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Influence of electrochemical deposition parameters on capillary performance of a rectangular grooved wick with a porous layer

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ABSTRACT

A wick is a key component of two-phase heat transfer devices. To balance conventional conflicting requirements between permeability and capillary pressure performance, a rectangular grooved composite wick combined with a porous deposition layer was fabricated on a copper plate using a combined technology of planing, electrochemical deposition and heat treatment. The permeability of this composite wick was tested experimentally by a forced liquid flow method to investigate the effect of electrochemical deposition parameters. Deposition current density was shown to affect permeability more intensely than deposition time. To overcome the difficulty of porosity measurement, a modified capillary performance parameter $K/(A_{iw}R_{eff})$ instead of conventional K/R_{eff} was proposed to evaluate the comprehensive capillary performance of the composite wick. In addition, an infrared (IR) thermal imaging method was employed to investigate capillary rising height and velocity, using ethanol as the test liquid. The influence of deposition parameters and wick types on the values of parameter $K/(A_{iw}R_{eff})$ was discussed. The results show that there is an optimal value of both deposition time and current density to maximize capillary performance of the composite wick. Comparative studies show that a composite wick features a better capillary performance with proper fabrication parameters than a plane-deposition or its preformed smooth grooved wick.

1. Introduction

Two-phase heat transfer devices, e.g., heat pipes, vapor chambers and capillary-pump loops, are extensively applied in thermal management domains such as electronic cooling systems, heat recovery equipment and spacecraft thermal regulation [1–4]. Their thermal performance is dependent chiefly on their inner working liquid circulation, which is closely dependent on their wick capillary performance such as capillary pressure (closely related to the effective radius of the channel, R_{eff}) and permeability (K) [3,5]. To characterize capillary performance of a wick comprehensively, a parameter K/R_{eff}, integrating both R_{eff} and K, is conventionally used as an indicator [6]. Since the maximum performance of a two-phase heat transfer device is always proportional to its capillary limitation [7], which is in direct proportion to K/R_{eff}, it is essential to analyze the parameter K/R_{eff} of a wick.

Smooth micro-grooves and sintered powders are two prevalent wick structures. Generally, a smooth grooved wick possesses high permeability but low capillary pressure properties. Conversely, a sintered powder wick offers large capillary pressure but small permeability [6,7]. For a wick, a smaller effective hydraulic radius induces higher capillary pressure but lower permeability [8,9]. To enhance thermal performance, a high capillary pressure as well as a high permeability at the same time is preferred for a wick. Several composite wicks have been proposed and investigated [10–14]. Tang et al. [10] investigated a composite wick with sintered copper powders covered onto triangular grooves, which exhibited better capillary performance than a single wick. Vasiliev et al. [12] presented a composite wick with porous coatings covering longitudinal grooves, and they discovered that porous coatings could enhance wettability as well as heat transfer. Franchi et al. [13] fabricated a hybrid wick by sintering a nickel biporous layer onto copper meshes. They concluded that their composite wick could significantly enhance the thermal performance of its heat pipe over conventional designs. Wang et al. [14] developed a composite wick made of triangular grooves covered by a thin porous layer. The evaporation performance of their composite wick was

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Nomenclature

A_w	entire flow area of sample in cross-section, mm^2
A_{iw}	flow area of a composite groove in cross-section of sample, mm^2
A_{is}	entire area of a composite groove in a composite wick, mm^2
d	sample width, mm
g	gravitational acceleration, m/s^2
H	groove depth, mm
h	capillary rising height, mm
i	deposition current density, mA/cm^2
K	permeability, m^2
K_s	permeability of smooth grooved wick, m^2
K_c	permeability of composite wick, m^2
L	sample length, mm
n	groove number in a composite wick
Q	liquid flux, ml/min
R_{eff}	effective pore radius, μm
S_c	the slope of fitting line between dh/dt and $1/h$, mm^2/s
t	capillary rising time, s
W_1	groove width, mm
W_2	groove spine width, mm
Δm_ε	weight of porous deposition layer, g
ΔP	pressure drop, kPa
Δt	the sampling interval of IR images, s
K/R_{eff}	capillary performance parameter, mm
$K/(A_{iw}R_{eff})$	modified capillary performance parameter, mm^{-1}
μ	liquid viscosity, Pa s
ε	porosity
δ	sample thickness, mm
$\delta_{\varepsilon\to s}$	equivalent thickness of deposition layer converting from porous into solid, mm
τ	measuring moment, s
σ	surface tension, mN/m
ρ_l	liquid density, mg/mm^3
ρ_{cu}	copper density, mg/mm^3
dh/dt	capillary rising velocity, mm/s

found to be 3–6 times higher than that of a conventional grooved wick, partially owing to the improvement in the capillary pressure.

