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Effect of foaming configuration on expansion

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Foamed metals are attractive engineering materials offering, in particular, the benefit of a high energy absorbing capacity. The powder metallurgy route is an attractive method for making Al foam components as it offers the possibilities of near net shaping. Producing foam products from powders involves mixing and compacting metal powder with a gas-producing foaming agent such as TiH_2. The resulting precursor is then heated above the decomposition temperature of the foaming agent and the melting point of the metal powder. This causes the molten compact to expand, resulting in a highly porous material with closed cells [1, 2].

The process of foaming metal powders is very rapid, taking only a few minutes, and the structure and density of the foam changes dramatically with time during this process. In the initial stages, small round pores form which grow, coalesce and elongate and with further holding, and as the foaming agent is exhausted, the cells collapse resulting in an increase in foam density [3]. The rapid nature of the process makes reproducibility of the pore structure difficult to obtain. A number of different foaming configurations can be used, including the use of either free or constrained foaming and either single or multiple precursors [4]. This study investigates the effects of such configurations on foaming behavior and reproducibility.

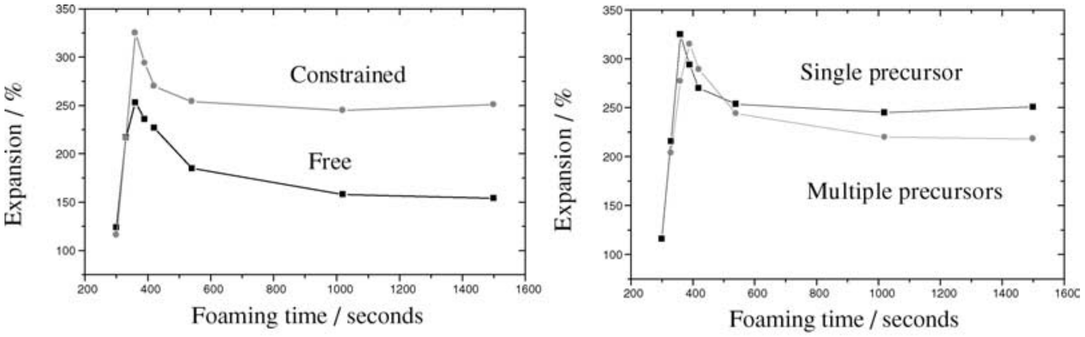
48 μm Al powder, 99.9% pure, was mixed with 0.6 wt% of 33 μm TiH_2 powder, 99.6% pure, in a turbula mixer for 20 min. Foamable precursors, with densities greater than 99% of theoretical, were produced using uni-axial compaction, to a pressure of 650 MPa, in lubricated tool steel dies. The precursors were heated for different times in an oven preheated to 800 °C, in air, whereupon the samples were removed from the furnace and cooled in air. 22 mm diameter samples, weighing 10 g, were foamed on a stainless steel substrate and in a vertically-standing 22 mm diameter stainless steel tube, both of which were coated in a boron nitride-based release agent. Five 13 mm diameter precursors, each weighing 2 g, were foamed together in the 22 mm diameter stainless steel tube in order to assess the effect of using multiple precursors to produce a single foamed piece. Single and multiple precursor samples, foamed in the tube and expanded to just below the maximum expansion, were sectioned into samples 22 mm in diameter and 18 mm long. The mechanical behavior of these samples under compression was measured using a JJ Lloyd testing rig at a cross head speed of 0.5 mm min^{-1}. Load-displacement data were recorded on a PC and converted to engineering stress and strain.

Fig. 1a presents the percentage foam expansions as a function of the heating time for the two different expansion methods. Both foaming methods show that a maximum expansion is reached after heating for 360 s, whereupon the foam starts to collapse. In the case of the freely expanding foam, the structure attains a maximum expansion of 253% and the collapsed foam tends to a "steady state" expansion of approximately 150%. For foaming in the tube, the maximum expansion is 325% and the collapsed foam tends to a "steady state" expansion of approximately 250%. The variability in foam density at the maximum expansion, measured by foaming 8 samples for 360 s, and expressed as the mean and one standard deviation, is 0.736 ± 0.055 g/cc for free foaming and 0.634 ± 0.018 g/cc for constrained foaming. These results indicate that significantly improved reproducibility in density is achieved when foaming in the tube.

