International Journal of Heat and Mass Transfer 123 (2018) 1120–1127

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Nano-textured surfaces using hybrid micro- and nano-materials for efficient water cooling

Min-Woo Kim [a,1], Tae Gun Kim [a,1], Hong Seok Jo [a], Jong-Gun Lee [a], Scott C. James [b], Mun Seok Choi [c], Woo Yeong Kim [c], Jae Sin Yang [c], Jeehoon Choi [d,*], Sam S. Yoon [a,*]

[a] School of Mechanical Engineering, Korea University, Seoul 02841, Republic of Korea
[b] Depts. of Geosciences and Mech. Eng., Baylor University, Waco, TX 76798, USA
[c] MS AUTOTECH, 1023 Nogokli, Nanamyun, Gyungju 780-851, Republic of Korea
[d] LG Electronics Inc., Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form 28 February 2018
Accepted 28 February 2018

Keywords:
Water cooling
Heat removal
Nanotextured surface
Nanomaterials

ABSTRACT

Water cooling heat transfer was enhanced by texturing the heated surface with various micro- and nano-materials. The increased surface area by texturing facilitated not only enhanced convection, but also turbulent mixing, which increased the effective heat-transfer coefficient. A heated copper substrate was textured with electroplated copper oxide, sprayed silver nanowire, or sprayed copper micro-particles. Sprayed micro-particles were subsequently nano-textured by sand blasting with kanthal (Mo_2Si) nanoparticles. Because of the extremely high hardness of kanthal, sand blasting dimpled the surface to increase the total surface area. Optimal texturing was identified for each material. Hybrid cases combining two different texturing materials were also investigated. All cases were quantitatively compared and that with the highest effective heat transfer was identified. Texturing materials were characterized by scanning electron microscopy and X-ray diffraction. The coating methods are simple, rapid, and scalable and may be cost-effective texturing schemes for various electronics cooling applications.

1. Introduction

Artificial intelligence, the internet of things, big data, cyber-physical systems, and advances in hardware, described as emerging technologies of the fourth industrial revolution, have been combined with web connectivity to impact all disciplines, economies, and industries [1]. These technologies are often based on cloud computing, which is internet- and sever-facilitated computing technology where shared resources, software, and information are provided. Most cloud-computing infrastructures offer services delivered through server-routed data centers. These centers use computing hardware and software products that are specifically designed to deliver cloud services including multi-core semiconductor processors and cloud-specific operating systems. Importantly, advances in high-performance servers hinge on stringent thermal management. Semiconductor chips can require up to 150 W of heat dissipation and cooling solutions are now becoming a limiting factor in technology development. The normal operating temperature of a central processing unit (CPU), graphic processing unit (GPU), and other chips is generally below 70 °C and the reliability of these chips decreases by 10% for each 2 °C increase above this normal operating temperature [2]. To maintain reliability, there is an obvious need for rapid heat removal from CPUs and other chips.

Active air-cooling technology consisting of finned heat sinks combined with fans that transfer heat to outside of the server enclosure. However, air cooling has significant energy demands itself. The total amount of heat transferred from servers into the data center increases the demand on computer room air conditioning (CRAC). Power consumption by data centers constitutes over 0.5% of global power use [3] with power consumption by the CRAC accounting for about 30% of this energy consumption [4–6]. Miniature loop heat pipe systems were introduced to improve air cooling, but have failed widespread commercialization because their complicated fabrication and integration lead to high costs [7–9]. Without technical advances, the CRAC will not be able to economically satisfy the thermal management requirements for servers of the future.

Recently, water cooling has been highlighted as a viable approach for thermal management of data-center severs, although disadvantages include coolant leaks, corrosion fouling, the

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* Corresponding authors.

E-mail addresses: choijeehoon@gmail.com (J. Choi), skyoon@korea.ac.kr (S.S. Yoon).

[1] These authors have equally contributed.

https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.120
0017-9310/

significant weight of the systems, and the required pumping power [10–14]. Because water has a much higher thermal conductivity, heat capacity, and heat-transfer coefficient than air, the heat dissipation rate using water is much higher than that for air. Heat sinks (called cold plates) on the server enclosure are cooled by circulating water so that a large amount of heat can be directly transferred away from the chips through flexible tubes so that the process is much less influenced by the ambient temperature inside the enclosure [10]. Another advantage is that water cooling is not limited to a single component, but can be set up to cool CPU, GPU, and other components simultaneously within the same system [10,15]. Overall, water cooling provides an efficient solution for the thermal management of data-center servers.

To enhance the capability of the heat sink, researchers have suggested increasing the surface area in contact with water, improving mixing to enhance convective heat transfer, and using micro-scale finned structures [16–20]. However, increasing surface area runs counter to the miniaturization trend while the confined spaces of sever-rack mounts increase pressure drop and associated power consumption. Moreover, the costs of complicated fabrication and integration of finned structures can be prohibitive. Therefore, rapid, simple, and scalable texturing methods at the micro- and nano-scale are desired. At the same time, their micro- and nano-scale structures must not hinder coolant flow through increased capillary pressures. This is important not only to minimize coolant pressure drop, but also so that a continuous supply of coolant can carry heat away from the server.

