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Enhancement of critical heat flux and superheat through controlled wettability of cuprous-oxide fractal-like nanotextured surfaces in pool boiling

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ABSTRACT

Highly nanotextured surfaces fabricated by electroplating are demonstrated in pool-boiling applications. Nickel-chrome wires were electroplated with copper and then annealed to cuprous oxide before being subject to Joule heating in a water bath. Vapor bubbles formed whose buoyant rise removed heat and promoted cooling. Hydrophobic and hydrophilic nanotextured surfaces could be tuned by varying the electroplating time. A hydrophobic surface enhanced bubble dynamics to locally decrease the surface temperature of the wire, which, in turn, enhanced superheat and the effective heat transfer coefficient. Conversely, a hydrophilic surface, characterized by a "fractal-like" surface decorated with numerous nucleation sites, increased the overall heat removal and thus the critical heat flux. These nanotextured surfaces were characterized by scanning electron microscopy and their pool boiling dynamics were visualized with a high-speed CCD camera. Theoretical heat-transfer estimates compared well with experimental data.

1. Introduction

Compact computing hardware devices have seen tremendous growth with increased market penetration of the Internet. These electronic devices have been miniaturized by nanoelectronics. However, advances in nanoelectronics are hindered by stringent thermal management requirements. For example, the normal operating regime for silicon chips typically requires a chip temperature below 70 °C. Above this, chip reliability or efficiency decreases by 10% for every 2 °C temperature rise [1]. Thermal management is also challenged by the demand for greater heat flux.

Fan-based air cooling cannot achieve the necessary cooling requirements at a sufficiently low noise level, especially given the confined space constraints of these devices [2]. The high heat transfer coefficients associated with pool boiling is an attractive solution because these systems can transfer a lot of heat at low wall superheats [3]. Pool boiling heat transfer has been proven in a wide variety of applications from nuclear power plant reactor cooling to vapor chambers, thermosyphons, and others, although improvements in critical heat flux (CHF) and heat transfer coefficient are still sought [4–6].

Heat transfer in pool boiling depends not only upon the number of nucleation sites, but also upon the corresponding rate of bubble formation, both of which are associated with surface-liquid interfacial characteristics such as surface wettability and surface roughness. Surface-liquid interfacial characteristics can be classified into two broad categories: hydrophilic and hydrophobic. Hydrophilic surfaces have a high surface density of nucleation sites, which serve to increase CHF [7–9]. On the other hand, hydrophobic surfaces (with fewer nucleation sites per unit area) release bubbles more frequently [10–13]. These frequently release bubbles increase convective cooling resulting in a decreased surface temperature and correspondingly larger superheat (ΔT) and effective heat transfer coefficient. It is important to note, however, that the enhanced superheat promoted by the frequent bubble release of a hydrophobic surface does not guarantee an increase in CHF, which is always increased by a hydrophilic surface (more

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nucleation sites and more total bubbles). These two ends of the spectrum (hydrophilic and hydrophobic surfaces) cannot exist simultaneously, but if the effects of each are understood, the surface can be properly tuned to optimize either superheat or CHF.

In this study, we electroplate a nickel-chrome (NiCr) wire with nanotextured cuprous oxide (Cu_2O) before running Joule heating experiments. The degree of nanotexturing is controlled by changing the electroplating time, forming anything from a moderately rough hydrophobic surface to a spikey, fractal-like hydrophilic surface with many nucleation sites. We develop these nanotextured surfaces and compare the effects of their morphology on superheat and CHF enhancement so that the most appropriate surface for a particular application can be selected.

2. Experimental

2.1. Materials

A NiCr wire (ThyssenKrupp VDM) with average diameter of 0.296 mm (R_0) with initial wire resistance of 15.4 ohm/m was used for pool boiling test. A copper-plating solution composed of 500 mL of distilled water, 80 g of copper sulfate (Sigma-Aldrich), 25 g of sulfuric acid (Matsunoen Chemicals), 2.5 g of hydrochloric acid (Sigma-Aldrich), and 50 g of formaldehyde (Sigma-Aldrich) was used to electrodeposit copper onto the surface of the wire. To obtain a homogeneous solution, it was magnetically stirred for 1 h at room temperature (25°C).

