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Fabrication and capillary characterization of micro-grooved wicks with reentrant cavity array

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ABSTRACT

Micro-grooved wicks with reentrant cavity array (MGRAs) were fabricated with orthogonal Ploughing/Extrusion method for the application in the ultra-thin aluminum vapor chambers. Capillary rise tests using both ethanol and acetone as the working fluid were conducted by a novel IR-thermal imaging method. The experimental results indicated that the MGRAs yielded larger capillary height than the micro-grooved wicks (MGs) and the MGRA-1 exhibited the highest capillary rise rate of all samples studied. In addition, the permeability was characterized in the force flow tests. It was found that the MGRAs obtained comparable permeability to that for the MGs, revealing that they were able to enhance the capillary rise with little penalty of pressure drop. With regard to the capillary limited heat flux, the capillary parameter $K \cdot \Delta P_{cap}$ was employed to evaluate the performance of the wicks comprehensively. The comparison of $K \cdot \Delta P_{cap}$ between the prediction with/without the gravitational effect showed that the Washburn's Law greatly underestimated the $K \cdot \Delta P_{cap}$ after the initial stage, so the gravitational effect should be taken into account when comparing the samples. In this case, $K \cdot \Delta P_{cap}$ determined in the ethanol and acetone tests were similar. Besides, the MGRAs yielded higher $K \cdot \Delta P_{cap}$ than that for the MGs, except for the MGRA-3/MG-3 couple, justifying the prominent performance of the MGRAs. Despite the fact that the MGRA-2 failed to obtain the largest capillary height, it showed the largest $K \cdot \Delta P_{cap}$ among all MGRAs due to the good balance between the capillary pressure and permeability. Thus, it may be the optimum choice of all MGRAs in this study.

1. Introduction

Heat spread and dissipation from microelectronics packages are posing an increasing challenge due to the large heat fluxes encountered. Vapor chamber heat spreaders, a novel kind of phase change cooling devices, is proven a promising solution to provide efficacious thermal control in confined space, e.g., for high-power LEDs [1], CPU [2] and hard disk drive [3], etc. Nevertheless, a major bottleneck in enhancing the thermal performance of the vapor chamber is the capillary limited mass flow rate and phase change incipience in the wicks [4]. Therefore, in order to enhance the performance of vapor chambers, various modified wick structures have been proposed in the past decade. Tang et al. [5] developed a multi-artery vapor chamber with sintered copper powder porous layer on both the evaporator and condenser sections. The experimental results indicated that the vapor chamber attained a thermal resistance of less than 0.08 K/W and a maximum heat flux of 300 W/cm^2 without inducing the boiling or capillary limit. Ji et al. [6] designed a copper foam based vapor chamber and conducted a comparative study with other types of vapor chambers in literatures. The results showed that the current design obtained better heat transfer performance, attaining the lowest thermal resistance of 0.09 K/W and maximum heat load of 170 W. The superior performance of the foam based vapor chamber was attributed to the multi-scale pore sizes of the porous wick. Peng et al. [7,8] investigated a novel vapor chamber based on leaf-vein microgroove system fabricated by chemical etching. The vapor chamber performed good temperature uniformity and small thermal resistance due to the enlarged condensable area and the prevention of liquid blocking [9]. Different types of micro-grooved wick with cylindrical, conical and pyramidal pillared geometries were fabricated by Ranjan et al. [10]. The comparative study of the grooved wicks with the conventional sintered particle wicks revealed that the employment of micro-pillared structure led to a 10-fold enhancement in the maximum heat transport capability of the device.

In general, the vapor chambers available at present are copper-based (CBVC), which are relatively heavy and thick, e.g., the thickness ranged in 6–15 mm in Refs. [11–13]. In order to meet the

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Nomenclature

MGRA	micro-grooved wick with reentrant cavity array
MG	micro-grooved wick
P/E	Ploughing/Extrusion method
λ, γ	major/minor ploughing edge
A_p, $A_p{}'$	major/minor extrusion face
A_f, $A_f{}'$	major/minor forming face
A_c	clearance face
α	rake angle, °
κ	clearance angle, °
β	extrusion inclination angle, °
θ	forming angle, °
B_0	tool width, mm
L_t	tool thickness, mm
L	sample length, mm
D_{pe}, P_{pe}	P/E depth/pitch, mm
D, P	groove depth/pitch, mm
K	permeability, m^2
v	fluid surface velocity, m/s
μ_w	liquid viscosity, mPa·s
$\varDelta P$	pressure drop, kPa
$\dot{m}$	mass flow rate, kg/s
A_c	cross-sectional area of all stream-wise grooves for the wick, m^2
ρ_w	density of water, kg/m^3
q_c	capillary limited heat flux, kW/m^2
λ_w	latent heat of water
$\varDelta P_{cap}$	capillary pressure, kPa
$h/H(t)$	capillary height, mm
t	time, s
V	volumetric flow rate, m^3/s
$K\cdot\varDelta P_{cap}$	capillary parameter, N

