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## TWO-CRITERIA ANALYSIS OF CASTING TECHNOLOGIES OF METAL AND COMPOSITE FOAMS

### DWU-KRYTERIALNA ANALIZA OCENY METOD WYTWARZANIA ODLEWANYCH PIAN METALOWYCH I KOMPOZYTOWYCH

The determination of potential areas of application for metal foams allows to precisely define properties these materials are expected to have. The characteristics of metal foams are strictly related to their cellular structure, which in turn depends on the manufacturing method and materials used. Obviously, metal foam producers should strive to make these materials using inexpensive, or cost-effective technologies, yielding possibly good quality and being environment-friendly. This paper briefly characterizes the manufacturing of metal and composite foams by casting methods. We determine an optimal manufacturing method based on a matrix diagram for metal and composite foams satisfying the two - criteria: "manufacturing costs" (depending on the price of production equipment and labour, cost of materials for foam manufacturing, environmental impact) and "foam quality" (depending on the manufacturing precision, homogeneity of the structure, pore size, shape, and volumetric fraction).

*Keywords:* metal and composite foams, manufacturing methods, matrix chart analysis

Określenie potencjalnych obszarów zastosowań pian metalowych pozwala sprecyzować wymagania dotyczące właściwości tych materiałów. Są one ściśle związane ze strukturą komórkową determinowaną metodą wytwarzania oraz zastosowanym materiałem wyjściowym. Należy dążyć do wytworzenia tych struktur metodami tanimi, dającymi najlepszą jakość wyrobu a przy tym możliwie przyjaznymi dla środowiska naturalnego. W niniejszej pracy, krótko scharakteryzowano wytwarzanie pian metalowych i kompozytowych metodami odlewniczymi. W pracy opisano jak określić optymalny sposób wytwarzania w oparciu o schemat macierzy dla pianek metalicznych i kompozytowych spełniających dwa kryteria: "koszty produkcji" (w zależności od ceny urządzeń do produkcji i pracy, kosztów materiałów do produkcji pianki, oddziaływania na środowisko) oraz "jakości piany" (w zależności od precyzji wykonania, jednorodność struktury, wielkości porów, kształt i frakcję objętościową).

#### 1. Introduction

Metal foams have many unique properties that make them an attractive material for components of machines, vessels and other vehicles, mass products found mainly in cars – car body elements absorbing impact energy, increasing stiffness) and improving the comfort of use by reducing vibration and noise. Foams find applications in aircraft designs, civil engineering and road infrastructure. Their low density makes foams an ideal filler material for layered structures of high stiffness. With low thermal conductivity, foams can be used as heat insulators, while vibration absorbing property makes foams adequate for vibration damping linings. Under load foams are subject to substantial deformations, the characteristic that leads to such applications as impact energy absorbers, explosion impact reducers, or packaging. Cellular materials may have either isotropic or anisotropic properties. According to definitions in the works [1, 2, 3] metal foams are:

- porous materials, whose structure can be described as geometrically disordered distribution of pores in a metal matrix;

- metal material containing in its volume a large number of pores filled with gas.

Chemical foaming of liquid metal and blowing gas into liquid metal are among the most common casting methods of making metal foams. Metal-ceramic composites, with widely varied proportion of the components, broaden the range of functional properties of foams, and increase possibilities of controlling these properties. The introduction of reinforcement phase into metal combined with the gas blowing method of foam making leads to easier formed and stiffer porous structures. As it is possible to regulate the gas flow rate in this method, we can affect gas density, strictly related with structure homogeneity, the size and shape of pores, and their volumetric fraction in the entire casting space. The method is cheap and environmentally friendly, but requires experience due to still troublesome reception of thermally unstable foams after the manufacturing process. The high temperature may lead to deformations of porous structure, consequently product quality may deteriorate. Besides, it may be difficult to maintain the desired size and shape of pores, due to imprecise control of process parameters, mainly gas temperature and pressure.

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- Such problems do not exist in the other foam making method: foaming with chemical agents of liquid metal. The use of chemical foaming agents allows to precisely design porous structures, the volumetric fraction, shape and size of the pores by maintaining proper weight proportions. The disadvantage of the method, high cost of foaming agents, substantially increases foam manufacturing, even if the equipment is simple and inexpensive. The foaming agent used in the method, titanium hydride ( $\text{TiH}_2$ ), unfortunately has some restrictions. It is a flammable, dangerous solid material. It should be stored away from heat sources, hot surfaces, sources of sparking, naked flame and other sources of ignition, which makes the process of metal foam making more difficult. A promising, cost-effective alternative to  $\text{TiH}_2$ , still in the phases of investigation, is marble powder of synthetic calcium carbonate ( $\text{CaCO}_3$ ). Much cheaper than other foaming agents and more friendly for the natural environment in terms of manufacturing and use.

