DOI: 10.21062/mft.2022.051 http://www.journalmt.com

Properties of Aluminium Cellular Materials Produced by Powder Metallurgy Using the Foaming Agent TiH_2

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A considerable attention is paid to the production and monitoring of the properties of metallic cellular structures and the properties of aluminium foams, respectivly. Foam structures can be manufactured in three basic ways (by blowing the external gas into the melt, by melt gasification due to the thermal decomposition of the foaming agent, by the melting of the foamable preform which contains foaming agent particles). The paper addresses to our publication [18] and furthermore focuses on the investigation of mechanical properties of two types of foamed AlSi12 aluminium alloy samples. Samples (150×25×10 mm) were produced by powder metallurgy using a foaming agent TiH_2. The characteristics features of the produced foam structures (relative density, porosity, volume fraction of solids, Young's modulus of elasticity) were studied on AlSi12 alloy samples. In addition, the porosity of samples and continuity of their air cells were monitored usign the scanning electron microscope.

Keywords: Aluminium alloy foam, Powder metallurgy, Foaming agent, Physical properties, Structure

1 Introduction

Historically, the idea of a producing "lightweight metal systems", respectively metal cell materials has started since 1926 [1]. At the beginning, cellular materials were constructed from basic metallurgical materials [2], [3]. Over time, their production has started to expand, and new design technologies have begun to emerge. At the same time, these cellular materials (cellular structures) began to more favourably refer to "foams" and to metallic "metal foam" materials [3]. As BANHADT points out [4], the use of language in this field of research is often inaccurate. BABANHART [4], the term "foam" means a mixture of gas and a solid phase in which the gas bubbles are isolated from each other while the solid matrix is random, which originates from the liquid phase in which gas bubbles are arranged loosely. The production and properties of metal foams are systematically investigated and their technical applications can be found in e.g. [5], [6], [7]. In our previous publications the selection of suitable foaming agents for the production of aluminium foams were investigated and particularly, this paper focuses on the aluminium cellular materials produced by powder metallurgy. The use of titanium hydride as a foaming agent for the production of aluminium cellular materials has been investigated by many researches who based investigation mostly on the practical skills and knowledge coming from the manufacturing metallic cellular systems. The production of metal foams with TiH_2 foaming agent was studied by BANHART [4] and MATIEVIC [8], MATIEVIC carried out the experiment by pursuing the thermal decomposition of TiH_2 powder. Instead WANG [9] followed an idea of the compaction and sintering of titanium hydride. RASOOLI [10] observed the decomposition kinetics of titanium hydride under condition of the temperature range from 673 K 1273 K. The results showed that the temperature range from 673 K to 873 K, the decomposition of the TiH_2 powder is controlled by the internal diffusion of hydrogen atoms along the titanium dioxide layer (Ti_2O_3). BAUMGÄRTNER [11] characterized the production of aluminium foams by powder metallurgy (PM), using the foaming agent TiH_2. He concluded that the entire technological process requires was sensitive to all the necessary manufacturing principles. Technical factors influencing the production of aluminium foam were a size of the densification pressure, the process temperature and the weight content of SiC. They reached the following values: pressure = 430 MPa, temperature = 750 °C and SiC = 3 wt. %, particle size 37 μm. At the same time, the particle size of the aluminium powder is about 45 μm. TiH_2 foaming agent with a purity of 97.5%, a particle size of 40 μm. KENNEDY [12] monitored and evaluated the foaming effect of TiH_2 powder. The TiH_2 powder was mixed with a pure aluminium powder and subsequently heat treated to form foam precursors. Based on TiH_2 differential scanning calorimetry at the pressure of 101 325 Pa, it was found that hydrogen is normally released at about temperature of 495 °C. In our study, important values of foamed parts aluminium alloy AlSi12 were calculated by Equations already presented in [13, 14]. Important findings about aluminium alloys have been taken from [15]. Our paper [16] focused on the prediction of the foaming process in the production of aluminium foams. In this study, we focused on the structure and determination of the properties of aluminium foams. Paper [18] is focused on the ecological production of porous aluminum materials.

