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International Journal of Heat and Mass Transfer xxx (2018) xxx-xxx





International Journal of Heat and Mass Transfer

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

Supersonically sprayed nanotextured surfaces with silver nanowires for enhanced pool boiling

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ARTICLE INFO

Article history: Received 27 November 2017 Received in revised form 21 February 2018 Accepted 22 February 2018 Available online xxxx

Keywords: Supersonic spraying Silver nanowire Pool boiling Superheat temperature Critical heat flux

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 ($h_{\rm eff}$), 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 $h_{\rm eff}$ 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.

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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-powerdensity laser components, optical components, and mobile Internet devices as depicted in Fig. 1. This has inspired many studies

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.092 0017-9310/© 2018 Elsevier Ltd. All rights reserved. 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 selfsintered and thus well connected. The AgNWs modified the wall surfaces of microchannels to improve heat transfer. Surfacemodification 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 $h_{\rm eff}$ 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, $h_{\rm eff}$ 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 μ m, 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 $1.2 \text{ mL} \text{ min}^{-1}$ 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 ($k_{Al} = 210 \text{ W} \text{ m}^{-1} \text{ K}^{-1}$) 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 ($k = 0.02 \text{ W} \text{ m}^{-1} \text{ K}^{-1}$) within a Teflon case ($k = 0.25 \text{ W} \text{ m}^{-1} \text{ K}^{-1}$) 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, $k_g = 2.89 \text{ Wm}^{-1} \text{ K}^{-1}$) 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.

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Fig. 2. Schematic of the plate pool-boiling facility. (a) Cross-sectional view of the experimental setup (boiling chamber) and the electrical components. (b) Condenser unit installed on the top of the boiling chamber.



Fig. 3. Top and cross-sectional SEM images of AgNWs on a Cu substrate for N = (a) 1, (b) 5, and (c) 10. Scale bars are 600 nm. (d)–(f) Optical profiler images of supersonically sprayed AgNW films with N = 1, 5, and 10. (g) SEM images of the same samples after pool-boiling tests of 5–6 h.

Before testing, preheaters and ceramic heaters were used to set the water saturation temperature for 30 min with water temperature fluctuations of less than ± 0.1 °C. The voltage was increased in increments of 10 V every 15 min; this process was repeated until pool boiling was achieved and the substrates reached the CHF, identified as the last steady-state heat flux value before the temperatures increased sharply. In addition, all pool-boiling tests were conducted in atmospheric air.

Table 1

Roughnesses, roughness factor (r), thicknesses, and Rohsenow's constants of AgNW layers for different N.

Ν	1	5	10
Roughness [nm]	29	93	222
r	1.54	2.56	2.71
Thickness [nm]	35	144	255
C _r	25	15	10



Fig. 4. X-ray diffraction pattern of a supersonically sprayed AgNW Cu substrate.

2.4. Characterization

The morphologies of the tops and the cross-sections of AgNWtextured surfaces were characterized by a field-emission scanning electron microscope (FE-SEM, S-5000, Hitachi) and the surface roughness as were measured by an optical profiler (Veeco, NT-1100). The presence of silver was confirmed by X-ray diffraction (XRD, SmartLab, Rigaku). Snapshots of pool boiling, static water contact angle (SWCA), and dynamic water contact angle (DWCA) were captured with a high-speed camera (Phantom 9.1, Vision research Inc.) at 3400 frames per second (fps). The bubble size and number of bubbles nucleating on the textured substrates were measured by an image-capture and image-measurement solution (I'MEASURE 3.0, ING PLUS).

3. Results and discussion

3.1. AgNW nanotexturing

Fig. 3a–f shows the various morphologies of the AgNW layers for N = 1-10 passes. The AgNWs are well adhered to the substrates and clearly interconnected. These rigid connections remain robust even after the pool-boiling test as shown by the SEM images in Fig. 3g. Although the Cu substrate is visible at low N, AgNWs cover the entire substrate for $N \ge 5$, while the roughness values increased as listed in Table 1. The thickness of the AgNW layer increased from 35 to 255 nm for N = 1-10, respectively. At low N, pores are non-uniform because the AgNWs are deposited randomly; the pore sizes ranged over several hundred micrometers. However, with increasing N, the pore sizes decreased to several micrometers; the paths through which the bubbles escaped simultaneously grew increasingly complex. Fig. 3c may appear porous because of the high roughness value of N = 10. However, from Table 1, the layer thickness was approximately 255 nm, while the corresponding roughness was ~222 nm according to the optical profiler measurement. Because the thickness and roughness



Fig. 5. For *N* = 0, 1, 5, and 10 passes of AgNW deposition, comparisons (a) between experimental (symbols) and theoretical (curves) heat fluxes. (b) WCA versus *N* and (c) snapshots of WCAs for *N* = 0, 1, 5, and 10. The needle diameter is 0.25 mm.

were of the same order of magnitude, this roughness value appropriately describes the surface.

