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Enhancement of Heat Transfer in PCM by Cellular Zn-Al Structure

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Abstract

Development of open cellular metal foam technology based on investment casting applying the polyurethane pattern is discussed. Technological process comprises preparing of the ceramic mold applying PUR foam as the pattern, firing of the mold, pouring of the liquid Zn-Al alloy into the mold and washing out of the ceramic material from cellular casting. Critical parameters such as the temperature of mold and poured metal, design of gating system affected by metalostatic pressure allowed to produce castings with cellular structure characterized by the open porosity.

Metal cellular foams with the open porosity embedded in phase change material (PCM) enhance heat transfer and reduce time operations in energy storage systems. Charging and discharging were performed at the laboratory accumulator by heating and cooling with flowing water characterized by the temperatures of 97-100°C. Temperature measurements were collected from 7 different thermocouples located in the accumulator. In relation to the tests with pure paraffin, embedding of the metal Zn-Al cellular foam in paraffin significantly decreases temperature gradients and melting time of paraffin applied as PCM characterized by the low thermal conductivity. Similarly, reduction of discharging time by this method improves the efficiency of thermal energy storage system applied in solar power plants or for the systems of energy efficient buildings.

Keywords: Innovative foundry technologies and materials, Metal cellular foam, Porous Zn-Al structures, Investment casting, Heat transfer and energy storage

1. Introduction

Cellular metals can be applied for heat exchangers, radiant burners in combustion engines, battery electrodes, flame arresters, acoustic dampers and in the chosen physical and chemical processes depending on the type and size of porosity as well as on the alloy composition [1], [2]. More recently, open cell metal skeletons due to their high thermal conductivity were used in the thermal energy storage systems in order to enhance the heat transfer capability of phase change materials (PCMs). PCMs can

store heat in the form of latent heat of fusion e.g. recovering waste heat from the industrial sources or storing the excess of energy from solar panels. Unfortunately PCMs are characterized by the very small thermal conductivities (ca. 0.15 W/mK for paraffin, 0.5 W/mK for salts), what prolong their melting times and as a result extend the charging/discharging cycles of the heat accumulators. In order to improve heat transfer inside PCM, different cellular or porous materials such as preforms from graphite fibres, encapsulated or silica catalysts, cellular metals can be embedded in PCMs [3-5]. Recently, the most promising materials are high porosity cellular metal skeletons exhibiting

very high specific surface area and relatively large thermal conductivities (for Zn-Al alloy - 110.0-115.0 W/mK), only slightly reducing the heat transport based on mechanism of convection [5-7].

One of the most effective method of manufacturing of metal cellular skeletons is lost wax investment casting. Instead of wax pattern the polyurethane foam (PUR) with the appropriate number of pores per inch (PPI) is applied to produce the thin channels as a casting cavity in ceramic mold. Character of this process involves the accurate selection of some important technological parameters. In this regard the essential requirements should be fulfilled [8]:

- lack of reaction between ceramic mold material and the molten casting alloy,
- suitable strength of the ceramic mold during filling with the molten metal,
- proper gas permeability of the mold,
- easy removal of ceramic material from the casting surface.

Moreover metal pouring and casting technological parameters, due to the narrow and relatively long mold channels must be extremely precise. According to M. Cholewa et al. [9], supported by simulation of mold filling process for composite skeleton castings especially the metalostatic pressure has the important effect on the quality of filling. Additionally, gas permeability of the ceramic mould can be improved by subjecting it to higher firing temperatures than normally applied [10]. The next difficult technological step is the removing of ceramic material from the porous casting structure after solidification of the cellular metal. Therefore, common washing out process can be intensified by applying of polymer-modified binders to decrease the strength of ceramic moulds after burnout process [11].

In this work the manufacturing method of Zn-Al metal skeleton was developed and produced castings were embedded in the liquid PCM in the thermal storage accumulator subjected to the thermal charging – discharging tests.

2. Experimental methods

The manufacturing process of the cellular Zn-Al alloys, based on the investment casting was based on the following basic steps:

1. The preparation of the pattern using polyurethane elastomer filter foam (PUR), 10 ppi (pores per inch), open cell structure, producer: Interchemall - Poland, its processing, joining with the designed gating system.

2. Pouring of the ceramic molding material inside the elastomer filter foam and the subsequent firing in order to burn out PUR foam.

3. Supported gravity casting in an autoclave with Zn-Al alloy (ZL5) (thermal conductivity of 110.0 – 115.0 W/mK) delivered by the Foundry Works Szopienice – Poland.