2 Method and material

Several important results of foamed materials produced by powder metallurgy were sumamrized and futher discussed in [16]. This method is used by Leichmetall Kompenzzentrum Ranshofen (LKR). The aluminium powder or aluminium alloy powder is first mixed with a foaming agent powder (TiH_2 or ZrH_2). A foamable semi-finished product in the form of bars, wires or various open profiles is produced by cold pressing followed by hot extrusion (solid state) and these blanks are placed in a foaming steel mould and heated above the melting temperature in the mould. An aluminium melt is formed which fills the cavity of the mould. At the same time, the heating of the foaming agent produces hydrogen, which appears in a form of the gas bubbles in the melt forms. By cooling the foamed aluminium melt with hydrogen bubbles below the melting temperature it is produced the aluminium foamed material with a continuous surface layer (crust) and a porous internal structure. Figure 1 shows a schematic of the principle of aluminium foam production by powder metallurgy. The production of aluminium foams is very demanding and complex. It is required to use the specific equipment for their production and during the production process, a number of metallurgical principles must be continuously observed.

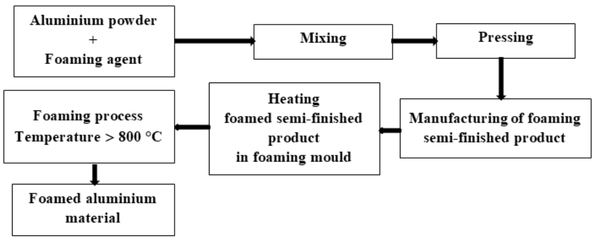


Fig. 1 *Scheme of production foamed aluminium alloy by powder metallurgy by LKR technology [6]*

The semi-finished product is placed in a foamed steel mould and heated above the melting point of aluminium (aluminium alloy). This is followed by melting of the aluminium powder and simultaneous thermal decomposition of the foaming agent TiH_2, which releases hydrogen. The hydrogen creates pores in the aluminium alloy melt. The aluminium foam melt fills the cavity of the foam mould and determine its shape when the mould cavity is completely filled with molten aluminium alloy hydrogen (may indicate deliberately created mould leaks). This is followed by rapid cooling of the foam steel mould below the melting temperature of the aluminium or aluminium alloy. This process produces analuminium alloy foam with a continuous surface layer (crust) and an internal porous structure. AlSi12 aluminium alloy powder was used to produce the test foam castings and titanium hydride (TiH_2) has been used as the foaming agent.

In the metallurgical process it was necessary to follow the principles of good practice, including the amount of ingredients used and technological parameters (temperature, time, etc.). The foaming process was carried out in a special frothed steel mould with a cuboid cavity of 150 x 50 x 10 mm. Tab. 1 shows the chemical composition of AlSi12 alloy as determined by a Q4 TASMAN spectrometer on the foamed test specimens obtained. Fig. 2 shows a foamed aluminium AlSi12 alloy, dimensions: 150 x 25 x 10 mm.

Tab. 1 *Chemical composition aluminium alloy AlSi 12*

Chemical composition aluminium alloys AlSi 12 [weight. %]								
Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Al
11.9	0.6	0.1	0.2	0.06	0.1	0.09	0.15	Balance

Note: The spectrometerr works with an accuracy ± 5 (wt%).

(a) (b)

Fig. 2 *Produced foamed parts (150×25×10 mm) samples of foamed aluminium alloy AlSi12, made by LKR technology*

Fig. 3a shows the dimensions of the produced samples. Fig. 3b is a view of a sample of AlSi12 alloy. The aluminium foam cells of the AlSi12 alloy test specimens were made in two sizes, as shown in Fig. 3c and Fig. 3d. Group I. aluminium foams had a cell size of 1 to 3 mm (Fig. 3c), group II. aluminium foams had a cell size of 3 mm to 5 mm (Fig. 3d).

