International Journal of Heat and Mass Transfer 79 (2014) 989–1001

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Development of a two-step electrodeposition process for enhancing pool boiling

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ARTICLE INFO

Article history:
Received 17 August 2014
Accepted 25 August 2014

Keywords:
Pool boiling
Heat transfer enhancement
Porous
Microporous
Multiscale enhancement surfaces
Electrodeposition

ABSTRACT

The continuous development of high performance chips and the growing miniaturization trend in the electronics and microelectronics industry require efficient systems to remove large amounts of heat over a small footprint. Pool boiling has the ability to remove large heat fluxes at small values of wall superheat and this can be further augmented by using porous or microporous surfaces. In this work, a two-step electrodeposition technique involving application of high current density for a short time, followed by a lower current density for a longer time was investigated. This technique allowed a close control of the pore size and porous layer thickness. The electrodeposition process was carefully studied and parameters for creating different morphologies of enhanced surfaces were obtained. Thickness of the coating was in range of 50–100 μm. After testing a variety of morphologies for pool boiling heat transfer with distilled water, a maximum heat flux of 1400 kW/m^2 and a significant enhancement in heat transfer coefficient (HTC) of 179 kW/m^2 °C was obtained from a copper chip with cauliflower-like morphology using an initial current density of 400 mA/cm^2.

1. Introduction

There is an increased demand for dissipating high heat fluxes from electronic chips as faster and high power devices are being developed in various fields including industrial equipment, military and space applications, and high-end computing. The conventional air cooling systems are not able to meet these demands due to their low heat transfer coefficients (HTC), low specific heat and high specific volume. Improvement in HTC will result in reducing the size of cooling equipment. Compared to most other cooling techniques, pool boiling is being investigated by many researchers due to its ability to carry large amounts of heat at low wall superheat without any moving parts [1]. Pool boiling heat transfer can be further enhanced with active devices like ultrasonic vibrations, electrostatic fields etc., or passive techniques such as porous/microporous surfaces, structured surfaces like finely cut grooves, finned or knurled surfaces, integrated micro-nanostructures, etc. Microporous coatings are attractive due to their ability to improve both critical heat flux and HTC. The present work is focused on development and control of the process for deposition of microporous surfaces for enhancing pool boiling heat transfer using the electrodeposition technique.

2. Literature review

A recent exhaustive literature review provides details of various manufacturing techniques to obtain porous enhanced surfaces [2]. The manufacturing techniques discussed in [2] can be broadly classified into five different categories as shown in Fig. 1.

Porous surfaces have been studied quite extensively in literature. Bergles and Chyu [3] created porous surfaces on bronze using a proprietary technique, achieving 250% enhancement in HTC with water and 400–800% with refrigerants. Anderson and Mudawar [4] created a surface by vapor blasting on copper to create a microporous surface, achieving an enhancement of 170% in critical heat flux (CHF) when tested with FC-87. You et al. [5], Memory et al. [6], and Golobic and Ferjancic [7] created microporous surfaces using a spray gun and fine powder of copper or other metals and their oxides and spraying them on the surfaces. You et al. [5] tested these surfaces with FC-72 and achieved an enhancement of 280% in CHF. Memory et al. [6] investigated pool boiling of R-114 on finned, structured and porous tubes and found that the enhancement with

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.062
0017-9310/

Nomenclature

Abbreviations	
CHF	critical heat flux
HTC	heat transfer coefficient
SEM	scanning electron microscope
A	area of the electrode
A_1	nucleation rate
B_y	bias error
°C	degrees celsius
C^*	concentration of copper ion
D	diffusion coefficient
E_{pa}	anodic peak potential
E_{pc}	cathodic peak potential
F	faraday constant
I_{pa}	anodic peak current
I_{pc}	cathodic peak current
I_d	diffusion controlled current
i	value of instantaneous current
k_{cu}	thermal conductivity of copper
M	molar mass
i_m	maximum current in chronoamperometry
n	number of electrons
Py	precision error
q''	heat flux
T	temperature
t	time duration of electrolysis
t_m	time at maximum current during cyclic voltammetry
U_p	uncertainty in a given parameter
U_y	uncertainty
x	distance
Greek symbol	
ρ	density

porous surfaces was significant only at low heat fluxes. Golobic and Ferjancic [7] created a porous medium of different metals and their oxides on a ribbon heater and tested with FC-72, and achieved 29–130% enhancement in CHF. Chang and You [8] applied a mixture of copper powder, binder and a carrier fluid (Methylethylketone) on a copper surface and heated it in an oven to evaporate the carrier liquid. With this porous medium consisting of copper held together by binder, they achieved 100% enhancement in CHF and 30% enhancement in HTC when tested with FC-72.