Material is another crucial element affecting wick performance. Among common industrial materials, copper is one of the most attractive materials for heat transfer. Due to poor water wettability, copper may restrain its performance [15,16] in two-phase heat transfer domains. Therefore, several techniques have been presented to improve the wettability of copper. Nam et al. [7] made some superhydrophilic micropost arrays on a copper substrate by a hybrid technique of electrochemical deposition and controlled chemical oxidation. Liu et al. [17] successfully developed a superhydrophilic porous layer on a copper plate with approximately a 0° water contact angle using electrochemical deposition in conjunction with heat treatment.

In this work, a rectangular grooved composite wick combined with a porous deposition layer was fabricated on a copper plate by combining planing, electrochemical deposition and heat treatment. Permeability and capillary performance of this composite wick were experimentally investigated by a forced liquid flow method and a capillary rate-of-rise test, respectively. Effects of deposition parameters on the capillary performance of the composite wick were analyzed to optimize the electrochemical deposition process.

2. Experimental

2.1. Fabrication of the composite wick

A rectangular grooved wick combined with a porous deposition layer (simplified as composite wick) was fabricated by three main processes, which are preformed groove planing, electrochemical deposition and heat treatment, accompanied by some auxiliary processes, e.g., copper plate preparation, surface protection and surface cleaning, as shown in Fig. 1. All experiments were done at an ambient temperature of 27 ± 1 °C.

2.1.1. Pre-formed groove planning

Preformed grooves in a rectangular shape, with 0.5 mm groove width (W_1), 0.5 mm spine width (W_2), 0.505 mm groove depth (H), 8 groove numbers (n), were machined on a copper plate (99.9 wt%) using a planing technology. Some post-treatments followed to clean groove specimens, including polishing and ultrasonic cleaning. All specimens have the same overall size: $80 \times 10 \times 2$ mm^3 (length, L × width, d × thickness, δ).

2.1.2. Electrochemical deposition

After coating a surface protection layer onto the outer surface of grooves with types of electrical insulation, a porous layer was constructed on the surface of the preformed grooves by an electrochemical deposition method [17]. First, an electrolyte with 1 mol/L H^+ and 0.02 mol/L Cu^{2+} was prepared using HCl (36–38 wt%) and $CuCl_2 \cdot 2H_2O$ (99.0 wt%). Second, an electrochemical deposition process was carried out, using a wick specimen as a cathode and a copper plate as an anode. These two electrodes were placed vertically, 100 mm apart. A direct current (DC)-regulated power supply (QJ21005X, Ningbo QJE Electronic Limited Company, China) was employed to supply deposition power, with current density varied from 10 to 80 mA/cm^2. Lastly, all specimens were cleaned with deionized water, dried in a thermostatic drying box (100 °C, 30 min), and then cooled to ambient temperature in air.

2.1.3. Heat treatment process

A heat treatment process was carried out in a box-type furnace (ZSJ-45/45/60, ACEM, China) to improve the wettability of the aforementioned porous deposition layer [17]. To prevent oxidation of as-prepared wicks, experiments were carried out under gas protection. Pure nitrogen gas was pumped into the furnace to flush out air, and then hydrogen gas (99.7 wt%) was flowed into the furnace, maintaining a pressure of 0.3 MPa. A stage heating method was used with a programmable temperature controller to adjust the heating rate. First, the heating rate was maintained at 10 °C/min below 500 °C. Second, the heating temperature was maintained at 500 °C for 60 min. Third, the temperature was naturally cooled to 200 °C. Lastly, wick specimens were taken out of the furnace and cooled to room temperature in air. Table 1 lists the processing parameters for wicks.

2.2. Permeability measurement

A forced liquid flow method [18,19] with deionized (DI) water as the test liquid was utilized for the permeability measurement of composite wicks. As shown in Fig. 2, the test apparatus com-