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Thermal performance of the flat micro-heat pipe with the wettability gradient surface by laser fabrication

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ABSTRACT

The flat micro-heat pipe (FMHP), a high-efficiency heat conducting device, mainly depends on the phase change backflow in the internal micro-groove to enhance the heat transfer. Thus, the smaller capillary structure and higher capillary flow capability are the key factors to enhance the thermal performance. The grooved structure is processed by pulsed fiber laser to achieve a larger capillary force. Combined with the surface properties modification of laser interaction with metal and the theory of gradient wettability surface driving force, different capillary structure and wettability surface are prepared. Then gradient wettability surface are regulated through immersing the samples into hydrogen peroxide solution. The thermal performance of the FMHP with different capillary structure as well as gradient wettability surface is carried out and the gradient structure contrast is investigated. Results indicate that the capillary structure of FMHP with a wettability gradient distribution of the contact angle varied from 0° to 45° possesses a higher thermal power of 50 W and lower thermal resistance of 0.002 °C/W. The minimum thermal resistance of the heat pipe with gradient wettability surface is tenfold lower than that without gradient wettability surface.

1. Introduction

Thermal conductivity of flat micro-heat pipe (FMHP) has already exceeded any known metal at present [1]. As a kind of heat-conducting device suitable for high heat flux, FMHP has been widely applied in electronic components, precision instrument power supply and the electronic device of aerospace with its excellent isothermality and high thermal conductivity. Because of the features and applications, there are many researchers carried on the experiment to analyze the influence factors of wick structure, working fluids, evaporation and condensing to enhance the heat transfer performance.

The wick structure is an important factor in limiting the heat transfer of the FMHP. The thermal conductivity of the wick is mainly affected by the capillary backflow of the working liquid inside the pipe. Therefore, increasing the ability of capillary flow by fabricating a capillary structure with a larger capillary force can enhance the thermal transfer efficiency. In the preparation of internal capillary structure of FMHP, the wick used as internal reflux has two types including the grooved and sintered. The sintered wick has a strong capillary pressure, but the backflow resistance between the wick and inner wall of the tube is large, resulting in a strong contact thermal resistance. Meanwhile, the sintering process is complex and the structure of the wick is easily damaged. However, different from the sintered wick, the grooved wick mainly depends on the performance of the capillary grooved structure. When the amount of capillary force backflow cannot satisfy the evaporation, the evaporative section easily dries up and the tube wall temperature will rise sharply, causing the tube to burn out. Thus the strength of capillary capacity is restricted by the groove heat pipe working ability. The microstructure is mainly expressed in the improvement of the capillary force driving the liquid backflow, and the smaller capillary structure is, the larger capillary force can be achieved. There are also many methods for the preparation of capillary grooved wick. Chen et al. [2] processed hetero-groove structure on the silicon substrate by the method of Bosch deep reactive ion etching (DRIE). And then the effect of liquid flows was analyzed with different shape of the grooves structures. The result indicated that the straight channel with different channel width could raise the capillary flow. Cao et al. [3] used the electrical discharge machines (EDM) to process the groove with the structural parameter of 100 μm width and 250 μm depth on the copper micro heat pipe. The effective thermal conductance of the heat pipe was on the order of 40 times that

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Nomenclature

a	groove interval, μm
A_v	steam chamber cross-sectional area, m^2
b	groove width, μm
h	groove depth, μm
L	length of micro channel, m
$\triangle T$	temperature difference, °C
R	thermal resistance, °C/W
q	heat flux, W/m^2
P_c	capillary driven force, N/m
P_a	gradient driven force, N/m
Q_{max}	maximum amount of thermal power, W
k	heat conductivity co-efficiency, W/(m °C)

Greek symbols

p	density, kg/m^3
σ	surface tension of liquid, N/m
θ	contact angle, °
η	absolute viscosity of liquid, Pa·s
θ_{max}	maximum contact angle, °
θ_0	condensing section contact angle, °
θ_x	contact angle of x section, °
θ_e	evaporative contact angle, °

of copper based on the external cross-sectional area of the miniature heat pipe.

In order to further enhance the capillary force of the grooved wick and promote the liquid working medium circulation flow, the inner wall of the FMHP processed to gradient wettability surface is a kind of effective method to improve the capillary flow and thermal performance. Heat transfer enhancement [4] is one of the potential applications among the various applications of the gradient wettability surface. The gradient wettability surface causes the imbalance of young's force for working liquid and the formation of the Marangoni effect, which facilitating the circulation of liquid flow [5], and increasing the heat transfer in heat pipe.