4. The breakdown of the ceramic mold and rinsing of the ceramic material from the cellular metal casting.

Due to the small size of PUR foam dendrites – bridges, which diameter ranged from 100-150 μm , the PUR foam was covered with a thin layer of wax in order to increase the diameters of

channels and thus to decrease the risk of misruns occurrence. Ceramic slurry for molding was prepared from Randolph Ransom - type R&R® ARGENTUM™. Investment material was composed of: matrix - quartz <50% + cristobalite <50% and binder - CaSO₄. Then the temperature was raised to a point where the combustion and gasification of polyurethane foam proceeded.

Heat transfer rate tests were performed applying the heat accumulator filled with paraffin as the PCM. The chamber of the accumulator was heated from the bottom, whereas side walls were insulated. Therefore inside of the accumulator the semi-directional heat flux in the height direction was achieved. Measurements of the heat transfer efficiency of paraffin with embedded Zn-Al cellular metal was evaluated on the base of temperature difference at points along the height from the bottom (heat source) to 20 and 40 mm locations at the height of the accumulator. Temperature measurements from 7 thermocouples were collected by numerical method using the 8-channel adapter of Adam 4018 Type.

3. Results and discussion

3.1. Microstructure

Flowing of metal through the narrow cavity channels can be compared with infiltration of porous material. Therefore some process parameters were analysed and determined experimentally. Temperatures of the poured Zn-Al metal alloy and ceramic mold were relatively high though to avoid chemical interactions and established at the optimum level close to 400°C. Attempts with applying higher metalostatic pressure sometimes led to leaking of metal through microcracks in the mould. Generally depending on the porosity of polyurethane foam characterized by pore per inch (PPI) the similar porosity of cellular metal was achieved.

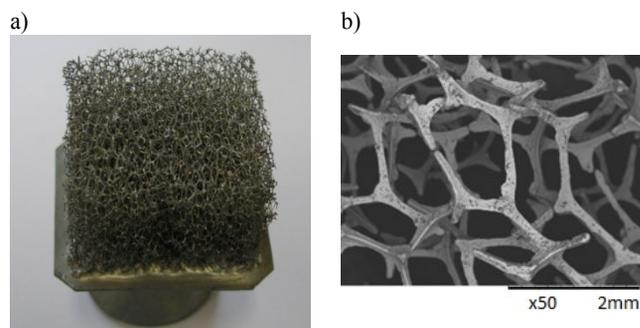


Fig. 1. View of cellular Zn-Al metal foam attached to the plate (a), open cell porous structure with some misruns (b)

Metal cellular structure showed at Fig.1a was produced from 10 PPI foam without covering with wax. Its final porosity was high, though thickness of cell dendrites and strength were relatively small. During charging and discharging, when PCM solidifies and shrinks, such structure is highly loaded and after several cycles can be deformed and damaged. Moreover when

PUR foam is too fine, even at optimal condition, metal cannot completely fill cavity and misruns shown at Fig. 1b can appear.