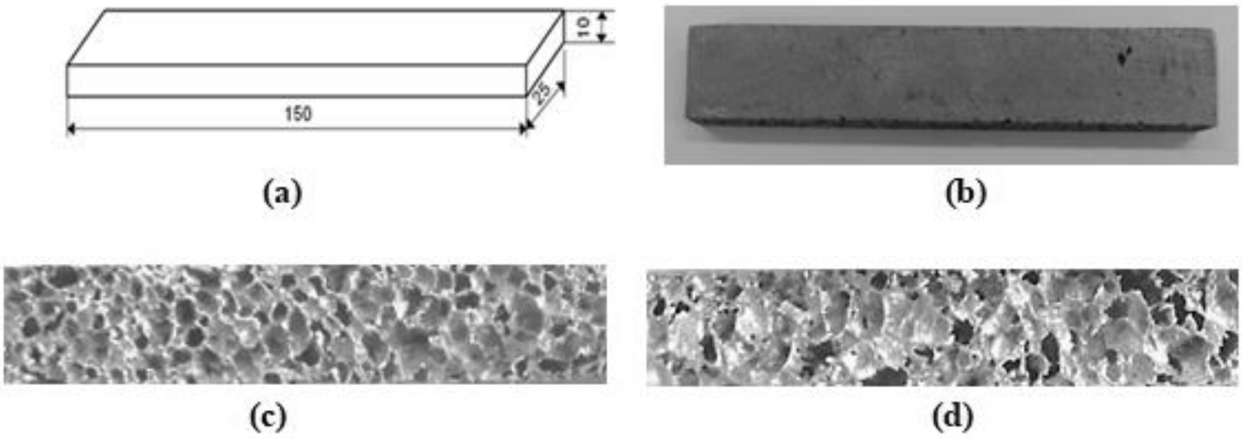


Fig. 3 *Scheme and dimensions of samples (a); view of sample (b); group I. foam cells (c); group II. foam cells (d)*

3 Results

The produced samples of aluminium foamed materials were analysed. For determination of their weight, the RADWAG WPS, model 4000/C/2 electronic equipment, company RADWAG, Poland was used, see in Tab. 2. At the same time, physical values were calculated based on their material characteristics, which are shown in Tab. 3.

3.1 The physical properties of foamed aluminium AlSi12 alloy

Five manufactured samples group I and group II foamed AlSi12 were evaluated for their weight, which was statistically treated and their above-mentioned material properties were additionally calculated, see in Tab. 2.

Tab. 2 *Weight values of foamed AlSi12 alloy samples and their statistical evaluation*

Statistical evaluation of the weight of foamed samples from AlSi12 alloy								
Sample	Specified sample weights [g]					Average weight [g]	Weight standard deviation [g]	Coefficient of variation weight [1]
GRUPI.	15.39	16.47	18.74	17.25	16.83	16.94	1.09	7.21×10^{-2}
GRUPII	11.30	12.35	12.54	12.94	11.97	12.14	0.51	5.10×10^{-2}

Note: Weight is ± 0.01 g.

To evaluate the properties of prepared foaming aluminium alloy material, a methodology was developed to determine the relevant physical-material characteristics or other relevant quantities. Such an evaluation of the produced aluminium foamed materials involves the determination of the following quantities:

a) Determination of foamed aluminium alloy density ($\rho_{Al.F.}$):

$$\rho_{Al.F.} = \frac{m_{Al.F.}}{V_{Al.F.}} \ [kg \cdot m^{-3}] \qquad (1)$$

Where:

$\rho_{Al.F.}$…Aluminium foam density [$kg \cdot m^{-3}$],
$m_{Al.F.}$…Weight of aluminium alloy foamed [kg],
$V_{Al.F.}$…Volume of aluminium alloy foamed ($4x10^{-5}$ m^3).

b) Determination of the foamed aluminium alloy density (ρ_{REL}):

$$\rho_{REL} = \frac{\rho_{Al.F.}}{\rho_{Al.B.}} \ [1] \qquad (2)$$

Where:

ρ_{REL}…The relative density [1],
$\rho_{Al.F.}$…Aluminium foam density [$kg \cdot m^{-3}$],
$\rho_{Al.B.}$…Aluminium foam density base material (without foaming) [$kg \cdot m^{-3}$].

c) Determination of material porosity (P) is the ratio of the density difference between the base material and foamed aluminium alloy (Al.F.) to the density of the base (no foamed aluminium – Al.B.):

$$P = \left(\frac{\rho_{Al.B.} - \rho_{Al.P.}}{\rho_{Al.B.}}\right) \times 100\ [\%] = \left(1 - \frac{\rho_{Al.P.}}{\rho_{Al.B.}}\right) \times 100\ [\%] \qquad (3)$$