The improved foam expansion in the tube is due to several factors. When foaming in the tube, the area of the expanding surface is smaller, and is invariant with foam expansion, thus reducing the work required to produce a change in volume. During expansion, the surface area across which gas can burst through the surface skin and cause cell collapse is also reduced, enabling larger expansions to be realized. Beyond the maximum expansion, and when large-scale collapse occurs for free foaming, the tube mechanically supports the foam. The work of adhesion between the liquid metal and the tube, which is positive even for non-wetting systems, supports the weight of the foam enabling large expansions to be maintained after long holding times. Reducing the influence of processes that contribute to large-scale foam collapse reduces the variability in foam density, improving the reproducibility.

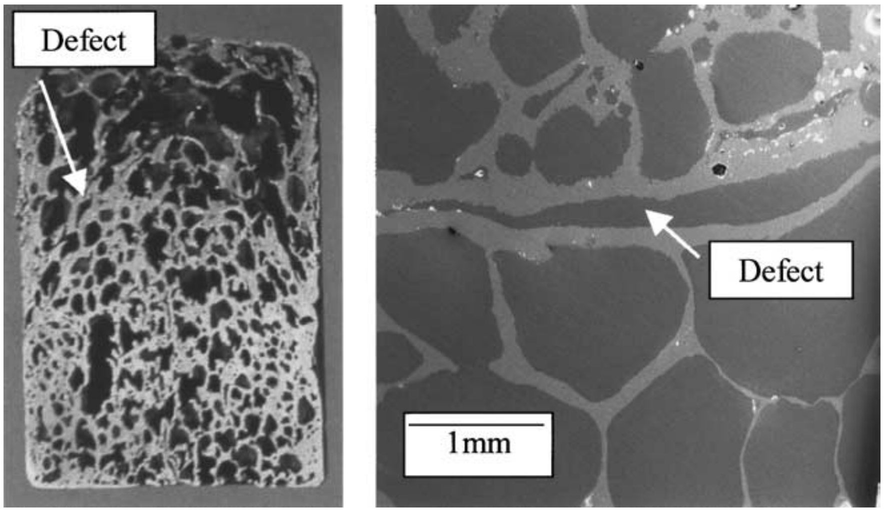
Fig. 1b compares the percentage foam expansions as a function of the heating time for single and multiple precursors. The maximum expansion is reached more slowly for the multiple samples, due to poorer contact and poorer heat transfer from the tube wall, and slightly lower maximum and "steady state" expansions, of 315 and 220% respectively, are observed. The variability in density, measured by foaming 8 sets of multiple precursors for 390 s, was 0.649 ± 0.024 g/cc, similar to that previously measured for constrained expansion of a single precursor.

Fig. 2a shows the pore structure for a multiple precursor sample expanded to approximately 150%. Discontinuous planes where the individual precursors meet are visible and indicated by the arrow. A higher



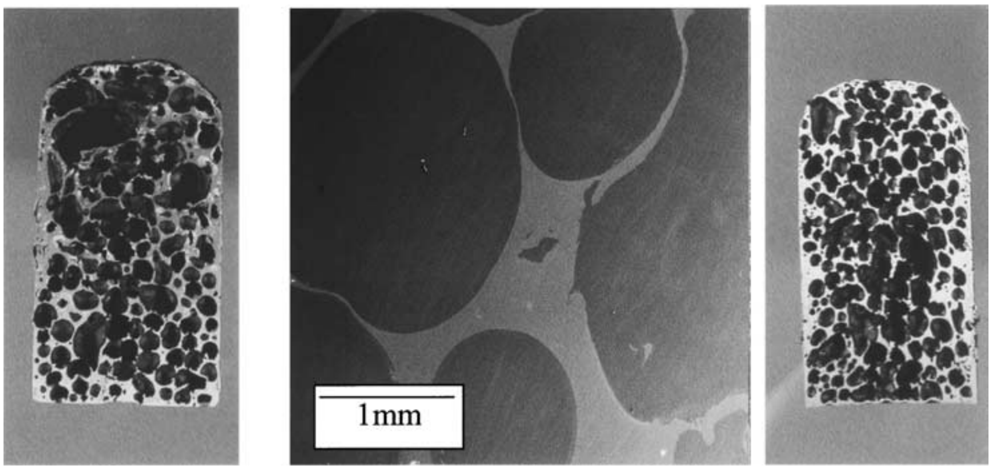
(a) (b)

Figure 1 Foam expansions as a function of holding time for (a) constrained and free expansion and (b) single and multiple precursors.



