The similarity of the water system to the real foam making system

J. Grabian

[a] Institute of Basic Technical Sciences, Maritime University of Szczecin,
ul. Podgórna 51/53, 70-205 Szczecin, Polska
Corresponding author. E-mail address: j.grabian@am.szczecin.pl

Abstract

Cellular structures are characterized by a number of unique properties that can be successfully utilized in the construction of machines and vehicles. Their low density makes them an ideal filling material for laminated structures.
The use of the proper method of foam production affects its structure (e.g. the distribution, openness and size of pores, wall thickness between pores etc.), consequently the material properties are affected. Another important issue is the material itself used for metal foam production, as materials meeting increasingly new requirements are being sought, among which are metal composite materials.
This work presents theoretical considerations referring to foam making by comparing the water system to a real foam production system.

Keywords: Foam, Metal-matrix composites

1. Introduction

Metal solidification is an exothermic process [1], and the heat of solidification from the liquid metal is released to the environment, mainly increasing the temperature in the space of foam formation [2–4]. In favourable conditions a large number of emerging bubbles undergoes solidification so that the amount of foam covering the surface of liquid metal increases. This process hampers the conditions in which solidification heat is carried away, to the extent that the foam production process may be interrupted. The required thermal conditions can be maintained by cooling and carrying away the foam. Another factor facilitating the reduction of local temperature is the movement of liquid ceramic-metal composite in the foam making space [5–6]. This movement is naturally caused by air bubbles flowing upwards, but it can also be forced by a rotor with tiny holes located externally through which the air is supplied to the liquid metal. The reduction of foam temperature below the temperature of metal solidification will cause the foam to change into the solid phase.

The description of the above process implies that foam production from metal-ceramic composites by the gas blowing method depends on a number of factors, and for the process to be maintained the following conditions have to be satisfied:
- stable temperature and physical properties of the liquid metal,
- fixed parameters of the supplied air streams,
- fixed movement of the liquid metal near the space of foam formation,
- stable thermal conditions in the foam formation space,
- specific conditions of cooling and carrying away the foam produced.

The process of making foams from metal-ceramic composites can be presented by describing the similarity of the water system to the real foam making system.

2. The similarity of the water system to the real foam making system

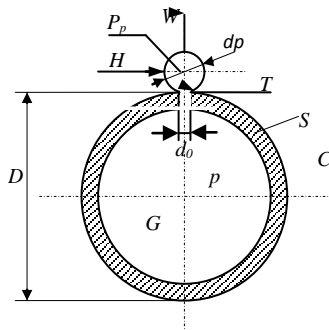The system in which metal foam is produced is a three-phase system shown in Figure 1.

Fig. 1. Diagram of the system of gas blowing during the metal foam production: G – gaseous phase, S – solid phase, C – liquid phase, p – blown gas pressure, p_n – mean pressure of gas in a bubble, w – linear velocity of the rotating element surface, W – displacement force

The real system is composed of the solid material element that disperses gas, gaseous phase forming the bubble and liquid phase forming the foam. The liquid phase is molten aluminium or its alloy, or a suspension of solid particles in this liquid. The gas-dispersing element has a shape of perforated tube that may be motionless or rotating to ensure greater dispersion of gaseous bubbles.

The only difference in the model system is that water is used instead of the liquid metal phase.

2.1. The similarity of the motionless system

Two motionless systems as per Figure 1, differing in the liquid phase, will be similar if:

$$dp_1 = dp_2 \text{ [m]} \tag{1}$$
$$n_1 = n_2 \text{ [1/s]} \tag{2}$$

where: n – frequency of bubble formation [s^{-1}]. The indexes 1 and 2 refer to, respectively, the model and real systems.

