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Capillary rise of liquids in thermally sprayed porous copper wicks

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ABSTRACT

Porous copper coatings, which act as wicks for liquid transport, were fabricated using a flame spraying process. Channels to enhance liquid flow were made in some of the porous copper coatings by placing pieces of aluminum wire mesh on the copper substrate before spraying. Coatings were made with porosity varying from 2 to 44%, and groove width ranging from 0.16 to 0.53 mm. The capillary performance of the coatings was evaluated experimentally by measuring the rate-of-rise of ethanol in the coatings. The capillary performance of the porous copper strips were evaluated by standing them vertically in a pool of ethanol and measuring both the rate of liquid rise using an infra-red camera and their weight increase. The rate of rise increased with coating porosity, and decreased with channel width. Increasing channel size improved the permeability of the coatings to liquid flow while decreasing their width increased capillary pressure and the height to which liquid rises. An analytical solution of capillary rise in porous media was used to predict the rate of liquid rise as a function of the effective porosity of the coatings, which combines the volume of both the pores and the channels in the coating.

1. Introduction

Porous metal wicks are used in a number of devices such as fuel cells, heat pipes [1,2] and vapor chambers [3]. A typical vapor chamber consists of a sealed chamber, partially filled with a volatile liquid, on whose inner surface a porous metal layer is deposited. One surface of the vapor chamber is placed in contact with a heat source so that liquid at that location evaporates, carrying energy with it in the form of latent heat. The vapor diffuses to the other side of the chamber, which is kept at a lower temperature, where it condenses. The condensing liquid is transported back to the evaporator by capillary forces in the porous wick. If the capillary pressure driving flow in the wick is insufficient to return liquid to the hot end as rapidly as it evaporates, there will be dry-out and consequent failure of the vapor chambers. It is therefore essential to create a porous layer with a structure that maximizes both the capillary pressure and the mass flow rate of liquid [1].

Wicks in vapor chambers are typically made using woven wire meshes or sintered powders that are spot welded or sintered to the inner surfaces of vapor chambers [1,2,4]. The pore size distribution depends on the powder size and the sintering process, and can be difficult to control precisely. These methods require the use of a mandrel to preserve the shapes of the wicks and keep them pressed against the skins during sintering and bonding, which makes it difficult to make vapor chambers with complex shapes. In regions where bonding is not complete there is reduced contact between the wicks and the skins, creating hot spots and diminishing the overall heat transfer performance of the vapor chambers [5].

A number of new techniques have been proposed to fabricate porous wicks that can have a controlled pore size distribution. Ji *et al.* and Hansen *et al.* [6,7] chose highly porous copper and nickel foams as the capillary wicks that sintered to the inner surface of vapor chambers, respectively, and the performance of the vapor chambers were tested. Gheitaghy *et al.* [8] used electrodeposition to create porous copper coatings on copper surfaces containing 0.5 mm deep channels created by electro-discharge machining. By controlling the evolution rate of hydrogen bubbles generated during electrodeposition, different porosities of the coating layers could be created. Chen *et al.* [9] used an ion etching process to create 35 μm high posts on surfaces and showed that the rate of capillary rise of methanol depended on the shapes of the posts. Kim *et al.* [10] fabricated porous layers by brushing a mixture of nickel powder, solder paste, and a solvent onto a surface that was placed in an oven where the solvent vaporized and the solder melted, fusing the nickel powder particles into a porous coating. Though these techniques have given interesting results in laboratory experiments, they are generally time-consuming and expensive to implement and none of them have been shown to be viable for commercial production.

The objective of this work was to develop a method of creating porous metal wicks by flame spraying, a common industrial process that can be easily used for production at a commercial scale. Spraying porous layers directly onto metal surfaces gives a strong bond between the wick and the wall of a vapor chamber, eliminating the need for sintering in a vacuum changer and a mandrel to hold the powder

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Nomenclature

d_1, d_2	horizontal, vertical distance from the torch tip (mm)
W_1, W_2	top, bottom groove width (mm)
x	coating thickness (μm)
Ra	surface roughness (μm)
A_a	artery cross-section area (mm^2)
A_w	coating cross-section area (mm^2)
r_e	effective pore radius (mm)
g	gravitational acceleration ($kg/m^2 s$)
k	permeability (mm^2)
h	capillary rise height (mm)
t	capillary rise time (s)
dh/dt	capillary rise velocity (m/s)
V_t	total volume of liquid (cm^3)
V_a	volume of liquid in arteries (cm^3)
V_w	volume of liquid in coatings (cm^3)
h_c	characteristic length (mm)
t_c	characteristic time (s)
h^*	dimensionless height
t^*	dimensionless time
W	Lambert function

