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Experimental study of saturated pool boiling heat transfer with FeCrAl- and Cr-layered vertical tubes under atmospheric pressure

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ABSTRACT

This study compares the nucleate boiling heat transfer coefficient (NBHTC) and critical heat flux (CHF) of two candidate coatings, FeCrAl and Cr, being considered for accident-tolerant fuel (ATF) cladding applications. To form an intrinsic surface roughness, the tube surfaces were initially grinded with 800 and 60 grit sandpapers, and then, FeCrAl and Cr were physically deposited using the direct current magnetron sputtering technique. The FeCrAl- and Cr-layered surfaces became hydrophilic on the lumped nanostructures and superhydrophilic on the particulate nanostructures, respectively. When subjected to the pool boiling conditions of vertically-oriented tubes, the NBHTC and CHF of the FeCrAl-layered tube increased by 24% and 34%, respectively, with the exception of the similar NBHTC generated by the 60 grit sandpaper. In contrast, the NBHTC of the Cr-layered tube decreased by 15% due to the suppressed nucleation on the particulate nanostructures, while CHF increased by 27%. The CHF enhancement was analyzed based on the liquid spreading behavior of a water droplet from the morphological changes. The capillary flow rate, which is a product of the liquid spreading rate, u_s, and arithmetic roughness height, R_a, resulted in a more accurate prediction of the CHF than the equilibrium contact angle. Additionally, the potential boiling performance of the FeCrAl and Cr coatings were discussed by comparing the pool boiling results of the vertical tube and horizontal plate orientations.

1. Introduction

Following the hydrogen risk generated by the existing nuclear fuel system of the Fukushima accident, great attention has been focused on the development of functional accident-tolerant fuel (ATF) claddings [1]. The first priority of the ATF requirements is to suppress the high temperature steam reaction, resulting in the reduction of hydrogen generation. Through abundant experimental testing regarding the improved oxidation resistance, several candidates are available to achieve this objective, such as stainless steel [2], FeCrAl [2–4], and Cr [5,6].

Surface coatings are a practically deployable means of applying these candidate materials to the nuclear fuel cladding system because maintaining the current cladding material (a zirconium-based alloy) is essential for preserving the neutron economy. In this regard, technical focus has been placed on testing the mechanical and thermal functions of the coating and improving the adhesion strength between the candidate material and body material in high temperature steam environments [5,6].

However, the surface coating encounters a boiling issue because the typical coating process inevitably retains surface structures at the micro/nanoscale that are capable of generating significant changes in the boiling performance. Over the past few decades, numerous researches have demonstrated that the surface structures apparent at the micro/nanoscale are able to delay a boiling crisis and improve boiling efficiency. The microscale structures possess several micro-cavities that increase the nucleation site density [7–11], and moreover, the micro/nanoscale structures enhance the liquid wicking characteristics, which effectively delay the formation of irreversible dry patches due to the additional momentum of rewetting liquid [12–14]. Thus, improving the surface structure design directly leads to achievable enhancement of the nucleate boiling heat transfer coefficient (NBHTC) and critical heat flux (CHF).

Although remarkable boiling enhancements (up to 200%) on the micro/nanostructured surfaces have been recently reported [15,16], the microscale roughness and porous structures may exhibit inappropriate properties for nuclear fuel cladding surface applications. This is because the microstructures and porous

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Nomenclature

V	voltage (V)
I	current (A)
D	diameter (mm)
L	length (mm)
r	radius (mm)
r_c	cavity mouth radius (μm)
P	pressure (Pa)
R_a	arithmetic roughness height (nm)
R_{sm}	arithmetic roughness pitch distance (μm)
q''	heat flux (kW/m^2)
K	surface factor
h_{fg}	latent heat (kJ/kg)
g	gravitational acceleration (m/s^2)
Q	wicked volume rate (m^3/s)
A_c	cross-sectional area of microflow channel (m^2)
A_{heated}	heated area (m^2)
u	velocity (m/s)
h_{pv}	peak-to-valley height (μm)
N_c	number of microflow channel
$D_{contact}$	length between the liquid droplet edges (mm)
$l_{contact}$	length of the contact diameter (mm)

Greek letters

ρ	density (kg/m^3)
σ_{lv}	surface tension of water (N/m)
θ	contact angle (°)
ϕ	heater orientation (°)

Subscripts

o	outer
e	equilibrium
r	receding
v	vapor
l	liquid
t	total
s	spreading
c	channel
w	wicking
$grav.$	gravitational
CHF	critical heat flux

medium are vulnerable to surface oxidation and easily lose their structural integrity in the thermal-hydraulic conditions of the core [17]. Thus, the candidate surfaces should essentially satisfy the following requirements for nuclear-level cladding surface design: the coating material is an ATF candidate, the surface roughness is lower than the technical limit (< 0.3 in R_a), and the surface structures and coated layer are not porous.