The diameters of detaching bubbles can be calculated by comparing the displacement force W and the force of bubble adhesion to the substrate R [7], which are equal to:

$$W = \frac{\pi dp^2}{\delta} \cdot \gamma \text{ [N]} \tag{3}$$
$$R = \pi do \cdot \delta \text{ [N]} \tag{4}$$

where
  γ – specific gravity of the liquid phase [N $\cdot$ m^{-2}]
  δ – surface tension of the liquid phase [N $\cdot$ m^{-1}]

Therefore:

$$dp^2 = \frac{6 do \delta}{\gamma} \text{ [m]} \tag{5}$$

Using the equation (1) we can write:

$$\frac{do_1}{do_2} = \frac{\delta_2}{\delta_1} \cdot \frac{\gamma_1}{\gamma_2} = C \tag{6}$$

Consequently, the similarity of the systems in terms of bubble size can be obtained by changing one of the values.

The frequency at which bubbles of the same diameter separate from the substrate depends on the intensity of the gas flowing through the hole do. The gas flow intensity V will then equal:

$$V = \frac{n \cdot dp^2}{\delta} \text{ [m}^2 \cdot \text{s}^{-1}] \tag{7}$$

On the other hand, the gas outflow rate will be equal to:

$$V = \pi do^2 \sqrt{2gh} \text{ [m}^2 \cdot \text{s}^{-1}] \tag{8}$$

where
  g – gravitational acceleration [m$^2 \cdot$s^{-1}],
  h – height resulting from pressure difference.

$$h = \frac{AP}{\gamma} \tag{9}$$

where $\Delta p = p - p_{p_{śr}}$ $$\tag{10}$$

Since the relation between p_p and dp is linear, then:

$$Ap = p - 2\delta \left(\frac{1}{dp} - \frac{1}{do} \right) \tag{11}$$

By comparing the relations (7) and (8) we can write that

$$n = \frac{\delta do^2 \sqrt{\dfrac{2g \cdot \Delta p}{\gamma}}}{dp^3} \text{ [s}^{-1}] \tag{12}$$

Then

$$\frac{\Delta p_1}{\Delta p_2} = \frac{\gamma_2}{\gamma_1} \cdot \frac{dp_2^6}{dp_1^6} \tag{13}$$

Using the relations (10) and (11) and knowing the ratio $\dfrac{dp_1}{dp_2}$ we can calculate the values of pressures p_1 and p_2 for similar systems, differing in the liquid phase.

2.2. The similarity of systems with the rotating gas-dispersing element

The gas bubble will separate from the rotating gas-dispersing element when the force resulting from the hydrodynamic resistance H exceeds the value of transverse force T, resulting from the strength of bubble-substrate bond [7-12].

This author has failed to find in the technical literature a criterion of similarity for systems such as the one shown in Figure 1, where the gas dispersing element is rotating [13]. However, a certain analogy can be found between these systems and mixers [8–9]. In mixers the Weber number is used as a similarity criterion [8]. The Weber number characterizes the process of gas dispersion in liquids and has this form:

$$W_{em} = \frac{n^2 \cdot D^2 \cdot \rho}{\delta} \tag{14}$$

where
n – number of agitator revolutions [s^{-1}],
D – agitator diameter.

As the similarity condition has this form:

$$W_{em1} = W_{em2} \tag{15}$$

taking the equation (14) into account, we can write that

$$\frac{n_1}{n_2} = \sqrt{\frac{\gamma_1}{\gamma_2} \cdot \frac{\delta_2}{\delta_1}} \tag{16}$$

If we maintain the previously assumed values ρ and δ and the calculated do and p, the above relation allows to calculate the value of n_1 and n_2 ensuring the similarity of systems with different liquid phases.

2.3. The scope of application of the relations presented in sections 2.1–2.2

Wężyk [13] states referring to Orzechowski [14] that the relations given in sections 2.1 and 2.2 are valid if there are no interactions between adjacent bubbles that might cause their deformations, even division into smaller bubbles. This is illustrated in Figures 2 and 3.

