Materials Letters 132 (2014) 349–352

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

Low temperature sintering of copper biporous wicks with improved maximum capillary pressure

Jeehoon Choi [a,b,*,1], Yuan Yuan [b,1], Wataru Sano [b], Diana-Andra Borca-Tasciuc [b,**]

[a] Zalman Tech Co., Ltd., Seoul, South Korea
[b] Mechanical, Aerospace, and Nuclear Engineering Department, Rensselaer Polytechnic Institute, Troy, NY, USA

ARTICLE INFO

Article history:
Received 23 February 2014
Accepted 14 June 2014
Available online 26 June 2014

Keywords:
Low temperature sintering
Sintered wick
Copper nanoparticles
Loop heat pipe

ABSTRACT

Copper nanoparticle films were successfully sintered at low temperatures of approximately 280 °C onto copper microporous wick substrates. Scanning electron microscopy was used to investigate the morphology of the nanoporous layer. The permeability and maximum capillary pressure measurements were carried out on the sintered biporous media before and after nanoparticle layer coating. It was found that the nanoparticle film enhanced the capillary pressure of the porous media up to two times although it also affected permeability. These materials have applications in loop heat pipes and miniature loop heat pipes systems, which are envisioned to become mainstream computer cooling technologies.

1. Introduction

Loop heat pipes (LHP), first developed in 1972 [1], and their miniature counterparts (mLHP [2–5]) are emerging as key technologies for thermal management of advanced electronics and computers [6–11]. These systems are closed loops and dissipate heat by phase change. The working fluid evaporates at the hot side, condenses in the condenser and is recirculated via capillary forces in a porous wick. The porous wick lines the entire length of the general heat pipes or vapor chambers [2], while is restricted to the evaporator in mLHP [5,10,11]. However, in either case it is the main component of the system as it provides the driving force and the area for heat transfer and evaporation. Therefore, there is an increased interest in developing wick materials with improved transport properties in order to allow for higher cooling rates and/or cooling system miniaturization [12–14].

In principle, the porous wick must exhibit high capillary driving force (or high capillary pressure) to overcome the total pressure drop along the fluid circulation path and ensure sufficient liquid feedback to avoid dry-out [15]. This is usually realized by minimizing the effective pore radii at the liquid–vapor interface. On the other hand, the wick must possess low hydraulic resistance (i.e. high permeability) to enable high flow rates of the working fluid, required in order to achieve high cooling rates. This is realized with high porosity, maximized pore radii and efficient internal pore configuration. Therefore, optimizing both the capillary pressure and permeability is a challenge since their dependence on the pore size is opposite.

To address this challenge, biporous wicks, which have two characteristic pore sizes, have been proposed as an improved alternative to monolayer porous media. Two types of biporous wicks have been explored: (1) with large clusters consisting of small particles and having an internal pore configuration [16–20] and (2) with double layers, having the main layer consisting of large, usually microscale particles/pores and a second layer of small (nano) particles/pores on the surface [21,22]. The role of the small pore size layer is to provide increased capillary pumping, while the function of the large pore size domain is to maintain a high permeability [21–24]. In addition to improved flow characteristics, biporous wicks have been also shown to exhibit enhanced heat transfer performance [15,25–27]. However, while these wicks are documented to have superior thermal and fluid transport properties, the added complexity associated with double porous layer fabrication can be a real threat to technology transfer as cost is always a main concern in commercial applications. Therefore, the main objective of this paper is to explore a low cost, low temperature method for sintering nanoporous copper layers onto microporous copper substrates to form biporous wicks. Fluid transport properties relevant to loop heat pipe applications, namely maximum capillary pressure and permeability, were also

---

* Corresponding author. Tel.: +82 70 4941 6199/1 518 423 0735.
** Corresponding author. Tel.: +1 518 276 2010.
E-mail addresses: jhchoi@zalman.co.kr, choijeehoon@gmail.com (J. Choi), borcad@rpi.edu (D.-A. Borca-Tasciuc).

[1] These authors contributed equally.

http://dx.doi.org/10.1016/j.matlet.2014.06.090
0167-577X/

characterized to understand how they change with the addition of the nanoporous layer.

2. Experimental

Copper microporous wicks were sintered using high temperature isothermal furnace through the process described in detail in Ref. [14]. The starting material was pure copper powder with 100–150 μm diameter particle size from YEI-CHANG Technology, Inc. as shown in Fig. 1. The dimensions of the microporous wick samples were as follows: diameter of 4.2 ± 0.001 cm, thickness of 3 ± 0.1 mm and porosity of 0.5 ± 0.02.

The samples were coated with a nanoporous layer in a subsequent step. Copper powders of 300 nm particle diameter were procured from SkySpring Nanomaterials Inc. The copper nanopowder was spread onto the top surface of the microporous wick to form a film of ~0.4 mm in thickness. This was then placed in a graphite mold and introduced in the center of a heat pipe-based nearly-isothermal furnace heater. The furnace temperature reached to steady state (~280 °C) in about 40 min, and the sample was left to sinter at this temperature for 6 h, after which it cooled to room temperature while the furnace vacuum was left on. Following the sintering process, the nanoparticle-coated porous media was cleaned with acetone in ultrasonic cleaner to disperse excess particles.

