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Research Paper

Effect of fabrication parameters on capillary pumping performance of multi-scale composite porous wicks for loop heat pipe

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HIGHLIGHTS

- Multi-scale composite porous wick was proposed for two-phase heat transfer device.
- Nanostructures were fabricated on the sintered copper powders.
- Capillary pumping performance was studied based on the IR thermal imaging method.
- Effects of wick fabrication parameters were investigated to optimize the design.

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ABSTRACT

In this study, a new multi-scale composite porous wick (MCPW) is proposed for the loop heat pipe to guarantee the thermal reliability of the microelectronics packages. The MCPW, which is featured with the nanostructures distributed on the sintered copper powders, can effectively enhance the capillary performance through modifying the properties of the copper powders. In this study, a number of MCPWs were developed by the sintering and alloying-dealloying treatment. Based on the infrared radiation (IR) thermal imaging method, the capillary rate-of-rise tests were used to the evaluate the capillary pumping performance, and the effects of the porous substrate and nanostructures were investigated in detail. The results indicated that morphologies of the copper powders, including powder size and powder type, would influence the capillary performance. The larger powder size and irregular type were better for liquid rise. Meanwhile, nanostructures on the powder surface played a dominant role in forming the hydrophilic surface on the copper powders, which could achieve the higher capillary height and rising velocity of working fluid for the wick. The optimum choice for the nanostructures formation was NaOH solution under the corrosive time 24 h.

1. Introduction

Thermal management of microelectronics packages, such as light emitting diode, CPU and hard disk drive, are becoming increasingly challengeable due to the large heat flux and high heat dissipation. Loop heat pipe (LHP), as a two-phase heat transfer device, can provide high capability of transferring heat efficiency passively between heat source and heat sink with little temperature difference. Moreover, in contrast with the traditional heat pipe, LHP presents several significant advantages, including long distance heat transferring, flexible configuration, various working orientations and so on. In 1972, Gerasimov and Maydanik [1] first created LHP to satisfy the demand of satellites and aerospace technology for highly-efficient heat transfer devices. Maydanik et al. [2], Peterson et al. [3] and Launay et al. [4] presented the details of the operational mechanism of LHP, respectively. Nowadays, LHP is widely used in the thermal management of spacecraft as well as the cooling of electronic devices, such as solar photovoltaic [5], PC [6], LED [7] and air-cooled heat exchanger [8], etc.

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When LHP works normally, heat is removed by means of the circulation of working fluid enclosed inside the pipe. The vapor with latent heat is delivered from the evaporator to the condenser. Then the liquid is pumped back to the heat source under the action of the wick inside the evaporator. During this operation process, the wick, usually composed of porous media, mesh or micro groove, is considered as an important component that provides capillary force to drive the liquid circulation and supplies flow channel for the working fluid. In the porous wick, the flow rate of vapor releasing the porous media is generally determined by the following equation [9],

$$\dot{m} = \frac{\pi}{128}\left(\frac{\rho_v \sigma_{lv}}{\mu_v}\right)\left(\frac{\varepsilon d_e^3}{t}\right) \tag{1}$$

where $\dot{m}$ is the mass flow rate of vapor; ρ_v, σ_{lv}, and μ_v are vapor density, surface tension and dynamic viscosity, respectively; ε, d_e and t are the wick properties, namely porosity, effective pore diameter and thickness of the porous media. It can be seen that large pores can lead to large vapor mass release. Nevertheless, the wick capillary force ΔP_{cap} can be written as,

$$\Delta P_{cap} = \frac{4\sigma}{d_e} \tag{2}$$

The pores have opposite effect on the capillary pressure. There exists a dilemma in the wick between the vapor release and liquid suction. While the capillary pumping of wick is not adequate for the required liquid to the evaporator, there will be dry-out phenomenon in the evaporator. Therefore, various modified wick structures have been proposed and studied to address the above problem. Byon and Kim [10] investigated in the capillary performance of a bi-porous wick experimentally and presented the liquid flow characteristics inside the wick with high speed camera. They found that capillary regimes in the wick was decided by the relationship between particle and cluster, and the 125/675 µm bi-porous wick was 11 times larger than that of a 125 µm mono-porous sample. Huang et al. [11] treated axially grooved aluminum wick based on the method of alkaline corrosion and carried out capillary rate-of-rise test to measure the capillary performance. The results showed that the corroded aluminum wick could achieve the better capillary performance parameter by about 155% higher in contrast with the conventional wick. Deng et al. [12,13] developed a novel composite wick by covering the copper powders on the V-grooves, and they proposed the capillary performance parameter ($\Delta P_c K$) to evaluate the capillary characteristics of the composite wick. The results showed that the composite wick could effectively enhance the capillary performance because of the additional rising channels provided by the gaps between grooves and powders. Recently, researchers have also been devoted to the study of the multiscale porous wicks, allowing to different pore sizes to induce various characteristics. Xu et al. [14] designed and investigated in the loop heat pipe with composite multiscale porous wick. A groove multiscale wick was manufactured by sintered copper powder, with other size powders sintering above as the second layer. The LHP could operate properly under the anti-gravity condition and achieve a synergy between thermal conduction and thermal insulation owing to the composite wick. Furthermore, carbon nanotubes were incorporated into the wick structures by Weibel et al. [15]. The resulted hydrophilic wicking surface improved the wick performance and reduced the surface superheat up to 72% through the capillary-fed boiling test.

