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Mechanical and Thermal Properties of Aluminum Foams Manufactured by Investment Casting Method

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Abstract

A method for the open-cell aluminum foams manufacturing by investment casting was presented. Among mechanical properties, compressive behaviour was investigated. The thermal performance of the fabricated foams used as heat transfer enhancers in the heat accumulator based on phase change material (paraffin) was studied during charging-discharging working cycles in terms of temperature distribution. The influence of the foam on the thermal conductivity of the system was examined, revealing a two-fold increase in comparison to the pure PCM. The proposed castings were subjected to cyclic stresses during PCM's subsequent contraction and expansion, while any casting defects present in the structure may deteriorate their durability. The manufactured heat transfers enhancers were found suitable for up to several dozen of cycles. The applied solution helped to facilitate the heat transfer resulting in more homogeneous temperature distribution and reduction of the charging period's duration.

Keywords: Mechanical properties, Innovative foundry technologies and materials, Metal foams, Investment casting, Compressive strength

1. Introduction

Materials with cellular structures have been researched and developed for many years due to their complex nature, unique properties and a wide variety of base materials, morphologies and fabrication methods. Natural cellular materials, such as wood, cork, coral, sponges, foam, honeycombs or trabecular bones have been known and used for centuries. Through inspiration by them, multiple new materials have been developed, including metal foams – composite metallic materials with randomly oriented gas-filled pores, that have attracted much attention during the last decade.

Lightweight metal foams, especially aluminum ones, offer a very interesting combination of properties that allow them to find application in a wide variety of industries. Thanks to their low density and high relative compressive strength they are an attractive material in automotive and aircraft branches, where mass reduction allows a significant decrease in fuel consumption [1]. Open-cell metal foams can be used as heat exchangers in thermal energy storage (TES) units due to their high surface to volume ratio and structure enhancing flow mixing [2, 3]. Their high specific surface area offers many other applications, such as catalytic beds [4, 5], condensers in chemical reactors and filters [6, 7], or mechanical waves isolation for noise cancellation [8]. Additionally, their unique structure that enhances specific energy absorption enables their wide application as a material for vibration absorption [9], explosion wave protection [10] and crash energy absorption [11]. They also can be used for the production of biomedical implants, for example as bone implants due to their similar shape to the cancellous bone [12].

Numerous methods for metal foam production have been developed over the last four decades. The most popular ones are based on liquid and powdered metal processing. Powdered metals can be processed via sintering, gas entrapment, slurry foaming, pressing metal-filler mixtures or extrusion of polymer/metal mixtures. Liquid metal processing includes methods such as direct foaming with gas or blowing agent, solid-gas eutectic solidification (gasars), powder compact melting, spray forming or casting [13]. The last-mentioned method is carried out in various techniques, using space holders such as salt grains that can be infiltrated with molten metal and washed away, or, researched in this paper, investment casting method which requires a pattern (e.g. from polyurethane foam, wax or polylactide 3D print) that is used to create a mould and then burned out before filling the mould with a chosen metal alloy.

The investment casting method utilizes PUR foam as a pattern. Aluminum foams acquired by this process are researched in terms of their compressive and thermal performance in order to explore the usability of such foam morphology as a heat exchanger material. The investment casting technology offers significant advantages in the field of metal foams. Most importantly – it allows precise tailoring of cell geometry, pore size and relative density to the current needs, which additionally allows producing foams of great structure uniformity, as opposed to other casting methods offering random pore distribution, such as the salt space holder technique. An important advantage of investment casting is also the non-corrosivity of mould materials as opposed to the space holder method in which salt particles are a corrosive agent, especially when not all pores in foam are open and salt particles cannot be washed away. Another great asset of this method is very high precision which allows producing foams with fine structures and small details. That is why many researchers and manufacturers chose this method for their work, for example, DUOCEL® foam produced by ERG Materials and Aerospace Corp. In spite of already being widely applied across various industries, this kind of material is still examined because of metal foams complicated nature due to numerous factors influencing their performance in mechanical and thermal properties. Schüler et al. thoroughly examined the deformation and failure behaviour of Al open-cell foams produced by investment casting in [14]. They analysed pore and strut collapsing mechanisms and examined foams performance in different compression test modes. They also investigated the influence of heat treatment on foams mechanical properties and microstructure in [15]. Luksch et al. in [16], on the other hand, tested foams behaviour in ex-situ and in-situ microtensile tests on the level of material microstructure to determine the influence of grain structure, microporosity, microcracks and inclusions on the performance of the foam and possibly explain the scattering of the test results that is usually present in metal foam research. Sathaiah et al. in [17] studied the connection between the foams morphology and thermal conductivity in foams created via the salt space holder method. Qu in [18] researched different techniques to enhance the heat transfer capability of phase change materials (PCMs), comparing metal foams to different solutions. Tian and Zhao in [19] have used open-pore metal foams as heat exchangers in a numerical investigation of phase change materials heat transfer abilities.