A primary feature of metal foams is high porosity, usually ranging between 75 and 95%. Consequently, foam density makes up 5-25% of the density of metal the foam is made of. Densities of common foams made of aluminium oscillates in the 0.15-0.5 g/cm<sup>3</sup> range [4, 5, 6]. Foam manufacturing from pure metals or their alloys allows to change their characteristic parameters. We describe basic methods of metal foam production, with emphasis put on two casting methods: chemical foaming and gas blowing. Then we use a matrix diagram to indicate an optimal method of manufacturing foams, based on two major criteria and their components: manufacturing costs, and foam quality. The matrix analysis is a common quality tool [12, 13] used while choosing, for instance, a method for identifying the best solution that satisfies a specific quality criterion and offers a prompt answer, e.g. when planning to implement a specific technology [14, 15].

## 2. Production of Metal and Metal-Composite Foams

Metal foams can be made by a variety of methods, as shown in Figure 1.

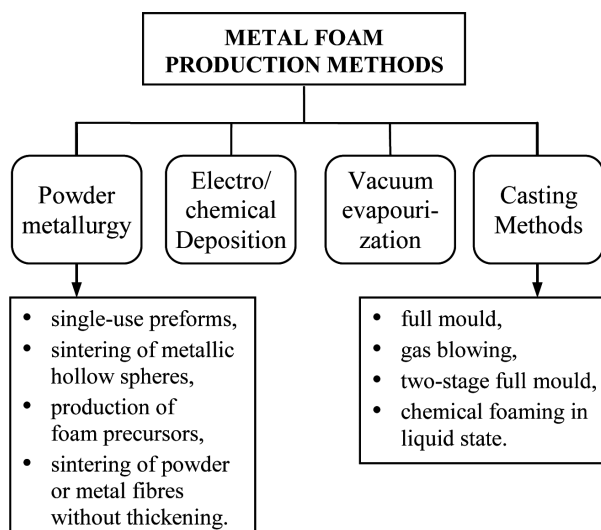


Fig. 1. Methods of metal foam production (source [6])

The variety of foam production methods yield diverse products: foams differ in pore size, relative density, porosity etc. Powder metallurgy and casting methods are the most common. The former technology has a number of variations:

- single-use preforms**; a mixture of Al and NaCl is densified / thickened and sintered in the presence of liquid phase; the method yields 85% foam porosity %, while pores range in size from 0.3 to 1 mm;
- sintering of empty metal balls**, which creates porosity oscillating between 80% and 87%;
- production of foam precursors**, consisting in thickening a mixture of Al and Cu powder, with  $\text{TiH}_2$  and sodium bicarbonate ( $\text{NaHCO}_3$ ) and cold sintering of the product or at high temperature; the obtained porosity ranges from 63% to 89%;
- sintering of powder or metallic fibres without thickening**; the porosity obtained by this method oscillates between 63% and 89%.

This paper focuses on casting methods, of which four have been distinguished here:

- full mould**, where liquid metal, for instance aluminium, is injected under pressure for 0.2 second into a mould filled up with polystyrene particles. With porosity of 73% to 86%, pore size varies from 1 to 3 mm;
- gas blowing**, where gas is directly blown into liquid metal (Fig. 2); the method is technologically difficult, but allows to choose from a variety of foamed materials and foaming gases, which in turn permits to obtain diverse structure and properties of the foam. For this reason the method, using modern materials, i.e. metal-ceramic composites, is presented in this paper. Compared to other technologies of porous structures, the method is relatively inexpensive and environment-friendly, because instead of chemicals in the process of foaming gas is used, e.g. the air. The porosity obtained in this method oscillates between 78% and 92%, while pore size ranges from 1 to 8 mm.

