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Thermal performance of a novel porous crack composite wick heat pipe

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ABSTRACT

A novel porous crack composite wick flattened heat pipe (PCHP) has been developed for electronic device cooling. PCHP was fabricated from grooved–sintered wick cylindrical heat pipe (GSHP) by phase change flattening technology. The composite wick was composed of porous sintered powder structure and axial micro-crack channels. The crack channels of composite wick were characterized and the calculation models of thermal resistance and capillary limit of PCHP were built. An experimental setup was used to test thermal resistance and heat transfer limit. The results showed that the parameters affecting thermal resistance from the most significant to the least one were wick thickness, powder diameter, flattened height, and tear number. The optimal wick thickness of PCHP for the maximum heat transfer limit was about 0.45 mm at flattened height of 3 mm. Heat transfer limit of PCHP increased with powder diameter while decrease of powder diameter could enhance anti-gravity ability of PCHP. Heat transfer limit of PCHP increased with flattened height. The effect of tear number on thermal resistance and heat transfer limit of PCHP could be neglected.

1. Introduction

High performance electronics requires heat transfer devices with high heat conductivity, quick thermal response speed, small size and high reliability to dissipate heat [1–3]. The heat pipe has received increased attention due to its excellent thermal performance [4]. The thermal performance of heat pipe for high power electronics cooling is usually governed by their wick structure [2,5]. The wick structure provides the capillary pressure and flow path to drive working liquid transferring from evaporation section to condensation section of heat pipe. However, it is difficult for homogeneous wick to satisfy two contrasting demands such as large capillary ability and high liquid permeability [6]. The grooved wick has high liquid permeability, yet limited capillary ability while the properties of sintered wick are in reverse [1,2,7]. Therefore, composite wicks have been developed to balance the contradictions between high capillary ability and high permeability.

Many researches have shown that thermal performance of composite wick heat pipe was usually higher than that of monoporous wick, such as biporous wick, modulated wick, powder-mesh composite wick and sintered–grooved composite wick. Semenic et al. [8,9] fabricated biporous wicks with two characteristic pore sizes by sintering clusters of powder together. Biporous wicks improved performance through increased capillary pressure and permeability. Wang and Catton [10] investigated a composite wick with a thin porous layer on the triangular grooves. Modeling analysis results showed it could improve capillary force and extend evaporation surface. Hwang et al. [11] fabricated modulated wick which was comprised of periodic stacks and grooves over a thin and uniform wick. The wick provided extra cross-sectional area to enhance axial capillary liquid flow and extend extra evaporation surface area with a moderate increase in conduction resistance of wick. Franchi [7] fabricated a composite wick by solid state sintering fine metal powder onto the layers of coarse pore copper mesh. The wick structure enhanced evaporation heat transfer at the liquid/vapor interface and the extension of the capillary limit. Tang et al. [12–14] and Li et al. [15] fabricated sintered–grooved wick by sintering copper powder in or over grooves. Experimental results showed that composite wicks enhanced both the permeability and capillary force compared to sintered wicks, and exhibited much larger capillary pressure than grooved wick. Above all, thermal performance of optimized composite wick can be enhanced by increase or balance of capillary pressure or permeability.