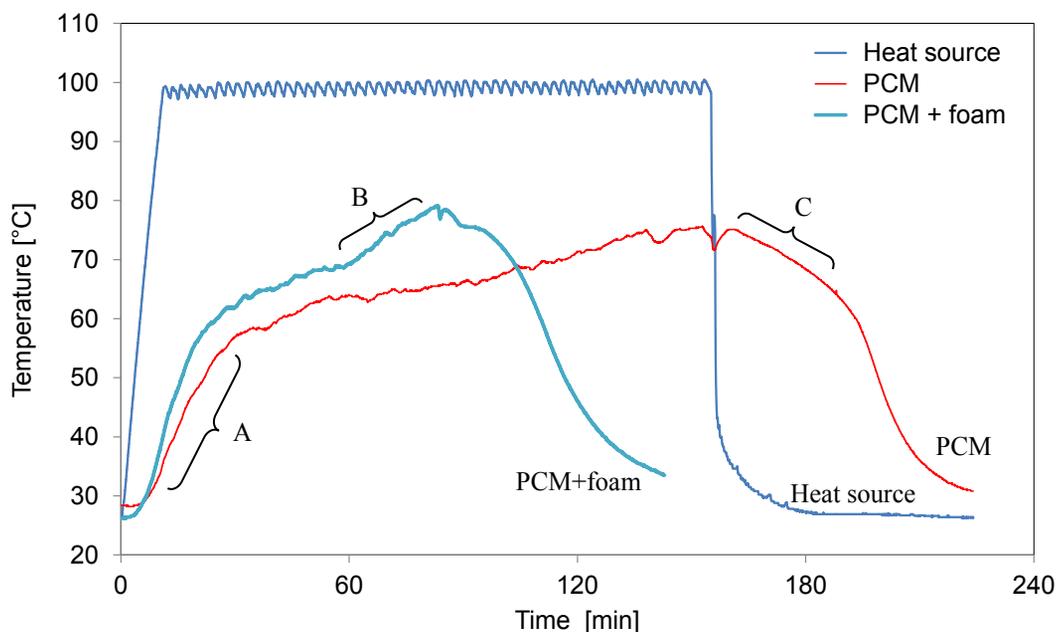


Fig.2. Temperature profiles for water heat source (Heat source) in the heat accumulator (distance of 20mm from the heat source) with only PCM paraffin (PCM) and with embedded in PCM metal cellular Zn-Al structure (PCM + foam). Distance A corresponds to preheating period of PCM (paraffin) to the melting point, B - to preheating of molten PCM, C – solidification of molten PCM.

Another problem was the chemical reactions and formation of complex compounds at casting surface comprising Si, Mg, Al and Zn at too high applied temperatures. Sometimes phases forming from these elements grow and spread over large volume of adhered to the ceramic mould. Then washing out is very difficult or even impossible in inner area of the cellular metal structure.

3.2. Heat transfer properties

Charging and discharging with heat energy of the accumulator with the inner chamber of 60x60x40 mm was performed by means of hot water (97-100°C) as a heat source and cold water (21°C) with flow rate of 3 ml/s. Temperature measurements from 7 points, in the centre and at the walls were performed in tests with metal cellular structure embedded in PCM paraffin and for comparison only with pure paraffin. Average charging time needed for the complete melting of paraffin is shown in Table 1.

Charging time of the experimental accumulator (until complete melting of PCM) only with paraffin takes about 2-3h what is over two times longer than for PCM with Zn-Al metal cellular structure. Increase of temperature proceeded in similar manner, see Fig.2, though its rate is much higher. At the beginning of the charging process the transferred energy preheat paraffin to the temperature close to the melting point (Fig.2 A area).

Table 1.

Melting time of paraffin during charging of accumulator without and with metal cellular foam.

Chamber	Melting at the wall	Complete melting
Paraffin	75-120 min	135-170 min
Paraffin + foam	55 ± 3 min	65 ± 2 min

It takes about 15 and 25 min. correspondingly for system with Zn-Al cellular structure and without it. Subsequently, to melt paraffin characterized by latent heat of fusion of 175 kJ/kg, high amount of energy must be transferred. Therefore more time is needed for system with pure paraffin (over 1h) and distance on the graph significantly increases in relation to this one with the metal cellular structure. Afterwards paraffin becomes liquid (Fig.2 B area) and its temperature quickly increases due to occurred convection (despite of small thermal conductivity of paraffin of about 0.15 W/mK). Critical and essential parameter used to evaluate heat transfer is temperature gradient between heat source and center of the chamber. In the case of the accumulator only with paraffin initially it reaches 27°C and next stabilizes with 10°C. For the system with embedded metal cellular structure these values are 18 and 3°C respectively.

For the thermal energy storage system also important is discharging characteristic. Flowing water, which cools the bottom of the accumulator, causes slow decreasing of temperature until 60-70°C when solidification of paraffin is completed. In the system containing paraffin with metal cellular structure it occurred after 20 min. whereas without this structure after 37 min.

It indicates for the effectiveness of heat dissipation by metal Zn-Al cellular structure in the paraffin as the PCM in this case.

4. Conclusions

Manufacturing method of Zn-Al metal cellular structure based on investment casting was developed. Manufactured structures were applied for enhancing of the heat transfer in the energy storage systems. Performed investigations led to the following conclusions:

- application of the modified polyurethane foam (10 ppi - pores per inch) as a pattern for the investment casting allows to prepare the ceramic mold suitable for manufacturing of cellular metal structures,
- crucial parameters affecting metal flow during casting are: temperature of the mould, Zn-Al alloy pouring temperature, metalostatic pressure,
- produced open cellular metal structures embedded in phase change materials PCM (in these investigations - paraffin) were applied in order to improve the heat transfer and efficiency of the heat storage system,
- ZnAl metal cellular structure embedded in the paraffin significantly improves thermal conductivity of the system paraffin-porous cellular structure and significantly reduces melting time of paraffin,
- by applying the system paraffin-metal cellular structure, charging and discharging time of heat accumulator can be reduced 2-3 times comparing to the system with paraffin, without porous structure.

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