Spherical bubbles (e.g. Fig.2 q1–q3 and Fig. 3 a1) are formed when their diameter does not exceed 5–7 mm. With diameters ranging within 8–10 mm the bubbles assume the shape of a flattened ellipse (Fig. 3 a2 and a3). When the diameter is more than 10 mm the bubbles acquire the shape of slightly flattened spherical cap (Fig. 3a4). In larger bubbles internal circulation of gas occurs, which may cause their further deformation (Figs. 3).
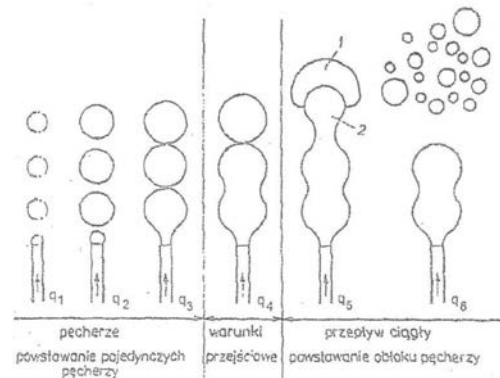

Fig. 2. Effect of gas flow intensity on the process of bubble formation [14]
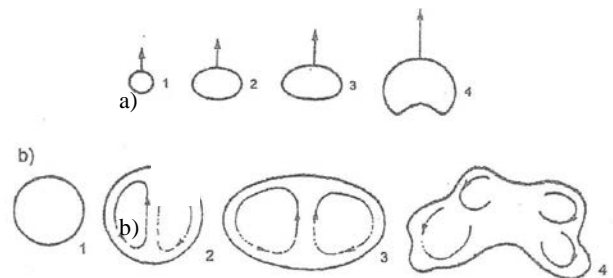

Fig. 3. Gas bubble shapes [14] depending on: a) bubble size, b) internal gas circulation

3. Calculations of the similarities of systems where the liquid state is water, aluminium and solid particles suspension in aluminium

Calculations for the water-liquid aluminium, indexed 1, and water-aluminium composite with a content of 2000 solid particles, denoted with index 2, were made by using the relations 6, 13 and 16. The value $do_1 = 0.33$ mm was assumed for calculations, and the remaining values concerning the properties of liquids - components of the two systems are given in Table 1. The values of apparent viscosity of the liquid composite suspension were calculated from the Einstein formula [1, 11]. The relevant results are shown in Table 2.

4. Conclusions

The similarity of three-phase systems, in which gas bubbles are formed and liquid phases are different, is confirmed by the values of quotients $\dfrac{do_1}{do_2}$, $\dfrac{\Delta p_1}{\Delta p_2}$ and $\dfrac{n_1}{n_2}$ in which:

do – diameter of the hole in which a bubble forms,

Δp – pressure difference between mean pressure inside the bubble and that inside the gas dispersing element,

n – number of revolutions of the gas dispersing element.

The indexes 1 and 2 refer, respectively, to the model and real systems.

To build a real system based on the model test results one should:

– collect the values δ and γ for both systems,

– determine experimentally the values do_1, Δp_1 and n_1,

– calculate from the relations given in section 2.1 the values do_2, Δp_2 and n_2 for the real system.

The above given relations and procedure are valid for the conditions in which bubbles are formed by detaching from the substrate and when no interactions take place between them during their outflow. The upper diameter limit for such bubbles is about 5–7 mm. This value corresponds to the upper diameter limit of pores in metal foams.

Table 1.
Properties of the liquids used in the tested systems

Liquid	Specific gravity $\frac{N}{m^3}$		Surface tension N/m		Dynamic viscosity $\frac{N \cdot per\ mille \cdot s}{m^2}$	
	value	source	value	source	value	source
1 Water	10.2000	[8]	0.914	[12]	0.0010	[8]
2 Liquid aluminium	23.800	[12]	0.860	[10]	0.0021	[11]
3 Liquid aluminium +20%SiC	24.800	[x]	0.860	[10]	0.0017	[xx]

[x] – value calculated from the specific gravities of the components,
[xx] – value calculated by using the Einstein formula [1].

Table 2.
Calculation results

	Liquid in the model system	Liquid in the real system	Quotient		
			$\frac{do_1}{do_2}$	$\frac{\Delta p_1}{\Delta p_2}$	$\frac{n_1}{n_2}$
1	Water	Liquid aluminium	0.446	0.078	0.63
2	Water	liquid aluminium +20%SiC	0.429	0.084	0.65

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