Permeability and maximum capillary pressure of biporous media were measured with an in-house built apparatus described in detail in Ref. [14]. The experimental procedure is briefly outlined next. In permeability measurements, pressurized water at constant head (up to 3 m; set by a pressure compensation reservoir elevated above the measurement section) was applied through the sample. Meanwhile, the pressure was measured immediately before and after the wick, and the permeability, k_h, was calculated based on Darcy's law as [9,28]:

$$k_h = \frac{\mu t_w \dot{m}}{\rho A \Delta P_w} \tag{1}$$

where, t_w is the thickness of the sample wick, ρ is the density of the testing fluid (water), μ, the viscosity of the testing fluid, A is the cross-sectional area of flow), $\dot{m}$ is the mass flow rate (measured with a scale and a stopwatch), and ΔP_w is the pressure drop across the wick. Prior measurement, calibration was performed without the sample to account for parasitic pressure drop, which was later subtracted from the data recorded during on each sample. Data points recorded for the full range of measured flow rates were also plotted to verify their linearity and thus the applicability of Darcy's law.

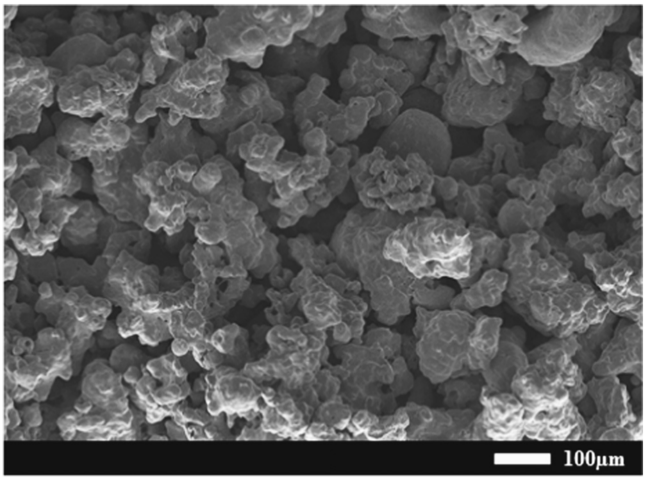

Fig. 1. Scanning electronic microscopy image of pure copper powder with 100–150 μm diameter particle size.

Following permeability measurement, the maximum capillary pressure was measured using the same apparatus and the bubble point method [14]. Briefly, a pocket of air was first established below the wick, with a column of water above the wick and the wick saturated. The test section inlet pressure was then increased incrementally until the formation of air bubbles was observed on the wick surface at the outlet side of the test section. The highest observed steady-state pressure before the breach of air through the wick was then recorded as the maximum capillary pressure.

3. Results and discussion

The porous media after sintering the nanoparticle film is shown in Fig. 2a. Compared to monoporous sample, the surface of the biporous wick became very smooth after sintering.

The morphology of biporous wick was characterized by scanning electron microscopy (JSM-6390A from JEOL, Inc.). Examples of SEM micrographs are shown in Fig. 2b–d. These images confirm that the copper nanoparticle film was successfully sintered on the surface of microporous media. From cross-sectional images, such as Fig. 2c, it was estimated that the thickness of the nanoparticle layer was ~40 μm.

During the low temperature sintering process, the coalescence of copper nanoparticles is driven by the reduction of the surface area. In contrast to bulk material, the nanometer-sized copper particles possess higher ratio of surface to volume atoms and their thermodynamic properties are strongly influenced. Therefore, the threshold of the temperature to activate atomic transport decrease as the particle size decreases [29]. This phenomenon is the well-known size dependent sintering temperature depression based on the Gibbs–Thompson theory [30].

The permeability and maximum capillary pressure of the biporous wicks were measured twice, changing the surface facing the incoming flow. In the first measurement the nanoporous layer was placed at the inlet, while in the second measurement this layer was placed at the outlet of the test section. The results are displayed in Table 1 together with permeability and maximum capillary pressure of the original samples (without nanoporous film). For permeability, the relative error was determined using propagation method and found to be 13% for all measurements. For maximum capillary pressure the error was set by the accuracy of the pressure gage and is 0.08%.

As seen from Table 1, there is good agreement between the results obtained on the two samples taking into account that transport properties of sintered wicks usually span over at least an order of magnitude range. This is usually due to multiple factors, including change in internal pore configuration from sample to sample (especially when the particles are of shapes other than spherical, as is the case for the copper micropowder used for the monoporous wick shown in Fig. 1) as well as oxidation during transport properties measurements. Particles may also become dislodged during tests and carried out further inside the wick obstructing the flow and consequently leading to modified flow property results.

For both samples it can be seen that after surface coating with copper nanoparticles the capillary pressure increases. The increase is less significant for Sample 1, however the maximum capillary pressure shows an increase of a factor of two for Sample 2. It should be noted that the irregularly shaped interparticle bonding, which is typical to nonuniform particle shape and size, results random pore variability in the sintered wicks. On the other hand, permeability also decreases about one magnitude although it remains in a range acceptable for loop heat pipe system applications. The increased capillary pressure will overcome higher pressure drop in the flow loop of the cooling system, allowing for larger separation distance between the heat source and heat rejection side. Moreover, the nanoparticle film at the top of the biporous wick is expected to also increase the vaporization