(a) (b)

Figure 2 Images showing defects caused by the merging of expanding precursors during the early stages of foaming.

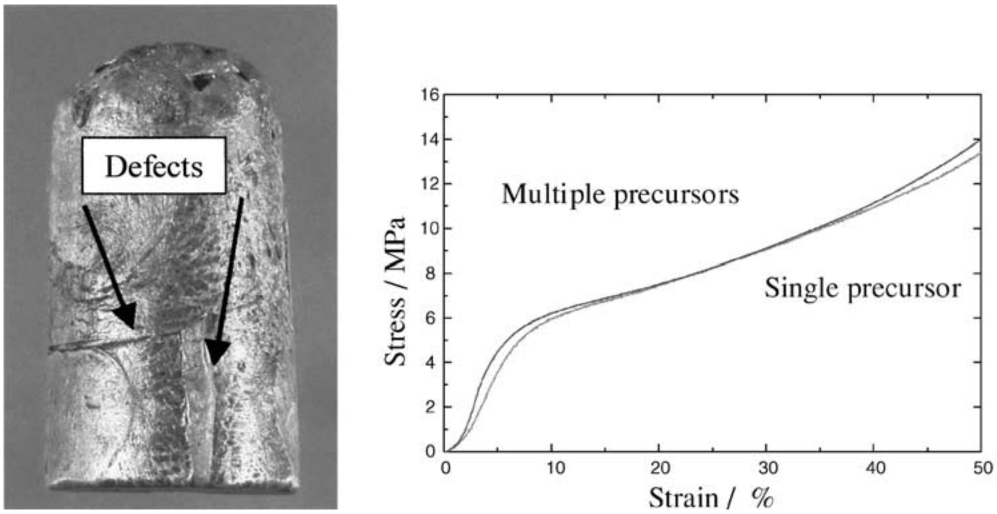


(a) (b) (c)

Figure 3 Images of pore structures for fully expanded samples with (a) and (b) multiple precursors and (c) a single precursor.

magnification scanning electron micrograph of this defect is shown in Fig. 2b. A gap is clearly observed between precursors that are in different stages of expansion, the lower precursor, nearer to the tube wall, has large pores and thin cell walls, the upper precursor having a less well developed foam structure and thick cell walls. The light phase observed is particles of the TiH_2 foaming agent.

As the expansion increases, however, the defects are no longer observed. Fig. 3a shows the pore structure for a multiple precursor sample expanded by approximately 200% and at this point the precursors have merged into what appears to be a single expanding body. Fig. 3b shows a scanning electron micrograph of the typical continuous cell structure observed. With larger expansions it is evident that the increased movement of liquid and relative motion between the expanding precursors eliminates the boundaries to produce a single expanding foam body similar to that presented in Fig. 3c for an expanding single precursor.



(a) (b)

Figure 4 (a) The outer surface of a foamed sample and (b) stress-strain curves for foams made from single and multiple precursors.

Fig. 4a shows the outer surface of a foamed multiple precursor sample before sectioning for mechanical testing. The boundaries between the prior precursors are clearly visible as surface defects, and are indicted by the arrows, but sectioning such a sample, as shown earlier in Fig. 3a, revealed no internal defects. Fig. 4b presents the compressive stress-strain plots for samples made from multiple and single precursors expanded to a density of 0.7 ± 0.01 g/cc, close to, but just before, the maximum expansion. The yield stress and energy absorbed are similar for both samples, and well within the usual scatter observed for these materials.

In summary, constrained foam expansion offers not only benefits in increased expansion, but also in reduced collapse and increased reproducibility. The use of multiple precursors during constrained foaming results in only a small decrease in expansion and reproducibility, but early in the foaming process, defects between merging precursors are formed. For expansions greater than approximately 200%, the internal defects between merging precursors are removed by large-scale liquid movement and there is no detriment to the mechanical properties even if the boundaries between the precursors are clearly visible on the outer surface.

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