requirement of light weight and compact physical size for applications in aviation and aerospace industries, ultra-thin aluminum vapor chambers (UAVC), which take the advantage of light density of aluminum alloy along with favorable thermal conductivity [13,14], and characterized by the thickness of less than 2 mm for the entire device [15], are believed to be the next-generation phase change cooling devices. It is seemingly that the traditional wicks for the CBVC are not applicable for the UAVC. Porous material has been widely used for the CBVC due to its prominent capillary performance [16,17]. However, it is difficult to fabricate Al powders sintered porous materials as a result of the inert mass propagation of aluminum oxide film on the surface of the Al-particles. Although other types of Al porous materials can be produced with MEMS procedures, e.g., by growing CNTs [18] and anodizing [19], the high cost and low efficiency make them infeasible strategies on large-scale production. Worse still, the performance of the aluminum porous coating deteriorates dramatically after being tested for several times if the coating peels off [20] or transform in morphology due to the chemical reaction between the coating and the fluid [21]. Therefore, grooved wick structures are better choices in this case. Further modifications of the traditional groove wicks have to be conducted before they can be applied for the UAVC. The reason is that due to the limited thickness of the substrate for the UAVC, the grooves are generally shallow, e.g., the groove depth was only 0.11 mm in an aluminum vapor chamber with a thickness of 2.17 mm [22], and thus the capillary pressure is insufficient to compensate the pressure drop at high heat flux. Ploughing/Extrusion (P/E) method can probably address the problems above. Similar to traditional machining methods, micro-grooves can be manufactured using general machine tools, e.g., planning, turning and milling machines, which is cost-effective and facile. However, contrary to the traditional machining methods which remove the metal from the base material, the P/E procedure does not remove the surface metal but force it to deform into high fins on the top of the grooves [23]. As a result, deep groove with high aspect-ratio can be obtained on a thin substrate, e.g., Tang et al. [24] discovered that the fin structures on the P/E grooves protruded 0.15 mm above the upper surface of the substrate. Following studies showed that the parallel P/E grooves exhibited favorable capillary performance [25] as a result of the high aspect ratio, roughened surface and secondary grooves. Such method has been successfully applied to the field of outer-fin tubes [23,26] as well as heat pipes [27]. Based on the concept of capillary valve effect [28,29], the capillary performance of P/E wicks can be further enhanced with reentrant cavities on the side wall because of the threshold pressure as the meniscus propagates into the cavities. Besides, the reentrant cavities, which serve as vapor trap, contributes to the enhanced bubble nucleation [30–34], leading to a dramatic improvement in the thermal performance of wicks [35,36].

In order to combine both merits of the P/E grooves and reentrant cavities, micro-grooved wicks with reentrant cavity array (MGRAs), featured with high aspect ratio grooves and reentrant cavities on the side walls, are fabricated by orthogonal Ploughing/Extrusion method. The manufacturing process and finished structures are characterized with SEM images. Micro-grooved wicks (MGs) without reentrant cavity array are also fabricated by P/E method. Comparative studies between the MGRAs and MGs, and the effect of varying the reentrant structures of the MGRAs is investigated with regard to the capillary rise height, permeability as well as the capillary parameter $K\cdot\varDelta P_{cap}$ for a comprehensive evaluation.

2. Manufacturing and characterization of the MGRAs

The wick structures in this study were fabricated by Ploughing/Extrusion (P/E) method on aluminum alloy substrates (T6-6061). Different from traditional techniques, which removes the redundant metal from the matrix to form a desired structure [37,38], the metal remains attached to the matrix after the forming process and transforms into fins on the top of the grooves (i.e., a non-chip process). Therefore, the P/E method enables the fabrication of high aspect-ratio micro-grooves in a facile and economical way, and has been successfully applied to produce high-performance outer pin–fin tube [23], micro V-grooved wicks [25] and heat pipes [27].

Fig. 1 displays the schematic and photograph of the P/E tool. The tool was made out of W18Cr4V by electric-wire discharge machining (WEMD) and then grinding for face finishing. The P/E tool includes a major ploughing edge λ (line E–F), two minor ploughing edges γ (A–F) and γ' (J–F), major extrusion face A_p (ABEF), minor extrusion face A'_p (JIEF), major forming face A_f (CBED), minor forming face A'_f (HIEG) and clearance face A_c (EDG). The major angles include the rake angle α, clearance angle κ, extrusion inclination angle β, and forming angle θ. The cross section of the tool is shown in section O–O which is in a wedge shape. Other dimensions include the tool width B_0 and thickness L_t. Despite its similarity to a common planar tool, there are three distinctions for the P/E