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Saturated pool boiling of FC-72 from enhanced surfaces produced by Selective Laser Melting

J.Y. Ho, K.K. Wong, K.C. Leong *

School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Republic of Singapore

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ABSTRACT

This paper presents the results of an experimental investigation on the saturated pool boiling heat transfer performances of microstructured surfaces fabricated by the Selective Laser Melting (SLM) technique. A plain surface and intrinsic micro-cavity and micro-fin surfaces of different configurations were produced from AlSi10Mg base powder using a Gaussian distributed Yb:YAG laser and the surfaces were tested in a water-cooled thermosyphon with FC-72 as the coolant fluid. In comparison with the commercially available plain Al-6061 surface, the SLM produced surfaces show significant enhancements in heat transfer coefficients and CHF. A maximum heat transfer coefficient of 1.27 W/cm^2·K and up to 70% improvement in the average heat transfer coefficient as compared to a plain Al-6061 surface was achieved with the microstructured surfaces. In addition, the highest CHF value of 47.90 W/cm^2, which corresponds to 76% enhancement in CHF as compared with plain Al-6061, was similarly obtained with the microstructured surfaces. Through experimental observations, it was determined that the enhanced heat transfer performances of the SLM fabricated surfaces were due to presence of inherent surface grooves and cavities created from the laser melting process. In addition, analyses of the possible thermal transport mechanisms due to the presence of surface micro-features were also elucidated. Finally, using the Rohsenow model, a general correlation was developed to characterize the pool boiling curves of the SLM fabricated surfaces by incorporating the effects of the surface micro-features, where the predicted heat fluxes were determined to be within ±20% of the heat fluxes obtained from the experiments. In summary, the present work demonstrates the promising use of SLM in fabricating intrinsic microstructured surfaces for enhancing pool boiling heat transfer.

1. Introduction

Nucleate pool boiling from microstructured surfaces has been extensively studied in the last thirty years. Through experimental investigations [1–5], these surfaces were shown to possess significant improvements in both heat transfer coefficients and critical heat fluxes (CHFs) as compared to plain surfaces. Mechanisms such as enhanced bubble motions [6], liquid–vapor–solid interactions [7] and capillary wicking actions [8] were suggested to be the main contributing factors for their enhanced thermal performances. With its immense cooling potential, microstructured surfaces are viable solutions to many thermal management challenges associated with high-heat-flux applications such as in the cooling of electronic devices, nuclear reactor core and power plants. However, with the increasing demand for heat flux removal, especially for electronic devices, the development of more efficient pool boiling surfaces remained vital. Consequently, in the recent years, many novel microscale surface modification techniques and fabrication technologies have been explored which seek to further improve the pool boiling performances of microstructured surfaces.

1.1. Direct coating

The direct coating of nano/micro-sized particles onto the boiling surfaces is a modification technique which has been widely studied. Processes such as electrochemical deposition, chemical vapor deposition (CVD) and direct powder sintering were often employed in the treatment of these surfaces and their heat transfer performances were extensively investigated. For instance, microporous coated surfaces fabricated using the electrodeposition method were developed by Li et al. [9] and also by Furberg and Palm [10]. Using the evolution of hydrogen bubbles during the electrochemical process as a dynamic masking template,

* Corresponding author.
E-mail address: mkcleong@ntu.edu.sg (K.C. Leong).

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Nomenclature

A	area (m^2)
C_{pl}	liquid specific heat (J/kg·K)
C_b	cavity base diameter (μm)
C_d	cavity depth (μm)
C_m	cavity mouth diameter (μm)
C_p	cavity pitch (μm)
D_b	bubble diameter at departure (m)
F_d	fin diameter (μm)
F_h	fin height (μm)
F_p	fin pitch (μm)
F_s	fin separation (μm)
G_d	groove depth (μm)
G_m	groove mouth gap/diameter (μm)
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (W/cm^2·K)
$h_{b,t}$	maximum heat transfer coefficient (W/cm^2·K)
h_t	heat transfer coefficient based on total heat transfer area (W/cm^2·K)
h_{fg}	latent heat of vaporization (kJ/kg)
q	heat rate (W)
q''	heat flux (W/cm^2)
r	surface roughness factor
T	temperature (°C)

