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SELECTED ASPECTS OF MANUFACTURING OF ALUMINIUM SPONGE

The present article describes selected aspects of investment casting technology for manufacturing of open-cell aluminium. The main focus is, among others, on the precursor thickening. Two groups of total 30 samples were produced, basing on open-cell polyurethane foam used as the precursor. Each of the two sample groups was thickened with a different type of suspension consisting of carbonaceous substances and organic binders. The influence of the coating mixture type was compared, leading to conclusions regarding the desired composition and fluidity of the suspensions. Both sample groups of the obtained open-cell aluminium had stochastic cell distributions, the average pore diameter was 5.2 mm and the PPI index was 8. The apparent densities were respectively: 0.485 g/cm^3 and 0.312 g/cm^3, which reflected the impact of the precursor coating. Additionally, samples from both groups differed in quality.

Keywords: metal sponge, aluminium sponge, investment casting, precursor thickening

1. Introduction

1.1. Porous metals

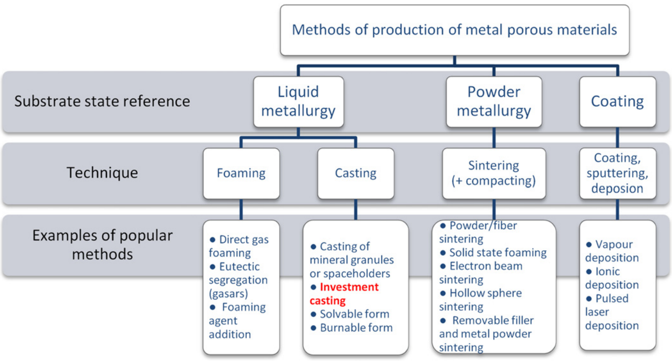
Porous materials with metal skeleton are becoming increasingly popular. They are valued materials in various engineering fields: from automotive industry, through aviation, medical usages, military and even space applications [1,2]. Different examples of these materials are distinguished with respect to the skeleton material – foams and sponges can be made of aluminium, copper, magnesium, nickel, titanium or even gold, as well as of a range of alloys [3-10]. Porous metals are also divided into classes due to the type of porosity and skeleton's structure. The following major groups may be distinguished: closed-cell metal materials, open-cell metals, sponges, gasars, and others [11-13].

1.2. Methods of production

Behind such a wide variety of types of porous metals is, naturally, a broad scope of manufacturing methods. In general, production routes can be divided into three major fields: powder metallurgy, casting techniques and deposition methods (Table 1) [1,14]. Each branch includes a number of specific manufacturing techniques; however, due to the purpose of this article, the authors limit themselves to describing in detail only the investment casting, which was used by them to produce the studied porous material.

TABLE 1

Production routes for porous metals, the method used in the presented study is marked in red



1.3. Investment casting – the chosen method

Investment casting is a widely used manufacturing route in which a pattern (also called a precursor or a template) made of wax or polymer spaceholder is covered (resulting in a shell mould) or cast (resulting in a block mould) with a refractory material. Next, during thermal treatment, the pattern burns or melts out of the refractory mould, leaving cavities to be filled later with molten metal in the process of casting [15-18]. With respect to diverse materials used as patterns, as well as mould substances and different processing parameters the method has many variances [19]. The methodology assumed in the present

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research consists of the following steps: the use of a polyurethane foam as the pattern, casting it with plaster, heating of the composite to burn out the polymer and then vacuum casting of such prepared mould with aluminium. The final step is the mould removal after quenching the cast – see: Fig. 1.

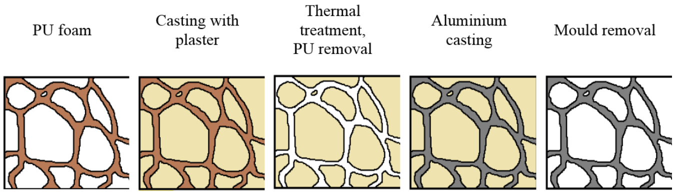

Fig. 1. Stages of the used method of investment casting

1.4. Thickening of the pattern

One of the important aspects in the production of metal sponges by investment casting is assuring that the cavities in the mould are wide enough for the molten metal to penetrate. This becomes a crucial issue in case of the use of polymer sponges as precursors, because of the considerably small thickness of the sponges' struts. In result, too narrow channels in the mould may be obtained. To avoid problems with penetration of molten metal into the mould, increasing of thickness of the polymer foam struts is necessary. It was reported that thickening could be realized by covering of the pattern with wax or spraying it with acrylic paint [2,20]. In the present research, the authors pursue the novel concept of thickening of the polyurethane template: with the use of a mixture of carbonaceous substances and binders. Two variants of coating are compared, resulting in conclusions related to the composition of the carbonaceous suspensions. It is worth noticing that the use of carbonaceous substances is also reported to be successful in production of porous zirconia [21].