Few studies have investigated the surface effects of ATF cladding on the boiling performance while satisfying the aforementioned requirements. Seo et al. [18] introduced an FeCrAl coating fabricated by the direct current (DC) magnetron sputtering technique. Four types of FeCrAl structures were prepared by controlling the sputtering temperature to 25, 150, 300, and 600 °C. All of the FeCrAl coatings enhanced the CHF by approximately 14–42%, which indicates that the sputtering conditions are capable of changing the surface structures, thus, resulting in boiling enhancement. Also using the DC magnetron sputtering technique, Son et al. [19] fabricated Cr coatings on different grinded surfaces, thereby, investigating the roughness-augmented CHF enhancement. The CHF was enhanced by 79% with a surface roughness increase of 0.25 μm for R_a. Thus, the results emphasized the importance of the intrinsic surface roughness on the CHF enhancement and sputtering conditions. Kam et al. [20] examined the pool boiling CHF of an SiC-coating, Cr-coating, and bare Zircaloy-4. Compared to the bare Zircaloy-4, the CHF of the SiC coating increased by 150%, whereas the CHF of the Cr coating decreased by 70%. They concluded that the higher CHF with the SiC coating is a result of the improved wettability in comparison to the Cr coating. By applying the deposition of Cr_2O_3 nanoparticle, Cr_2O_3 coating (RF sputtering), and Cr coating (DC sputtering) to wire surfaces, Son et al. [21] showed that pool boiling CHF increases by 6%, 88%, and 93%, respectively. The major cause of CHF enhancement was originated from improved capillary action on modified surface structures. However, these studies focused on the pool boiling performance of horizontal plates and wire unlike the real fuel cladding geometry. Given that practical nuclear claddings are aligned with vertically-oriented tubes, a more realistic situation should be introduced, because the boiling performance significantly depends on the heater geometry and orientation [22,23]. Moreover, the candidate materials require a comparison at the same coating technique and boiling conditions.

This study compares the boiling heat transfer performance of FeCrAl- and Cr-layered vertical tubes. The surface coating was generated using the DC magnetron sputtering technique, which secures columnar film growth without generating porous structures. In addition, to investigate the roughness contribution to the boiling performance, the tube surface roughness was varied below 0.3 μm for R_a. The NBHTC and CHF of the FeCrAl- and Cr-layered tubes vertically heated were quantified under the pool boiling condition. Importantly, the CHF variation with the liquid spreading behavior was analyzed in order to understand the role of sputtered and roughened structures on the CHF enhancement. Finally, based on the results of previous research and those presented herein (*i.e.* previous horizontal boiling [18,19] and current vertical boiling, respectively), we discuss the potential boiling performance of the FeCrAl and Cr coatings for practical applications.

2. Experiments

2.1. Surface preparation

Prior to implementing the DC magnetron sputtering technique, the tube surfaces were initially grinded with 800 and 60 grit sandpaper in an attempt to examine the effects of intrinsic surface roughness on boiling enhancement. The grinded tube surfaces contain several micro-scratched lines, and their cross-sectional dimension has the potential to cause capillary wicking flow [19,24]. The FeCrAl and Cr depositions were then performed using the DC magnetron sputtering technique. The sputtering conditions are summarized in Table 1. In our previous study [18], it was found that the CHF of FeCrAl-layered surfaces increased non-monotonically with the substrate temperature of 25, 150, 300, and 600 °C. The highest CHF was observed at the substrate temperature of 150 °C because its roughness factor was the highest among the simulated substrate temperatures. Moreover, the roughness factor decreased as the exposure time increased from 1 h to 6 h. In this regard, the sputtering process was conducted at a substrate temperature of 150 °C for 1 h.