Interfacial criteria for ceramic particle stabilised metallic foams

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Abstract

Two critical phenomena have been considered during the production of particle stabilised metallic foams: i. stabilisation of the bubble/particle agglomerates rising through the liquid metal, and ii. stabilisation of the bubble/particle/gas interface at the top of the liquid metal. General interfacial criteria have been worked out for these two critical phenomena, allowing the selection of the material and size of stabilising particles. Ceramics have been selected based on these criteria for Al-foams (in order of performance): AlN (best), Si_3N_4, SiC, SiO_2.

Introduction

Metallic foams are porous metals with high porosity (from 50 to 99 %). In the last 3 decades different technologies have been developed for producing metallic foams [1]. One of the possible routes is to blow gas bubbles into liquid metals, and to stabilise the bubbles by microscopic ceramic particles. Such foams can be called „particle stabilised metallic foams" (PSMF). To our knowledge there has been no interfacial criteria developed for producing PSMF. The goal of this paper is to fill this gap, and provide a theoretical basis for the selection of stabilising particles for different metallic foams.

Critical phenomena for successful production of PSMF

If one blows gas bubbles into a liquid metal consisting of dispersed microscopic ceramic particles, metallic foam can be obtained under certain conditions. There are two critical phenomena ensuring the formation of the foam:

Criterion 1: bubble - particles agglomerates should be formed while the bubble is rising through the liquid metal; the bubble/particles agglomerates should be mechanically stable, i.e. particles should be attached to the bubble covering most of its surface, and they should not be separated from the bubble while the bubble is rising through the liquid metal,

Criterion 2: the particles should stabilise the bubble/particle/gas and the bubble/particle/bubble interfaces effectively.

The fulfilment of both criteria can be ensured by interfacial forces acting on the bubble/particle/liquid metal interface. In the following chapters different forces relevant for the system will be considered, and the final interfacial criteria of successful metallic foam production will be derived. In the following equations for simplicity spherical particles with radii R_p and spherical bubbles with radii R_b will be considered with the ratio: $R_b >> R_p$.

Forces acting on the bubble-particle agglomerates

The following forces acting on bubbles, particles and bubble/particle agglomerates should be considered:

i. the well-known gravity induced forces

ii. the well-known drag force (the Stokes equation)

iii. the interfacial force acting on the particle at the bubble/liquid interface [2]:

$$F_{ip} = 2 \cdot R_P \cdot \pi \cdot \sigma_M \cdot (1 + \cos\Theta - x) \tag{1}$$

where σ_M - surface tension of the melt,

x - relative depth of immersion of the particle into the melt ($x = X/R_P$); where X is the absolute depth of immersion (if x=2, the particle is fully in the melt, while if x = 0, the particle is fully in the gas bubble) (see Figure 1.a)

Θ - contact angle of the melt on the planar surface of the particle in the gas atmosphere of the bubble (see Figure 1.b)

F_{ip} - force, having positive sign, if the particle is pushed into the liquid metal, and negative sign, if particle is pushed into the bubble.

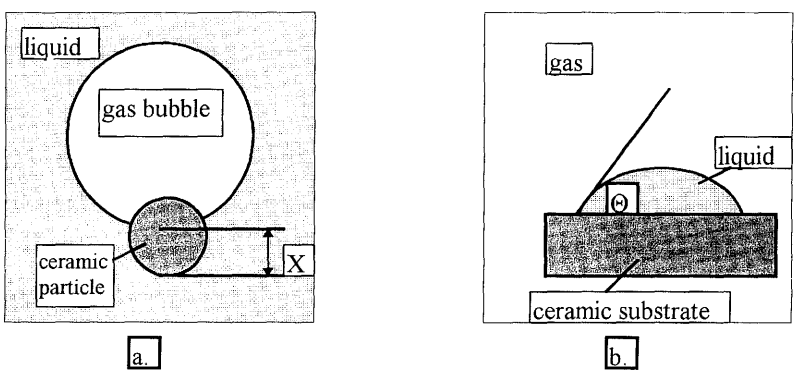

Figure 1. A ceramic particle sticked to a gas bubble in liquid metal (a) and a liquid metallic drop situated on a ceramic substrate (b)

