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Supersonically sprayed nanotextured surfaces with silver nanowires for enhanced pool boiling

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ABSTRACT

Rapid production of nanoscale-textured surfaces for microscale devices is important for commercial applications. In this study, we introduce a commercially viable method to fabricate nanotextured surfaces used in pool-boiling heat-transfer applications. Silver nanowires were supersonically sprayed onto copper substrates with good adhesive strength. The coating method required little time and could be adapted for roll-to-roll processing. The fabricated nanotextured surfaces showed a significantly increased critical heat flux (CHF) and effective heat transfer coefficient (h_{eff}), as evidenced by the release of numerous bubbles from nanotextured nucleation sites during pool-boiling. The silver nanowires were well connected either by self-sintering or due to the fusion induced by supersonic impacts with the copper substrate. The thickness of the coated layer could be controlled by the number of spray sweeps/passes and the optimal thickness for maximizing CHF and h_{eff} was identified. The nanotextured surfaces were characterized by scanning electron microscopy and by bubble formation and release as visualized with a charge-coupled device camera.

1. Introduction

With continuing advances in technology and the emerging fourth industrial revolution, efficient operation of electronic systems has become a central focus for the electronics industry. Most server systems transmit data from data centers through server clusters of computing hardware consisting of high-density chips. As the chips are miniaturized and their density is increased, the heat generation within the server increases, causing significant challenges. Traditional heat management using forced convection through finned heat sinks has limitations [1–3]; the cost of power consumption for cooling a computer room comprises approximately 30% of the data center's total energy consumption cost [4,5]. Pool-boiling heat transfer, which has a high heat-transfer rate, can be used to cool next-generation optoelectronic devices as well as compact, lightweight electronics such as high-power-density laser components, optical components, and mobile Internet devices as depicted in Fig. 1. This has inspired many studies on pool-boiling enhancement through surface modification, i.e., surfaces that have been roughened, extended, coated, or electroplated [6–12].

Implementing nanoscale structures as surface textures increases the density of nucleation sites, thus enhancing heat transfer by pool boiling. Nanostructures reduce the nucleation energy barrier observed at the onset of nucleate boiling (ONB), greatly reducing surface superheating [13–19]. This increases the critical heat flux (CHF), the effective heat transfer coefficient (h_{eff}), or both [20–22]. Such enhanced pool boiling is attributed to the capillary action in the matrix of nanostructure cavities that trap vapors [23,24]. In the future, pool boiling yielding higher heat fluxes must have an even lower h_{eff} while maintaining a high CHF. Thus, a complete understanding of the solid properties and geometrical parameters that influence pool boiling is necessary [25].

Many studies have investigated enhancements in pool-boiling heat transfer using copper, titania, and silicon nanowires (NWs). Previously, we introduced a novel supersonic spraying technique to deposit silver nanowires (AgNWs) on a heated copper substrate [26]. AgNWs were entrained into a supersonic stream of air and solvent that evaporated quickly, leaving deposited AgNWs. Under

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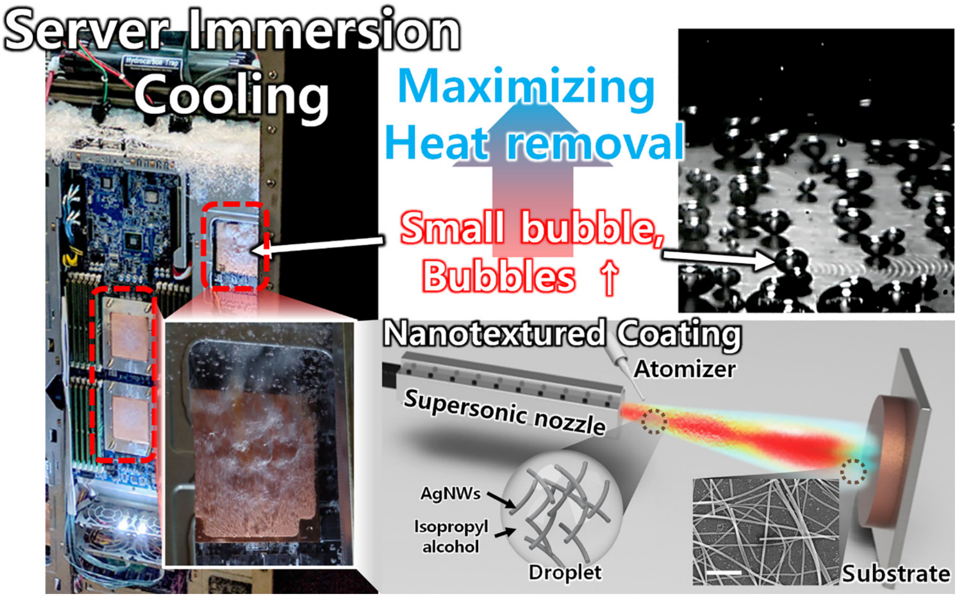