2. Experimental: the own manufacturing procedure

2.1. Polymer precursor samples

The material for the research was gifted by the company Recticel Flexible Foams from Wetteren, Belgium. It was a black open-cell reticulated polyurethane (PU) foam with the trade name Bulpren C 32520 (Fig. 2, left). According to the product's card and the producer's information [16], the material had net density (27÷31) kg/m^3. Cell distribution was stochastic and the average cell diameter determined with the use of the Visiocell technique [23-26] was $d_{PU} = 5200$ µm. Further characteristics of the material included [16]: strut thickness $t_{PU} = 292$ µm and pores per inch index $PPI_{PU} = 8$. Additionally, for the purpose of the present study, the porosity was determined: $\varphi_{PU} = (97.3 \pm 1.4)$ %, assuming the PU skeleton's density 1200 kg/m^3 [27]. The material was cut into two types of samples: group I consisted of 22 specimens of the size (4×4×6) cm and group II consisted of 8 specimens of the size (4×4×7) cm.

2.2. Covering of the precursors with the thickening coating

Thickening of the polymer precursor consisted in its uniform covering with a substance which would be fully burnt out (no residuals left) in thermal treatment of the mould. For this purpose, suspensions of carbonaceous substances and organic binders were used:

- carbonaceous substance:
  - A: petroleum coke ground to a grain size <60 µm;
  - B: pitch binder ground to a grain size <40 µm;
- binders:
  - C: water dispersion of a styrene-acrylic copolymer, viscosity (2000÷6000) mPa·s;
  - D: water dispersion of an acrylic copolymer, viscosity (5÷50) mPa·s;
- E: plasticiser – sodium lignosulphonate, aqueous solution with concentration 36%.

The suspension preparation consisted in mixing, using a laboratory stirrer, of appropriate proportions of the carbonaceous substance, plasticiser and aqueous solution of the binder diluted with water to the desired concentration.

For the two sample groups (I and II) two different suspension compositions were prepared. Detailed component proportions are given in Table 2 and Table 3. Group I was coated with the thickening substance made from petroleum coke, water dispersion of a styrene-acrylic copolymer and plasticiser (A+C+E), while group II was covered with the mixture of pitch binder, water dispersion of an acrylic copolymer and plasticiser (B+D+E). Samples from group II were coated with an additional layer consisting of aqueous solution of the binder (without the carbonaceous substance).

TABLE 2

Composition of the suspension – method I

Component	Weight fraction, %	
	Coating I	**Coating II**
Petroleum coke (A)	60	40
Plasticiser (E)	0.3	0.2
Water dispersion of a styrene-acrylic copolymer, aqueous solution with concentration 50% weight (C)	39.7	59.8

TABLE 3

Composition of the suspension — method II

Component	Weight fraction, %		
	Coating I	**Coating II**	**Coating III**
Pitch binder (B)	46	32	—
Plasticiser (E)	0.2	0.1	—
Water dispersion of an acrylic copolymer (D)	53.8	67.9	50
Water	—	—	50

Coating of polymer foams was performed in a multi-step process. Firstly, the polymer sample was immersed in the suspen-