No delamination of AgNWs from the substrate was ever observed. SEM images of the AgNW layer after pool boiling in Fig. 3g reveal that the AgNW morphology was unchanged on the substrate surface, even after 5–6 h of pool boiling (compare with Fig. 3a–c before pool boiling). Although AgNW coating was performed at 220 °C, the AgNWs were rarely oxidized, as shown in Fig. 4, where the peaks of the XRD pattern indicate only the presence of pure silver.

3.2. Validation

Using a simplified one-dimensional, steady-state heat-transfer model, the heat flux was estimated using Fourier's Law as:

$$q'' = k_{\rm AI} \frac{T_2 - T_1}{\Delta x_{12}} = k_{\rm AI} \frac{T_3 - T_2}{\Delta x_{23}} = \frac{T_1 - T_{\rm w}}{\frac{\Delta x_{\rm w}}{k_{\rm r}} + \frac{\Delta x_{\rm Cu}}{k_{\rm cu}}},\tag{1}$$

where T_1 , T_2 , and T_3 are denoted in Fig. 2, and Δx_{12} and Δx_{23} are equal to the 8-mm distances between thermocouples. The third term represents the thermal resistances of the grease and the sub-

strate, where Δx_g and Δx_{cu} are the grease and substrate thicknesses, respectively, and k_{cu} = 401 W m⁻¹ K⁻¹ is the thermal conductivity of the Cu substrate. Using Eq. (1), the water temperature is:

$$T_{\rm w} = T_1 - k_{\rm Al} \frac{(T_2 - T_1)}{\Delta x_{12}} \left(\frac{\Delta x_{\rm g}}{k_{\rm g}} + \frac{\Delta x_{\rm Cu}}{k_{\rm Cu}} \right). \tag{2}$$

The degree of superheating is estimated as $\Delta T_{sat} = T_w - T_{sat}$, where T_{sat} is the boiling temperature of water. Newton's Law of Cooling estimates:

$$h_{\rm eff} = \frac{q''}{\Delta T_{\rm sat}}.$$
(3)

To validate the experiments, the data were compared to Rohsenow's equation in Fig. 5a, although Rohsenow's equation is intended for application to smooth surfaces [28]. The preceding equation was modified by a constant C_r to consider surface roughening:

$$q'' = C_{\rm r}\mu_{\rm l}h_{\rm v} \left[\frac{g(\rho_{\rm l}-\rho_{\rm v})}{\sigma}\right]^{1/2} \left(\frac{c_{\rm p}\Delta T_{\rm sat}}{C_{\rm s,f}h_{\rm v}Pr_{\rm l}^n}\right)^3,\tag{4}$$



Fig. 6. WCA versus time: (a) static WCA, (b) dynamic WCA, and (c) snapshots of DWCAs for N = 0, 1, 5, and 10. The inner diameter of the needle is 4 mm.



Fig. 7. (a) q'' as a function of ΔT_{sat} with the ONB indicated, (b) h_{eff} as a function of q'', (c) comparison between q'' and WCA for N, (d) comparison between h_{eff} and WCA for N at q'' = 0.2 MW m⁻², and (e) R_b as N varied from 0 to 5.

where subscripts *l* and *v* denote the liquid and vapor states, respectively; μ , h_{v} , and *g* are the liquid viscosity, heat of vaporization, and gravity; ρ , σ , and c_p are the density, surface tension, and specific heat; and *Pr* is the Prandtl number. C_r varies according to the surface morphology ($C_r = 1$ for the uncoated case) and the data were matched by adjusting $C_{s,f} = 0.051$ using n = 1 for water [28]. As the thickness or *N* increased, C_r decreased from 25 to 10 as listed in Table 1.