AlSi12 alloy density is 2650 [kg·m⁻³].

d) Determination of the solid phase the foamed aluminium alloy volume fraction($V_{S.P.}$):

$$V_{S.P.} = 1 - P\ [1] \quad (4)$$

***e)* Determination of Young's modulus of elasticity aluminium alloy foamed ($E_{Al.F}$):**

The value was determined based on the relationship given by JERZ [13] and by MORENO [14]:

$$E_{Al.F.} = k \cdot E_{B.M.} \cdot (\frac{\rho_{Al.F.}}{\rho_{Al.B.}})^m\ [MPa] \quad (5)$$

Where:

$E_{Al.F.}$…Young's modulus of elasticity aluminium alloy foamed [MPa],

$E_{Al.B.}$…Young's modulus of elasticity aluminium alloy base [MPa],

$\rho_{Al.F.}$…Foamed aluminium alloy density [kg·m⁻³],

$\rho_{Al.B.}$…Base aluminium alloy density [kg·m⁻³],

m…Constant for elastic modulus calculation m = 2 [13], m = 1.5 to 1.7 [14],

k…Constant for calculation of the modulus of elasticity k = (0,1 to 4), [14]. For calculate was used of k = 0.1, m = 1.5.

Based on Equations (1)–(5), the selected importamt material proprties of the produced foamed material on the produced aluminium alloys AlSi12 were calculated and summarized in Tab. 3.

Tab. 3 *Basic properties of base material and foamed aluminium alloys (manufacture powder metallurgy) – group I. and group II. samples*

Determination of mean values of properties of the monitored AlSi12 aluminium foam, Group I. and Group II.			
Properties	Physical quantity	Value	
		Group I.	*Group II.*
Weight of foamed sample ($m_{Al.F.}$)	[kg]	1.69×10^{-2}	1.21×10^{-2}
Volume of foamed sample ($V_{Al.F.}$)	[m⁻³]	4.00×10^{-5}	
Density of foamed aluminium alloy or density of the discretized structure of the foamed aluminium alloy ($\rho_{Al.F.}$)	[kg·m⁻³]	423	303
Relative density of the foamed aluminium alloy ($\rho_{REL.}$)	[1]	1.6×10^{-1}	1.1×10^{-1}
Porosity of foamed aluminium alloy (P)	[%]	84	89
Volume fraction of the solid phase of the foamed aluminium alloy ($V_{S.P.}$)	[1]	0.16	0.11
Stress tension (σ_{STRES})	[MPa]	32	24
Yield stress ($\sigma_{0.2}$)	[MPa]	4.9	2.5
Young's modulus of tensile elasticity of foamed aluminium alloys (determinate from test of tensile strength)	[MPa]	171	90
Young's modulus of tensile elasticity of foamed aluminium alloys (calculated)	[MPa]	480	312

Note: $E_{B.M.\ (AlSi12)}$ = 75 000 [MPa]

3.2 The mechnical properties of foamed aluminium AlSi12 alloy

Compressive strength test of a sample made of aluminium powder metallurgy, see in Fig. 4. The test specimens were 25 x 25 mm, the area of the test specimen was 625 mm². Fig. 5 shows the stress-strain relationships for two test specimens (group I. and group II). Fig. 6 shows the stress-strain relationship for the tensile test of two samples of the foam produced (group I. and group II.).