Fig. 1. Schematic of the AgNW coating process on a Cu substrate. The scale bar is 600 nm.

supersonic impact with the substrate, the AgNWs were self-sintered and thus well connected. The AgNWs modified the wall surfaces of microchannels to improve heat transfer. Surface-modification techniques for microelectromechanical systems (MEMS) are well established [27]; however, MEMS are often not practical because they require lengthy and expensive intermediate procedures. The rapid production of nanoscale textures is necessary for commercial viability, which the supersonic spraying method can provide.

In this study, we explore the feasibility of using nanotextured AgNWs for applications that require enhanced pool-boiling heat-transfer. The number of spray sweeps or passes governs the thickness of the AgNW coating. The effects of coating thickness on surface wettability, CHF, and h_{eff} in pool boiling were investigated. Enhanced wettability is expected to increase the supply of coolant to a heated surface, which in turn increases the CHF. The increased nucleation sites formed by AgNW deposition increases the amount of nucleated vapor bubbles, which decreases the surface temperature of the heated plate. Therefore, h_{eff} increases. All these connected phenomena are demonstrated in this study. The nanotextured surfaces are visualized with scanning electron microscopy (SEM), while the bubbles formed at the nucleation sites are observed with a high-speed charge-coupled-device (CCD) camera.

2. Experimental setup

2.1. Texturing materials

AgNWs (Aiden, Korea) with an average diameter of 20 nm and length of 15 μm, were used to coat a Cu substrate. The concentration of AgNWs dispersed in isopropyl alcohol (IPA) was 0.15 wt%. Using this solution, the AgNW precursor was prepared by dilution with IPA (Duksan, Korea) at a weight ratio of 3:1.

2.2. Supersonic spraying

A schematic of the process is shown in Fig. 1. The AgNW precursor (AgNW dispersion) was injected at an optimized position in front of a de Laval nozzle at a flow rate of 1.2 mL min^{-1} through a syringe pump (Legato 210, KDS). The precursor was atomized by an ultrasonic atomizer (Sonic & Materials, Inc.) and accelerated into a supersonic air jet issuing from a de Laval nozzle operating at 4 bar and 220 °C. Although the atomized precursor contained IPA solvent, this was fully evaporated in flight. Therefore, only AgNWs were deposited onto the Cu substrate, which could be positioned with a motorized stage at a scanning speed of 4 cm s^{-1} in orthogonal directions.

2.3. Pool boiling

Pool-boiling tests were conducted with the experimental setup shown schematically in Fig. 2. The experimental setup consisted of a test chamber, a condensing unit connected to a circulating water chiller, two DC power-supply units, a data-recording unit, and a ceramic heater assembly to support and transfer heat to the copper substrate. The working fluid for all pool-boiling tests was water.

Four cylindrical cartridge ceramic heaters connected to the power supply were attached to an aluminum rod ($k_{Al} = 210$ W m^{-1} K^{-1}) and three 1-mm-thick K-type thermocouples (Omega Inc. with accuracies of ±0.75%) were spaced along the rod to measure the local temperatures, denoted as T_1, T_2, and T_3. In addition, the rod was encapsulated in an insulator consisting of glass fiber ($k = 0.02$ W m^{-1} K^{-1}) within a Teflon case ($k = 0.25$ W m^{-1} K^{-1}) to minimize heat loss.

Teflon tape was applied to eliminate water leaks from the Cu substrates and to minimize conductive heat loss along the edges of the substrates. To reduce contact resistance, thermal grease (DOW CORNING, TC-5026, $k_g = 2.89$ W m^{-1} K^{-1}) was applied to the contact area between the copper substrates and the aluminum rod.

Water at 5 °C was circulated through the spiral tube of the condensing unit connected to the chiller (AP15R-30-V11B, VWR Ad). A K-type thermocouple, similar to those described previously, was used to measure the temperature of the coolant (distilled water). The test chamber was sealed with a silicon O–ring and three preheaters were placed in the test chamber to maintain the temperature throughout testing. A data recorder (LR8400-200, HIOKI) was used to measure the temperature at each position of interest in the test.