In view of the above situation, it is essential to conduct experiments to access the capillary performance. One of the potential methods is to measure the transient rate-of-rise of liquid [16]. Chen et al. [17] investigated the capillary limits of micro-wick structures experimentally. CCD camera and optical microscope were used to capture the liquid flow characteristics in the inclined wick. Zhou et al. [18] also combined the camera with the experimental setup to measure the capillary suction of porous wick. Moreover, the dynamic liquid in the wick was also visualized with high speed camera by Byon and Kim [10]. However, the rising height of working fluid is difficult to record accurately due to the transparent and colorless working fluid. Thus, some studies were presented concerning on the rate-of-rise test, including mass changing curve recorded by electronic balance [19], fluorescent visualization method [20], and mass flow rate at wick's dryout threshold [21]. Due to the different radiation energies for wick and working fluid, the infrared radiation (IR) thermal imaging method was proposed by Tang et al. [22] to record the rise of meniscus. During the measurement, ethanol was used as the working fluid, and a measuring line with a location point was drawn accurately along the wick based on the color. Then the movement process of the point could be obtained to present the rising velocity of the wetted height.

Based upon the analysis above, the present work developed a multiscale composition porous wick (MCPW) for the loop heat pipe. The novel wick, featured with nanoporous structures distributed on the sintered copper powders was manufactured through the alloying-dealloying (AD) process. In the present study, the capillary performance of the wick was assessed by means of the rate-of-rise test with IR camera. To better understand the influence the fabrication parameters on the MCPW and achieve the best capillary performance, it is necessary to perform investigations to get comprehensive information for the design optimization. The effects of the nanostructures on the wick, powder size, powder type, corrosive time and corrosive solutions were studied, respectively. It is expected that the data can provide useful information for its application in the heat dissipation area.

2. Experimental details

2.1. Sample preparation

As shown in Fig. 1, the fabrication of the MCPW consists of the two main procedures: powder sintering treatment of porous copper substrate and alloying-dealloying treatment for nanostructures. Firstly, the copper powders were filled into the sintering mode and sintered by the loose sintering method, as shown in Fig. 2(a). During solid-sintering process, the mode was heated under the protection of the hydrogen atmosphere. The furnace (17300-30, Haoyue furnace Co. Shanghai, China) temperature was maintained at 900 ± 10 °C for one hour. In

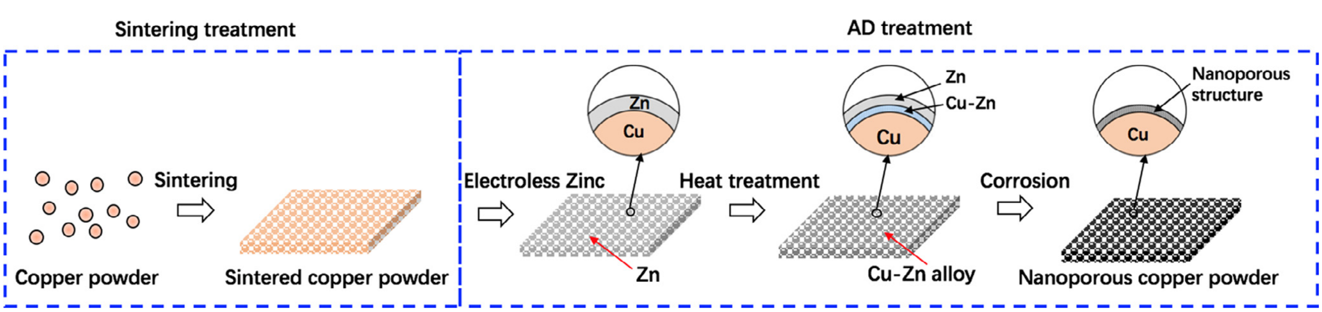

Fig. 1. Schematic illustrations of fabrication the MCPW.