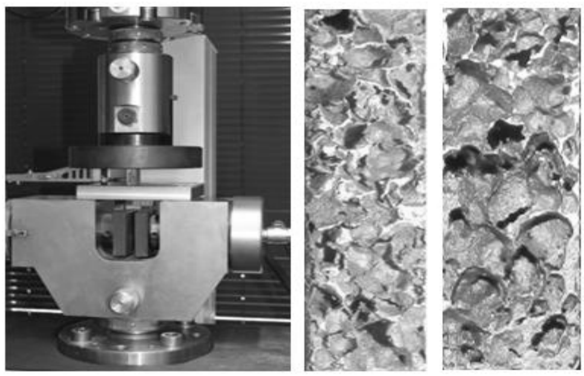
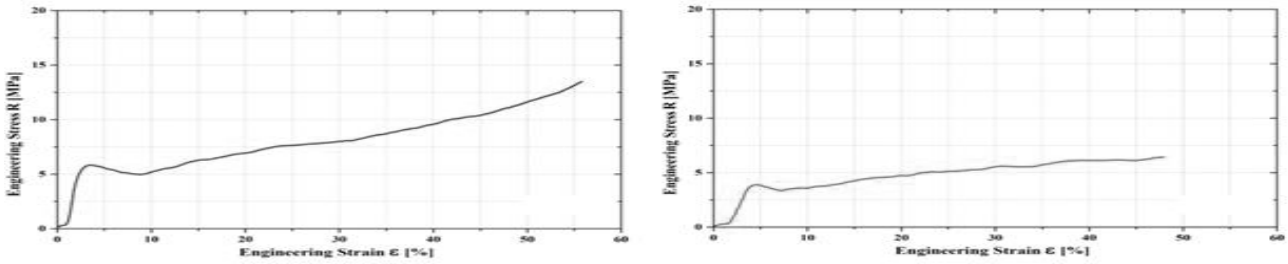
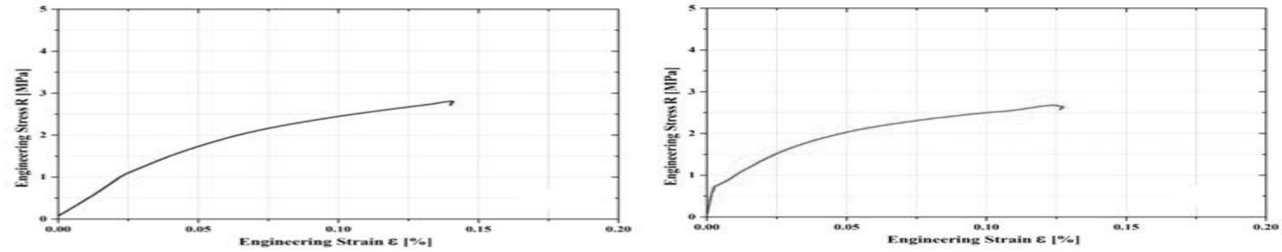


Fig. 4 *Strength test of a sample aluminium powder metallurgy*



(a) (b)

Fig. 5 *Stress-strain pressure test, (a) – group I. sample; (b) – group II. sample*



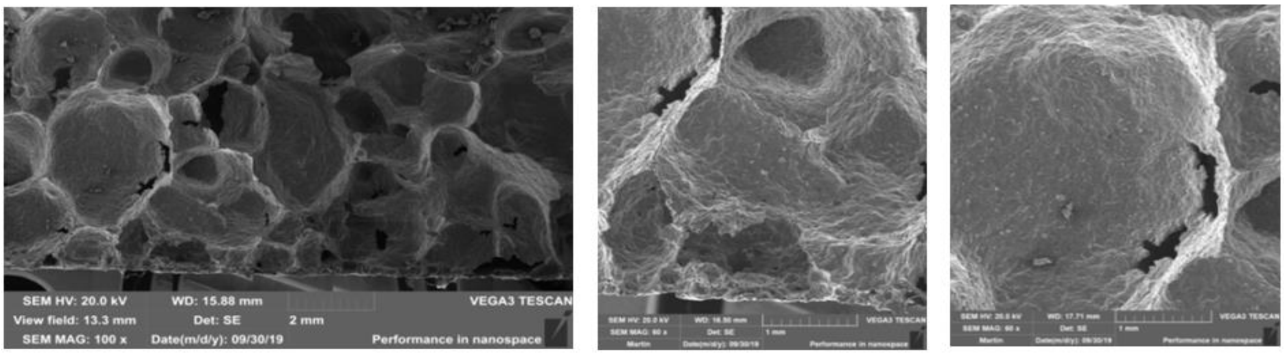
(a) (b)

Fig. 6 *Stress-strain tension test, (a) – group I. sample; (b) – group II. sample*

Based on the graphs in Fig. 5 and Fig. 6, the strength, yield strength and Young's modulus values were obtained and the values are shown in Tab. 3.

