USE OF THE MICROWAVE ENERGY FOR ALUMINUM WASTE FOAMING

LUCIAN PAUNESCU[1*], MARIUS FLORIN DRAGOESCU[2], SORIN MIRCEA AXINTE[2,3], ANA CASANDRA SEBE[4]

[1]*Junkoeko SRL, 3 Filaturii Road, Slobozia, Ialomita County 920049, Romania*

[2] *Daily Sourcing & Research SRL, 95-97 Calea Grivitei, sector 1, Bucharest 010705, Romania*

[3] *University "Politehnica" of Bucharest, Faculty of Applied Chemistry and Materials Science, 1-7 Gh. Polizu street, sector 1, Bucharest 011061, Romania*

[4] *Cosfel Actual SRL, 95-97 Calea Grivitei, sector 1, Bucharest 010705, Romania*

Abstract: The paper presents an aluminum foam experimental technique using the microwave energy. The raw material was recycling aluminum waste processed by ecological melting and gas atomizing to obtain the fine powder required in the foaming process. The powder mixture was completed with dolomite as a foaming agent. The products had a fine and homogeneous porous structure (pore size between 0.4-0.9 mm). The density (1.17-1.19 g/cm^3), the compressive strength (6.83-7.01 MPa) and the thermal conductivity (5.71-5.84 W/m·K) had values almost similar to the foams made by conventional methods.

Keywords: aluminum foam, dolomite, powder, microwave, aluminum waste

1. INTRODUCTION

The foaming method of solid materials allows to obtain closed-cell porous products, with high rigidity, low apparent density and low thermal conductivity, suitable for their using as lightweight building materials. Foams obtained from recycled glass waste and other silicates and, to a lesser extent, metal foams, are well known. All these are heat-insulating, fireproof, waterproof, ecologically harmless, vibration damper etc. [1].

The paper is focalized on the production of metal foams and particularly, the aluminum foams. The raw material is aluminum waste, melted and atomized with high-pressure nitrogen converging jets. The particle size of the powder aluminum is below 63 μm. The manufacture of aluminum powder was made in the Romanian company Junkoeko SRL of Slobozia [2].

According to the literature [3-12], several foaming techniques are known and can be grouped into two fundamental categories: molten metal foaming procedures (by gas injection or using foaming agents) and procedures based on the foaming of metal precursors (called powder metallurgy procedures).

[*] Corresponding author, email: lucianpaunescu16@gmail.com

The most common foaming agents for aluminum and its alloys are titanium (or zirconium) hydrade widely used in melting processing methods and in powder metallurgy. Titanium hydrade (TiH_2) is a foaming agent preferably because its thermal decomposition temperature is close to the melting temperature of the aluminum and its alloys. But the use of TiH_2 has some disadvantages, being very expansive and dangerous during operation. Therefore, other alternatives are attempted, including different carbonates (calcium, magnesium, dolomite, etc.) [6, 13-17]. The calcium carbonate ($CaCO_3$), used as foaming agent in the molten processing method, is already a viable alternative for TiH_2. The use of calcium carbonate in the powder metallurgy procedure has not yet been sufficiently investigated. The processing of aluminum and its alloys through powder metallurgy is interesting due to the low temperature of the foaming process and implicitly, the reduction of energy consumption [13-18]. The silicon carbide (SiC) is extensively used to reinforce aluminum in the form of a composite by powder metallurgy at sintering temperatures above the melting point of aluminum. In this process, silicon carbide also acts as a foaming agent [19-21]. The heating techniques used worldwide for metal foaming and particularly, aluminum foaming, are conventional. One paper mentions the use of microwaves in the production of Al_3Ti foam by the combustion synthesis of mixed powder compacts, the compaction pressure being between 25-200 MPa. According to [22], microwaves were used as an ignition method (in air) of the precursor. A 0.5 kW and 2.45 GHz single-mode cavity was used. The microwave power was set at 0.2-0.45 kW. The heating was performed until the precursor ignited.

The metal aluminum foams are usable as lightweight and high-strength components in aeronautics and other special purpose buildings that require physical characteristics mentioned above.

Further, experimental results obtained in the company Junkoeko in the foaming process of the powder of aluminum waste, using the microwave energy, are presented.

