Optimisation of Mould Filling during PM Metal Foaming

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Abstract

Different problems with manufacturing uniform metal foams by filling moulds and following the powder metallurgical foaming route were identified and analysed. To solve some of these problems, we studied foaming in cylindrical and rectangular moulds under different conditions by means of *in-situ* X-ray radioscopy. We found which precursor configuration is suitable to achieve a better foam uniformity for cylindrical moulds. Moreover, we applied foaming supported by gas pressure variations. Gas pressure release at a desired temperature allows us to trigger foam expansion. This way foam expansion takes place in a few seconds and the precursors can be expanded up to the point desired, controlling exactly the mould filling. This method leads in an increase of pore size homogeneity and improves the uniformity of density distribution.

1 Introduction

Metallic foams can be produced by the powder metallurgical route (PM route). This route consists of mixing metal powders with a blowing agent, usually TiH_2, followed by hot compaction to a dense foamable precursor. The latter can be carried out via extrusion, rolling or uni-axial pressing (1). The bulk precursor is finally heated up in a furnace during which the evolving foam expands freely or in a mould. For filling a mould, one or more precursor pieces are placed inside the mould in a well distributed way. In the course of foaming, the precursor starts to expand due to the gas generated by the blowing agent. This process is very sensitive to thermal conditions and, therefore, a lot of effort was put into controlling temperature in a satisfactory manner. For industrial applications, the demand is focused onto uniformly dense foam pieces of a given shape produced in a mould (2). Additionally, uniform pore size distributions are often required. There are several factors known to influence the uniformity of pore structure and the extent of density fluctuations inside the foam, e.g. temperature gradients in the precursors (3) or the sometimes undefined precursor distribution inside complex moulds. The thermal contact points between precursor and mould determine heat flux and therefore the starting points of foaming. Moreover, due to the poor reproducibility of expansion even when using similar precursors, it is challenging to fill a mould by precisely 100%. Therefore, mostly an overflow in the mould is used which ensures complete filling but leads to material losses, foam flow and varying densities.

X-ray monitoring of the foaming process is a useful tool that can be used to visualise foam evolution inside a mould *in-situ*. Foam expansion dynamics and pore structure development can be observed, giving hints concerning structure formation and ways to improve foaming. In addition, quantitative analysis of expansion, density evolution or coalescence can be performed (4). The aim of this work is to identify some of the problems associated with mould filling with metal foam and to find favourable configuration of precursor arrangement inside a mould.

2 Experimental

Foamable precursors were produced following the PM route. The aluminium alloys selected for the experiments were standard foaming alloys like AlSi6Cu4, AlSi9 and AlSi11. Elemental powders were mixed with 0.5 wt.% TiH_2 and then either uniaxially hot compacted (15 min, 400 °C, 300 MPa) or extruded (325 °C). Square (side width = 16 or 36 mm) or cylindrical (length = 10 or 100 mm, diameter ≅ 35 mm) tubes were used as moulds (FIGURE 1). Some of the cylinder moulds where prepared for X-ray observation by replacing the two 2-mm thick end caps of the tube by 0.2-mm thick stainless steel foils to permit X-ray transmission in axial direction. The cylindrical moulds were loaded with precursor material in different ways and placed inside a pre-heated furnace. The configurations used included vertical and sample centred (VC), horizontal and sample down (HD) and horizontal and sample centred (HC) (FIGURE 2). The cylindrical precursors used here were extruded ones, with nearly radial expansion, and therefore ideal for filling a cylindrical mould. Uniaxial compacted precursors were used for filling the square moulds.

FIGURE 1: Cylindrical mould used for different foaming configurations.

