

Effects of process parameters and alloy compositions on the pore structure of foamed aluminum

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Abstract

A study was carried out to understand the dependence of the structures of foamed aluminum (FA) on the process variables and to seek an effective measure to overcome the difficulties in preparation of FA by melt foaming process. The following variables were examined: thickening-stirring time, addition of thickening agent, foaming temperature, addition of foaming agent, and the solidification behavior of the alloy. It was found that the slurry viscosity and foaming temperature have very strong effects on the density of FA. Selecting a suitable thickening agent for a required density is very important. Excessive high foaming temperature would result in unnecessarily large pores and non-uniform distribution. It may become easier to obtain a uniform pore distribution if selecting an alloy that has a wider solidification range.

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1. Introduction

The concept of cellular metals has gained much attention in recent years. The applications cover a variety of fields, from physics to chemistry, engineering and underwater acoustics, etc. One example is foamed aluminum (FA). Its relatively high stiffness and yield strength achievable at low density create an opportunity for ultra-light structures, with integrally bonded dense face sheets. Its large compressive strains achievable at nominally constant stress impart a high energy absorption capacity at force levels relevant to crash and blast amelioration systems [1–3].

There are several approaches to the manufacturing of FA. Among them melt foaming has been thought to be a cost-saving and flexible process. Generally speaking, the process can be divided into five main steps:

- (i) melting aluminum or its alloy ingot;
- (ii) modifying the melt with some thickening agent (for instance, MnO_2) to make it become a viscous fluid;
- (iii) introducing gas releasing metal hydride (usually TiH_2) into the melt;
- (iv) keeping the slurry at a given temperature for a certain time, allowing TiH_2 to decompose and release hydrogen gas;
- (v) solidifying.

Some difficulties exist in the process that may limit the development of it. One of them is believed to be how precisely controlling the pore structures through controlling process parameters since, as yet, there is little understanding of how process variables and in particular, how the solidification behavior of alloys influence the structures of FA. Another problem arises from the premature decomposition of foaming agent, hence the time interval is very short between introduction of foaming agent and foam generation, resulting in large bubbles non-uniformly dispersed throughout the casting and rather scattering porosity. The objective of this investigation is therefore to clarify the dependence of pore structures on the solidification characteristics of alloys as well as several main process parameters in order to find an effective measure to overcome these difficulties for fabricating satisfactory FA products.

2. Experimental

Two metals, commercially pure aluminum and aluminum–10% magnesium alloy, respectively, were selected. The former tends to solidify layer by layer, forming columnar dendrites that are aligned and attached to the mold, while the latter tends to solidify in “mushy” fashion, forming equiaxed dendritic structures that grow radially inside an undercooled melt. MnO_2 powder was used as thickening agent with mean size of 20 μm and TiH_2 powder as foaming

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agent with mean size 40 μm. To overcome the premature decomposition of foaming agent, a surface filming treatment was performed on the TiH₂ particulates in advance [4]. It was found that after surface filming the temperature of degassing occurrence was retarded and shifted towards higher temperature, from 808 to 911 K, which certainly provides sufficient time for stirring operation and avoids the premature decomposition of TiH₂ to some degree. Melting and stirring were performed in a resistance-heated furnace. The density of each specimen was calculated from measurement of its mass and volume, and pore size was determined by intercept method.

3. Results and discussion

3.1. Effect of viscosity on the foamed structures

Thickening operation is necessary to obstruct the flotation of gas released from TiH₂ due to rather low viscosity of molten aluminum. The authors indirectly examine the influence of viscosity by changing stirring time and the addition of MnO₂. It is shown that the density of FA has a very strong dependence on the viscosity of the slurry. From Fig. 1, the densities continue to decrease with increasing stirring time until 20 s, and after that time they seem to keep constant. In contrast, the densities almost linearly increase with addition of MnO₂, as shown in Fig. 2, which suggests that MnO₂ have a much stronger thickening effect than stirring alone. As MnO₂ powder is taken into the melt, the stirring action applied continues to shear these powder agglomerations which contain air and thus continues to create additional oxides throughout the melt, resulting in much higher viscosity.

