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Microstructure, capillary performance and gas permeability of biporous copper fabricated by tape casting

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ABSTRACT

Biporous copper was successfully fabricated by tape casting process using 0–1.5 wt.% of $C_7H_{10}N_2O_2S$ as the foaming agent. The influences of the foaming agent content on the pore structure, capillary performance and gas permeability were investigated. The results indicate that with increasing content of the foaming agent, the pumping rate increases, while the porosity and gas permeability fluctuate. It is suggested that biporous copper prepared by tape casting could be a good choice as the wick structure for heat pipe.

1. Introduction

Porous metals have applications in many areas, including construction, automobile, chemistry, computer, military and civilian facilities, because of their many attractive properties, such as very low weight, high permeability, high thermal conductivity, high stiffness and high specific surface area. The structure of porous metals can be classified as closed cell and open cell, depending on the pore connection state. Closed-cell porous metals are mainly used in energy absorbers because they can undergo large deformation under a relative low and almost constant compressive stress. Open-cell porous metals are mainly used in the fields of heat dissipation, filtration, separation and catalyst supporter, owing to that the capillary structure of the open and small cells could act as fluid channels [1–4]. They, however, are not suitable in applications of high heat flux condition because their monoporous structure limits the process of heat and mass transfer in the open-cell porous metals [5]. It has been found that biporous structure [6], which consists of two different types of pores, could improve the heat transfer capability of heat pipes owing to good compromise between high capillary performance and high gas permeability. This is because small pores maintain sufficient capillary force for system while large pores reduce liquid hydraulic resistance and provide additional area for evaporation of liquid. Capillary performance and gas permeability are two very important parameters to balance the relation between pressure drop and mass transport through porous media [7]. Gas permeability depends on the parameters of pore structure, such as porosity, pore connectivity and pore size distribution [8]. It should be taken into consideration before preparing biporous materials that small pore size leads to high capillary pressure, and that high permeability results in high capability of fluid transmission. Copper exhibits a higher thermal conductivity [9] ($\lambda = 390$ W/m·K) than most other metals, such as nickel, titanium and stainless steel, and is frequently used as the wick material in heat pipes with desirable properties [10]. Therefore, it is a good choice for the application of heat pipe because it balances the contradiction between high capillary performance and high gas permeability.

Porous metals could be prepared by liquid state processing, solid state processing, electro-deposition technique and vapor deposition [3]. However, for high melting metals such as Cu, Ti, Ni, and Fe, solid state processings, such as sintering of metal powders and fibers, foaming of slurries, and metal powder/binder methods, are more suitable than other methods [11]. Among the preparation methods of porous metals, tape casting [12] is the best way to form large scale, thin and flat ceramic, polymer or metallic sheets [13], and is usually applied to control the pore size distribution and thickness of porous metals in order to get multi-scale pore distribution and thinner thickness. Rak and Walter [14] applied tape casting and sintering to fabricate titanium porous sheets with a thickness of 370 μm, a porosity of 36.2% and an average pore size of 22 μm by using TiH_2 as the foaming agent. Liu and Canfield [15] prepared desirable porous Ni sheets with a thickness of 25–200 μm, a porosity of 50% and a mean pore size of 0.6–0.9 μm by

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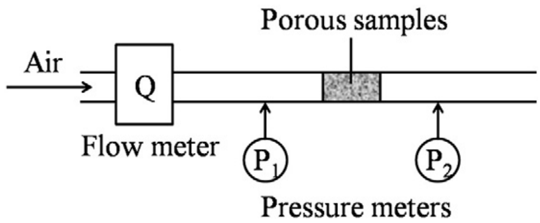

Fig. 1. Schematic model of the in house measurement system for permeability.

tape casting and reactive material processing method. It has been found that those porous metals could not be used as the wick structure in heat pipe because the low porosity and small pore size limit the heat and mass transfer in porous metals.

In this paper, biporous coppers were prepared by tape casting and foaming agent was used to regulate the pore structure. The effects of foaming agent on pore structure, capillary performance and gas permeability were investigated.

2. Experimental

2.1. Material preparation

In this paper, the typical processing of porous copper sheets by tape casting and using foaming agent involves two steps:

2.1.1. Aqueous copper slip preparation

The slips consist of 55 wt.% of commercial copper powders (Alfa Aesar, −325 mesh, 10% max +325 mesh, 99% metal basis), polyvinyl alcohol (PVA, Sinopharm Chemical Reagent Co, Ltd. (SCRC), China, 10 wt.% copper powders) as binder, polyethylene glycol (PEG 600 Sinopharm Chemical Reagent Co, Ltd. (SCRC), China, 1 wt.% copper powders) as plasticizer, $C_8H_{18}O$ (Sinopharm Chemical Reagent Co, Ltd. (SCRC), China,0.5 wt.% of copper powders) as degasifying agent, and 38.95 wt.% of deionized water as solvent. Like the conventional water based tape casting, slips were firstly prepared before casting. In this process, according to the designed mass fraction, PVA powders and PEG 600 dissolved completely in deionized water at 368 K by magnetic stirring for 2 h. The solution was degassed by $C_8H_{18}O$ and cooled to the room temperature. Copper powders were then added to the solution and the mixture was stirred evenly. Finally, in order to control the pore distribution of the porous copper sheets, $C_7H_{10}N_2O_2S$ with different weight percentages of slips: 0%, 0.5 wt.%, 1.0 wt.% and 1.5 wt.%, was added into the slips and mixed well.