As the usual size of the particles is in the range of 10 μm, the magnitude of the gravity force is much lower than that of the interfacial force. Hence, the particle will be in equilibrium at the liquid/gas interface at the following value of x (when $F_{ip} = 0$): $x^{eq} = 1 + \cos\Theta$.

Criterion 1: Stability of the rising bubble/particle agglomerates

In order to ensure stabilisation of bubbles by particles, the particles should be sticked to the bubble, and rising with it through the liquid metal. If the influence of the dynamic effect is ignored, the particles will be sticked to the bubbles, if the equilibrium value of parameter x^{eq} will be less, than 2. Then, from the equation given above, the first simplified criterion can be found as: $\Theta > 0°$. Obviously, if the bubble meets the first particle during rising through the melt, the particle will be rolling down along its interface, and will be stabilised at the bottom of the bubble (see Figure 1.a). As the bubble-particle agglomerate will be rising up with a certain speed, the drag force will be tearing the particle from the bubble. Considering the force balance at the critical value of x = 2, the first criterion of the stable bubble-particle agglomerate for 1 particle, ignoring dynamic effects is expressed as:

$$\cos\Theta_1 < 1 - \frac{2 \cdot R_b^2 \cdot g \cdot \rho_M}{3 \cdot \sigma_M} \tag{2}$$

where g - acceleration due to gravity,
ρ_M - density of the melt.

For a Al-melt and 1 mm bubble radius, Eq.(2) provides: $\Theta > 10^\circ$. Taking into account more particles sticked to the bubble, and also the role of dynamic effects, coefficient „2" in Eq. (2) should be changed to „8". Then, for a Al-melt and 1 mm bubble radius: $\Theta > 20^\circ$.

Criterion 2: Stability of the bubble/particle/gas interface

The bubble/particle/gas interface separated by particles will be stable, if the buoyant force pushing the bubbles up are compensated by the interfacial force keeping the bubbles down (see Figure 2). Using the well known equation for the buoyant force and Eq.(1) used for the particle situated in the bubble / liquid metal / gas „sandwich" the second criterion can be derived as:

$$\cos\Theta_2 > \frac{3 \cdot D_1 \cdot \sigma_M \cdot n^* + h \cdot R_b^2 \cdot \rho_M}{6 \cdot R_p \cdot \sigma_M \cdot n^*} \tag{3}$$

where D_l - is the smallest thickness of the liquid metal bridge between the two gas phases, stabilised by the particles (see Figure 2),
n* - is the effective number of particles taking part in the separation (n* > 1),
h - is the macroscopic thickness of the foam.

Analysing Eq.(3) one can see that all parameters on the right hand side are positive and therefore the contact angle obviously must be $\Theta < 90^\circ$. In other words, such a ceramic particle should be chosen as foam-stabilising agent, which is wetted by the liquid metal. For Al-foam with R_b = 1 mm, D_l = 10 μm, h = 50 mm, R_p = 15 μm, the right-hand side of Eq.(3) is higher than 1, i.e. there is no solution for the contact angle. A solution, however, can always be found, if the particles are large enough, as increasing R_p will decrease the value of the right-hand side of Eq.(3). For the same foam, using particles with R_p = 25 μm the condition of the stability is $\Theta < 53^\circ$.

