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Effects of viscosity on cellular structure of foamed aluminum in foaming process

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The effects of melt viscosity on the foaming process and the structures of foamed aluminum have been examined. Methods for measuring the melt viscosity, pore structure, and foaming process are introduced. To increase the stability of the foaming melt and get the sample with a uniform pore distribution, a proper viscosity is needed. Further, the structure of foamed aluminum can be controlled by adjusting the Ca addition and other process parameters. © *2000 Kluwer Academic Publishers*

1. Introduction

It has been more than fifty years since the method of melt foaming was proposed for preparing foamed aluminum [1], which is a kind of cellular solid with a macroscopic structure. Foamed aluminum is always regarded as a function material. It is widespread in automotive, railway, aerospace and the other applications [2–4]. This material generally has a closed cell structure. Properties, such as sound absorption, heat transfer, impact energy absorption characteristics, of foamed aluminum are sensitive to the cellular structure [5]. This material could be produced by two methods, powder metallurgy and melt foaming [6–8]. Especially, the melt foaming method, adding a foaming agent to molten aluminum, is relatively useful for commerical production of foamed aluminum for its low cost. Because the melt foam is an unstable system, and the further, the gas is released instantaneously as soon as the foaming agent meet the melt, the process of melt foaming is difficult to control.

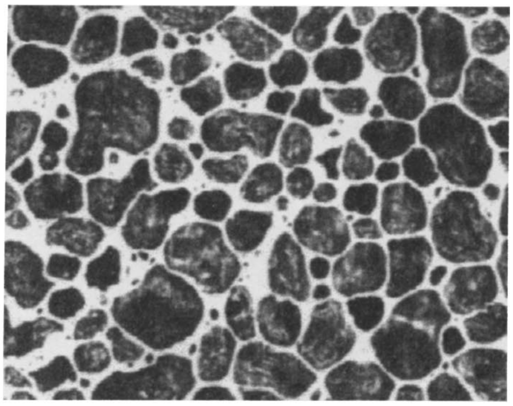
Melt viscosity may affect the pore structure of foamed aluminum. In foaming process, a suitable viscosity may increase the stability of the melt foam and reduce the variations of foam structure until they are solidified. An unsuitable viscosity often causes a non-uniformly distribution of bubbles during the foaming process. Too low viscosity always leads to rapid floating of bubbles, and too high viscosity suppresses the formation and the growth of bubbles. It finally leads to the non-uniformly structure of the sample. Therefore, it is important to control the viscosity carefully in the foaming process. Then, however, to measure the viscosity of the melt in real time is very difficult due to the high temperature. H. Ueno and S. Akiyama [7] measured the viscosity of aluminum melt by measuring the torque moment of the paddle axle using a complication apparatus. We provide a method [9–10] to do the real time measurement of the viscosity by measuring the voltage of paddle motor in the period of stirring.

The pore structure is a primary determinant to the physical properties of this material. Average diameter and porosity are used to act as the only references for structure description. However, in order to study the relations between the melt viscosity and the structure, more detailed structure references are needed. In this paper, the area and diameter of every pore on the section of foamed aluminum sample are determined by a scanning technique.