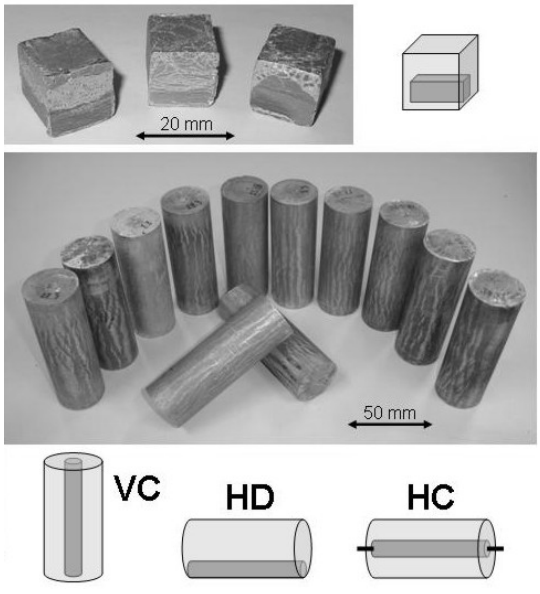

FIGURE 2: Square (up) and cylindrical foams (down) produced with different configurations of pre-cursor and mould.

X-ray radioscopy was used to observe the foaming process. Different X-ray transparent furnaces including a pressure furnace and a lamp furnace were used for this purpose. These systems are described elsewhere in detail (4,5). Additionally, a method for filling a mould with the assistance of gas pressure release was employed. It consists of pressurising the furnace chamber with argon at up to 20 bar prior to foaming. After heating the sample, uniform gas nucleation occurs. After the entire precursor has been melted, the gas pressure is released in a few seconds until the foam completely fills the mould. The heating power is switched off simultaneously, thus controlling the time between expansion and

solidification of the foam. X-ray tomography was applied to examine the foam pore structure in 3D. With help of the commercial software Avizo pore size distributions could be calculated.

3 Results and discussion

3.1 Problems during mould filling

It is known that temperature gradients inside the foaming furnace lead to inhomogeneous cellular structures in the foam (6). One reason is the very sensitive temperature response of blowing agent decomposition, of cell wall stability and of the coalescence rate of the liquid foam. Furthermore, we find an expansion dynamic coupled with time and temperature, with different pore coalescence and drainage (7). Using thermo-couples is a good way to control the temperature variations (3,8), but on the other hand we observed that they can work as heat sink and lead to an inhomogeneous foam expansion in their presence (FIGURE 3). This makes a good temperature control very hard, as the thermocouple itself modifies the temperature distribution. Furthermore, the influence of the thermal contact between mould and precursor was shown to induce a foaming expansion front from the contact surface at the mould wall (FIGURE 4). Quantitative analysis showed an expansion front moving with ~0.3 mm/s towards the top of the precursor.

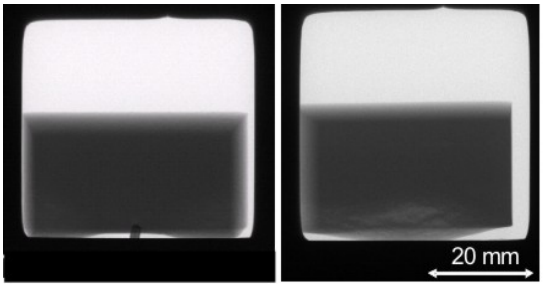

FIGURE 3: Influence of thermocouple in an expanding AlSi9 + 0.5 wt% TiH_2 precursor acting as thermal sink. Left: with thermocouple and right: without.

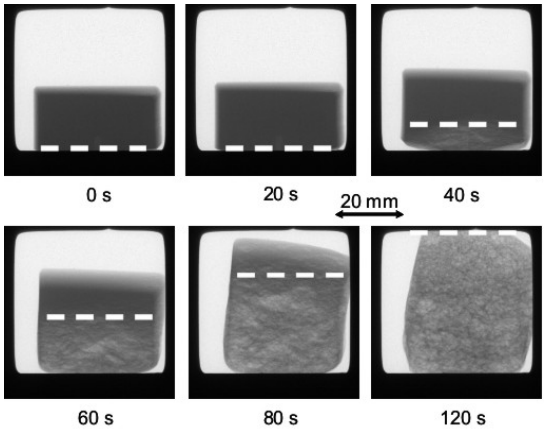

FIGURE 4: Radioscopic images of an expanding AlSi9 foam at T = 680 °C. White dash lines denote the expansion front moving with ~ 0.3 mm/s.