2. METHODS AND MATERIALS

2.1. Methods

The method adopted to produce foams from aluminum powder consists in the use of dolomite as a foaming agent during the thermal treatment under the influence of microwave radiation. As noted above, carbonates are safer foaming agents and allow more homogeneous porous materials than hydrides, although their testing through the powder metallurgy procedure is not yet complete [16].

The raw material used in the process of metal foaming was the powder aluminum, obtained by inert gas atomization of the metal heated at a temperature higher with over 150 ºC than the aluminum melting point (i. e. over 810 ºC). The powder resulted after the atomization had the particle size below 63 μm. The adopted foaming agent (dolomite) had also a very fine granulation below 40 μm. The metal powder and the foaming agent were dosed in three weight ratios (between 99/1 – 98/2) and homogeneously mixed, then the mixture was wetted with water (about 15 wt.%) and pressed into a metal crucible with removable wall. The microwave irradiation was performed in a 0.8 kW-microwave oven (Figure 1a) typical of those used in the household area, adapted for high temperature operation (up to 1200 ºC). A ceramic tube (Figure 1b) made of microwave susceptible material with the wall thickness of 3.5 mm was used for the microwave field absorption. The ceramic tube and the metal crucible containing the powder mixture were placed on several ceramic fiber mats. The ceramic tube had a silicon carbide cover with thickness of 10 mm, provided with a central hole of 30 mm to viewing the mixture surface with a radiation pyrometer mounted above the oven. The ceramic fiber mats fixed on the sidewall of ceramic tube and above the cover ensured the thermal protection of the metal crucible. A detail of the placement into the oven of the thermally protected ceramic tube is shown in Figure 1c. The microwave heating peculiarities compared to those of the conventional heating, i.e. initiating the thermal process inside the microwave susceptible material and the need for its protection to avoid the heat loss outward. The microwave heating advantage is the selective heating, avoiding the energy wasting, which under the conditions of conventional processes is first used to heat up massive components of the oven.

The basic principle of the aluminum foaming process is the thermal decomposition of the foaming agent (dolomite) in two stages, according to the TG-DTA analysis previously determined [16, 23]. The first stage begins at 440 ºC and the second begins at 740 ºC. The two stages occur according the following chemical reactions [16]:

$$CaMg(CO_3)_2 = CaCO_3 + MgO + CO_2 \quad (1)$$

$$CaCO_3 = CaO + CO_2 \qquad (2)$$

a b c

Fig. 1. The experimental microwave oven and its accessories: a—0.8 kW-microwave oven; b—ceramic tube; c—the placement into the oven of the thermally protected ceramic tube.

By comparison, in the case of TiH_2, the decomposition process begins at 430 ºC and is completely finished at 660 ºC [16]. During the decomposition process, the gas (carbon dioxide or hydrogen, respectively) is released inside the matrix of the precursor. The melting point of aluminum is 660 ºC [23]. Thus, it meets a partially softened mass and partially melted and then completely melted. It is recommended [16] that the foaming agent begins decomposing after the matrix melting to obtain a homogeneous porous structure. Under these circumstances, the gas remains in the form of bubbles in the foamed matrix. By cooling, the bubbles blocked in the mass of the material will form a porous structure.

2.2. Materials

The materials used during the experiments were aluminum powder (below 63 μm), resulting from gas atomization of recycled metal waste and dolomite (below 40 μm) as a foaming agent. Unlike TiH_2 commonly used for the production of aluminum foam, which has a coarse microstructure, the dolomite [$CaMg(CO_3)_2$] is characterized by a fine microstructure with homogeneously dispersed particles, according to the SEM images of the samples [16], there being the premise of obtaining a final product with an uniform porous structure.

2.3. Characterization of the samples

The aluminum foam samples after the processes previously described were subjected to tests for determining the physical, mechanical and morphological features. The following characteristics were investigated in laboratory: density, porosity, compressive strength, thermal conductivity and microstructure of the samples. The density was calculated by dividing the measured mass of the foam to its volume. The porosity was calculated by the direct method of comparing the bulk volume of the porous sample and the volume of the melted and cooled material without pores, experimentally measured [24]. The compressive strength was measured for the sample dimensions 30x30x45 mm with a 40 tones-uniaxial press and the thermal conductivity was determined by the guarded-comparative-longitudinal heat flow technique, according to ASTM E 1225 - 04. In order to identify the pores distribution, the aluminum foam samples were sectioned with a diamond cutting device and examined with a Smartphone Digital Microscope.

