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Assessing the potential for multi-functional “hybrid” porous Al-phase change material structures

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ABSTRACT

This study reports the potential for porous aluminium structures, containing porosity in the region of 50-80%, to provide enhancement of the rate of energy capture in phase change materials, whilst being capable of providing a basic mechanical function. The energy stored and the time for thermal exchange between warm water (at 65°C) and porous aluminium, pure PCM and an Al-PCM hybrid structure was measured. It was observed that the melting of the PCM within the hybrid structure can be greatly accelerated by the continuous, porous aluminium structure. The energy uptake per second was found to follow an approximately linear dependence on the thermal effusivity for the material. This knowledge was used to predict the potential for enhancement of the rate of energy capture, by varying the porosity in the structure, whilst also estimating the detriment to the energy storage density and the mechanical strength. Appreciating this trade off in performance and properties is vital to the design of multi-functional porous structures.

KEYWORDS

Porous materials; Metallic composites; Thermal properties; Energy storage and conversion

1.0 INTRODUCTION

Heat storage using phase change materials (PCMs) is an increasingly attractive technology in many engineering applications such as solar energy storage, waste heat recovery, and micro-electronic cooling [1]. PCMs provide a high heat storage density and require only a moderate operational temperature variation [2].

The major disadvantage of phase change materials is their low thermal conductivities which slows the rate of phase change by creating a wide internal temperature distribution [2]. This can prolong the charging and discharging periods for a thermal management system and potentially limits the useful power that can be extracted from the energy storage medium [1, 2].

In order to increase the rate of heat transfer within PCMs and improve phase change time, several approaches have been followed including dispersion of high conductivity materials such as carbon fibres and metal particles [3] into PCMs and the impregnation of PCMs into highly conducting porous materials [4,5]. Simulation and experiments have shown the potential for porous Al – PCM hybrid structures to be used for thermal management in Li-ion batteries [6,7]. The use of a continuous porous network could also be exploited as a load-bearing structural component (for example for managing the heat evolved from batteries in electric cars and supporting the batteries themselves).

This paper reports the thermal performance offered by porous Al parts made by the infiltration of beds of sacrificial (porogen) particles which typically have porosities between 55-85%. Such structures made from pure aluminium, have compressive yield stresses between 1 and 5 MPa [8] and thus have the capacity (especially if sheathed in an outer Al skin) for both significant storage of PCMs and to support service loads.

2.0 EXPERIMENTAL METHODS

Porous metals were made by vacuum infiltration, using molten 99.5% Al at a 0.5 bar pressure difference, of 1.4 - 2.5 mm salt granules (Hydrosoft) that were tap filled and preheated to 600°C in a 35 mm diameter stainless steel mould. Infiltrated samples were machined into 26.5 mm diameter cylinders, 60 mm long and the salt beads were dissolved away in warm water. The resulting porous metals had a density of $0.75 \pm 0.02 \text{ g cc}^{-1}$, corresponding to approximately 72% porosity. Typical porous metal structures are shown in Figure 1 and are characterised by near-spherical pores connected by 0.5-0.6 mm diameter windows.

Porous samples were vacuum infiltrated at 80°C with 99% purity methyl stearate (Sigma-Aldrich, reported melting range, 37-41°C, heat of fusion, 240 J g⁻¹ [9]). By measuring the change in mass it was determined that 95% of the porosity was filled, with the porous Al structure holding 20 g of PCM.

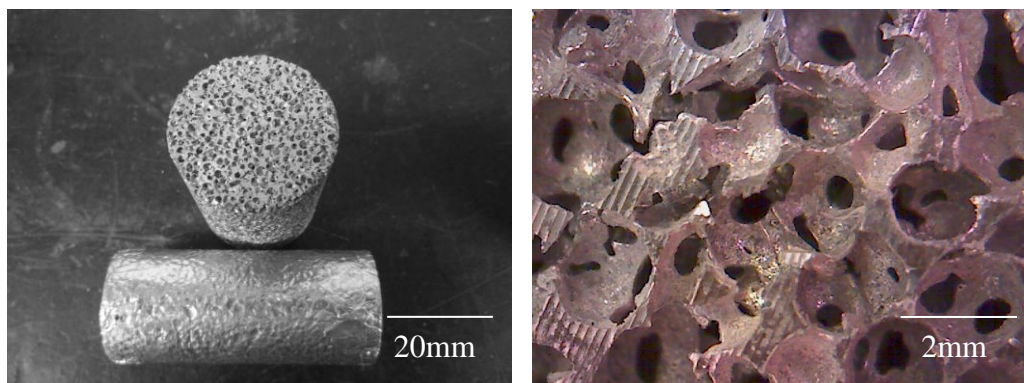


Figure 1: Images (left) of the porous metal and the foil-wrapped sample and (right) of the pore structure