2.1.2. Tape casting and subsequent processing of slips

The slips have appropriate viscosity and fluidity and that is beneficial to form porous copper sheets with suitable thickness. Slips were cast automatically on carrier tape and the gap between the doctor blade and carrier tape was adjusted at 2 mm. The green tapes were dried at 313 K for 2 h and then stripped from the film. Tapes were placed into furnace and foamed at 383 K in air for 2 h. After foaming, the material was submitted to the decomposition of the binder in furnace at 773 K in air for 4 h. Finally, the samples were sintered in an Ar–5%H_2 atmosphere for 3 h at1073 K, 1173 K and 1273 K, respectively.

2.2. Characterization

The microstructure of the samples was examined by Hitachi S-4800 scanning electron microscope (SEM) operated at 10.0 kV. Using water as the working fluid, capillary performance was observed by studying the pumping rate recorded by electronic analytical balance [16]. Porosity, average pore size and pore size distribution were measured by Micromeritics' AutoPore IV 9510 Automatic Mercury Porosimeter. Based on the mercury intrusion data, the fractal dimension was calculated from the formula [17]:

$$\ln\left(W_n/r_n^2\right) = C + D\ln\left(V_n^{1/3}/r_n\right) \tag{1}$$

where W_n is the accumulated surface energy, r_n is the pore radius, V_n is the pore volume, D is the fractal dimension, and C is the constant.

As shown in Fig. 1, gas permeability was tested by the in-house measurement system under the room temperature with air used as working medium. The samples were cut into 29 mm in diameter. The permeability was calculated by Eq. (2) [18].

$$K = \frac{\mu Q t}{A(P_1 - P_2)} \tag{2}$$

where K is the permeability, μ is the dynamic viscosity of air as used for calculation is 1.8×10^{-5} Pa·s[19], Q is the rate of the flow, t is the thickness of the sample, A is the cross section area of the sample, and P_1 and P_2 are the inlet pressure and outlet pressure, respectively. P_1, P_2 and Q were measured by using this system.

3. Results and discussions

Fig. 2 shows the typical morphology of the porous copper sheet fabricated by tape casting and the microstructure of the samples at different sintering temperatures. Fig. 2a shows the typically sintered biporous copper with thickness in the range of 800–950 μm. Fig. 2b–d indicates that the higher the sintering temperature, the larger the bonding region between the copper particles and the smaller the number of the pores. Hence, the route of sintering processing in an Ar–5%H_2 atmosphere for 3 h at 1173 K was used in order to facilitate the study.

Table 1 summarizes the pumping rate, porosity, fractal dimension and gas permeability of samples a–d with foaming agent content in the range of 0–1.5 wt.%. It can be concluded that samples processed by tape casting exhibit better capillary performance and permeability. Li et al. [16] investigated the capillary performance of porous Ni using water as the working fluid and their results showed that the pumping rate increased to about 0.1 g/s when the porosity was in the range of 71%–72.8% and the mean pore size in the range of 0.51–0.6 μm. Yang et al. [20] used N_2 as the working fluid to investigate the gas permeability of Ti–48Al–6Nb porous alloys and their results demonstrated that

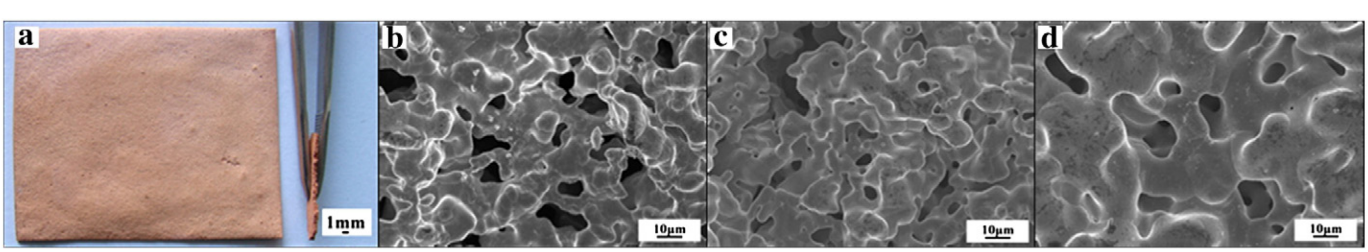

Fig. 2. Morphology of porous copper sheet and SEM images of samples sintered at different temperatures: (a) typical biporous copper sintered at 1173 K, (b) 1073 K, (c) 1173 K and (d) 1273 K.