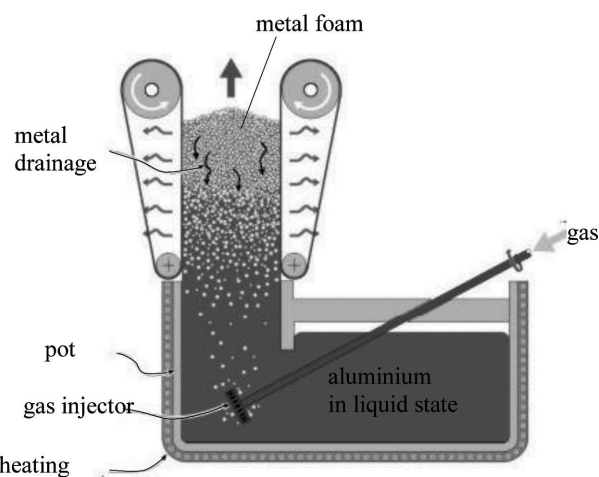


Fig. 2. A diagram of the gas blowing method [7]

The study herein described took place at the Maritime University of Szczecin. We have designed and made prototype equipment for continuous foaming of a composite material. The composites have AlSi9 alloy matrix and SiC particles reinforcement with varied weight proportions (15% to 25%).

The material was separately prepared outside the foaming device, satisfying technological requirements for suspension composites [8], by the mechanical stirring method. 15-20 μm particles were added to molten metal by stirring the batch and maintaining a temperature of 720°C.

The prepared composite was put into the melting pot of the foaming device, and the temperature was again brought to 720°C. Once the temperature became stable, and the agitator kept turning, a rotor was placed in the pot moving at 150 revolutions per minute, delivering gas to the liquid metal at a rate of 8 litres/min. The composite was foamed with air.

- **Two-stage full mould**, where pores of polymer foam are filled with plaster, the mould is heated at 700°C, then the preform is infiltrated with liquid metal; the obtained porosity reaches 98%, while pores have diameters from 1 to 5 mm.
- **Foaming in liquid state**, where a foaming agent (e.g. TiH<sub>2</sub>) is introduced into liquid metal along with agents increasing the viscosity of the metal, for instance Ca or Mg. The porosity obtained by the method ranges from 85% to 95%, while pore size is approx. 5 mm. The method is schematically presented in Figure 3. This is at present the most common method of producing metal foams.

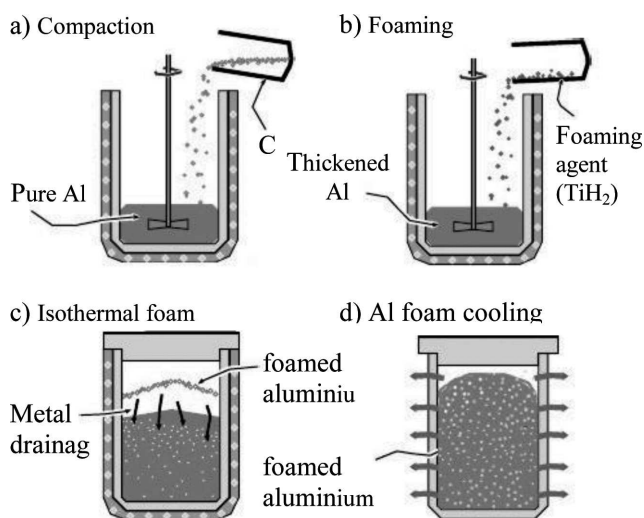


Fig. 3. A diagram presenting the chemical foaming method [6]

The method yields adequately high degree of foam structure homogeneity. Besides, the method permits to make required shape products without costly machining. For instance, in the FORMGRIP process of making foaming agents, preliminary thermal treatment of TiH<sub>2</sub> creates an oxide layer on its surface, decreasing hydrogen permeability; thus undesired hydrogen precipitation is avoided during the mixing of TiH<sub>2</sub> in liquid aluminium (silicon carbide is added to improve the viscosity of molten metal). The protective film slows down the process of decay to the extent allowing uniform distribution of TiH<sub>2</sub> particles across the whole volume of the metal [9].

Figure 4 presents characteristic porosities and pore sizes obtained by various casting methods of metal foam production.