The thermal response of porous metal samples was determined by placing them into water at a pre-determined temperature and measuring the temperature change in the water and in the sample using an embedded K-type thermocouple. The water and the container were pre-heated to 70°C and allowed to cool within an expanded polystyrene block until they reached the target temperature of 65°C, which was set to ensure full melting of the PCM. With an insulating lid in place, the water cooled at less than 0.1°C min⁻¹. On reaching the target temperature, the samples (at 21°C) were immersed in the water. In order to give a consistent measure of the “charging” time, the time taken to reach 95% of the maximum temperature gain (and thus 95% of the total energy stored), was determined. Both empty and filled porous Al samples had adhesive-backed Al foil wrapped around them to eliminate water ingress into the porous structure (and PCM leaching out) to enable a fair comparison between filled and unfilled structures. The “charging” behaviour for PCM was also measured by immersion of a 21 g block of PCM, encapsulated within a tight-fitting latex sheath, and measuring the drop in

temperature of the water as the PCM melted.

3.0 RESULTS AND DISCUSSION

Figure 2 shows the charging behaviour for the empty and filled porous Al samples. Immersion occurred approximately 80 s after data were recorded and it can be seen that the sample and water temperatures converge as thermal equilibrium is achieved. The reproducibility of the process (for more than 4 repeats) and the measurement procedure was high, with equilibrium temperatures and times agreeing within 3%. The empty sample shows rapid heating, reaching 95% of the maximum temperature change in 26 s. The plot for the PCM-filled Al sample exhibits a thermal arrest close to 34°C as a result of melting of the PCM. This large heat requirement (the latent heat is more than twice the sensible heat for the temperature rise observed) slows the “charging” time to 139 s. As monitoring of the melting PCM sample was impossible, the change in water temperature with time for the different samples is presented in Figure 1, where it can be inferred that the poorly-conducting PCM takes 333 s to “charge”.

The energy stored was calculated from the temperature change for the sample. The equilibrium temperature was also determined from a simple heat balance (ignoring the small thermal mass of the beaker in which the water was held) and predictions were always within 5% of the measured values. A comparison of the performance of the different (yet similar sized) samples is given in Table 1. The energy stored is, as expected, very different for the different materials and structures, with the capacity to store energy being highest per unit mass and volume for the PCM. Although the empty sample reaches thermal equilibrium soonest, the rate of energy uptake (or power, in W) is highest for the Al-PCM sample which stores the most energy.

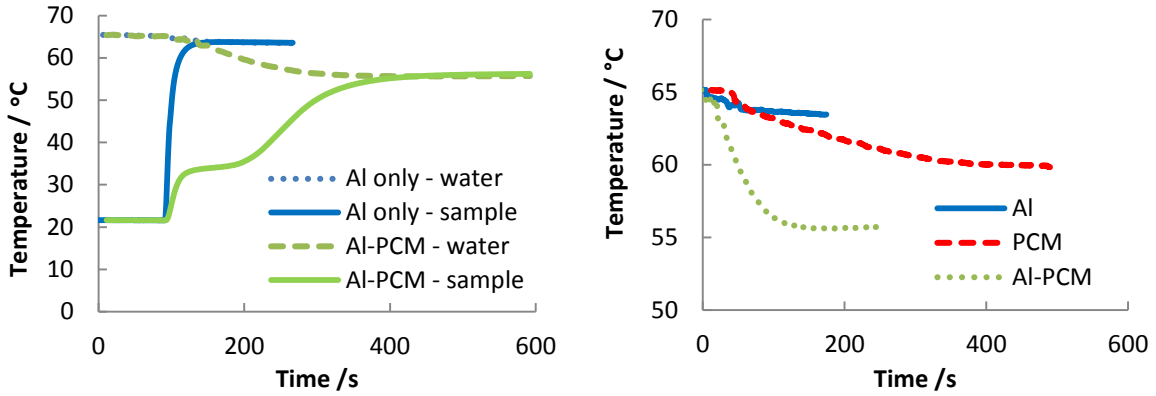


Figure 2: Heating and cooling curves for (left) empty and filled porous Al samples and water and (right) for water only, for all samples

Table 1: Summary of the thermal performance and properties for the samples

	Energy stored			$t_{95\% \text{ charge}}$ (s)	Power (W)	Diffusivity (mm^2s^{-1})	Effusivity ($\text{Wmm}^{-1}\text{K}^{-1}\text{s}^{0.5}$)
	(J)	(J g^{-1})	(J cm^{-3})				
Al empty	1024 ± 12	39 ± 0.5	31 ± 0.5	26 ± 0.8	37 ± 1.2	33	3.6
PCM	6786 ± 27	322 ± 1.2	270 ± 1.1	333 ± 2.2	19 ± 0.5	0.1	0.5
Al-PCM	7110 ± 18	153 ± 0.5	215 ± 0.6	139 ± 1.6	50 ± 1.1	10	6.3