Researchers have used nano-textured surfaces (copper-plated nanofibers, graphene oxide flakes, and silver nanowires) to enhance heat-transfer rates [21]. These nano-textured surfaces yield large heat-transfer areas even within confined spaces while enhancing the turbulent mixing of the fluid to increase the heat-transfer coefficient. Silver nanowires have shown the most promise. To successfully deploy such a nano-textured surface on the heat sink for servers, however, it is necessary to efficiently dissipate the chip-produced heat and to ensure that components can be easily manufactured in an industrial setting. Therefore, this paper reviews how texturing with silver nanowires can satisfy the cooling requirements in a fashion that is easily adopted.

Herein, we compared the water-cooling performance of various textured surfaces fabricated by supersonic cold spraying (CS), electroplating (EP), and sand blasting. Metals, such as copper and silver with micro- and nano-scale architecture were deposited and their cooling performances were systematically evaluated and compared. The best coating conditions were identified.

2. Experimental setup

2.1. Water cooling system

The experimental setup of the water-cooling system is shown in Fig. 1. The water-cooling experimental setup consists of the water chiller (Lab. Companion, RW-0525G), heat sink, temperature recorder (MV-1000, YOKOGAWA, Japan), and power supply. The water chiller supplies cold water at 7 ± 0.5 °C to the heat sink. Warm water returns to the water chiller to cool.

As shown in Fig. 2a, the heat sink consisted of top and bottom covers (aluminum with dimensions of 10 × 5 × 0.5 cm^3), sealing rubber, the middle frame, and the copper-plate substrate (9.5 × 4.5 × 0.7 cm^3) which was textured with micro- and nanomaterials. The sealing rubber prevented water leaks. Fig. 2b illustrates the overall heat-transfer scenario through the heatsink. Power was supplied to the heater and its temperature measured at T_1. It should be noted that the substrate surface temperature (T_s) was slightly less than T_1 because heat flowed through the copper medium by conduction, which was quantified using Fourier's Law. Flow rates of 4, 8, and 16 g/s were quantified by measuring volumetric flow over by time. Temperature was measured at the three locations indicated in Fig. 2b: the cold water supplied at the inlet (T_{in}), heated water at the outlet (T_{out}), and the heater temperature, T_1, which was not the same as the substrate temperature, T_s, which was calculated using T_1 with Fourier's Law. T-type thermocouples (probe size of Ø 1.0 × 150 mm) with an accuracy of ±0.1 °C were used.

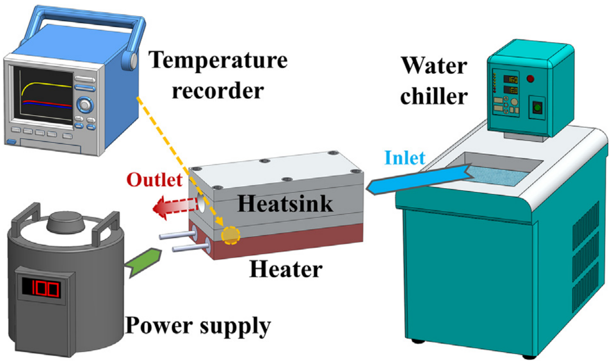

Fig. 1. Schematic of the water-cooling system. Cold water was supplied by the water chiller. The heatsink receives heat from the power supply and water was heated and recycled back to the chiller.

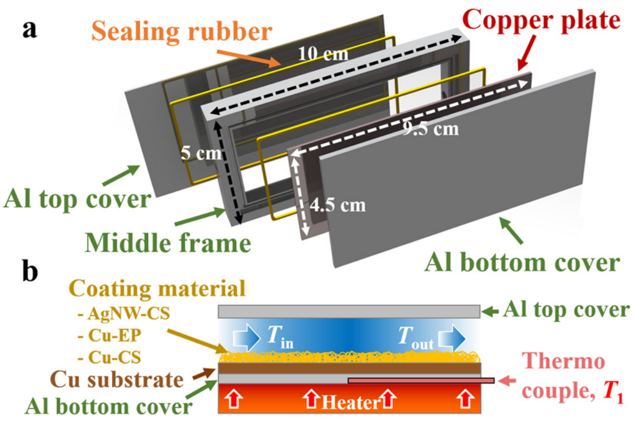

Fig. 2. Detailed schematics of the cooling test module. (a) Assembly of the heat sink. (b) The heat sink attached to the heater. Water entered the heat sink from the left and exited to right.

2.2. Cold sprayed (CS) AgNW and Cu

Silver nanowires (AgNW, Aiden Co., 0.15 wt%) were dispersed in isopropyl alcohol (IPA), average dimensions were 20 nm thick and 15 µm long. A magnetic stirrer maintained a homogeneous suspension of AgNWs, which were aged for 1 h. The AgNW-IPA solution was supersonically sprayed to attach AgNWs onto the copper substrate [21,22]. The supersonic cold spray (CS) setup consisted of a nozzle flowing compressed air over an atomizer to disperse AgNWs from the IPA solution onto the copper substrate. IPA evaporated quickly leaving only AgNWs deposited on the substrate.

The CS system compressed, heated, and accelerated air through a Laval nozzle (operated at conditions listed in Table 1) into which a particle feeder (Praxair 1264i, USA) entrained copper particles to deliver them to the substrate. Variously thick layers of copper particles, which were flattened upon impact, were developed.