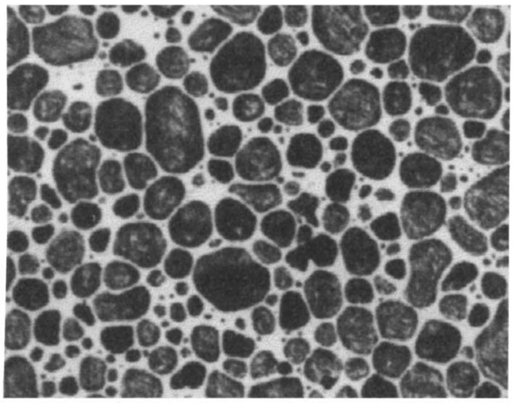
2. Experimental methods

2.1. Materials and process

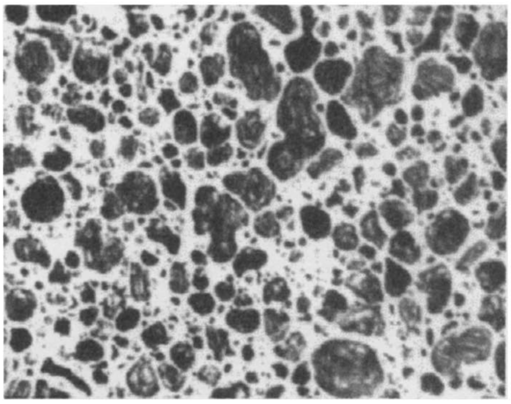
Foamed aluminum is produced by the melt foaming method. Matrix of foamed aluminum is based on pure aluminum (Al, >99.5 wt %), thicker that can adjust the melt viscosity is pure calcium (Ca, >99.9 wt %), foaming agent is hydride titanium powder (TiH_2, >98 wt %, 300 mesh). The foaming process involves the following steps: 1. Melt pure aluminum in a crucible to 973 K. 2. Modify the melt by adding pure calcium together with stirring at a constant speed of 700 rpm for 5–15 min to make the melt viscous. 3. When the viscosity (η) reaches 5–8 mPa · s introduce foaming agent into the melt and stir the mixture with a speed of 1200 rpm in order to disperse the powder rapidly and homogeneously throughout the whole melt. 4. Keep the mixture in the furnace for 2–3 min, so that the foaming agent powder may release gas and the bubbles may grow. 5. Remove



a Ca 0.5%



b Ca 1.0%



c Ca 2.0%

Figure 1 Images of foamed aluminum made with difference Ca additions. (Size: 32.6 × 25.3 mm^2, amount of TiH_2 : 1.4%) a. Ca 0.5%, b. Ca 1.0%, c. Ca 2.0%.

the mixture together with crucible from the furnace, cool the foamed melt to solidify the structure.

In generally, the structure of foamed aluminum varies with the processing parameters such as temperature, amount of addition agents, foaming time, and cooling velocity, etc [5, 10]. Fig. 1 shows cross-section images of the foamed aluminum samples produced by melt foaming method with difference additions of Ca (TiH_2: 1.4%, A: 0.5% Ca, B: 1.5% Ca, C: 2.5% Ca).

2.2. Viscosity and structure measurements

2.2.1. Viscosity measurement

The consumed power of a paddle motor is used to overcome the internal friction of the liquid being stirred [11]. This internal friction is closely related to the density and viscosity of liquid. The motor winding voltage is associated the power. Fig. 2 shows the relation between the winding voltage with the motor torque. When a liquid is stirred, the resistance from the liquid can be signified as the apparent but not the real concept of viscosity. The higher the apparent viscosity is, the higher motor power is needed, and the higher the winding voltage of motor is. Under the following conditions, the consumed power of a paddle motor may stand for the melt viscosity. 1. Fixed size and shape of the paddle and crucible. 2. Fixed relative position between the paddle and crucible. 3. Fixed rotation speed and fixed amount of the melt. After standardization [10], the relationship of the winding voltage U with the apparent viscosity η of the aluminum melt is got (Fig. 2). Therefore, the apparent viscosity of aluminum melt can be known by measuring the winding voltage of motor.

Adding calcium into aluminum melt can increase the apparent viscosity of the melt (Fig. 3). From Fig. 3, we can see that the viscosity increases remarkably with Ca addition and with stirring time. The reaction of Ca with atmosphere leads to destruction of the compact oxide film of aluminum melt surface. It promotes the oxidation of aluminum. In the melt, the more the addition of Ca, the stronger the oxidation is, the more amount of oxide is, and hence the higher the apparent viscosity is. However, the increase range of viscosity declines with the increase of Ca. Actually, even stirring the melt

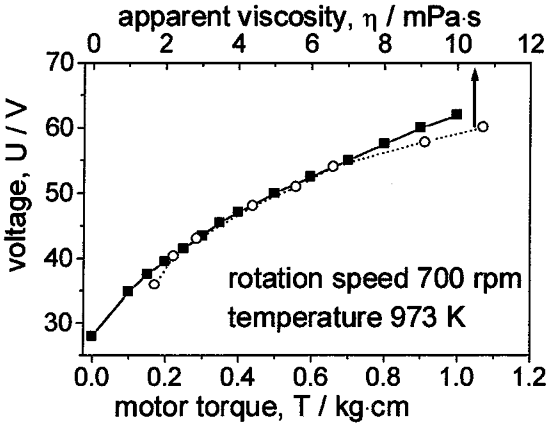


Figure 2 Relation of motor voltage with apparent viscosity of aluminum melt.