It is clear that by adopting a hybrid Al-PCM system, an increase in the rate at which energy can be stored (and, no doubt, released) is opposed by a decrease in heat storage capacity. The thermal diffusivity (α) and thermal effusivity (e) for the different materials (defined in Eq 1 and for which values are given in Table 1) can be estimated using established scaling rules for the thermal conductivity, λ , of the porous metal [10] (and assuming that filling the structure with PCM will do nothing to enhance the conductivity) and using a rule of mixtures approach to estimating the volumetric heat capacity (ρC_p). Although only for 3 points, Figure 3 shows that the trend in power has a linear dependence upon the thermal effusivity, which is a measure of the

rate at which a material can absorb heat, rather than the thermal diffusivity, which is related to the speed at which thermal equilibrium can be reached. In fact the thermal diffusivity does not increase in the same order as that for the power, rather it follows the order for the time taken to reach equilibrium.

$$a = \frac{\lambda}{\rho c_p} \qquad e = \sqrt{\lambda \rho C_p} \qquad \text{Eq1}$$

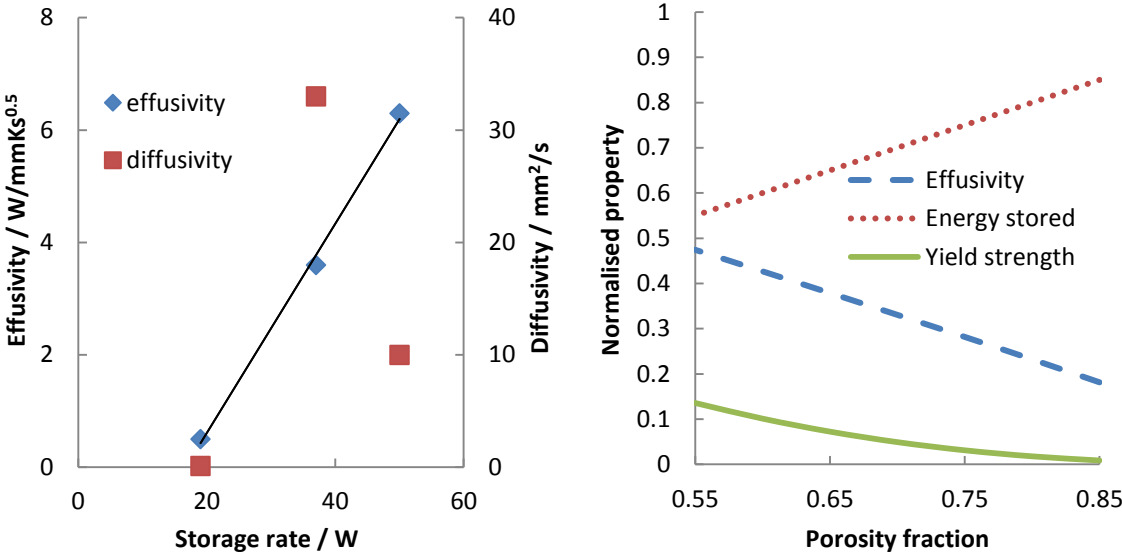


Figure 3: Relationship between energy storage rate (power) and thermal diffusivity and effusivity (left) and (right) porosity and thermal and mechanical properties

Thus, the balance between energy storage rate (effusivity), storage per unit volume and strength can be evaluated as a function of porosity within the hybrid Al-PCM structure. This is shown in Figure 3, over an interval of porosity typical for these structures, where each of the terms is normalised. In the case of the fraction of energy stored, it is simply calculated for the latent heat of PCM melting and thus for this simplification the proportion of energy stored per unit volume, compared with pure PCM, is the same as the porosity. The effusivity and strength are normalised with respect to the properties of solid aluminium (for the strength using established scaling laws for these structures [11]). It is apparent that by increasing the porosity

from 55 to 80%, and thus increasing the latent heat storage by 45%, the effusivity, and hence the power, would decrease by 51% and the compressive yield strength by 87%. These are highly significant margins which need to be considered in the design of any multi-functional thermal management system.

4.0 CONCLUSIONS

This study has shown that melting of PCM can be greatly accelerated within a hybrid PCM-porous aluminium structure containing 70-75% porosity. The energy uptake per second for porous aluminium, pure PCM and an Al-PCM hybrid structure was found to follow an approximately linear dependence on the thermal effusivity for the material. Using this relationship a clear balance between increasing the rate of energy storage to the detriment of both the energy storage density and mechanical strength was presented.

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Figure Captions

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