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Sub-mm sized bubbles injected into metallic melts

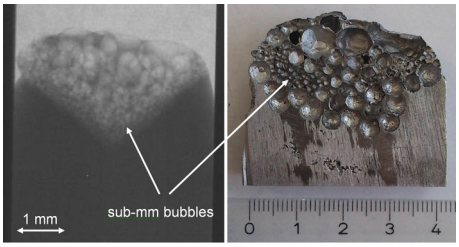
F. García-Moreno[a,b,*], B. Siegel[a], K. Heim[a,b], A.J. Meagher[a,b], J. Banhart[a,b]

[a] Tecnical University Berlin, Hardenbergstraße 36, 10623 Berlin, Germany
[b] Helmholtz Centre Berlin for Materials and Energy, Hahn-Meitner-Platz 1, 14109 Berlin, Germany

HIGHLIGHTS

- The bubble size decreases upon reducing the cannula diameter.
- The bubble size decreases upon increasing the gas flow rate.
- The bubble size decreases by oscillating the cannula.
- Sub-millimetre bubbles can be produced, stabilised and collected as foam.
- Small bubbles with a narrow size distribution tend to align in planes.

GRAPHICAL ABSTRACT



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ABSTRACT

Liquid metal foams containing small equally sized bubbles are expected to be stable, with high liquid fractions. We concentrate on foaming processes of Al-alloy melts following the gas injection route and review briefly the theory about bubble formation in a liquid by gas injection. Several strategies of reducing the bubble size are presented. We discuss how the size and geometry of the gas injector, the gas pressure control and the oscillation of the injector influence bubble size. We also combine some of the strategies and demonstrate that it is possible to produce sub-millimetre bubbles in liquid Al-alloy by gas injection. X-ray observation of the process allows us to evaluate in situ the changes in bubble size during foam formation in the molten state. Through metallographic cross-sections we can corroborate the bubble size distribution once cooled down and solidified. Alignment of bubbles could be observed and, therefore, even ordering could be possible in future as it is the case in aqueous foams. Finally, we compare metal foam with aqueous foams, emphasising similarities and differences, and discuss possible applications of micro cellular metal foams.

1. Introduction

Aluminium foams combine good mechanical properties such as high stiffness, high energy absorption or damping capabilities with low density [1]. One well-known method to produce closed-cell metal foam is the injection of gas into a melt [2–5] to which μm-sized solid particles (e.g. SiC, TiB_2, Al_2O_3 or $MgAl_2O_4$) have been added for stabilisation [5–12]. These particles can be added directly to the melt or synthesised in situ by chemical or metallurgical reactions [13–15]. The precise interactions that stabilise particle-reinforced foams are not yet known and subject of current and recent research [6,16–18]. It is known from studies of single liquid metallic films, that serve as a model for isolated cell walls, that films are more stable the smaller their area is [19]. Obviously, to achieve smaller film areas smaller bubbles are required. Additionally, according to the Young–Laplace law, smaller bubbles possess a higher inner gas pressure and their curvature becomes more spherical. The corresponding foams become wet under the influence of

* Corresponding author at: Helmholtz Centre Berlin for Materials and Energy, Hahn-Meitner-Platz 1, 14109 Berlin, Germany. Tel.: +49 30 806242761; fax: +49 30 806243059.
E-mail address: garcia-moreno@helmholtz-berlin.de (F. García-Moreno).

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capillary action, as it can be observed in aqueous foams [20]. Films are then strongly curved and the area in which their thickness is close to the critical cell wall thickness (40–100 μm) [21] is small.

Large pores in metal foam components lead to pronounced statistical scatter of properties, while isolated centimetre-long cavities may even be a source of structure/mechanical failure. The frequent occurrence of such pores is a drawback for commercial breakthrough. Therefore, it is desirable to have a more uniform cell size distribution and smaller cell sizes, preferably in the sub-millimetre range. There is a clear and well-known dependence of the mechanical properties of metal foams from density [1,22] and theoretical models to describe the relationship [23]. Metal foams with sub-millimetre bubbles are assumed to be superior concerning mechanical properties due to their more spherical structure independently from a higher density, but there is no reliable proof of this until now. It is challenging to vary bubble sizes and foam liquid fraction – corresponding to foam density after solidification – independently, as they are linked to each other [24]. Another argument for small pores is that even if their size dispersion is the same as for large pores, a given component would contain more pores, which leads to less variance of mechanical properties since the chance of big cavities or structural defects is reduced.

In the present work, we apply different strategies to reduce the diameter of bubbles created by gas injection into a melt and combine several of them to achieve metal foams with sub-millimetre bubbles. We discuss the different mechanisms leading to smaller bubbles.