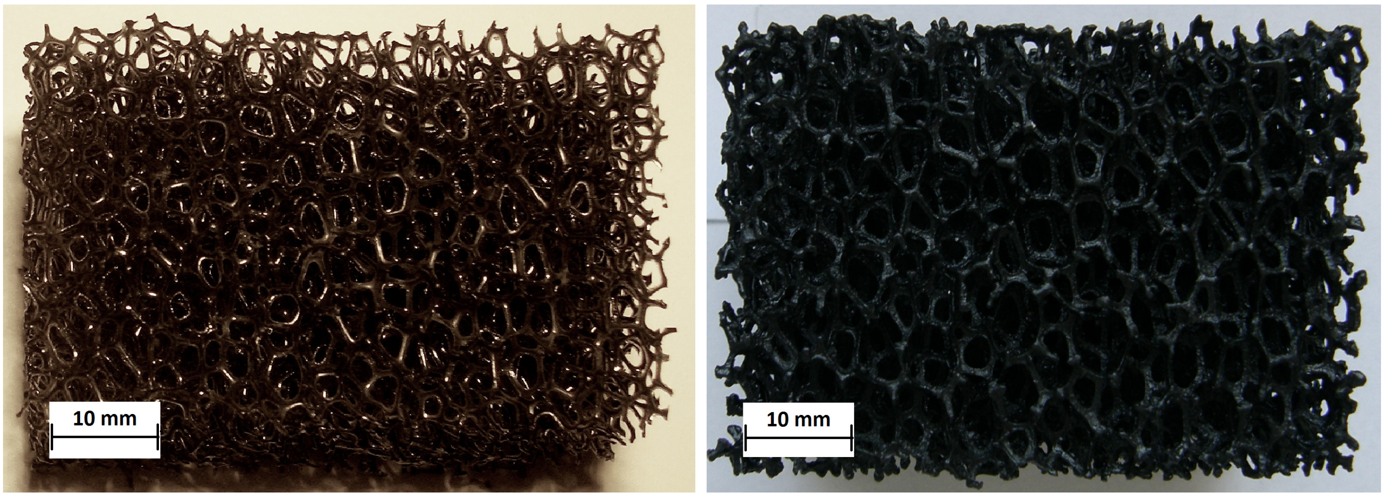

Fig. 2. Exemplary sample before coating (left) and after the thickening procedure (right); thickening by method I

sion and the covering substance excess was removed by squeezing of the sponges between two rotating rollers. The next step consisted in drying of such coated samples in the temperature 110°C for 2 h. Then, the procedure was repeated: the samples were immersed in the suspension for the second time and, after removing of the covering substance excess by blowing with compressed air, they were dried again in 110°C for 2 h. The suspension in the second coverage had greater liquidity to allow for easier removal of its excess. This feature was obtained by the increase of the proportion of the binder (the proportion of the plasticiser in relation to the weight of carbonaceous filler remained unchanged). An exemplary sample before and after the thickening procedure is shown in Fig. 2.

2.3. The form

The material chosen for forms was moulding gypsum-bonded investment compound for casting precious metal alloys, which did not undergo considerable shrinkage [28]. The thickened precursors were supplemented with siphon shaped wax in order to build a gating system [17,29]. The assembly was next put in a perforated steel hollow and cast with liquid gypsum (plaster) in a vacuum chamber. In this way removal of air pockets from the moulding form was assured. After bonding, heating was performed in a chamber oven up to 720°C, in which temperature the chemically bond water was removed and the polymer-wax system melted and burnt out. The thermal process for the mould is illustrated in Fig. 3. The form in the steel hollow is shown in Fig. 4 (left). For both sample groups – I and II – the same moulding forms were prepared. The moulds' temperature was lowered to 685°C for casting.

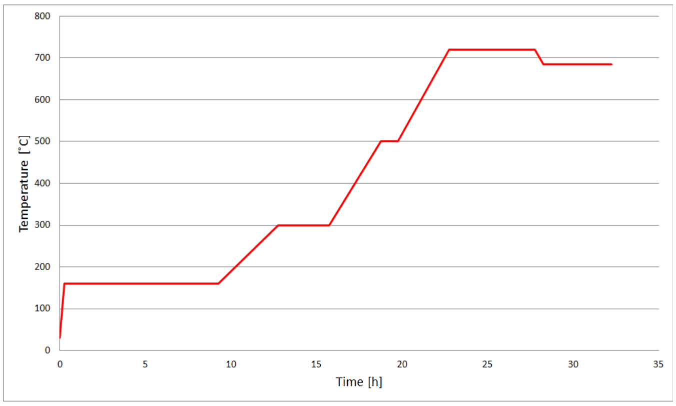

Fig. 3. Thermal process for one of the moulds

2.4. Casting

Pure aluminium crystallises in lattice A1, and hence is characterised with very good plasticity; its melting point is 660.4°C and the boiling point is 2060°C [30]. Aluminium chosen for the production of sponges was 99.9% Al.