This paper is focused on the evaluation of cast aluminum foams application as heat transfer enhancers in PCM-based heat storage units. PCMs are able to accumulate energy as latent heat during their phase change transition. As any structure immersed in the PCM is subjected to cyclic stresses during subsequent expansion and compression of the phase change material, their compressive properties are crucial for the unit's performance. When the inserted casting is not durable enough it suffers from fatigue and deforms, losing its beneficial influence on the heat transfer characteristics. The thermal behaviour of the unit was also investigated in terms of the temperature distribution. Hereby proposed heat accumulators containing composite PCMs (PCM+cast foam inserts) can be utilized to gather the excess of solar thermal energy from solar collectors or waste heat from technological processes.

2. Experimental methods

Aluminum foams of the chosen open porosity (92-93%, 10 PPI „pores per inch") were manufactured by the means of the investment casting method. The scheme of the process is shown in Figure 1. Polyurethane (PUR) foams were applied as the pattern for moulding. In order to strengthen the casting by thickening of the narrow struts of the pattern, they were covered thoroughly with casting wax. This step aimed also to facilitate fabrication and subsequent filling of the mould cavity by a liquid metal alloy. To avoid blinding of the pores, after covering it with wax, the PUR foam is subjected to additional heat treatment in an oven, to make the coating more uniform. Thus the pretreated pattern was completed with the wax gating system (a) and put in the casting flask (b). The moulding plaster was Gold Star XXX (quartz <50%, cristobalite <50%, $CaSO_4$ binder). After preliminary solidification, the mould was subjected to drying and further burn-out cycle with a maximum temperature of 730°C. During heating, the PUR pattern was destroyed by gasification leaving the intricate hollow space in the shape of the pattern within the hardened ceramic plaster (c). Afterwards, the selected highly flowable and corrosion-resistant aluminum alloy (AC 44200, Si, 10.5%–13.5%; Fe, 0.55%; Cu, 0.05%; Mn, 0.35%; Zn, 0.10%; Ti, 0.15%; Al, the rest) was poured into the hot mould under low pressure in an autoclave (d). Finally, the finished castings were carefully cleaned under pressure in water from the gypsum's remnants (e).

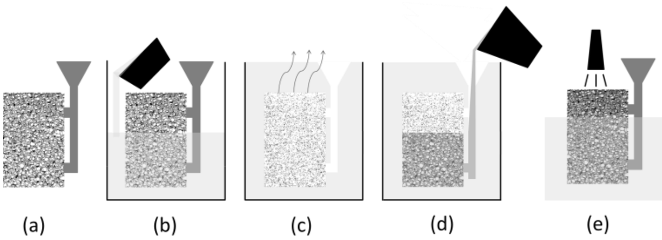


Fig. 1. Scheme of the investment casting process of metallic foams

To determine the compression behaviour of the manufactured open-porous foams, they were tested in accordance with the ISO 13314:2011 standard with a rate of 2 mm/min at the Instron 5892 testing machine. Microscopic observation of the foams structures was conducted with the use of the Hitachi TM-3000 Scanning Electron Microscope.

