Pore Size Control in Aluminium Foam by Standardizing Bubble Rise Velocity and Melt Viscosity

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Abstract. In recent years, aluminium foams have found use in a wide range of applications. The properties of these foams, as good structural strength with light weight have made them as a promising structural material for aerospace industry. Foaming techniques (direct and indirect) are used to produce these foams. Direct foaming involves blowing of gas to create gas bubbles in the melt whereas indirect foaming technique uses blowing agents as metallic hydrides, which create hydrogen bubbles. Porosity and its distribution in foams directly affect its properties. This demands for more theoretical studies, to control such cellular structure and hence properties. In present work, we have studied the effect of gas bubble rise velocity and melt viscosity on pore size and its distribution in aluminium foam. A 15 PPI aluminium foam, prepared using indirect foaming technique having porosity ~86% was used for study. In order to obtain metal foam, the bubble must not escape from the melt and should get entrapped during solidification. Our calculations suggest that bubble rise velocity and melt viscosity are responsible for vertical displacement of bubble in the melt. It is observed that melt viscosity opposes bubble rise velocity and help the bubbles to stay in the melt, resulting in porous structure.

1. Introduction

Metallic foams are obtained by solidifying melt containing well dispersed gas bubbles\(^1\) and can be used as structural material since they exhibit property combinations as of low density, high surface area, high stiffness-to-mass ratio, good energy absorption, great specific strength and stiffness, excellent heat transfer capability etc.\(^2\) Casting, powder metallurgy, metal deposition and additive manufacturing are commonly used methods to obtain these structures.\(^3\) Open-celled metallic foams and closed-cell metallic foams are two basic foam types. Generally, Low-Pressure Infiltration (LPI)
and additive manufacturing techniques are employed for open-celled foams and Gas Foaming techniques are used for closed-celled foams. These porous metals find frequent use in automotive, railway, aerospace and several other applications. High quality metal foams can be obtained by developing a well controlled porous structure so as to meet the requirements of these applications. Therefore, it is much required to have good pore control during fabrication as most of the properties, such as strength, sound insulation, heat transfer, impact energy absorption etc, of these foams are extremely sensitive and are directly affected by its pore size achieved and distribution. However, it is very difficult to control pore size using gas foaming techniques due to non-uniform distribution of the bubbles. Pore size and its distribution depends melt viscosity, bubble rise velocity, surface tension, fluid buoyancy and drag velocity. Therefore, it is important to control the melt viscosity during foaming process as it is seen that low melt viscosity often lead to rapid floating and escape of gas bubbles and high viscosities can cause suppression to formation of bubbles.

Property combination of low specific weight with good mechanical physical properties offer significant performance gains in aluminum foams. This has lead to growing interest in the development of light and stiff foam structures for various engineering applications. In particular, closed cell Aluminium foams have remarkable ability to absorb impact energy, which makes them appropriate for applications where effective utilization of impact energy is required as in car bumpers. Akiyama et.al prepared close-celled aluminium foams through gas foaming technique using Titanium Hydride (TiH$_2$) as foaming agent, where to control melt viscosity Calcium was added along with continuous stirring. They observed that the particle size of TiH$_2$ and melt viscosity directly affected the porous structure and concluded that a properly controlled melt viscosity leads to controlled porosity, which is required to obtain uniform cellular structure.

In this work, we have used closed cell aluminium foam prepared using same technique by adding TiH$_2$ as foaming agent to create hydrogen bubbles. These hydrogen bubbles are responsible for creating pores in the melt which upon solidification resulted in a porous aluminium structure. To control the pore size and its distribution inside these foams, theoretical calculations are done. For this study, the bubble size is assumed to be the same as the final pore size due to smaller bubble sizes formed. The final pore size distribution for solidified foam is obtained by calculating bubble rise velocity inside the aluminium melt as would be discussed in the following sections. It is also studied, the effect of additives as calcium on viscosity of this aluminium melt and its significance on the final pore distribution.