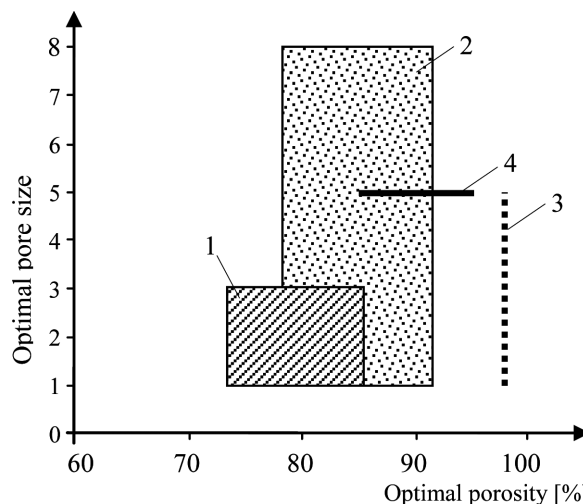


Fig. 4. Characteristic porosities and pore sizes for various casting methods of metal foam production: 1 – full mould, 2 – gas blowing, 3 – two-stage full mould, 4 – liquid state foaming [6]

### 3. Matrix analysis of foam making methods for two criteria: manufacturing costs and foam quality

The methods of metal foam making can be evaluated by description based on a matrix diagram. A graphic outcome of such description is given in Figure 5, illustrating the data obtained from the analysis as shown in Table 1. Optimization as used herein is understood as the choice of the best solution

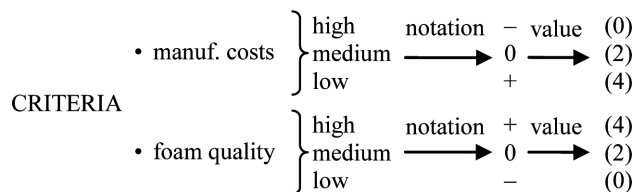


Fig. 5. Conventional grading adopted after [13] for a matrix diagram, assuming two criteria: manufacturing costs and foam quality

TABLE 1

A matrix diagram illustrating the identification of optimal casting methods of producing metal and metal-ceramic foams estimated for two major criteria: “manufacturing costs” and “foam quality”

Criterion	Notation	
Price of foam-making equipment and labour	+(4)	+(4)
Costs of materials for foam productions	0 (2)	– (0)
Environmental impact	0 (2)	– (0)
<b>Manufacturing costs</b>	Point value	
	8	4
<b>Manufacturing method</b>	<b>A</b>	<b>B</b>
Structural homogeneity	+(4)	+(4)
Size and shape of pores	+(4)	+(4)
Volumetric fraction of pores	+(4)	+(4)
<b>Manufacturing precision</b>	+(4)	+(4)
<b>Foam quality</b>	Point value	
	16	16

A – gas blowing, B – foaming in liquid state

satisfying specific quality criteria, e.g. costs, environmental impact, efficiency [10, 11, 12]. The optimal method for metal foam making has been identified on the basis of two major criteria and their subcriteria: “manufacturing costs”, including price of the foam making equipment and labour, costs of materials, environmental impact, and “foam quality”, depending on manufacturing precision, homogeneity of the structure, pore size and shape, and volumetric fraction of pores. As proposed in [13], we have adopted a conventional three grade scale for evaluating the methods against specific subcriteria (Fig. 6).

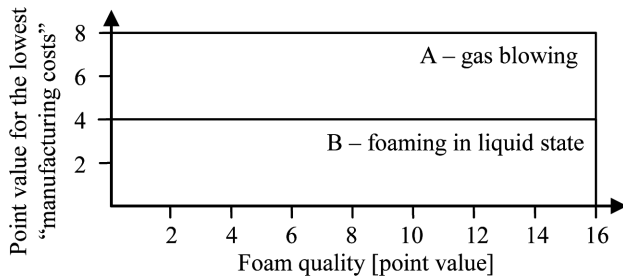


Fig. 6. An example graphical outcome of a matrix analysis of data (as per Table 1). The optimal method of manufacturing metal and metal-ceramic foams

#### 4. Conclusions

We have made a matrix analysis (see Table 1) and compared casting methods of foam making: blowing gas into liquid metal and chemically foamed liquid metal. The analysis is based on two major criteria and their subcriteria: “manufacturing costs”, including price of the foam making equipment and labour, costs of materials, environmental impact, and “foam quality”, depending on manufacturing precision, homogeneity of the structure, pore size and shape, and volumetric fraction of pores. It follows from the analysis that the gas blowing method (A) is optimal one for making metal and metal-ceramic foams. With the lowest production costs (highest point value on the X

axis, Figure 6), the method yields good quality foam (highest point value on the Y axis – Figure 6).

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