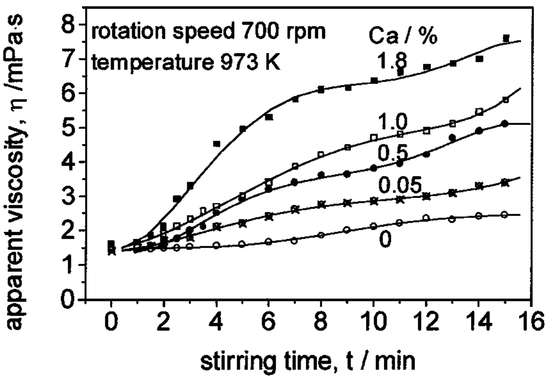


Figure 3 Relation of stirring time and Ca content with apparent viscosity.

in atmosphere can increase the viscosity too. It can be seen from Fig. 3 that the apparent viscosity increases with the stirring time without any addition of calcium. The reason is that vortex caused by stirring destroys the oxide film of the melt and introduces oxygen from air into the melt causing the oxidation of aluminum. In foaming process, the apparent viscosity of melt can be controlled by adjusting the Ca additions.

2.2.2. Cellular structure measurement

We consider the structure of foamed aluminum in a macroscopic scale. Foamed aluminum made by the melt foaming method has a closed pore structure. In this paper, the shape of pores of this material should be grouped into two kinds: sphere (called cavity, the size is generally small) and polyhedron (called cell, large size). In the continuous metallic matrix of a cross section, cells or cavities are separate. In general, a cell is made of walls (thin membranes) and borders (Plateau borders) [12] providing a closed structure. Although great amounts of small spherical cavities are widely scattered in thicker walls and Plateau borders, actually, we will see that the volume percentage of all small cavities is not large [5].

Fig. 4 shows the structure.

In order to describe the macroscopic structure of foamed aluminum, following concepts should be declared.

a. Area porosity (A_A): area percent of pores in cross section

$$A_A = \left(\frac{\Sigma A_i}{A}\right) \times 100\%$$

(A_i: pore area, A: section area)

b. Number density (n_A): pores number (n) per unit area

$$n_A = \frac{n}{A}$$

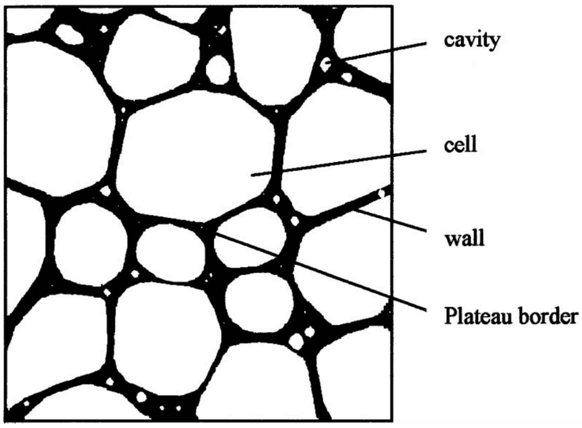


Figure 4 The close up image of foamed aluminum shows the structure of cells and walls.

c. Pores diameter (d_i): in cross section, it is an equivalent diameter and equals the diameter of sphere with the same area

$$d_i = \sqrt{\frac{A_i}{\pi}}$$

d. Area pore size distribution ($\mathbf{N_A}$): a group of pores number classified with diameter per unit area

e. Bulk porosity (V_V): volume percent of pores

$$V_V = \left(\frac{\Sigma V_i}{V}\right) \times 100\%$$

(V_i: pore volume, V: volume of sample)

In general, bulk porosity is always calculated with sample's mass (M) and volume (V).

$$V_V = \left(1 - \frac{M}{\rho V}\right) \times 100\% \qquad (\rho\text{: matrix density})$$

According to Deless law [13], area porosity equals bulk porosity.

$$A_A = V_V$$

By scanning technique, the area and equivalent diameter of cells (or cavities) can be counted. The image of polished crossing section of a sample is recorded as a date file with the form of ".BMP" by a scanner (maximum resolution: 1200 × 1200 dpi). In cross section of a foamed aluminum sample, the ability to reflect light of the parts being polished is stronger than that of surface of cells and cavities being cut open. Therefore, in the image, the metallic matrix is bright and cavities or cells are dark. After treatment, the image is converted into white and black one. Because cells and cavities are separate, we can mark every cell and cavity down and count their area and diameter out with the aid of a computer. In this paper, the resolution is 400 × 400 dpi, the measured area is 32.6×25.3 mm^2.

