespace.fr) [37]. This facility is quite similar to that described in detail in Refs. [38,39], which was used during the MASER-12 sounding rocket. It is composed of two racks (Fig. 1a): one containing the experimental apparatus (Fig. 1b) and the other for the electronics and control system. The solidification device is a two-zone furnace, with a longitudinal temperature gradient imposed by two heaters separated by a gap. The gradient furnace enables directional solidification with thermal gradients within a range of 5–15 K/mm. The heater gap has a “hole” of 5 mm × 5 mm for the X-ray transmission. The X-ray radiography system figures a microfocus X-ray source with a molybdenum target and a 3 μm focal spot (Fig. 1b). It provides a sufficient photon flux with two peaks of energy at 17.4 keV and 19.6 keV that ensure a good image

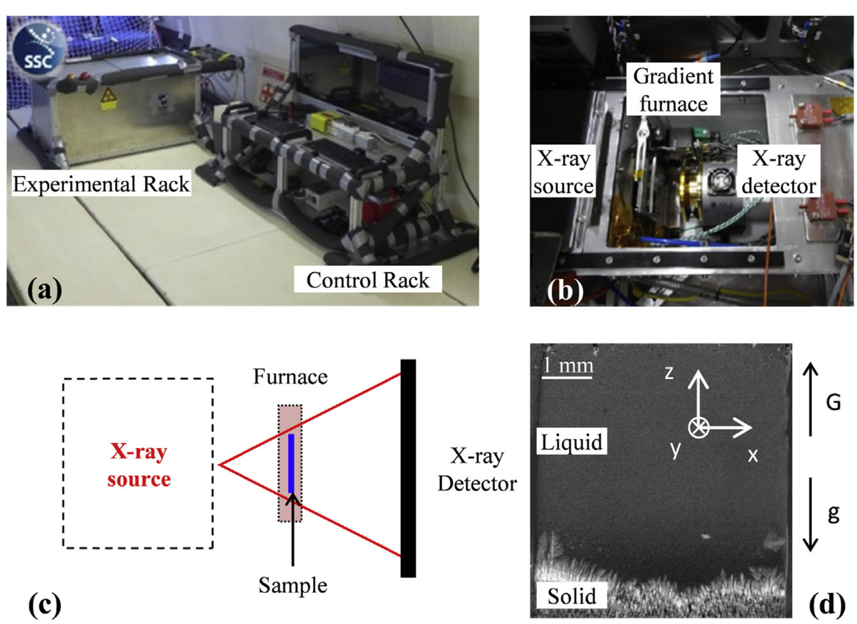

Fig. 1. (a) XRMON-Parabolic Flight Facility in Novespace Airbus A300 Zero-G, (b) Picture of the solidification furnace and X-ray systems in the experimental rack, (c) Sketch of the X-ray radiography system, (d) Example of radiograph after image processing.