3.2 Filling a cylindrical mould with different configurations

Filling a cylindrical mould uniformly with metallic foam was found a challenging endeavour. Previous attempts with uniaxial pressed precursors showed the need of extruded precursors for improved symmetry (9). In our approach we tested different configurations (VC, HD and HC) described in the experimental part. All the samples have a satisfactory appearance from the outside, characterised by a smooth surface, see FIGURE 2. FIGURE 5 shows radioscopic images of representative foam cylinders foamed in each of these conditions. In these images the foams appear to have a regular cellular structure. Detailed observations and further analysis of the density maps reveal that there are still fluctuations in pore size and density (FIGURE 6). Due to the cylindrical geometry of the sample and under consideration of an almost parallel beam the attenuation curve should follow a circular function with $y = 2\sqrt{(1-x^2)}$ for a homogeneous density distribution in the HD and HC condition.

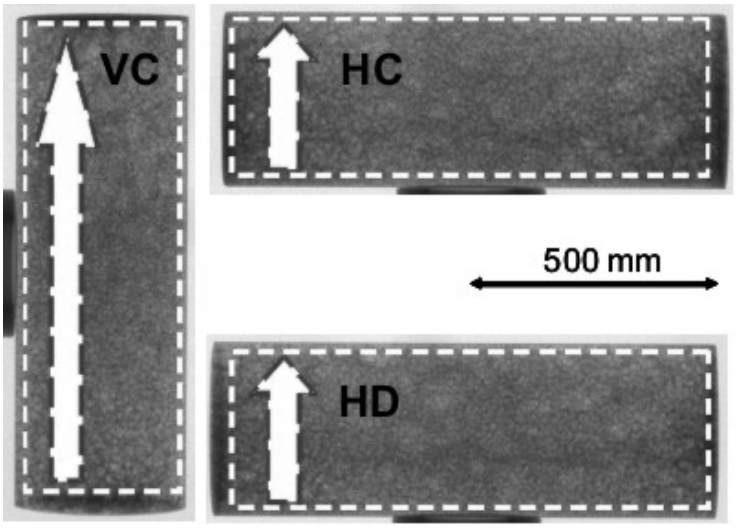

FIGURE 5: Radioscopic images of cylinders foamed under different configurations. The dashed lines denote the region used for density measurement. The arrows indicate the direction of density integration.

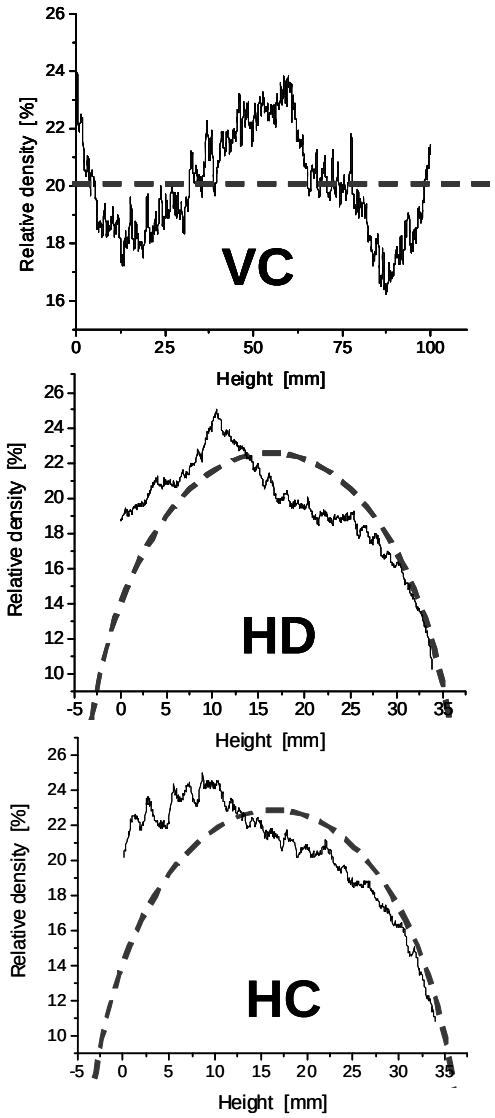

FIGURE 6: Foam density profiles of samples in FIGURE 5. Dash lines denote the expected result for a homogeneously distributed density.