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Nomenclature

A_c	area of crack channels
$A_{c,l}$	cross section area of wick
$A_{c,v}$	cross section area of vapor chamber
A_s	area of sintered powder structure
A_{wick}	cross sectional area of composite wick
c_v	wetting peripheral length of vapor chamber
$D_{h,v}$	hydraulic radius of vapor chamber
d_s	average spherical powder diameter
f	friction factor of vapor flow
f_s	porosity of grooved–sintered wick
f_{wick}	porosity of composite wick
g	gravitational acceleration
h_{fg}	latent heat of vaporization
h_c	average crack depth
H	flattened height of PCHP
K	working liquid permeability
K_c	permeability in crack channels
K_s	permeability in sintered powder structure
k	heat transfer coefficient
k_{eff}	effective thermal conductivity
k_l	thermal conductivity of working liquid
k_s	thermal conductivity of particle material
L_a	length of adiabatic section
L_c	length of condensation section
L_e	length of evaporation section
L_{eff}	effective length of PCHP
L_{hp}	length of heat pipe
$\dot{m}$	mass flow rate in the wick
$\dot{m}_c$	mass flow rate in crack channels
$\dot{m}_s$	mass flow rate in sintered structure
m_w	mass of composite wick
n_c	average crack number
ΔP_{crack}	liquid pressure drop in crack channels
ΔP_s	liquid pressure drop in sintered structure
$\Delta P_{c,max}$	maximum capillary press drop
ΔP_g	gravity pressure drop
ΔP_l	working liquid flow pressure drop
ΔP_v	vapor pressure drop
N	tear number
q	input heat flux
Q	input heating power
Q_c	cooling power at condensation section
Q_e	heating power at evaporation section
$Q_{c,max}$	capillary limit
Q_{max}	heat transfer limit
R	thermal resistance
R_c	thermal resistance at condensation section
R_e	thermal resistance at evaporation section
r_{wick}	effective capillary radius of wick
T	temperature
ΔT	temperature difference
$T_{e,w}$	outer wall temperature at evaporation section
$T_{c,w}$	outer wall temperature at condensation section
T_v	vapor temperature of PCHP
v_w	volume of composite wick
w_c	average crack width
w_s	average crack distance
W_{hp}	width of PCHP
W_s	length of unbending surface

Greek symbols

α	contact angle
δ_s	wick thickness
δ_t	tear height
δ_w	wall thickness
μ_v	vapor viscosity
μ_l	working liquid viscosity
ρ_{Cu}	density of pure solid copper
ρ_l	working liquid density
ρ_v	vapor density
ρ_w	density of wick
σ_l	surface tension of working liquid
φ	heat pipe tilt angle
ζ	particle shape factor

A novel composite wick comprised of porous sintered powder structure and axial micro-crack channels was proposed to enhance miniature of flattened heat pipe. This composite wick was named as porous crack composite wick and its heat pipe was called porous crack composite wick flattened heat pipe. Composite wick satisfied high thermal performance needs that were combined with the advantages of high capillary due to porous sintered powder, and high permeability and low flow resistance due to micro-crack channels. The low cost and productive fabrication process for composite wick was investigated, and calculation models of PCHP capillary limit and thermal resistance were presented. An experimental setup was designed to test heat transfer limit and thermal resistance of PCHP with different wick structures.

2. Theory analysis

2.1. Characterization of composite wick

PCHP was fabricated from GSHP and crack channels were formed during phase change flattening process [16,17] as shown in Fig. 1. Porous crack composite wick was composed of porous sintered wick and axial micro-crack channels. Composite wick at bending section arc AFE and BCD was porous sintered powder without cracks while at the unbending sections AB and ED uniformly distributed axial crack channels. Assuming cross section shape of crack channel was reversed isosceles triangle based on the crack type-Mode I Crack, the micro-crack channels could be characterized by: average crack number n_c, average crack distance w_s, average crack width at the bottom w_c and average crack depth h_c as shown in Fig. 1. The calculation equations of n_c, w_s, w_c and h_c had been discussed in authors' another paper [accepted].

2.2. Thermal performance analysis of PCHP

2.2.1. Capillary limit $Q_{c,max}$

Heat pipe wick provided necessary flow path and capillary force to pump the liquid from condensation section to evaporation section. There existed a maximum value of capillary pumping force for a given wick structure. If the sum of pressure drop along the fluid circulation in PCHP was larger than the maximum value of capillary force, the liquid–vapor interface would recede to reach a new pressure balance. If the new balance was destroyed, heat pipe would be dry out due to lack of sufficient liquid returning to evaporate. So PCHP should have enough capillary force to maintain the