The experimental uncertainty in the heat flux measurements was quantified using the Holman model [20]. All heat flux data were acquired at steady state with errors within ±4.3%. Heat loss due to imperfections in the thermal insulation may contribute an uncertainty margin reaching ±4.6%. The total heat flux (q_t^r) consists of the heat flux transferred to the sample (q'') and the heat loss through the Teflon cylinder (q_c^r) surrounding the aluminum rod; thus, $q_t^r = q^r + q_c^r$. Radiative loss was neglected because the maximum operating temperature was below 200 °C. Fourier's Law was used to estimate q'' and the input, q_t^r , was measured. Therefore, the uncertainty of q_c^r/q_t^r was estimated as 4.6%.

3.3. Effect of nanotexturing on static and dynamic WCA

When hot spots occur, rewetting improved the cooling of the dry surface and enhanced boiling heat transfer (BHT) [29]. Wettability can be estimated through the water contact angle (WCA), which is related to the surface tensions between the solid (s), liquid (l), and gas (g) phases as in Young's equation [30]:

Table 2

Variation of the CHF values from previous studies with different substrate materials, shape, and size (*d*). All substrates were plain and uncoated.

Material	Shape	d [mm]	$\text{CHF} \ [\text{MW} \ m^{-2}]$	Ref.
Copper	Square	25	0.10	[40]
Copper	Circle	10	0.15	[41]
Si	Square	10	0.60	[42]
Copper	Circle	15	0.53	[43]
Copper	Square	10	0.48	[44]
Copper	Circle	30	0.20	Present

$$\cos\theta = \frac{\gamma_{\rm sg} - \gamma_{\rm sl}}{\gamma_{\rm lg}},\tag{5}$$

where θ is the WCA of a flat surface, and γ_{ij} is the surface energy per unit area between the interfaces i - j of solid–gas, solid–liquid, and liquid–gas. However, this equation is only applicable for smooth surfaces. Wenzel modified the equation to account for rough surfaces as:

$$\cos\theta' = r \frac{\gamma_{\rm sg} - \gamma_{\rm sl}}{\gamma_{\rm lg}} = r \cos\theta, \tag{6}$$

where θ' and *r* are the WCA on a rough surface and the roughness factor. When θ' increased in the range of $90^{\circ} < \theta' < 180^{\circ}$, the roughness factor increased because $r = \cos\theta' / \cos\theta$, where θ was constant in the range of $90^{\circ} < \theta < 180^{\circ}$. Similarly, when θ' decreased in the range of $0^{\circ} < \theta' < 90^{\circ}$, the roughness factor increased for a given constant θ value in the range of $0^{\circ} < \theta < 90^{\circ}$. This simple cosine behavior was consistent with the physically observed phenomena. For example, in the Cassie-Baxter case, increasing the roughness factor induced a more hydrophobic state. However, in the Wenzel state, increasing the surface roughness caused greater hydrophilicity. The latter case of the Wenzel state was observed in the wettability of the AgNW coated surface. In our study, as shown in Fig. 5c, the WCA of the uncoated substrate was constant at 69°; it decreased to 56.6°, 24.3°, and 17° as the roughness factor rincreased with increasing spray passes N = 0, 1, 5, and 10, respectively. The reported WCAs were averaged from 10 measurements. For Eq. (6), *r* increased because θ' decreased as *N* was increased as shown in Fig. 5b and Table 1.

The measurement of the dynamic WCA is important because in a real pool-boiling case, the coolant is always in dynamic motion relative to the substrate. Fig. 6a shows the dynamic WCA measured for N = 0, 1, 5, and 10 as a function of time. In each measurement, the water drop was released from the nozzle tip and spread, which caused an initially high WCA for all cases because of the curvature of the periphery of the expanding drop. Beyond t = 10 s, the WCA was static, which is in agreement with the trend of the static WCA shown in Fig. 5b and c. Fig. 6b is a magnified view of Fig. 6a at an earlier time during the spreading of the drop. The WCA was higher for N = 1 than for N = 0, although the difference was minor. This temporary hydrophobicity of the N = 1 case may facilitate the release of nucleated vapors (or bubbles) from the substrate. Meanwhile, the WCA difference between the N = 0 and 1 cases was greater at later time, promoting hydrophilicity for N =1. The subtle difference in surface roughness supplied by nanotexturing clearly altered the wettability of the substrate at various stages; this alteration over time can be exploited. For example, in pool-boiling applications, it is ideal to promote both hydrophobicity and hydrophilicity, even though this seems paradoxical. Hydrophobicity facilitates vapor release, which reduces the substrate temperature. Hydrophilicity promotes the supply of coolant to the heated substrate, allowing longer and more efficient contact between the coolant and the substrate. Thus, controlled alterations in wettability by nanotexturing can promote these features under optimal coating conditions.