Based on Albertson's patent [9], Kim [10] devised a technique to electrodeposit enhanced surfaces on copper substrates in multiple stages. In the first stage, they applied high current density to evolve hydrogen bubbles, simultaneously depositing copper and leaving behind copper foam. Porosity of this foam is reduced by slowly depositing additional copper at a lower current density. When tested with water, they obtained 250–700% enhancement in boiling performance and 50–60% improvement in CHF over a plain surface. El-Genk and Ali [11] created similar surfaces and tested them with PF-5060 which enhanced the CHF by 700% without temperature overshoots. Kim [10] prepared porous nickel surfaces by soldering the particles together using a plumbing solder, yielding 40–60% enhancement in CHF. Im et al. [12] created thin films of flowerlike CuO and tested with PF-5060, attaining 58% enhancement in CHF for flat surfaces and 30% for microgrooved surfaces.

The literature review indicates that microporous surfaces enhance the pool boiling heat transfer performance and increase its CHF. The results also indicate that the surfaces enhance boiling heat transfer not only for water but also for other fluids, suggesting that this enhancement technique could be used for electronic cooling applications.

3. Electrodeposition technique development

From literature review, it was evident that microporous surfaces in general yield high heat transfer coefficients and enhance the critical heat flux. Most of the techniques described in the literature utilize high temperatures and longer durations which are in excess of 1 h, resulting in safety and energy consumption concerns for large scale manufacturing. Binder-based techniques have limitations on wall superheat due to chemical stability of the binder. Also, precise control over thickness and pore quality is necessary to achieve good performance. The present day need is to develop a technique that overcomes these limitations and also is amenable for mass production at a low cost in order to gain commercial acceptance.

From the manufacturing processes discussed in the literature review, electrodeposition is a particularly attractive option for the following reasons:

- The process takes relatively less time.
- It involves room temperature, reducing hazards of warping or annealing due to higher temperatures.

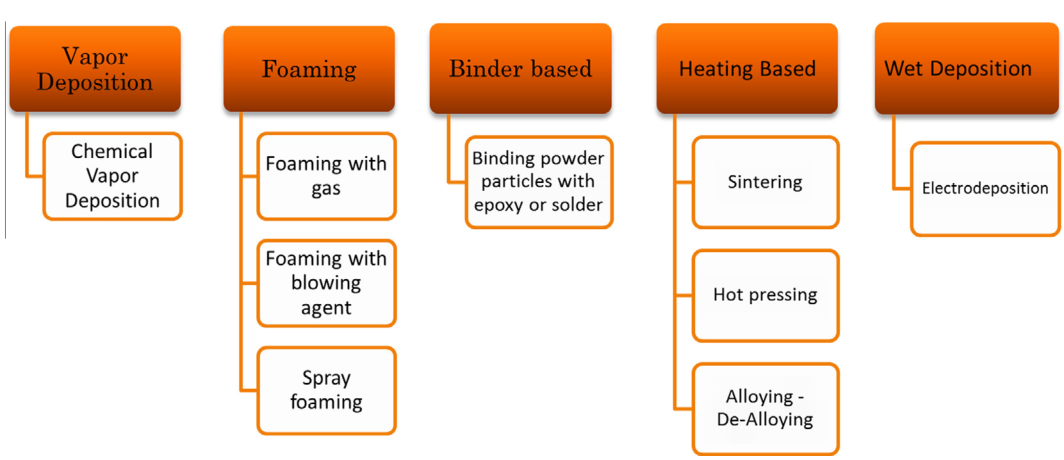

Fig. 1. Manufacturing processes to generate porous surfaces for pool boiling heat transfer enhancement [2].