Greek symbols

φ	void volume fraction (%)
ε	coating porosity (%)
ε_e	effective porosity (%)
γ	liquid filling ratio (%)
ΔP_{cap}	capillary pressure (Pa)
σ	surface tension of liquid (N/m)
μ	dynamic viscosity of liquid (Pa s)
ρ	density of liquid (kg/m^3)
ΔP_{cap} k	capillary performance parameter (N)

Subscripts

cap	capillary
e	effective
t	total
a	artery
w	coating

Abbreviations

ncsi	number of cell per inch
SLPM	liter per minute
gpm	gram per minute

against the wall, and assuring good heat transfer between the wick and vapor chamber surface. This also allows the vapor chamber surface to have shapes that are more complicated than a flat plate or a cylinder, making it possible to design vapor chambers in novel forms.

We made porous wicks by simultaneously injecting copper and aluminum powders into the flame spraying torch and spraying them onto copper substrates. After spraying the coatings were chemically leached using sodium hydroxide solution to remove aluminum and create a porous copper layer. Varying the feed rate of aluminum powder allowed the coating porosity to be controlled.

The capillary pressure in a porous wick increases as the radius of curvature of the liquid meniscus is reduced, which can be done by decreasing the pore sizes in the wick. However, this decreases the permeability of the layer, reducing the flow rate of liquid. Insufficient capillary pressure and low permeability of the wicks leads to dry-out of the working liquid during operation and failure of the vapor chamber. An ideal wick structure has a bimodal pore size distribution, combining both small and large pores that create large capillary pressure while also having passages for liquid flow [11]. We created channels for liquid flow in our porous coatings by placing pieces of aluminum wire mesh on the copper substrate before spraying, The mesh acted as a mask, creating a grid of open channels in the coating and greatly increasing its porosity. Groove width was controlled by using different wire mesh sizes.

The permeability and capillary pressure of a porous wick can be evaluated by a rate-of-rise test [12,13] in which the capillary force raises liquid upward against gravity until the capillary and hydrostatic pressures equilibrate. However, the position of the liquid front inside a porous wick is difficult to determine [9] because it is often not directly visible. Deng *et al.* [13] used an infrared camera to detect the liquid front in sintered wicks in the rate-of-rise test. The camera measured the change in temperature of the wicks as liquid infiltrated the pores in it, which allows the location of the liquid front to be determined.

The microstructures of the porous copper coatings were examined by taking scanning electron microscope (SEM) images and coating porosity, thickness and groove dimensions were measured using image analysis software. The capillary performance of the coatings was measured experimentally by recording both the height and mass of liquid rising in coated strips that were mounted vertically with one end immersed in a pool of ethanol. An analytical model of liquid-transport was used to determine both the capillary pressure and an effective permeability of each copper coating. The rate of liquid rise was calculated from an analytical solution of the transport equations and it was demonstrated that the predicted heights of the liquid front agreed well with experimental measurements.

2. Materials and methods

2.1. Fabrication of porous copper coatings

The flame spray system, shown in Fig. 1, was developed to simultaneously inject aluminum and copper powders into the flame and spray them onto copper strips. An external powder injector was attached in front of the flame spray torch (Flame Spray Technologies, P5II, Duiven, Netherlands) to introduce aluminum powder into the copper powder being sprayed. The location of the tip of the injector was specified by measuring the distances d_1 and d_2 from the front of the spray torch nozzle, as marked in Fig. 1. The torch was mounted on a computer-controlled, six-axis robot to produce a uniform coating. A

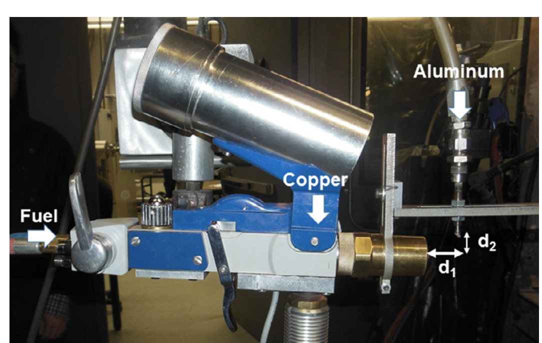

Fig. 1. Experimental set-up of co-injection flame spraying technique.