3.4. Effect of nanotexturing on the ONB

Fig. 7a and b shows the curves relating q'' and h_{eff} to ΔT_{sat} . The q'' curves of the AgNW-coated substrates, as shown in Fig. 7a, reveal an earlier ONB compared to that obtained with the uncoated substrate. Clearly, AgNW coating facilitates the rapid formation and release of bubbles. This was primarily caused by the AgNW nanostructures on the copper substrate surface. In addition, the ONB was delayed with increasing N. For N = 1, the ONB occured at the lowest ΔT_{sat} , which indicated the lowest surface temperature of the substrate. The CHFs of the coated substrates ranged from 0.5 to 0.7 MW cm^{-2} , while that of the uncoated substrate was 0.2 MW cm⁻²; therefore, nanotexturing increased the CHF value. Table 2 compares the CHF values of uncoated cases from the literature, ranging from 0.1 to 0.6 MW cm⁻². This variation is due to the differences in substrate materials, shapes, and sizes. Silicon generally yields higher CHFs than does copper, and smaller substrates yield higher CHFs than larger ones. The Zuber relation [31] prediction of the CHF for an uncoated substrate of 1 MW



Fig. 8. Schematic of the bubble-formation process on surfaces for (a) an uncoated substrate and for AgNW-deposited substrates with N = (b) 1 and (c) 5.

cm⁻² is a significant overestimate with excessive deviation from the actual experimental values summarized in Table 2 [32]. The CHF of the uncoated case in this study was approximately 0.20 MW cm⁻², slightly lower than other comparable values because of the larger substrates used here (d = 30 mm).

Further understanding can be obtained from Fig. 8a–c, which show how bubbles are formed and released from an uncoated substrate and from substrates with N = 1 and 5 AgNW-deposition passes, assuming identical q''. Bubbles formed at the cavities between the AgNWs and substrate for N = 1; no bubbles formed on the uncoated substrate, which had no cavities because of the polished surface. Up to the ONB, heat transfer was dominated by natural convection. As q'' increased, larger bubbles were formed on the uncoated (N = 0) substrate, while bubbles had already formed and been released on the coated substrate (N = 1); compare the images in the second row of Fig. 8a and b. Because the degree of

superheating required to initiate liquid vaporization at the liquidvapor interface depends upon the embryonic bubble radii, the coated case facilitated bubble formation and released bubbles more rapidly and efficiently. Cavities from nanotexturing act as nucleation sites and reduced the surface temperature. However, excessive cavities, as in Fig. 8c, trapped nucleated bubbles within the coated layer of AgNWs; these trapped bubbles acted as an insulating layer, which adversely affected the cooling process. As a result, higher h_{eff} were observed for N = 5 and 10 than for N = 1; see Fig. 7b.

Upon increasing *N* from 1 to 10, T_w increased (assuming equal q'') and bubble release was delayed. In addition, as shown in Fig. 7a, the ONB was delayed with increasing *N* and the pore sizes decreased (as depicted in the second row of SEM images in Fig. 3a-c). Bubbles at the top of the AgNW layer departed more easily, but the embryonic bubbles forming within the pores were prevented



Fig. 9. Photographs of pool boiling for natural convection, ONB, the highest h_{eff}, CHF, and transition for (a) uncoated substrate, (b) N = 1, and (c) N = 5.

from escaping, as shown in the inset of Fig. 8c. Therefore, thicker AgNW layers (i.e., N = 5 and 10) hindered the migration of the releasing bubbles, preventing efficient heat removal. This phenomenon led to a rapid increase in T_{w} . Fig. 7a and b consistently reflect this hindrance in bubble release while showing decreased superheating for increased *N*.

3.5. Effect of nanotexturing on boiling heat transfer

As seen in Fig. 7a, the CHF was the greatest at N = 5. While the substrate roughness depended on N as in Table 1, the CHF was not proportional to N. With the dramatic increase in roughness from N = 0 to 5, the CHF also increased from 0.20 to 0.65 MW m^{-2} because of the increased nucleation sites. However, the CHF decreased from 0.65 to 0.62 MW m⁻² as *N* further increased from 5 to 10, despite the accompanying increase in roughness. This is attributed to variations in porosity and wettability: with increasing *N*, the number of nanoscale pores increased, but the pore size decreased, as shown in Fig. 3a-c. The surface became more hydrophilic and the WCA decreased from 69° to 17° as shown in Fig. 5c. The larger number of nanoscale pores formed more nucleation sites and produced more bubbles, but these bubbles were easily trapped because the pores were too small, which induced an insulating effect that hindered cooling. This adverse effect decreased the CHF for N = 10 relative to that of N = 5.