3. RESULTS AND DISCUSSION

3.1. Results

During the experiments, three dolomite ratios were successively used in the powder mixture together the aluminum metal powder: 1.0, 1.5 and 2.0 mass %, constituting three different compositional variants noted from 1 to 3 in this order. Own preliminary tests indicated as optimal this value range of the dolomite ratio, thus as the precursors dosing was limited at the above ratios. The values of the main functional parameters of the foaming process with dolomite as a foaming agent are presented in Table 1.

Table 1. Parameters of the foaming process.

Parameter	Variant 1	Variant 2	Variant 3
Precursor amounts (g) - aluminum powder - dolomite - total (dry) - water addition - total (wet)	 198 2 200 30 230	 198 3 201 30.15 231.15	 198 4 202 30.3 232.3
Aluminum foam amount (g)	194.2	195.3	196.2
Process temperature (ºC)	705	720	735
Heating duration (min)	9.17	10.05	10.92
Heating rate (ºC/ min)	74.7	69.7	65.5
Specific energy consumption (kWh/ kg)	0.63	0.69	0.74

The experiments started from constant values (198 g) of aluminum powder in all the three variants. The variable parameter was the amount of foaming agent (dolomite), which varied between 2-4 g. The final temperature of the foaming process had slightly increasing values from 705 ºC (variant 1) to 735 ºC (variant 3) and implicitly, increased the heating time (from 9.17 to 10.92 min) and the specific energy consumption (from 0.63 to 0.74 ºC/ min). It should be noted the high energy efficiency of the foaming process using the microwave energy.

The main characteristics of the aluminum foam samples are shown in Table 2.

Table 2. Characteristics of the aluminum foams.

Variant	Density (g/ cm^3)	Porosity (%)	Compressive strength (MPa)	Thermal conductivity (W/ m·K)
1	1.19	55.9	7.01	5.84
2	1.17	56.7	6.93	5.78
3	1.16	57.0	6.83	5.71

The three aluminum foam samples have physical and mechanical characteristics in very narrow ranges. The density of the foamed products varies between 1.16-1.19 g/ cm^3 and the porosity is between 55.9-57.0%. The compressive strength is high enough for porous structure metallic samples and the thermal conductivity is within normal range (5.71-5.84 W/m·K) for a metallic material with a fine and homogeneous porosity.

Next, images of the three aluminum foam samples (overall and section) are shown in Figure 2 and their microstructural configuration is presented in Figure 3.

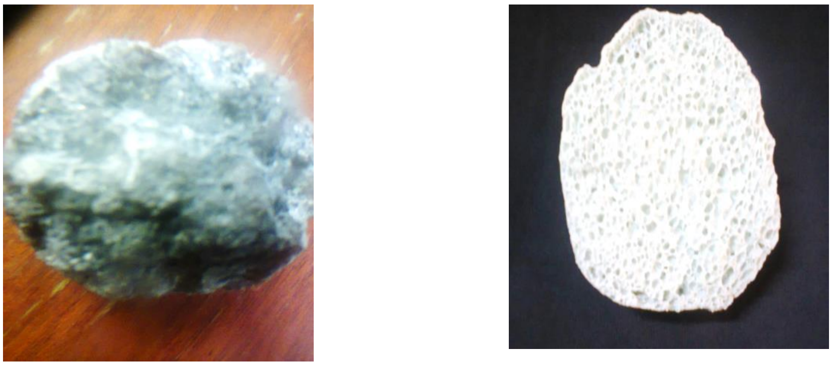
According to the literature [8, 16], all the samples above shown have a homogeneous spherical cell structure. The pore size is between 0.4-0.9 mm, reaching the highest values for the sample having the highest mass ratio (2%) of the foaming agent (sample 3).