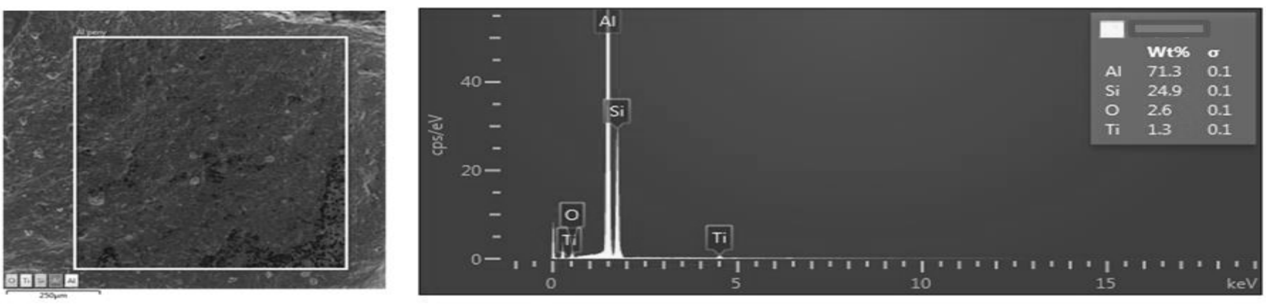
3.3 Structure of foamed aluminium alloy AlSi12

The interconnection of cells in the structures aluminium alloy AlSi12 was monitored via a scanning electron microscope (SEM) TESCAN (model Vega 3, company TESCAN, Brno Czech Republic HV 20.0 kV). Furthermore, EDX analysis was also performed and the chemical composition of the AlSi12 aluminium alloy in the selected location was founded. The obtained structures from the electron microscope of each sample, as well as the EDX analyses results are shown in Fig. 7–10.



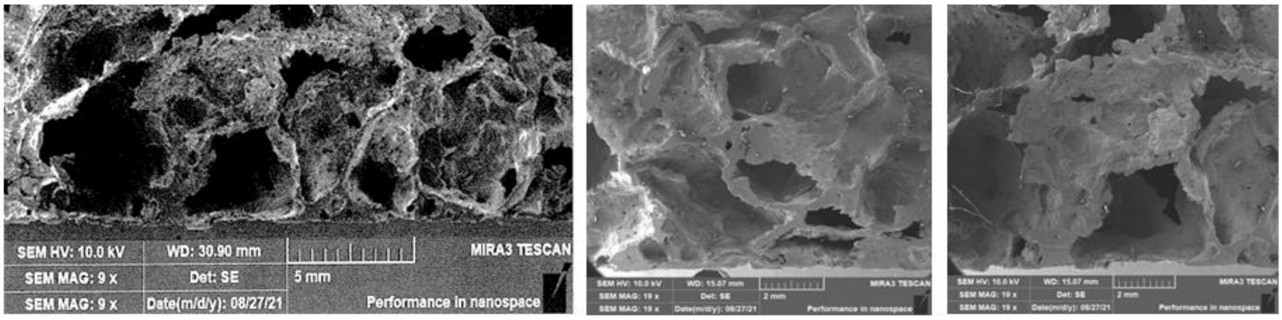
(a) (b) (c)

Fig. 7 *View of the structure of the foamed material of AlSi12 alloy (a); detail of the material (b), (c); scanning electron microscope (Vega 3 Tescan, SEM HV: 20.0 kV); group I. sample*



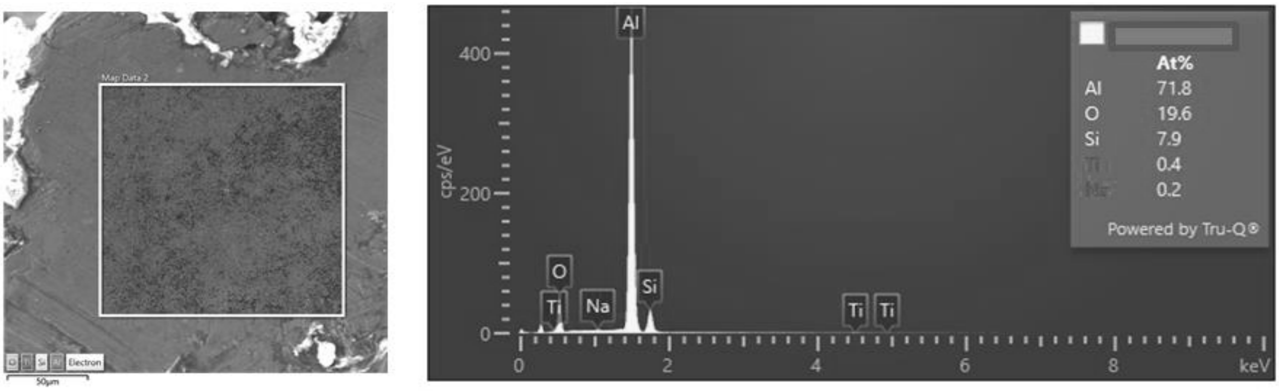
(a) (b)