3. Result

In foaming process, the porosity is relative to the height (H) of foaming melt. Actually, if the shape of crucible is column, the timely porosity of melt foam can been simply calculated with the height. Therefore, the curves of relationship between foaming melt height (H) and holding time (t) can reflect some internal information of the structure. The H-t curve can be divided into two stages, rising and dropping. The demarcation point is the time when height reaches the top. Fig. 5 respectively the relationships of melt height with holding time in difference melt viscosity (TiH_2: 1.4 wt %, origin height of melt: 33 mm, rotation speed for increasing viscosity: 700 rpm, stirring time for increasing viscosity: 10 min).

It is shown that the top point of H-t curve shifts right with the increase of viscosity. In dropping stage, dropping rate of the melt height reduces with the decrease of viscosity. Although the low viscosity melt (Ca 0%, $\eta = 2.1 \pm 0.3$ mPa · s) can reach the same

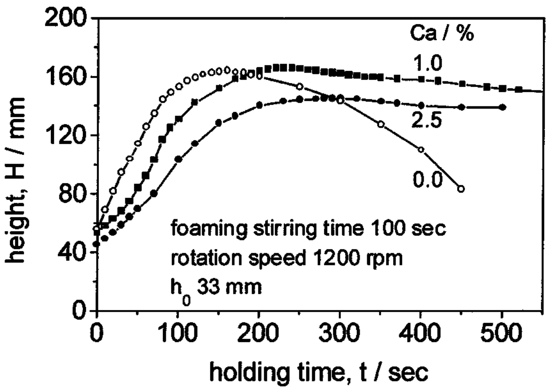


Figure 5 Relations of foaming melt height with holding time in difference melt viscosity.

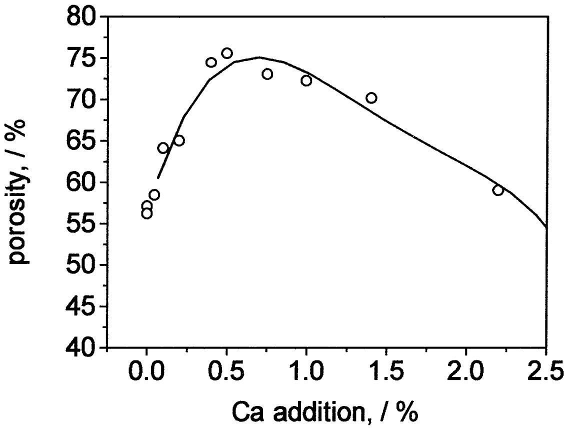


Figure 6 Effect of Ca addition on porosity.

height as the melt with $\eta = 5.0 \pm 0.3$ mPa · s (Ca 1.0%) in foaming process, the porosity of the final sample made with Ca = 0% is actually less than that of Ca = 0.5–2.0%. It is because that the film of bubbles is weaker and the escape of gas is easier in low viscosity melt than that of high or medium viscosity. To increase viscosity can strengthen the film, prevent the liquid from flowing out the film and inhibit the bubbles breaking. On the other hand, the maximum height that a melt with too high viscosity can reach ($\eta > 10$ mPa · s, Ca $> 2.5\%$) is less than that of $\eta = 3$–8 mPa · s (Ca = 0.5–2.0%). At beginning of the H-t curve, the rising rate of high viscosity melt is smaller than that of low viscosity. The reason is that too high viscosity suppresses the release of gas from foaming agent and the growth of bubbles.

In order to get a sample with the higher porosity, the viscosity of melt can not be too high or too low. Fig. 6 shows the relation of Ca addition with the samples' porosity.

Fig. 7 shows the area pore size distributions of the samples, which images are shown in Fig.1.

The number density (n_A) of sample A is $2.26 \times 10^5 (\mathrm{m}^{-2})$, B is $3.16 \times 10^5 (\mathrm{m}^{-2})$, C is $6.06 \times 10^5 (\mathrm{m}^{-2})$. It is obviously that the increase of viscosity prevents the bubbles from combining each other. Following with the increase of Ca addition, we can see that the pores number increases, the pores size decreases, and the number percent of large size cells decreases.