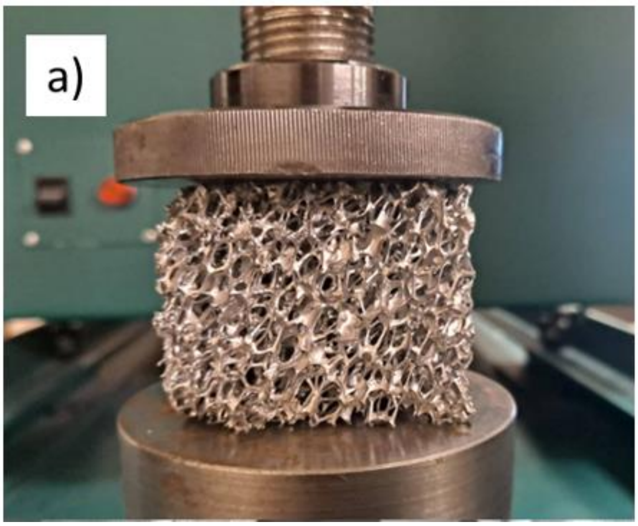
For the lab-scale evaluation of the thermal performance of the fabricated foams in the PCM-based heat storage unit the analysis of working cycles was conducted. The chosen PCM was paraffin RT-82 (supplied by Rubitherm). The metallic foam was immersed in the PCM chamber, which was insulated on its sides and charged from the bottom by the hot plate source. The obtained heat flux was assumed to be semi-directional. The temperature distribution was controlled by thermocouples located at the same height for the tests with and without aluminum insert – on the top (100 mm) and in the center (50 mm) of the unit. Measurements were collected using the 8-channel adapter of Adam 4018.

Manufactured samples of composite PCM (foam+paraffin) and reference of pure paraffin RT-82 were subjected to thermal conductivity measurements by the transient heat plane source method at room temperature in an isolated environment using the HOT DISK TPS 3500 device.

3. Results and discussion

3.1. Compressive behaviour

Compression tests were performed in a quasi-static mode. Figure 2a presents the 40 mm high sample mounted in a testing machine's holder during compression test, while Figure 2b shows the SEM micrograph of the foam as cast. The open-porous Al-Si12 structure consisting of regular 10 PPI cells possessed also some casting imperfections e.g.: risers or misruns resulting from the either too thick wax coating on the pattern or too thin channels preventing the metal flow in the mould.



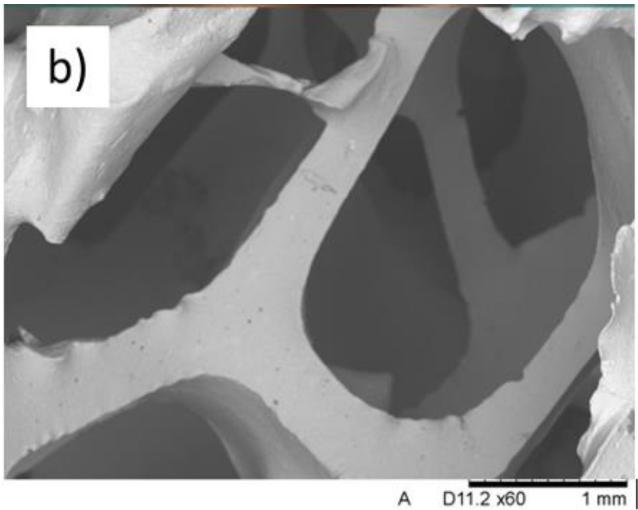


Fig. 2. Open-porous cast Al-Si12 foam: a) sample during compression test, b) SEM micrograph – general view

Figure 3 presents the compressive curves of the foam samples tested along the rise direction up to 70% strain. The observed destruction mechanism is typical for foam-like materials [20, 21]. Four main regions can be distinguished:

- A: the sample deforms elastically in a linear way up to the point of first maximum stress,
- B: start of plastic buckling of the cells,
- C: significant increase of the strain with no visible change in stress,
- D: densification, almost completely closed porosities begin to act like a solid body, causing a sharp rise in stress.

The majority of the energy absorbed by the foam is gathered during the load plateau phase, while the cellular structure is gradually collapsing in the whole volume of the specimen. Regions B and C correspond to respectively: stress peak and stress plateau with the zone of stress valley (a drop of stress value after B peak) between them [22]. As the material increases its density it is also becoming stiffer. Foams tend to exhibit higher compressive strength when tested in a rising direction compared with the transverse one [23].