Wettability is related to the rewetting of hot spots where bubbles form [33]. Bubble release is more efficient for hydrophobic surfaces [34–36]. At the same time, these hot spots must be rewetted after bubble release. This rewetting is best achieved by a highly wettable surface. These requirements seem contradictory; however, a Wenzel-type surface with high roughness can achieve both requirements to some extent. In summary, rapid release of bubbles and rewetting of hot spots (which the bubbles occupied before release) must both occur to yield the best possible cooling effect in Fig. 7c.

The pool-boiling test photographs were taken at 3400 fps under illumination by a 250-W halogen light to examine the details of bubble formation and release. Fig. 9 presents five boiling-test snapshots depicting natural convection, the ONB, the maximum $h_{\rm eff}$ CHF, and transition boiling (from left to right) for N = 0, 1, and 5. The bubble size and number varied significantly while the bubbles were in motion, impeding measurements of their sizes and numbers [37-39]. Nevertheless, we measured the average number of generated bubbles as noted in Fig. 7e. At the ONB, the bubble radius $R_{\rm b}$ and the number of bubbles $N_{\rm b}$ were measured. $R_{\rm b}$ decreased from 5.1 to 1.6 mm while $N_{\rm b}$ increased from 3 to 37 as N increased from 0 to 5; see Fig. 7e. Furthermore, the bubbles released from the surface were smaller for N = 5 than those for N = 0 or 1; in addition, boiling occured more rapidly with increasing N. The decreased size and increased number of the bubbles enhanced heat transfer. As a result, CHF also increased, as previously indicated in Fig. 7a. Film boiling occured relatively quickly for the uncoated case in Fig. 9a. The delays in film boiling for N = 1 and 5 are clearly and quantitatively demonstrated in Fig. 9b and c.

The $h_{\rm eff}$ in Fig. 7b shows a similar trend to that of the CHF, except for the N = 1 case. A single pass (N = 1) dramatically increased $h_{\rm eff}$ from 2.0 to 11 kW m⁻² K⁻¹, whereas $h_{\rm eff}$ decreased gradually upon increasing N from 5 to 10. As shown in Fig. 7a, the boiling curves for coated surfaces were shifted to the left because superheating is delayed. When the flux was constant at q'' = 0.2 MW m⁻² in Fig. 7b, $h_{\rm eff} = 2$ and 10 kW m⁻² K⁻¹ for N = 0 and 1, respectively; $h_{\rm eff}$ showed a fivefold increase. This trend was ascribed to the thickness and wettability of the AgNW layer. For thinner layers of AgNWs, the surface was relatively hydrophobic, as shown in Figs. 5 and 6c. Therefore, bubbles generated at the

hydrophobic surface were more rapidly released than those for more hydrophilic surfaces (N = 5 and 10 cases). In addition, thinner AgNW layers showed easier bubble release from the surface because the AgNW was in the form of a monolayer. When N was further increased, bubble trapping occured, as depicted in Fig. 8c. Therefore, $h_{\rm eff}$ decreased, as shown in Fig. 7d; however, the $h_{\rm eff}$ values for all coated cases were notedly greater than that for the uncoated case.

4. Conclusions

A heated surface was textured with supersonically sprayed AgNWs that enhanced pool-boiling cooling phenomena. Upon texturing, the CHF and $h_{\rm eff}$ were maximized by the increase in the number of bubble nucleation sites and rapid release of bubbles. However, excessively textured surfaces resulted in the trapping of nucleated bubbles, which inhibited bubble release and hindered efficient cooling. The measured CHFs compared favorably with theoretical estimates. The textured surfaces were characterized by SEM and a phenomenological description of the cooling dynamics was provided. The boiling processes with different textured surfaces were also visualized with a high-speed CCD camera. Thus, it was shown that AgNW-textured surfaces may enhance the cooling efficiency of various miniaturized electronic devices.

Conflict of interest

The authors declared that there is no conflict of interest.

Acknowledgement

This research was supported by the Technology Development Program to Solve Climate Changes of the National Research Foundation (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2016M1A2A2936760), NRF-2013R1A5A1073861, and NRF-2017R1A2B4005639. The research was also supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIP) (No. CRC-16-02-KICT).

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