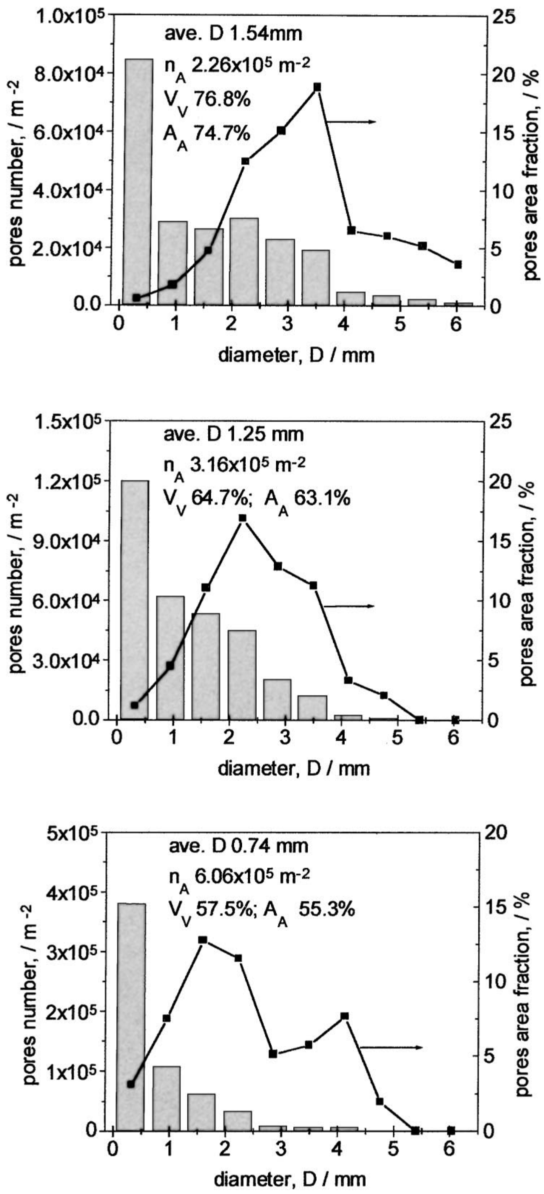


Figure 7 The area pore size distributions of foaming aluminum samples which images are shown in Fig. 1.

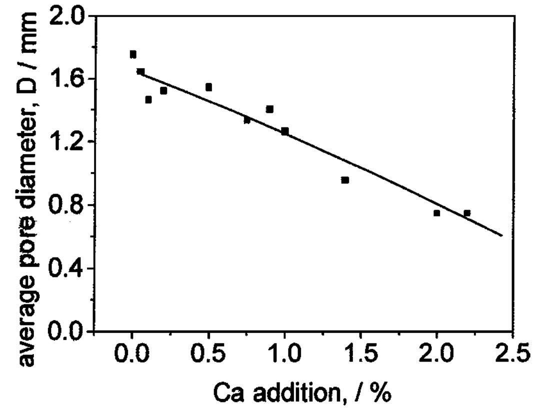


Figure 8 Effect of Ca addition on pore diameter.

Fig. 8 shows the relations of Ca addition with average pores diameter. The average diameter decreases with the increase of the viscosity of aluminum melt.

The viscosity of melt has a bearing on the uniformity of foamed aluminum. Local area porosity and pore

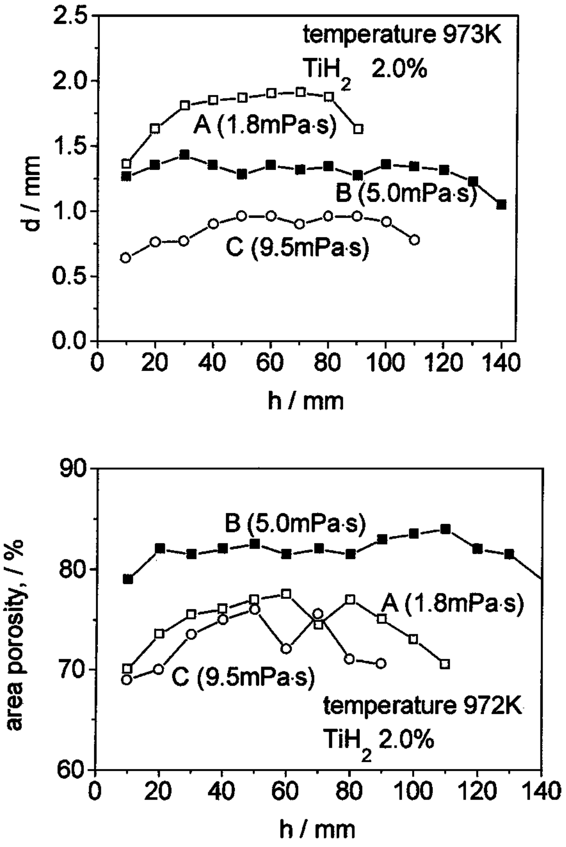


Figure 9 Effect of apparent viscosity on uniformity.

diameters of the cross section, which is got from every 2 cm along the foaming direction of height are shown in Fig. 9. It is shown that the area porosity and average diameter change with the increase of height, and a properly controlled viscosity is good for uniformity of the samples.