For any bubble to form and develop, the gas pressure must be sufficiently high to overcome the resistance generated by hydrostatic pressure of the melt, the surface tension as well as atmospheric pressure, i.e. [5],

$$P_n > P_a + P_h + P_c \tag{1}$$

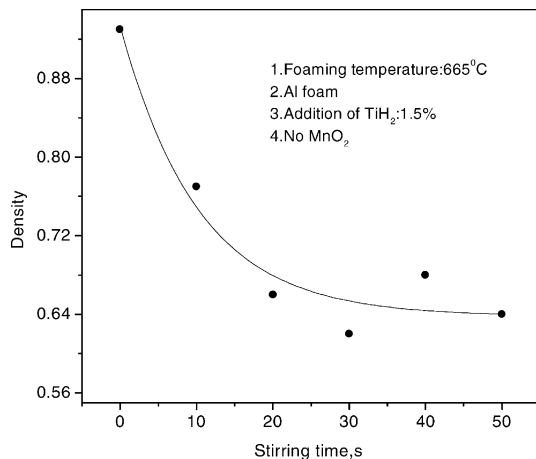


Fig. 1. Effect of stirring time on the density.

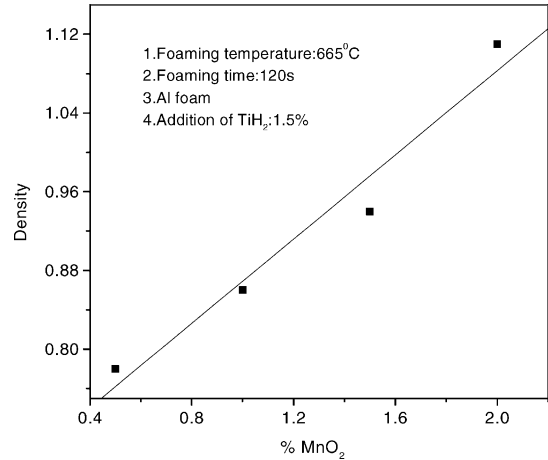


Fig. 2. Effect of MnO₂ on the densities.

where P_n is the pressure in the bubbles, P_a the atmospheric pressure, P_h the hydrostatic pressure of the melt at a depth of h , and P_c the additional pressure caused by the surface tension (σ) of the melt separately.

For Al and most of its alloys, the variation of σ is in general analogous to that of viscosity. If the viscosity is high, bubble nucleation and growth might be difficult and consequently the density of FA is high. Conversely, bubbles may be easy to evolve, and low densities obtained. Accordingly, it is suggested that thickening by MnO₂ may be undesirable for low densities because of its excessively strong thickening effect.

3.2. Effect of foaming temperature and the addition of foaming agent on the foamed structures

It is evident that bubbles increase as foaming agent increases, because more gas will be released from the agent, usually yielding low densities. On the other hand, increasing foaming temperature is accompanied with increasing P_n and decreasing P_c due to decreasing σ , so that bubbles will easily

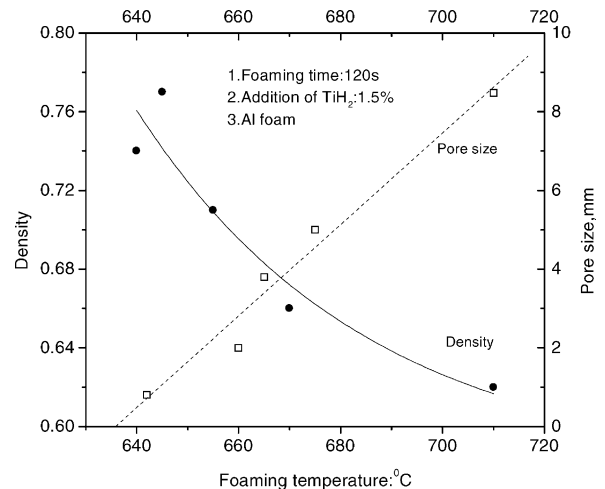


Fig. 3. Effect of foaming temperature on the structure.