2. Materials and Methods

Calcium (1.8 wt.%), used as thickening agent to adjust the melt viscosity is added to Aluminum, melted at 720°C in a Heat Treat Electric furnace for 1.5 hr. Titanium hydride (1.5 wt.%) is thereafter
added as foaming agent to the melt in order to form hydrogen bubbles. During this addition, the melt is stirred continuously to obtain a homogeneous melt and hence a uniform property foam material having porosity of \( \sim 86\% \). It was expected that this controlled method would result in cellular structure consisting of cells with uniform size and shape. However, we were unable to achieve the uniform cellular structure (size and shape) even after having cautions in the processing method, which finally resulted in reduced foam properties as compared to expected theoretical values, as was also observed by Suresh et al.\(^{10}\) To solve this problem, we tried to study and hence control the pore distribution inside foam, using set of calculations are discussed in next section.

3. Results and Discussions

As stated earlier, pore distribution in foam strongly depends on the bubble rise velocity inside the aluminium melt. To calculate the bubble rise velocity we have considered final pore size of 1mm radius, in 15PPI foam. A mold with dimensions 15*15*15 cm\(^3\) with 20 cm sprue length and 2 cm sprue diameter is used. Porosity is determined using relationship:

\[
\text{\% Porosity} = \left[ \frac{\text{Pore volume}}{\text{Bulk volume}} \right] \times 100 = 86.2\%
\] (1)

Pore size can be controlled by controlling the diameter of hydrogen bubble generated inside the aluminium melt. Pore size distribution of foam can be controlled by controlling the rising velocity of the hydrogen bubbles. Therefore, relationship between bubble size with final pore size, and bubble rising velocity with final pore distribution inside the aluminium foam is developed here. For simplifying the calculations, since the pore size is small (1mm) we have assumed the final pore size obtained to be equal to the size of the gas bubble.

Also as stated earlier, it is known that terminal rising velocity of hydrogen gas bubbles is strongly dependant on the viscosity, surface tension, buoyancy and apparent density of melt. Rising velocity is an indicative of how fast the gas bubbles will rise inside melt and finally lead to the pore distribution inside aluminum foam upon solidification. For calculations on bubble rise velocity, we have considered isolated spherical bubbles, as per relationship provided in Table 1, which is due to the dominant surface tension effect.

| Table 1. Relation between bubble size and shape |
|-----------------------------------------------|
| **Radius (cm)** | **Bubble Shape** |
| --------------- | ----------------- |
| < 0.01          | Solid Spheres    |
| 0.01 – 0.1      | Deviations from spherical |
| > 0.1           | Ellipsoidal       |

For an infinite stagnant fluid, the study of bubble rise velocity in two-phase (gas-liquid) fluid flow can be obtained using Stokes solution as:\(^{11}\)
\[ U_{\infty} = \frac{1}{18}gd_e^2 \left( \rho_1 - \rho_g \right) \frac{1}{\mu_l} = 3.747 \text{m/s} \] (2)

\( g = \text{Acceleration due to gravity (9.8 m/s}^2) \)

\( d_e = \text{Diameter of bubble (2 mm)} \)

\( \rho_1 = \text{Density of Aluminium melt (2375 Kg/m}^3) \)

\( \rho_g = \text{Density of hydrogen gas (0.0893 Kg/m}^3) \)

\( \mu_l = \text{Dynamic viscosity of Aluminium melt (1.38 mPa)} \)

Considering bubble rising velocities as 3.747m/s, the pore distribution in the foam can hence be determined. For this, we have considered five similar bubbles formed at different depths inside aluminium melt as shown in Fig 1. Using rising velocities for these bubbles as 3.747m/s, the rising distance covered by them at solidification start (~ 615°C, 30 sec)\(^{12}\) is 99 m. Here, it is assumed that rising velocity between two bubbles is constant over the time interval considering constant melt viscosity. The pore distribution inside the aluminium foam for these five bubbles can hence be determined precisely in this manner. Likewise we can consider large amount of bubbles forming inside the melt & hence can determine their exact distribution using the concept of rising velocity.