The chemical composition modification and the surface microstructure fabrication are the main two kinds of methods to regulate the wettability on the metal surface. The chemical composition modification including the vapor deposition [6], the chemical modification [7] and the illumination method [8], can cause the changes of the active molecules on the surface and form the gradient properties. Youngsuk Nam et al. [9,10] applied the electroforming and chemical deposition to fabricate the copper post-wicks on the silicon substrate. Then the copper post-wick structure was treated by the chemical oxidation, which can improve the wetting property and the capillary force. The performance of the micro post-wick provided both high effective transfer coefficients and high critical heat flux. Sun et al. [11] used the laser processing to derive a series of different interval of parallel grooves on the smooth silicon surface, and prepared a rough surface with a gradient surface morphology. Yoshihiro et al. [8] used the wavelength of 172 nm UV light to irradiate the SiO_2 surface, making the high surface energy group moving to the low surface energy group. Then the intensity of illumination time was controlled to cause the contact angle (CA) changing from 100° to 25° gradually gradient surface. The functional structure on the surface can further enhance the heat transfer performance of micro heat pipe.

In the aspect of theory of the gradient surface enhancing the heat transfer performance, Suman [12] investigated effects of surface-tension gradients on the performance of a micro-grooved heat pipe. They found that with a favorable surface-tension gradient, the liquid pressure dropping across the heat pipe can be decreased by 90%, and the maximum heat throughput can be increased by 20%. By contrasting with an unfavorable surface-tension gradient, the liquid pressure dropping increases by 150%, and the maximum heat throughput decreases by 15%. Qu et al. [13] studied a functional surface with the axial ladder contact angle distribution. The thermal performance of a triangular micro heat pipe was analyzed based on a one-dimensional steady-state model. Compared with the traditional micro heat pipe with a uniform contact angle distribution on its surface, the simulation results showed that a micro heat pipe with a functional surface can remove a greater amount of heat under the same condition.

The EDM could machine a deep groove, but when the width of the groove is less than 100 μm, the capillary structure may be difficult to obtain. Electrochemical machining method can fabricate all kinds of complex capillary structure directly in the micro heat pipe inner surface without any damage to the wall. But the processing time is too long and the process is impolite to the environment. Laser processing method can process the high aspect ratio and suitable capillary structure, and with the characteristics of the flexibility and non-contact processing, it won't cause damage to the pipe wall and is able to fabricate all kinds of complicated capillary structure. Also laser processing method used on the copper substrate can fabricate complex microstructure and change the molecular activity on the surface of copper substrate by high energy laser beam irradiation, so that both stability and superior performance of gradient surface wetting can be achieved [14].

In order to strengthen the FMHP heat transfer performance, the pulse fiber laser is used to fabricate different interval micro-grooves on copper substrates, and the different gradient surfaces are regulated. The gradient driving force model is established to analyze the change of driving force on different gradient wettability surface. The thermal performances of the FMHP with different capillary structure as well as different gradient wettability surface are carried out. Combined with theoretical analysis, optimal gradient distribution on the micro-groove surface can be achieved.

2. Experimental setup

Fig. 1 shows the structure diagram of temperature test system for FMHP. The experimental device is made of temperature information acquisition unit, the replaceable flat-plate heat pipe, heating system, condensation system, vacuum pump and liquid injection. The copper substrate with different grooved structures can be replaced easily and quickly. The upper cover plate, copper substrate and the lower cover plate are sealed together and fastened by the screw and silica gel to prevent liquid leakage and ensure the tightness well. In this device, the evacuation and the liquid injection can be carried out simultaneously in the replaceable flat-plate heat pipe. At one side of the heat pipe, the heater is cling to the shell of pipe, which supplies the thermal energy through the power source. And on the other side, the condenser provides a cold source to chilling and dissipates the heat from the heat source. Both of them form a cycle system and make the liquid moving in the evaporative and condensing section of the heat pipe. The temperature signal is measured by the four thermocouples and transmitted to the data acquisition card. K-type thermocouples with diameter of 1 mm are bonded on copper substrate surface, two points on the evaporator section (T1, T2), two on the condenser