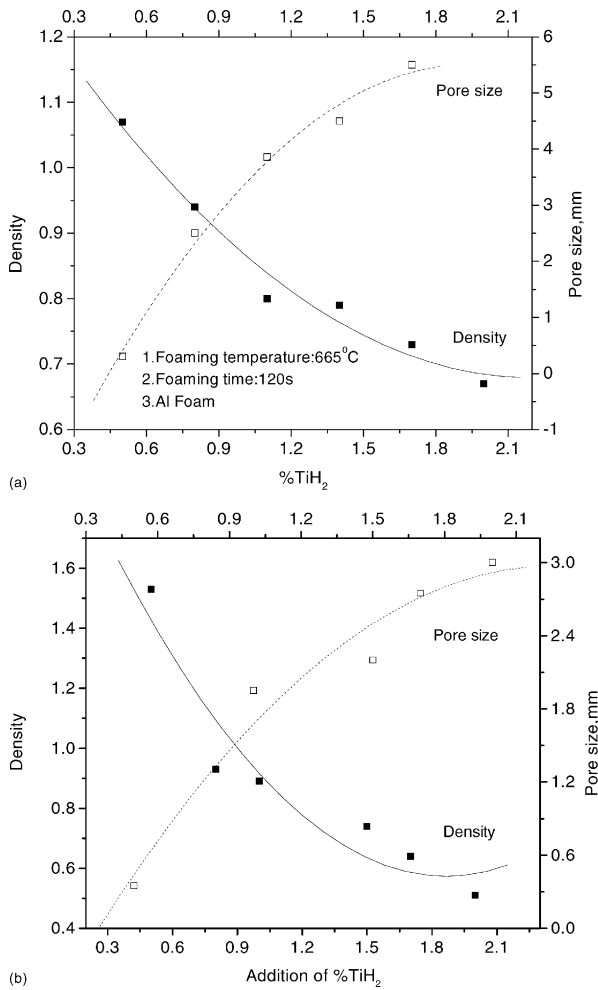


Fig. 4. Effect of foaming agent on the structures: (a) commercially pure Al foam; (b) Al-10% Mg alloy foam.

nucleate and grow, also leading to low densities. Thus foaming temperature and foaming agent addition have similar effects on the densities, as proven by Fig. 3, but the two parameters have significantly different effects on the pore size. Excessively raising foaming temperature would result unnecessarily large pores and non-uniform distribution, while increasing foaming agent can only make pore size moderately increase, as shown in Figs. 3 and 4. According to the present investigation, adding lower than 1.5% TiH₂ and foaming around 640–660 °C would be suitable for better product made of commercially pure aluminum.

3.3. Effect of solidification behavior on the foamed structures

From the fundamental theory of solidification, the distribution of any small particle or bubble throughout the casting is affected by the crystal growth mode. Under the

condition of columnar dendrite growth, crystals solidify with a smooth, compact front, continuously tapering the central flow channel during the whole solidification process. Bubbles move at two component velocities, V_R and V_U . The V_U is the up-floating velocity, resulted from the gravity difference between bubbles and the melt, and V_R the horizontally moving velocity, originated from the pushing effect of crystal growth. The V_U could be evaluated from Stokes' equation:

$$V_U = \frac{2r^2(\rho_L - \rho_g)g}{9\eta} \quad (2)$$

where r is the radius of the bubble, ρ_L the specific gravity of the slurry, ρ_g the specific gravity of bubble, g the acceleration of gravity and η the viscosity of the slurry, separately.

It could be inferred that, according to the temperature gradient across the section of the casting, the viscosity near the mold wall is higher, and r is smaller, and so is V_U . In the center, however, the case is quite the contrary. According to "Particle Pushing Theory" [6], bubbles within the boundary would be easily arrested by rapidly growing dendritic crystals (smaller V_U), while those in the inner region may be pushed to the center of casting, where they combined to form larger bubbles, resulting in such a non-uniform distribution as larger pores in the center and smaller ones in the boundary.

For alloys that have wider solidification range, on the other hand, they solidify in a "mushy" fashion, that is, the viscosity of the slurry is quite high, and extensive interlocking and bridging between dendrites will take place later in solidification, forming a cohesive network that blocks the bubbles and keeps them from moving and yielding a quite uniform pore distribution. By comparing Fig. 4a and b, it can be noted that, as the foaming agent increases, the pore size increases less significantly for Al-10%Mg alloy than for commercially pure aluminum, which can be attributed to the obstruction of the cohesive network. Both the analysis and experimental evidence have shown that manufacturing FA from alloys with a wider solidification zone might be more suitable.

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