It can be shown, that if the bubble/particle/gas interface is stable, the bubble/particle/bubble interfaces will be always stable in the same foam. There are two reasons for that. First, the foam thickness underneath the bubble-bubble interface is always smaller than the total foam thickness h, and therefore condition (3) becomes weaker for this case. Also, when 2 bubbles

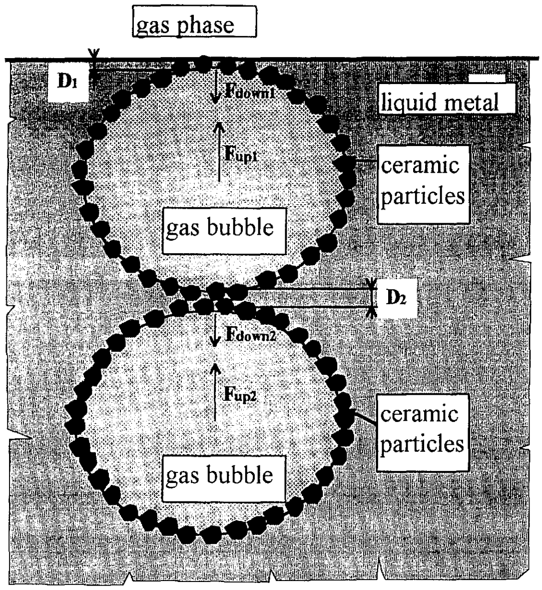

Fig.2. The schematic illustration of two top bubbles stabilised at the liquid metal / gas interface by the ceramic particles covering the interface of the bubbles

covered by particles come into contact, there are two layers of particles separating them from each other, and hence, they can ensure stabilisation of the interface easier compared to a single-layer particle separating the top bubble-layer from the gas phase. In other words, the separation D_2 in Figure 2 is always larger than separation D_1. Therefore, if Eq.(3) is satisfied, the metallic foam is fully stabilised.

The general criterion for materials selection

Materials science, based on correlation between properties and structure of metallic foams, has a task to „order" the „ideal" foam to be made of the certain metal with „cells" of certain size (R_b) separated by metallic bridges of the given thickness (D_1). Surface science, based on the above theoretical considerations, provides a basis for the selection of the material and size of the stabilising particles. The criteria can be given by joining Equations (2-3):

$$1-\frac{8\cdot R_b^2\cdot g\cdot\rho_M}{3\cdot\sigma_M} > \cos\Theta > \frac{3\cdot D_1\cdot\sigma_M\cdot n^* + h\cdot R_b^2\cdot\rho_M}{6\cdot R_p\cdot\sigma_M\cdot n^*} \tag{4}$$

If material science orders Al-foam with cells size of R_b = 1 mm, and D_1 = 10 μm, to be produced with thickness of at least h = 50 mm, the appropriate ceramic material can be selected based on Eq.(4). Introducing the given parameters into Eq.(4), as the first result one can find, that such a ceramic particle should be used, which is wetted by Al with a contact angle higher than 20°, but definitely lower than 90°. Also, ceramic particles should have a higher density than the melt (in order not to float to the surface), but with a density difference as small as possible (in order not to settle too quickly from the melt). In Table 1, the basic physico-chemical properties of some ceramics are collected. As one can see from Table 1, all ceramics listed have somewhat higher densities than liquid aluminium at its melting point (2,380 kg/m^3). Also, all ceramics meet the interfacial criteria (4). Choosing AlN particles (as being the „best" technological choice from Table 1), the right-hand side of criterion (4) provides us with the equation to find the size of the particle: $R_p > 23$ μm.

Table 1. Some relevant physico-chemical properties of some ceramics for producing Al-foams

Ceramics	density, kg/m^3	contact angle on Al [3]
AlN	3100	15 - 25
Si_3N_4	3100	25-35
SiC	3200	35-45
SiO_2	2600	50 - 60

Conclusion

An interfacial criterion has been derived to select stabilising particles for the particle stabilised metallic foam production. AlN, Si_3N_4, SiC and SiO_2 particles can be used for stabilising the Al-foam. Although the real structure of metallic foams differs from the simple model described in this paper, the basic criteria developed will remain approximately valid.

Literature

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