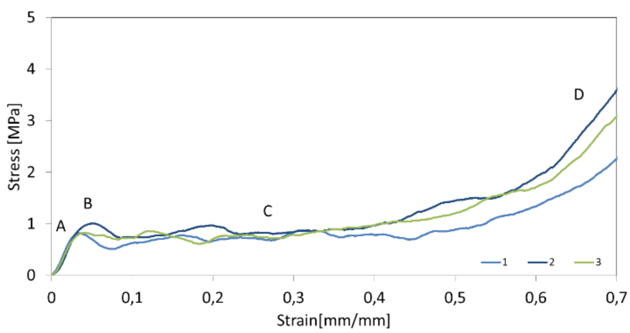


Fig. 3. Force vs compression curves with marked regions: A – elastic strain, B – plastic buckling, C – plateau phase, D – densification

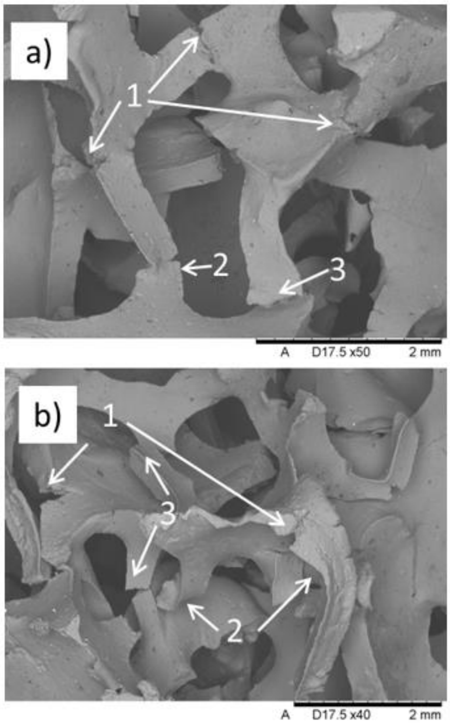
The energy absorbed by the foam per unit volume, when the strain reached 70% can be defined as:

$$\int_0^{\varepsilon 0.7} \sigma d\varepsilon \quad (1)$$

where σ and ε is respectively compressive stress and strain.

Using the formula (1) and measured area under curves maximum absorbed energy per unit volume was observed for sample 2 and equalled 87 J/mm^3.

Cracks are most likely to start at the casting defects (micropores or weakened struts) [24]. Figure 4 presents the view of the samples after compression tests. During compression the aluminum foam is subjected to variously directed stresses: some struts are compressed and tend to break in a brittle mode, while the others are twisted, bent and remain plastically deformed. The typical types of damages were marked in Figures 4a and 4b as 1, 2 and 3, corresponding respectively to: crack initiation places, plastically deformed struts and brittle fractures. Figures 4c and 4d show the observed fractures in higher magnification.



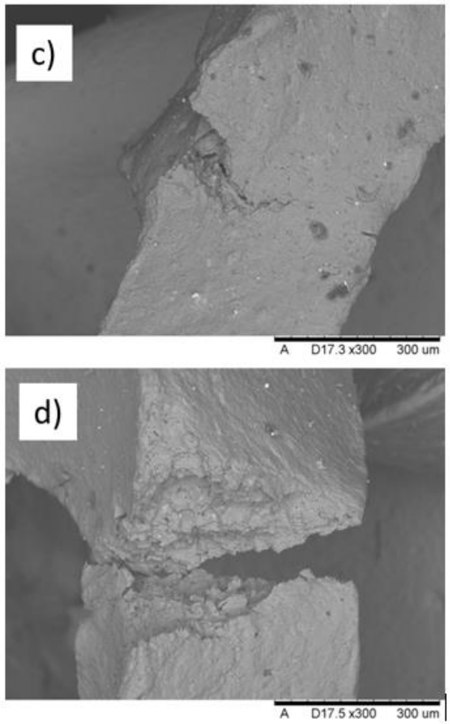


Fig. 4. View of the samples after compression tests: a), b) general view with marked damage types, c) crack initiation, d) brittle fracture

3.2. Thermal performance

Figure 5 compares the charging period (heating) during the working cycle of the PCM-based TES unit for the pure and composite PCM (RT-82+AlSi12 foam). Measurements obtained by the thermocouples imply that the application of metal cellular structure helps to increase the heating rate and the maximum temperatures reached. Thus reduced charging time improves the overall thermal efficiency of the accumulator. Similar behaviour was reported in the previous work of the Authors for Zn-Al foams [25]. The fluctuations observed at approx. 100°C for the center thermocouples located at 50 mm height correspond to the convection flow and mixing of the paraffin. As one can notice (see Fig. 5b), the cast foam inserts caused the temperature distribution in the deposit to be more uniform – lowering the maximum thermal gradient from approx. 70°C to 40°C.