Fig. 8 *EDS analysis and the evaluation with respect to the local chemical composition: (a) chemical composition of the AlSi12 alloy used; group I. sample*



(a) (b) (c)

Fig. 9 *View of the structure of the foamed material of AlSi12 alloy (a); detail of the material (b), (c); scanning electron microscope (Vega 3 Tescan, SEM HV: 20.0 kV); sample group II.*



(a) (c)

Fig. 10 *EDS analysis and the evaluation with respect to the local chemical composition: (a) chemical composition of the AlSi12 alloy used; group II. sample*

4 Discussion

The production of aluminium foam by powder metallurgy is a very complex metallurgical process. The process is based on mixing a suitable metal powder (e.g., aluminium or its alloy) with a foaming powder so that the mixture is as homogeneous as possible. This mixture of powders is cold pressed and then processed into the final foam blank at a certain temperature. These blanks are inserted into a foam steel mould where the foaming process is provided. The foaming mould is heated in an oven to a suitable temperature (depending on the particular aluminium or aluminium alloy). As a result of the appropriate temperature the material of the blanks (aluminium powder) is melted and at the same time the thermal decomposition of its foaming agent, in this case TiH_2 molten and foamed aluminium alloy fills the cavity of the respective metal mould. According to our calculations, the theoretical decomposition temperature of titanium hydride is 781 K (508 °C). In parallel, in order to successfully produce the foamed aluminium alloy, the metal foam mould with the semi-finished product must be heated to 508 °C. According to experience [13], commercially available titanium anhydride contains various phases of TiH_2 (15% TiH_2 to 62% TiH_2 decomposes at 600 °C). The presented results according to [10, 17], show that the temperature of the frothing mould in powder metallurgy have to reached the minimum temperature level of 800 °C and using the powder metallurgy technology applied by LKR (Leichmetall Kompenzzentrum Ranshofen).

5 Conclusion

The production of cellular systems by powder metallurgy from aluminium alloy AlSi12 can be achieved using gas cell sizes 1 to 3 mm - group I and 3 to 5 mm - group II with a certain choice of technology. These technological principles depend on the ratio of metal powder and powder foaming agent as well as conditions of pressing the powder mixture into a foamable precursor state. Furthermore, the foaming process of the precursor material and its heating to the melting temperature in the mould is important. Two types of materials were produced from aluminium alloy AlSi12 (materials of group I.) and (materials of group II.) The foamed alloy from group I. showed a density of 423 kg m^{-3}; relative density 1.6×10^{-1}; porosity 84 %, solid phase fraction

16 %, compressive strength 32 MPa, Young's modulus 170 MPa (calculated 480 MPa). The foamed alloy from group II. embodies a density of 303 kg·m^{-3}; relative density 1.1×10^{-1}; porosity 89 %, solid phase fraction 11 %, compressive strength 24 MPa, Young's modulus 90 MPa (calculated 312 MPa). Sample structures of the group I. and group II. show gas cavities and gas cells, respectively, of spherical shape with a diameter of 1-3 mm and 3-5 mm. Titanium residues were detected using EDS analyses in local areas of tested samples. EDX analyses confirmed that titanium hydride was used for foaming.

Acknowledgement

The work has been financially supported by the project "Hybrid materials for hierarchical structures", research goal: Composite materials and structures, research program: Materials and structures on the metal basis, reg. no. CZ.02.1./0.0/0.0/16_019/0000843 provided by the European Union and the Czech government.

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