Sample VC has two less dense regions in the first and last quarter of its length. The deviation from average density is about 2-4% of the relative density here. The low density region at the bottom can be explained by an increased temperature at the point of thermal contact between the precursor and the mould and a corresponding longer time spent in the liquid state. The upper low density region results from the temperature increase at the end of mould filling due to the contact of the foam with an overheated upper mould wall. The region in the middle is about 4% denser than the average and it seems that the precursor did not reach the same temperature here. Nevertheless, the are no radial density variations in the foams made under this configuration and therefore the density distribution has a cylindrical symmetry. For the HD and HC conditions, similar density profiles were found with a denser region at the bottom and a less dense part at the top, with a pronounced maximum in density at around 10 mm height (but smoother for HC) that nearly corresponds to the previous centre of the precursor. Although for both no cylindrical symmetry of the density distribution is achieved.

In-situ observation of foam development was performed on a small section of the cylindrical mould. Due to the radial symmetry of the mould and of the precursor expansion direction the results are believed to be representative for longer tubes. A series of images representing different stages during mould filling in configuration ‘HC’ is depicted in FIGURE 7. The radioscopic images show that the precursor in configuration ‘HC’ moves down during foaming as the

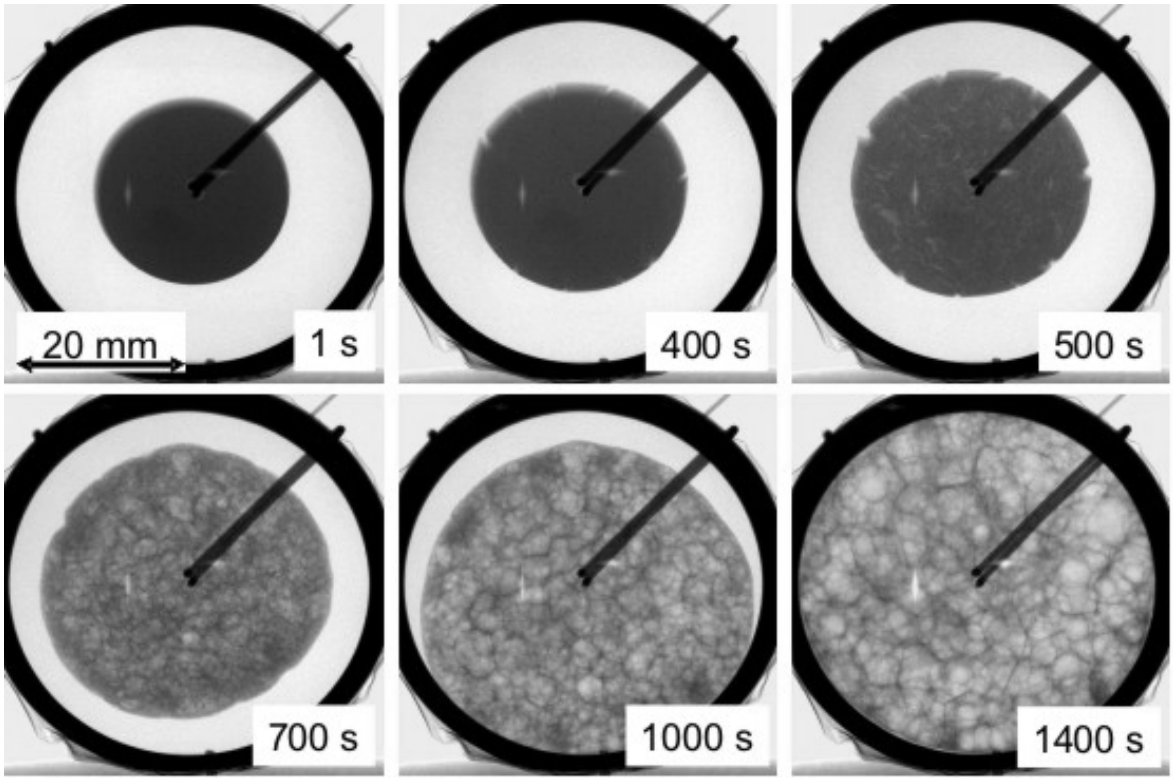

FIGURE 7: Series of X-ray images for different times since heating start of an extruded AlSi6Cu4 precursor expanding inside a cylindrical mould.

precursor softens and responds to gravity. Therefore, the bottom of the mould is filled first and towards the end of foaming overheating of the upper part again produces a region of lower density. This is the reason for the slight asymmetric density profile, although HC is the most satisfactory configuration.

3.3 Filling a square mould with pressure release assistance