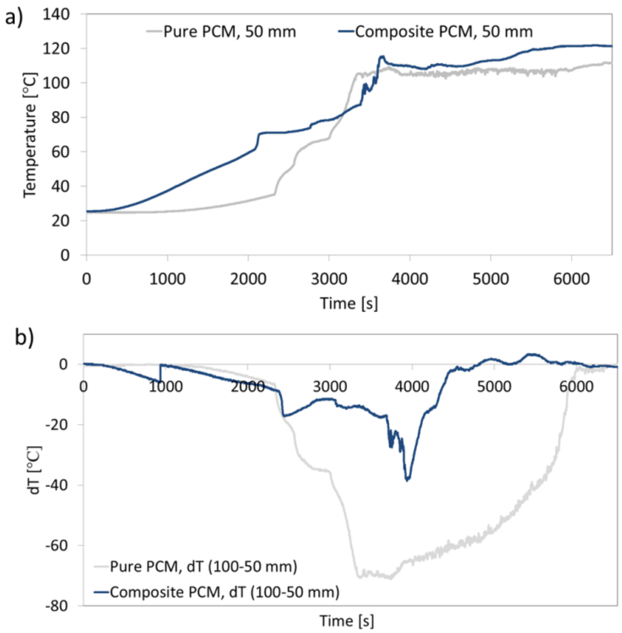


Fig. 5. Temperature vs time dependences for the accumulator with pure (P) and composite PCM (F): a) comparison of the charging stage, b) temperature gradient between top and center thermocouples (100-50 mm)

Results of thermal conductivity measurements are summarized in Table 1. It can be concluded that the paraffin reinforced with the manufactured aluminum foam, in comparison with the pure PCM, exhibits an approximately two-fold increase in thermal conductivity.

Table 1.
Results of thermal conductivity measurements

Description	Probing Depth	Temperature Increase	Mean Deviation	Thermal Conductivity
PCM - 1	17.0 mm	0.0166 K	2.105e-002 K	0.2876 W/mK
PCM - 2	18.0 mm	0.123 K	2.356e-002 K	0.2809 W/mK
PCM - 3	20.3 mm	-0.0229 K	2.079e-002 K	0.3047 W/mK
Mean Thermal Conductivity				**~ 0.2911 W/mK**
Compostite PCM - 1	2.76 mm	0.306 K	5.830e-003 K	0.5944 W/mK
Compostite PCM - 2	4.50 mm	0.129 K	4.781e-003 K	0.5979 W/mK
Compostite PCM - 3	3.92 mm	0.226 K	5.053e-003 K	0.5962 W/mK
Mean Thermal Conductivity				**~ 0.5962 W/mK**

4. Conclusions

Metallic foams cast from aluminum alloy via the investment casting method can be applied as heat transfer enhancers in PCM-based heat accumulators. It can be concluded that they:

- Exhibit sufficient compressive strength to withstand several dozen cycles of charging (heating: melting and expansion of the PCM) and discharging (cooling: solidification and compression of the PCM) of the TES unit, although any of the casting defects may be a possible location for the initiation of the cracking process;
- Facilitate the heat flow, causing the temperature distribution in the unit to be more uniform (reduction of the maximum thermal gradient by 30°C) and lowering the charging time;
- Allow a two-fold increase in the thermal conductivity in comparison to the pure PCM.

For a greater number of cycles, it is advisable to apply more solid and durable structures as heat transfer enhancers e.g. honeycomb-type elements. Metallic foams can find also alternative usage in heat accumulators based on hot air or zeolite materials, where they are not subjected to the described stresses.

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