2.2. Cuprous oxide nanotexturing on NiCr wire

First, a pure copper layer was electrically deposited onto the surface of the NiCr wire by copper-plating with various electroplating times (t_e), including 3, 7, 10, 60, 80, and 100 s. A 1-V potential was applied using a DC power supply (E3664A, Agilent Technologies). Next, the electrodeposited samples were annealed for 10 min at 300°C in air to develop the pseudo-fractal Cu_2O shown in Fig. 1. Such a unique morphology can only be obtained by oxidizing the pure copper electroplate by annealing in air [14,15]. The peaks in the XRD pattern (Supporting Information Fig. S1) revealed the presence of both Cu_2O and Cu after oxidation.

2.3. Pool boiling test

Supporting Information Fig. S2 is the overall schematic of the pool boiling test. A concentric-cylindrical glass chamber was built such that fluid flow in the annulus maintained the temperature of the inner glass cylinder. A thermostat bath (JEIO TECH, CW-05G) supplied constant-temperature (150°C) propylene glycol (PG with a boiling point of 188°C) to the annulus. The entire cylindrical chamber was wrapped in aluminum foil to minimize radiant heat loss. A 1-mm-thick K-type thermocouple (Omega) with an accuracy of ±0.3°C and a data recorder (MV-1000, Yokogawa) were used to measure temperatures. A DC power supply (HPS-300G, HANIL T&M CO.) was used to heat the NiCr wire. Power was increased stepwise from 0 V at a rate of 0.2 V/s until the wire broke. Aluminum plates that are chemically stable in water were used as electrodes in the inner glass chamber. All pool boiling experiments were conducted under atmospheric conditions.

2.4. Characterization

Morphologies of the pseudo-fractal Cu_2O layers were characterized by a field-emission scanning electron microscope (FE-SEM, S-5000, Hitachi) and an optical microscope (Metaphot Inspection Microscope, Nikon). The presence of Cu and Cu_2O was confirmed by X-ray diffraction (XRD, SmartLab, Rigaku). Water contact angles of the pseudo-fractal Cu_2O layers on NiCr wires were obtained by placing a water droplet onto the wire and taking snapshots with a high-speed camera (Phantom 9.1, Vision research Inc.).

3. Results and discussion

3.1. Fractal-like Cu_2O nanotexturing

SEM images in Fig. 2 show the variable morphology of the fractal-like Cu_2O layer subject to varying electroplating times (t_e) from 3 to 100 s. For short t_e (Fig. 2a, b, and c), the layer shows "rough particle" structures that have an average diameter of 550 nm with microporous spaces between particles. Dendritic growths on the particles were observed above t_e = 10 s, forming fractal-like structures that reached tens of micrometers in height

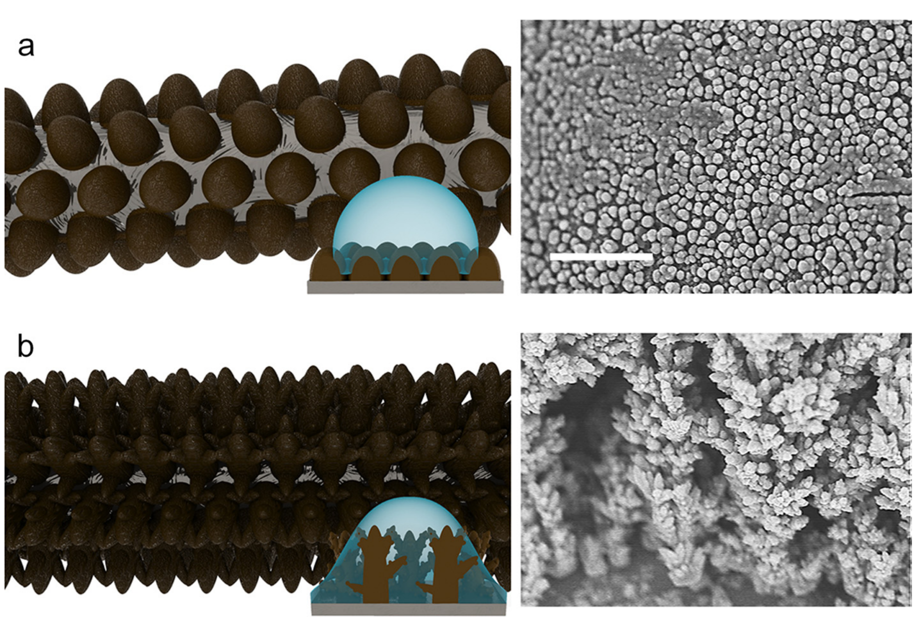

Fig. 1. Schematic and SEM images of the fractal-like Cu_2O a layers on NiCr wire as a function of the electroplating time: (a) t_e = 3 and (b) t_e = 100 s. The inset scale bar is 10 μm.