4. Discussion

The schematic diagrams of structure in foaming process are shown in Fig. 10. Shortly after foaming agent powder being scattered in the melt, nucleus of bubbles forms around the TiH_2 particle (Fig. 10a). Furthermore, the bubbles size increases with the decomposition of TiH_2 and at the same time new nucleus of bubbles are still forming (Fig. 10b). When volume percent of gas reaches a value, bubbles are crowed each other (Fig. 10c). The shape of big bubbles gives way to pressure and becomes in polyhedral, the cellular structure, which also can be called foam structure, takes the shape (Fig. 10d). The polyhedral bubble is called cell. Two adjoining cells share a wall and three adjoining cells share a curved triangular prismatic rod that called Plateau border. Many spherical small bubbles, which sizes have not grown big enough before solidified, lie in the Plateau borders and thicker walls.

Before the cellular structure forms, to increase the viscosity properly can prevent the bubbles floating, it is beneficial to a uniformity distribution of bubbles. However, too high viscosity of melt may lead to the non-uniformly distribution of the foaming agent powder, and it always lead to the non-uniformly of pore distribution.

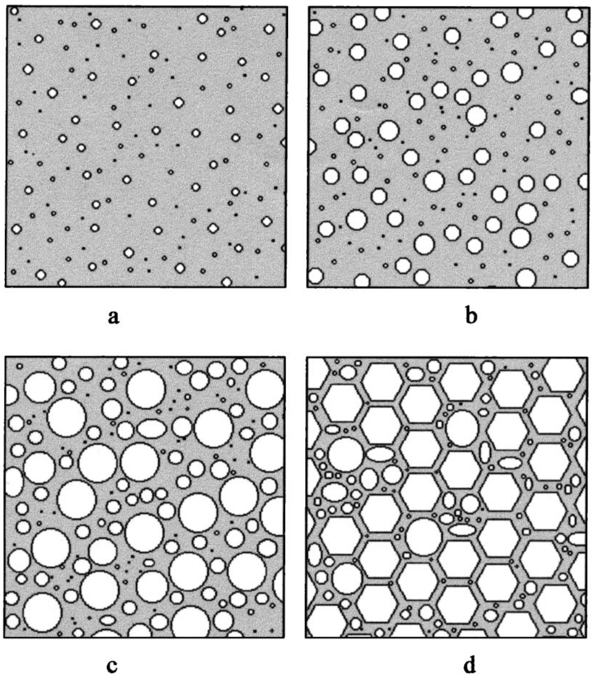


Figure 10 (a–d) The schematic diagram of melt foam structure in foaming process.

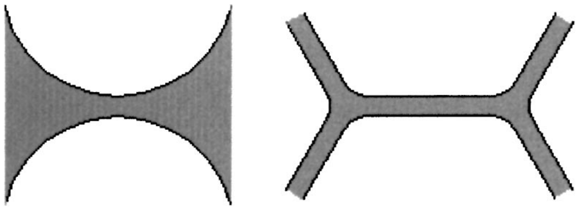


Figure 11 The formation process of the cell wall.

Viscosity may effect the melt on flowing in cell walls when the cellular structure forms. The formation process of the cell wall is shown in Fig. 11. When two adjoining bubbles grow big enough, the films of bubbles will press the melt between them. Under the pressure, melt runs out, two proximate films change into one thin membrane. The wall forms. The thickness of wall decreases with growing of bubbles until it is destroyed. The viscosity plays an important role in this period by changing the flowing velocity of melt. Therefore, low viscosity may also lead to the non-uniformly of pore distribution.

5. Conclusions

The viscosity of melt can influence the foamed aluminum structure such as uniformity, porosity, pore distribution, and pores diameter etc. To change the Ca addition and stirring time can adjust the viscosity of melt. With the increase of viscosity, melt foams become stability and the pores diameter become small. Nevertheless, a too high viscosity may prevent foaming agent powder from dispersing homogenized in the melt. The controllable cellular structure of foamed aluminum can be prepared by means of adjusting the viscosity. Properly controlled viscosity of melt is good for acquirement of high porosity and good uniformity of the cellular structure of foamed aluminum samples.

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