However, this vertical displacement of the bubbles is much higher such that, all gas bubbles formed get easily escaped into the atmosphere from the mold. So, we need to make changes in the melt such that the gas bubbles are entrapped inside the melt. As discussed in work by Akiyama et.al, calcium was used as thickening agent to increase the melt viscosity so as to hold gas bubbles inside the melt for longer time.

**Figure1.** Distribution of bubbles inside mold
The relative viscosity ($\mu_{rel}$) representing factor by which viscosity of the liquid is increased, through the addition of the calcium (1.8 wt.%) is given as: \[ \mu_{rel} = \frac{\mu_{sus}}{\mu_{liq}} \] (3)

$\mu_{sus}$ = Dynamic viscosity of the suspension

$\mu_{liq}$ = Dynamic viscosity of the aluminium melt (1.38 mPa)

The relative viscosity of the melt is dependent on the solid fraction ($\varphi$). Einstein\textsuperscript{14} derived an analytical relation for the relative viscosity for very dilute suspensions (low solid fraction $\varphi \ll 1$), as:

\[ \mu_{rel} = 1 + \frac{5}{2} \varphi \] (4)

Kunitz\textsuperscript{15} proposed relation that is valid for larger values of solid fraction, $\varphi >> 1$, as:

\[ \mu_{rel} = \frac{1 + \frac{3}{2} \varphi}{(1 - \varphi)^4} \] (5)

For 1.8wt.% of calcium added to aluminium melt, the solid fraction can be found out as:

$$\varphi = \frac{\text{wt. of calcium}}{\text{wt. of calcium} + \text{wt. of aluminium}} = 1.77$$

Substituting $\varphi=1.77$ in equation (5), we get $\mu_{rel}=5.36$

Substituting this in equation (3), we get $\mu_{sus}=7.4$mPa

Hence, after addition of 1.8 wt.% calcium, the aluminium melt viscosity has been increased to 7.4mPa from 1.38mPa. This increase in viscosity is high enough to hold bubbles inside the melt for longer times and hence help in achieving the desired pore structure.

4. Conclusion

This work is performed to have a better understanding & control over pore size and its distribution in aluminium foam to have better property control. The pore distribution in the melt is analyzed by calculating the vertical displacement of the bubbles which are formed using TiH$_2$ as foaming agent. Assuming gas bubble size as the final pore size (1 mm), since further expansion of the bubble cannot takes place once the solidification starts (~ 615°C), measurements to determine pore distribution inside aluminium foam are made. The small isolated gas bubbles rise in melt at 750°C, with rising velocity of $U_\infty=3.747$m/s. The final vertical displacement travelled by individual gas bubble which is the product of rising velocity ($U_\infty$) and solidification start time (30 sec) is then calculated as 99 m. This displacement of bubbles is much higher than the height of our mold used, which actually resulted in
obtaining a structure with very less entrapment of pores and hence observation of undesired porous structure. Therefore, the bubble rising velocity has to be opposed by some other parameter (like melt viscosity), which must allow the gas bubble to stay in the melt for longer time, thus resulting in a porous structure. The same is confirmed by Akiyama et al., who used Calcium as thickening agent to increase the melt viscosity. The final viscosity ($\mu_{sus} = 7.4$ mPa$^2$) of melt after calcium addition is then calculated theoretically which was same as of results observed by Liqun Ma et al.(5-8mPa). This increase in melt viscosity on calcium addition will help in entrapping the gas bubbles in the melt thus resulting in desired porous structure. Hence, it is extremely important to increase melt viscosity and study the effect of viscosity for entrapping these bubbles inside the melt. In our future works, we are trying to theoretically relate the melt viscosity with the bubble rising velocity so as to entrap these bubbles by reducing their rising velocities & hence control the final pore structure observed.

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