The melting process was performed in vacuum furnace VC3000d (Fig. 4, right). The metal, after melting in vacuum

Fig. 4. The plaster mould in the perforated steel hollow (left) and Indutherm furnace used for casting (right)

was superheated to 680ºC. The burned plaster mould was next placed in the furnace's flask chamber and after reaching of pressure below 1 mbar in both furnace's chambers, the mould was filled under the gravity force. Heating of the plaster mould above the aluminium's melting point allowed for the avoidance of the metal's crystallisation before complete filling of the cavity of the casting mould. For both sample groups (I and II) the same casting conditions were assumed.

2.5. Extraction of open-cell aluminium samples from gypsum moulds

Casts in moulds were quenched in order to prepare for the gypsum removal. Rinsing with water and sandblasting were used; however, it was observed that these methods were insufficient and did not clear the samples completely. Thus, additional methods were used, including:

- freezing of wetted cast-mould systems in order to crumb the gypsum – unsatisfactory;
- ultrasound crushing of the mould material (with the use of the emitter Techpan UD-11) – unsatisfactory;
- cleaning with a magnetic washer (with the use of the washer MR Hei-Standard Heidolph) in 40ºC for about 24 h – satisfactory only for the group II.

Despite the undertaken efforts, it was not possible to remove all gypsum from the specimens which were thickened by the method I. On the other hand, the samples from the group II were fully extracted from moulds. Further discussion of this fact is presented in the section 3.1.

The last part of the manufacturing process was gentle pickling of the obtained aluminium sponge in order to remove an outer oxidized layer. The etching mixture consisted of: orthophosphoric acid H_3PO_4, nitric acid HNO_3 and water. Samples were immersed for a few seconds in the mixture heated to 80ºC and then rinsed with water and dried.

3. Results and discussion

3.1. Structure of the produced aluminium sponge

The obtained open-cell aluminium had the geometrical structure which repeated the original polymer foam's structure. Therefore, it can be assumed that the produced aluminium sponge had the same general structural parameters as the precursor, *i.e.*: the stochastic cell distribution, the average cell diameter d_{Al} = 5200 μm and the pores per inch index PPI_{Al} = 8.

As has been mentioned above, the sample groups I and II differed in quality (Fig. 5). In the group I, in specimens' central fragments, some material of the moulds and structural imperfections were observed. A hypothesis was then proposed that this difference could be attributed to the thickening method. Authors presume that, since the suspension in the method I contained more carbonaceous substance and was more viscous, excess drops or thin films of the coating might have left in the interior of the precursor in the process of thickening. Later, in the phase of the moulds' thermal treatment the drops and films might have left additional and unintended cavities in the mould. The unwanted cavities might have been cast with aluminium causing structural imperfections of the obtained aluminium sponge's structure such like: metal drops, membranes or local gluts. The aluminium excess might have surrounded or interwoven certain mould portions and hence caused them to resist removal. In