2. Experimental

2.1. Material

AlSi9Mg0.6 (in wt.%) + 20 vol.% SiC particle (10 μm mean diameter), also commercially known as F3S20S, was molten and cast into a graphite mould of 70 mm × 15 mm × 35 mm size. This geometry facilitated remelting the sample inside an X-ray transparent furnace where gas injection experiments were conducted. To avoid particle settling the melt was held in the liquid state as short as possible and stirred before the experiments to provide a homogeneous particle distribution.

2.2. X-ray imaging

To image the gas injection process in liquid melts and to study the influence of parameter changes on bubble size we used an X-ray radioscopy setup composed of a micro-focus X-ray source and a flat panel detector, both from *Hamamatsu*, Japan (Fig. 1a). In this source, electrons are accelerated by a voltage of 100 kV at a current of 100 μA and are focused onto a tungsten target within a spot size down to 5 μm. The emerging conical X-ray beam is transmitted by the X-ray transparent furnace windows made of 2-mm thick BN plates with little absorption, but absorbed partially by the 20-mm thick Al alloy melt. For our experiments, a magnification factor of 1.2, corresponding to a pixel size of 42 μm is used and images are acquired at 1 fps. To allow for a higher imaging rate of 4 fps, 4 × 4 binning of detector pixels was also carried out.

2.3. Foaming

Fig. 1b shows a sketch of the gas injection furnace. The foaming chamber comprises two TiN heating plates with embedded carbon heating lines with a total power of 1200 W. They are oriented in parallel to the X-ray direction and covered with BN spray. The two 2-mm thick BN plates are oriented perpendicular to the heating plates and act as X-ray windows and a crucible for both the melt and the foam. Due to the heat insulation applied temperatures above 750 °C can be reached. The heating profile is controlled by a temperature controller *CAL 3300* from *CAL controls*, USA, and the corresponding reference temperature is measured directly at the melt by a thermocouple. A further thermocouple located at one of the heating plates protects the system from overheating. Foam is produced in the foaming chamber by first introducing the thin cannula into the melt from below driven by a stepper motor before conducting gas through this cannula. The motor also allows one to oscillate the cannula in the vertical direction with parameters ranging from 1.5 mm amplitude at 1 Hz up to 0.5 mm amplitude at 20 Hz. Argon (99.999% purity) was used as a foaming gas. Commercially available stainless steel cannulas with an inner diameter d_i = 0.2 mm and an outer diameter of d_o = 0.5 mm with either epidural, cylindrical or conical shape were used. Additionally, a smaller cannula with a reduced sickle-shaped opening was created by inserting a stainless steel wire of a diameter d_o = 0.15 mm

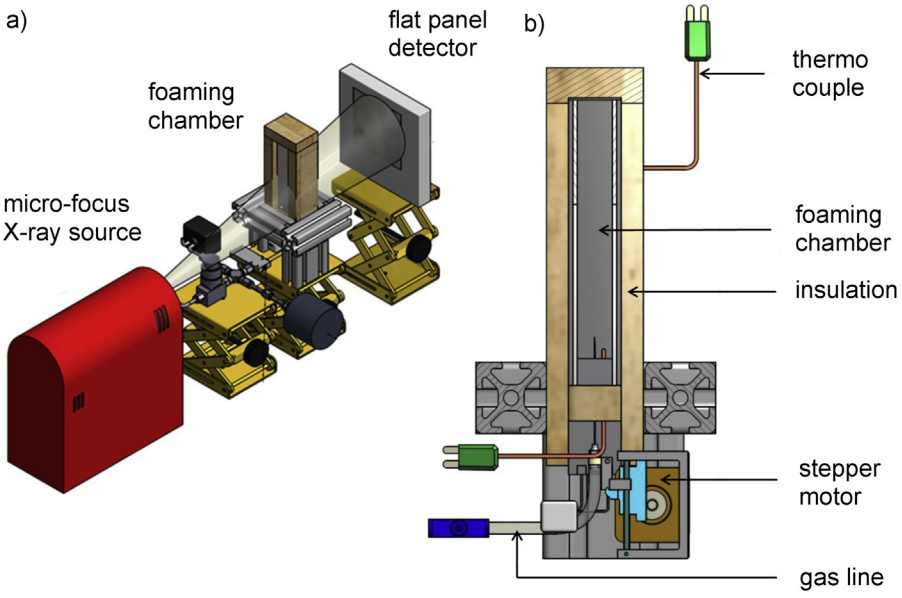

Fig. 1. (a) X-ray radioscopy setup composed of a micro-focus X-ray source, the foaming chamber and a flat panel detector and (b) sketch of the foaming chamber.