The advantage of using pressure release for filling a mould includes a more homogeneous pore nucleation due to the high ambient pressure during melting. In addition, foam expansion is uncoupled from temperature, allowing for achieving a more controllable temperature distribution in the precursor and a precise control of the instant of mould filling. X-ray radioscopy is again a useful tool to optimise the process. As a result, very uniform foam cubes (16×16×16 mm^3) could be produced. The small sample sizes are a consequence of the limited space in the pressure chamber. The results show the

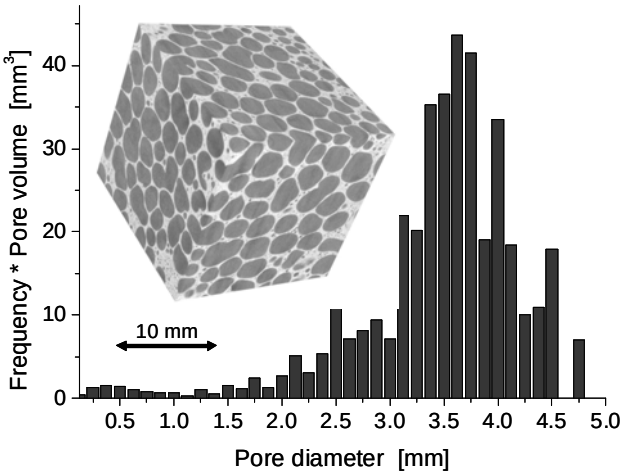

FIGURE 8: Tomographic reconstruction of an AlSi11 foam and the corresponding pore size distribution (d_{mean} = 3.6 mm).

potential of this method. In FIGURE 8 we present an example of the pore structure and distribution that can be achieved in AlSi11 foam with this method.

4 Conclusions and outlook

We have produced metal foams in cylindrical moulds under different configurations (VC, HD, HC) and found HC to be the most suited one for making uniform foams. Nevertheless, certain deviations in foam density (~ 2-4%) and pore sizes could not be avoided. We studied the foaming process in different mould geometries in-situ with X-ray radioscopy and could identify several problems during mould filling such as the adverse influence of thermocouples that can act as heat sinks. Additionally, problems associated with the limited thermal contact between some parts of the precursor and the mould were observed, leading to a foaming front inside the precursor moving with ~ 0.3 mm/s in the given configuration. Thermal gradients in the mould were found to influence mould filling and to yield non-uniform cell sizes. Improved density distributions and more regular cellular structure could be produced when foaming was assisted by pressure release. Thereby, the timing of the foaming process could be partially decoupled from the temperature course. It still remains a challenge to create a completely uniform foam in a mould. In future one could consider for in-situ observation some more improved configurations such as rotating the mould during foaming (10) or expanding a tube-shaped precursor from the inner surface of the mould to its inner (11).

Acknowledgements

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