3.2. Discussion

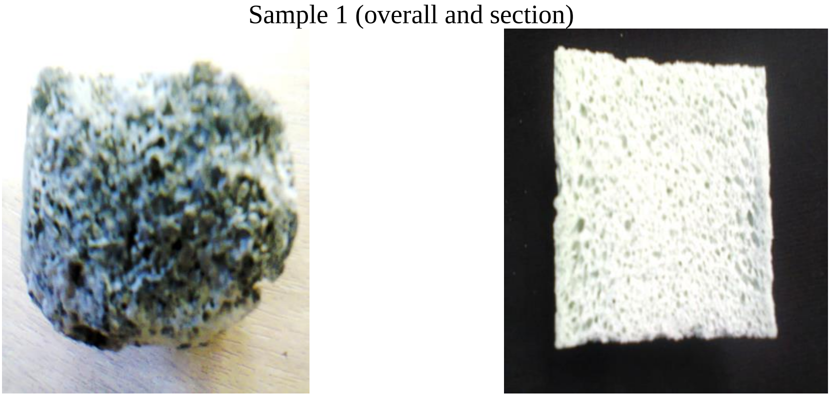
The production of aluminum foam using aluminum waste as a raw material (mainly post-consumer packaging) is one of the elements of originality of the research. Previously, the waste was melted under ecological conditions (protecting the environment from hazardous emissions of organic compounds) and atomized with inert gas in the form of a fine powder (below 63 nm). The second element of originality is the technique used to produce aluminum foam by the thermal effect generated by the microwave irradiation, energetically superior to other conventional methods.

The use of dolomite powder (as aluminum foaming agent) as a substitute for TiH_2 commonly used in similar processes is part of the world's tendency to avoid this expensive, unsafe material and generator of a coarse and inhomogeneous structure.

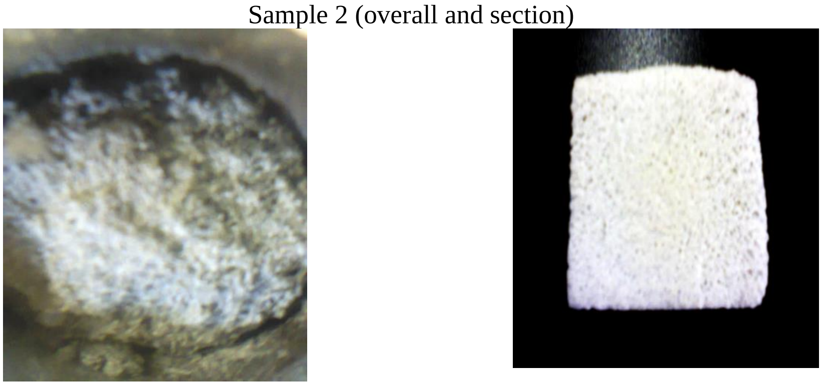
The experimental results confirmed the viability of the adoption of the microwave foaming process using dolomite as a foaming agent, the final products having physical, mechanical and morphological characteristics similar to those made by conventional methods.



Sample 1 (overall and section)



Sample 2 (overall and section)



Sample 3 (overall and section)

Fig. 2. Images of the aluminum foam samples.

Sample 1 Sample 2 Sample 3

Fig. 3. Microstructure of the aluminum foam samples.

4. CONCLUSIONS

The aluminum foam technology proposed in the paper is based on the use of the microwave energy as a source of unconventional, fast and economical energy compared to the conventional energy sources commonly applied in the world.

The raw material, aluminum, comes from recycling aluminum waste processed by ecological melting and atomizing with inert gas to obtain the fine powder (below 63 μm) required in the foaming process.

Dolomite was adopted as a foaming agent, replacing commonly used TiH_2, due to its superior safety in operation, homogeneity of foam structure and profitability.

By heating at 705-735 °C in a 0.8 kW-microwave oven, a product having a fine and homogeneous porous structure with a pore size between 0.4-0.9 mm, the density between 1.17-1.19 g/ cm^3, the compressive strength in the range 6.83-7.01 MPa and the thermal conductivity between 5.71-5.84 W/m·K.

The duration of the experimental process was only 9.17-10.92 min and the heating rate had very high values (65.5-74.7 ºC/ min).

The experimental results confirmed the viability of the adopted technical solutions. The foams had physical, mechanical and morphological characteristics almost similar to those made by conventional methods.

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