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Effect of fabrication parameters on capillary performance of composite wicks for two-phase heat transfer devices

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ABSTRACT

Advanced thermal management solutions for various applications have promoted the development of composite wicks for two-phase heat transfer devices (TPHTDs). In this study, a number of composite wicks by covering a layer of sintered copper powder on micro V-grooves were developed. A ploughing–extrusion (P–E) method, as a material-saving fabrication means, was utilized to process the micro V-grooves on copper plate as the base of composite wicks. Using an infrared (IR) thermal imaging method, the capillary rate-of-rise tests with ethanol and acetone were carried out to characterize the capillary performance, which integrates both capillary pressure and permeability. The effects of fabrication parameters, including groove depth and pitch, sintering temperature and time, on the capillary performance of composite wicks were focused on and examined for the purpose of design optimization. Test results show that there is an optimal groove geometry with the groove depth of 0.85 mm and pitch of 0.45 mm to achieve the maximum capillary performance, and sintering processes of 950 °C along with 30 min should be chosen. Both working liquid test results exhibit fairly good agreement and demonstrate that the IR thermal imaging provides an accurate means to evaluate the hydraulic properties of composite wicks.

1. Introduction

Two-phase heat transfer devices (TPHTDs), such as heat pipes, vapor chambers (heat spreader), loop heat pipes and capillary pumped loops have played an increasingly crucial role in thermal management of microelectronic systems, spacecraft components, heat recovery systems and light emitting diode (LED) lighting modules, etc. [1,2]. Relying on evaporation and condensation processes and the circulation of working liquid, TPHTD possess a large heat transport capacity. A wick, as a key element of TPHTD, provides the capillary pressure for driving the two-phase circulation, and also serves as the flow path for the return of working liquid. It is usually composed of homogeneous microgrooves, sintered powder, or meshes. For the aim of achieving high heat transfer rates, especially in high heat flux situations, a wick should have large capillary pressure and high liquid permeability to facilitate liquid return. However, these two demands are apparently contrasting for a homogeneous wick [3], as the former is usually maintained by porous structure with numerous of small pores, while the latter requires a grooved type. Therefore, homogeneous wicks must balance capillary pressure and liquid permeability to achieve some compromise in performance. In order to address this dilemma, more sophisticated, or composite wicks have been developed in both scientific and industrial areas [4–12]. Composite wicks with combination of sintered metal powders and mesh screens were proposed and tested by Canti et al. [4], and high capillary pressure head and low liquid and vapor pressure drop were registered. Hybrid wick flat heat pipes combined rectangular groove with meshed layers were proposed for cooling LED lighting module by Hsieh et al. [6], and superior thermal performances were achieved at inclined angles. In addition, Oshman et al. [7] developed a hybrid wick heat spreader with woven mesh bonded atop rectangular microgrooves and found that it was able to eliminate the gravitational effect on working liquid, thus can work at adverse gravitational and dynamic acceleration situations. Furthermore, composite wick combined rectangular grooves with deposited porous coating atop was developed and tested by Grote et al. [8] and Khrustalev et al. [9], and was further analyzed numerically by Khrustalev and Faghri [10]. The evaporative heat transfer coefficient and capillary pumping ability were found to increase significantly due to the presence of porous coating. Wang and Cotton [11] theoretically analyzed the evaporative heat transfer of triangular groove covered with a thin porous layer. The results exhibited a

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Nomenclature

A_p	cross-section area of the sintered porous layer (m^2)
g	gravitational acceleration (kg/m^2 s)
h	capillary rise height (mm)
h_g	depth of grooves (mm)
h_g/w	aspect ratio of grooves (dimensionless)
h_{pe}	ploughing–extrusion fabrication depth
h_t	total height of grooves (mm)
dh/dt	capillary rise velocity (mm/s)
p	pitch of groove
t	sintering time (min); capillary rise time (s)
T	sintering temperature (°C)
w	width of grooves (mm)
K	permeability (mm^2)
L	length of wick (mm)
m_p	mass of sintered powder (g)
r_m	meniscus radius (m)
r_{eff}	effective capillary radius (m)
W	width of wick (mm)

Greek symbols

ΔP	pressure drop (kPa)
ΔP_{cap}	capillary pressure (Pa)
ε	porosity, dimensionless
δ	thickness of wick (mm)
ρ	density of working liquid (kg/m^3)
ρ_{Cu}	density of solid copper (kg/m^3)
θ	liquid–solid contact angle, rad
μ	dynamic viscosity of ethanol (Pa s)
σ	surface tension of ethanol (N/m)

Subscripts

g	groove
pe	ploughing–extrusion
t	total
cap	capillary
p	pore
Cu	copper
eff	efficient

three to six times increase in evaporative heat transfer compared to the groove without a porous layer. Tang et al. [12] developed a composite wick consisted of micro-groove and sintered powder, and found that it exhibited a superior capillary pumping ability to the sintered and grooved wicks.