Greek symbols

σ	surface tension (N/m)
ρ	density (kg/m^3)
θ	contact angle (°)
ϕ	surface orientation (°)
φ	solid fraction
μ	viscosity (kg/m·s)
η	relative enhancement of h_t

Subscripts

ave	average
b	base
g	vapor
l	fluid
sat	saturated
t	total
w	wall
∞	bulk fluid

Constants

C_{sf}	constant in Eq. (8)
n	constant in Eq. (8)
s	constant in Eq. (8)

dendritically connected micro-pores structures were generated. Through high speed visualization of the boiling process, smaller bubble departure diameter and high frequency bubble departure were seen from these enhanced surfaces. The increase in latent heat transfer mechanism (up to 10 times) was suggested as the main reason for the improved heat transfer recorded [10]. Similarly, El-Genk and Ali [11–13] employed the two-stage electrodeposition approach and produced microporous copper surfaces consisting of nanodendritic layers. Their experimental results showed that nucleate boiling heat transfer coefficient and CHF of 13.5 W/cm^2·K and 27.8 W/cm^2 could be achieved respectively with the microporous surface of 171 μm thickness [12].

Chemical vapor deposition (CVD) is another novel coating technique which has been explored. Using plasma enhanced CVD, Ujereh et al. [14] synthesized highly ordered and vertically aligned carbon nanotubes (CNT) onto the boiling surfaces and their experimental results demonstrated that a maximum heat transfer coefficient of 18.2 kW/m^2·K could be achieved with the CNT-coated surface. More recently, CNT-coated surfaces were also investigated by Ho et al. [15] under different surface orientations and in saturated bulk fluid conditions. In their investigation, the average heat transfer coefficients of CNT-coated surface achieved up to 86% enhancement as compared to a bare surface. In addition, the modified Rohsenow correlation was also proposed by Ho et al. [15] to characterize the pool boiling curves of the surfaces at different orientations. Similarly, other coating methods such as direct sintering of spherical air-atomized copper particles [16], screen printing of copper powder-oil mixture [17] and cold spray coating of CNT-copper composites [18] have also shown to be effective in augmenting pool boiling heat transfer. In general, due to their ease of fabrication and ability to promote bubble formation, microstructured surfaces fabricated with direct coating techniques are attractive for many engineering applications. However, the presence of thermal contact resistance at the substrate-coating interface and the high tendency of coating degrading and peeling over time remained the main drawbacks in their implementation.

1.2. Intrinsic surface features

These drawbacks, however, can be overcome when the microstructured features are intrinsically part of the material surface. For instance, Kruse et al. [19] fabricated intrinsic mound-like microstructures on 304 stainless steel surfaces by ablating the surfaces with an ultra-fast laser. Experiments performed on these metallic surfaces indicated significant improvement in heat transfer coefficients (67.4 kW/m^2·K) over a plain surface with deionized water. Amongst the numerous intrinsic microstructured surfaces that have been investigated, micro-cavities and micro-fins were the most commonly studied. Artificial cavities and fins surfaces with enhanced pool boiling capability have been developed using conventional and non-conventional machining techniques, such as those investigated by Anderson and Mudawar [20], Yu and Lu [21], Hosseini et al. [22] and Chen et al. [23]. Apart from surface machining, micro/nano-electro-mechanical systems (MEMS/NEMS) techniques such as depositions, photolithography and etching processes that were traditionally used in semiconductor devices fabrication have also been employed to produce surfaces to enhance boiling. Numerous novel surfaces with highly ordered micro-sized fins and cavities features with significantly improved thermal performances have been successfully developed. Kubo et al. [4], for instance, fabricated surfaces with different arrays of micro-reentrant cavity and demonstrated the possibility of enhancing nucleate boiling heat transfer with these artificially created nucleation sites. Subsequently, Yu et al. [24] developed surfaces with cylindrical cavity array of diameters ranging from 50 μm to 200 μm and their experiments results showed that the maximum CHF of the enhanced surface was up to 2.5 times as compared to plain silicon. Lately, square micro-cavities of 53 μm diameter and 20 μm depth were also developed by Teodori et al. [25]. Through a combination of post-image processing and PIV measurements of the boiling process, they determined that the optimal heat transfer coefficient was achieved with the cavity separation of 400 μm.