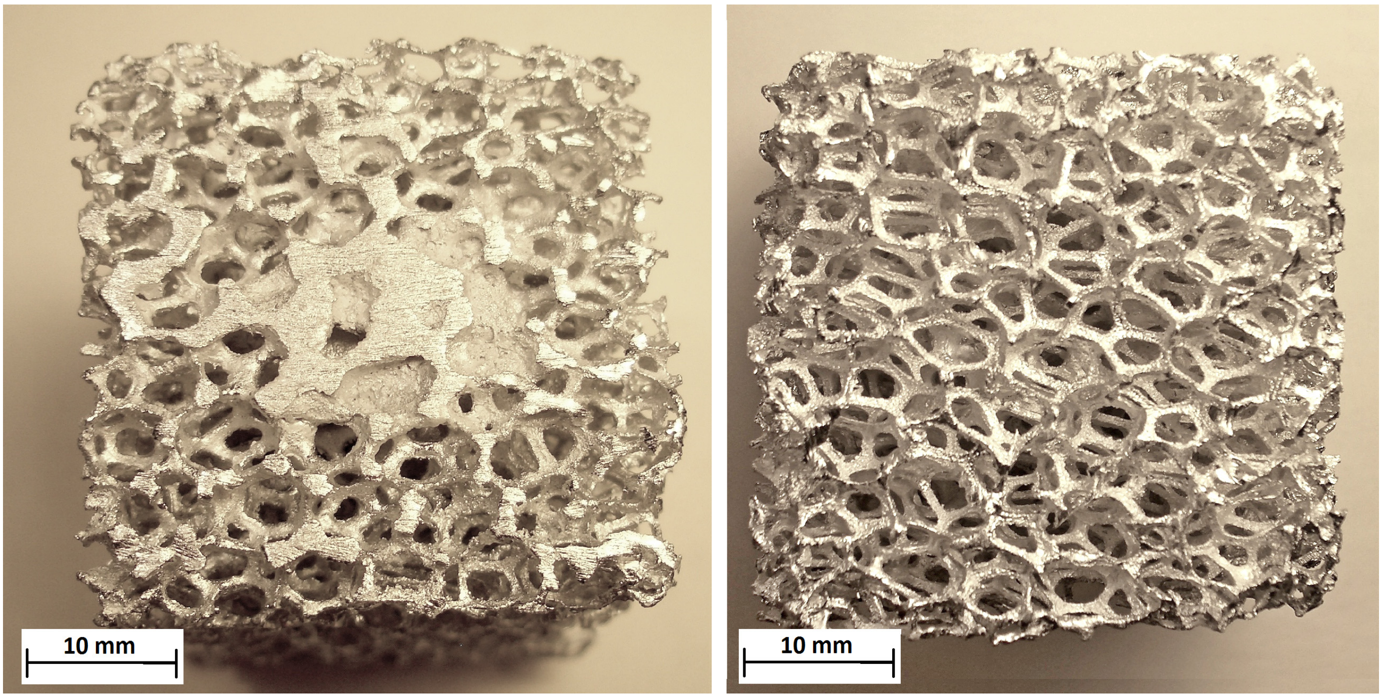

Fig. 5. Examples of obtained samples: made from precursors thickened by the method I (left) and the method II (right)

contrast, the samples thickened by the method II did not have visible imperfections and moulds' material was completely removed from them.

3.2. Density and porosity of the produced aluminium sponge

Differences in the structure between groups I and II were reflected, among others, in apparent density (Table 4). Additionally, relative density and porosity were determined for the group II (Table 5); for these calculations the skeleton's density was assumed as 2720 kg/m^3 [31]. If one compares the porosities of the primary polyurethane sponge and the resultant metal sponge, it can be observed that the process of thickening considerably changed the cross dimensions of struts and therefore the skeleton's thickness as a whole, resulting in adding of 8.8% volume to the skeleton:

$$\varphi_{PU} = 97.3 \pm 1.4\% \ vs \ \varphi_{\mathrm{Al}} = 88.5 \pm 3.0\%$$
$$\rightarrow \Delta = \varphi_{PU} - \varphi_{\mathrm{Al}} = 8.8\%.$$

TABLE 4

Apparent densities of samples' groups I and II

Thickening method	Apparent density ρ_{app} [g/cm^3]	Relative error [%]	Absolute error [g/cm^3]
I			
average	0.485	2.1%	0.010
standard deviation	0.060	0.7%	0.004
variability coefficient	0.125	31.7%	0.349
II			
average	0.312	2.0%	0.006
standard deviation	0.038	0.3%	0.001
variability coefficient	0.121	14.9%	0.121

TABLE 5

Relative density and porosity of samples from group I

Material characteristic	Value [%]	Relative error [%]	Absolute error [%]
Relative density			
average	11.48%	—	0.23%
standard deviation	1.39%	—	0.03%
variability coefficient	12.10%	—	12.13%
Porosity [%]			
average	88.52%	3.0%	—
standard deviation	1.39%	0.4%	—
variability coefficient	1.57%	14.6%	—

4. Conclusions

A novel method of template thickening in investment casting of metal sponges has been proposed and experimentally positively verified on the example of aluminium sponge. The coating mixtures consisted of carbonaceous substances, binders and plasticisers. The comparison of the two proposed compositions of thickening suspensions led, among others, to the following remarks:

- carbonaceous substance ground to a smaller grain size gives a better effect (<40 μm),
- binders should have viscosity on the level (5÷50) mPa·s.

Additionally, from a couple of methods used for cast extraction, the magnetic washer turned out to be the most effective one, while ultrasound crushing or consequent wetting and freezing did not result in successful gypsum removal.

The planned continuation of research regarding the production method involves attaining of better samples' parameters repetitiveness, calibration of other technological aspects such as temperature, the preform material and the form material. Also, minor adjustments of the thickening and techniques for clearing the cast from the mould would be advantageous. As for the further study related to properties of the material, whose production is reported in the present article, uniaxial compression tests were performed and an attempt to modelling of the material's compressing behaviour was proposed [32]. This could provide a valuable source for future comparison aimed at assessing the influence of technological aspects of production on the samples' mechanical response.

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