As enumerated above, the fabrication of composite wicks plays an important role in the thermal and hydraulic performance of TPHTDs. Thus, it necessitates an in-depth investigation on the fabrication methods and parameters of composite wicks for the optimization of TPHTDs. In general, the fabrication of microgrooves employs a rolling [13], dicing [14], wire electrical discharge machining (EDM) [15], chemical etching [16] or laser micromachining method [17]. The porous powder or mesh wick are generally fabricated by sintering [18–20]. There are sufficient researches concerning the effects of fabrication parameters on the performance of homogeneous wicks, such as Ma and Peterson [21], Hopkins and Faghri [13], Suman and Hoda [22], Hanlon and Ma [23], and Williams and Harris [24]. However, to the authors' best knowledge, except for the analytical study of the triangular groove covered with a porous layer regarding the effect of groove geometry on the evaporative heat transfer performance by Wang and Cotton [11], the fabrication parameter effects on the hydraulic and thermal performance of composite wicks of TPHTD are scarcely reported. In view of this situation, it is essential to conduct such experiments to provide an in-depth insight into this for the optimal design of composite wicks. It is also the focus of this work.

As stated before, capillary pressure and permeability of a wick are two key parameters for TPHTDs, which determine the capillary limit and the heat transfer performance. In general, these two parameters are characterized by experiment separately, as the capillary pressure of a wick is usually assessed by bubble point test [25] or capillary rate-of-rise method [26], and the permeability is determined by the forced liquid flow method [25]. In recent years, capillary rate-of-rise experiments coupled with analysis method have been found to be able to determine these two properties of a porous wick by Holley and Faghri [27]. Byon and Kim [28,29] also used capillary rate-of-rise experiments in conjunction with numerical simulations to characterize the capillary performance parameter (K/R_{eff}) of copper wicks with micropost arrays and bi-porous glass wicks. In order to characterize the capillary performance of wicks using capillary rate-of-rise tests, it is crucial to locate the risen meniscus accurately and obtain the capillary rise height precisely. Nevertheless, as most of the working liquid is colorless and transparent, the risen meniscus may be vague in wicks [27] if observed by optical sight, such as the CCD camera. While using another means, i.e., weight methods [27], the attachment of an outer meniscus may results in a large mass gain which cannot be distinguished from the final results [30]. Hence, this issue should be addressed to employ the capillary rate-of-rise method to characterize the capillary performance of wicks.

In our previous studies [12,31], a novel infrared thermal image method was developed to accurately record the capillary rate-of-rise processes of wicks using ethanol as working liquid, and the effects of copper powder size and shape on the capillary performance of composite wicks, which integrates both permeability and capillary pressure, were assessed. However, the influences of fabrication and geometrical parameters on the capillary performance of composite wicks are still unknown. It is necessary to perform such studies to get the comprehensive information for the design optimization of the composite wicks. In the present study, a material-saving microgroove fabrication method was presented, and the effects of groove depth, groove pitches, sintered temperature, sintered time and working liquid on the capillary performance of composite wicks were systematically evaluated.

2. Experimental

2.1. Fabrication of micro V-grooves and preparation of composite wick samples

The first step to fabrication the composite wick is to form the micro V-grooves in plates of pure copper. Unlike the aforementioned fabrication means [13–17], in this study we employed a ploughing–extrusion (P–E) method to fabricate the micro V-grooves. Upon developed by our research group [32,33], the P–E method, as a special kind of drawing process, enables the fabrication of high-aspect-ratio micro grooves material-saving, thus very economic. A specially designed tool, namely, ploughing–extrusion tool, was utilized in the fabrication process. By grinding using steel W18Cr4V, the P–E tool included a ploughing edge, a major extrusion face A_γ, a minor extrusion face A'_γ, a major forming face A_β, a minor forming face A'_β, and a tool flank A_α, as illustrated in