



Induced liquid-solid contact via micro/nano multiscale texture on a surface and its effect on the Leidenfrost temperature



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ABSTRACT

A significant increase in the Leidenfrost temperature (LFT) was observed on a micro/nano multiscale textured surface (MTS) compared with a polished surface (PS) and a micro rough surface (MRS). MTS was fabricated by anodic oxidation and has nano-scaled needles with micro roughness. It showed improved surface wetting characteristics (0° contact angle with liquid spreading). On the other hand, MRS was fabricated by mechanical polishing and it only has micro roughness. LFT on MTS and MRS increased by approximately 150°C and 30°C , respectively, compared with one for PS. The textures on each surface influenced the water droplet dynamics. The relationship between LFT and the dynamics of water droplet were studied by high-speed photography. The key phenomenon determining LFT was the rebound process of the droplet during a few milliseconds. On MRS and MTS, the rebound phenomenon of the droplet was disturbed by the surface-texture-induced liquid-solid contact even when the surface was initially at a high temperature over 300°C . The precursor wetting front, observed only on MTS and the capillary wicking phenomenon are likely the responsible mechanisms that significantly increased LFT on MTS.

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1. Introduction

When a liquid droplet impacts a solid surface held at a high temperature, it boils and disappears quickly. However, if the temperature of the surface is much higher than the boiling point of the liquid, the stable formation of a vapor layer prevents the droplet from contacting the heated surface. The vapor layer however, drastically decreases heat transfer between the solid surface and the liquid droplet. Therefore, the time for droplet evaporation dramatically increases and this phenomenon is called the Leidenfrost [1]. In general, the initial surface temperature corresponding to the maximum evaporation time of a droplet is defined as the Leidenfrost temperature (LFT) [2]. LFT has importance in many thermal engineering applications such as spray cooling of metallic alloys, rapid cooling of overheated components, firefighting, and steel quenching. In general thermal applications, LFT is undesirable due to low cooling efficiency.

LFT depends on various parameters such as the droplet size, the impact velocity, and the physical properties of the liquid and the surface. To enhance surface quenching, i.e., to increase LFT, previous studies intensively examined the effect of surface modifica-

tions. Traditionally, roughened surfaces used to promote liquid-solid contact for the rapid quenching [3–5]. It was suggested that promoting the liquid-solid contact could increase LFT by disrupting the vapor layer formation. Avedisian and Koplik [6] reported that LFT of a porous ceramic surface increases as its porosity increases. They suggested that the porous surface absorbs a part of the vapor flow under the levitated droplet, which increases the surface superheat required to maintain a sufficiently thick vapor layer to float the droplet. The effects of wettability and thermal properties have also been reported [7–11].

Several models and correlations have been proposed to predict LFT. The classical hydrodynamic instability model for a drop hovering on a vapor film was proposed by Berenson and Henry [12,13]. However, their model did not predict the experimental values for cryogenic fluids, or water [14,15]. This means that the wave model required for Berenson's equation is not appropriate for small drops [3]. To explain the influence of the thermo-physical properties of the surface, Baumeister and Simon [3] developed a superheat limit model [16] that included characteristics of the surface. Their analytical solution agreed well with experimental data of LFT for various surface materials and liquids.

The above classical theories do not explain the recently reported significantly higher LFTs on micro/nano textured surfaces. For example, in recent film boiling heat transfer experiments, the

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Nomenclature*Roman symbols*

A	dispersion constant (J)
D_0	initial droplet diameter (m)
g	gravitational constant (m/s^2)
h_e	evaporative heat transfer coefficient ($\text{W/m}^2 \text{K}$)
h_{lv}	latent heat (kJ/kg)
k	thermal conductivity (W/m K)
P_s	surface tension pressure (N/m^2)
P_r	evaporating vapor recoil pressure (N/m^2)
q_t	total heat transfer rate (W/m)
R	radius of curvature (m)
T	temperature ($^\circ\text{C}$)
t_R	Residence time (ms)
u	velocity (m/s)

Greek symbols

δ_0	non-evaporating region thickness (m)
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η	evaporation mass flux (kg/s m^2)
θ	contact angle ($^\circ$)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ν	kinematic viscosity (m^2/s)

Abbreviations

PS	polished surface
MRS	micro rough surface
MTS	multiscale textured surface

Subscripts

l	liquid
v	vapor
wall	heater surface

use of nanofluids significantly elevated LFT to $\sim 500^\circ\text{C}$ [17,18]. It was documented that such a significant enhancement is governed by a different mechanism. One of the hypotheses to explain such a significant elevation in LFT on a micro/nano-textured surface is the surface-texture-induced liquid-solid contact. Kim et al. [10,11] reported that LFT increased on rough, hydrophilic, and nano-porous surfaces because of frequent intermittent contacts. They reported that microscale roughness induces frequent liquid-solid contacts. On a nano-porous surface, during intermittent contacts, the velocity of the expanding vapor interface, generated from heterogeneous nucleation exceeds the critical velocity of the Kelvin-Helmholtz instability [11]. This can destabilize the vapor and increase LFT. Kruse et al. [19] also reported that intermittent contacts and capillary wicking induced by deposited nano particles increase LFT. Several researchers have also explained LFT the capillary wicking phenomenon [20,21]. Kim et al. [22] suggested that vapor slip on heated nanotube surfaces could cause of LFT increase.

Those previous works suggested the liquid-solid contact induced by capillary wicking as common hypothesis for the reason of the observed enhancement of quench. However, this hypothesis has not been directly confirmed by visual observation. Also, a doubt is remaining in the claim that capillary wicking acts even on a very high temperature conditions. Furthermore, the experimental results so far did not separate the effects of the surface wettability that affects the liquid-solid dynamic interactions and the morphology, i.e. micro/nano multiscale texture, related to the effective surface area, since the modified surfaces accompanied changes in both aspects.

In the present study, we endeavored to clarify the mechanism of known quenching enhancement of modified surfaces by separating effects of the wetting and surface roughness, and to visually observe the phenomena closely especially focusing in the liquid-solid interaction dynamics. For this purpose, we used three kinds of modified surfaces for quenching experiments: MTS (Multiscale micro/nano textured surface), MRS (Micro roughness surface) and PS (Polished surface). The first is a newly developed one with multiscale structures, having a super hydrophilic nature. The second has a similar wettability and overall roughness with the first, but without the structures. The third has similar wettability to the former two, but without structures or roughness. An extraordinary increase of LFT specially on MTS was measured, and also succeeded, for the first time, in visualization of the hypothesized cap-

illary wicking phenomenon accompanying the quenching process that explains the unusual quench enhancement.

2. Experimental method

We measured the lifetime of an impinging droplet on heated test surfaces as a function of the surface temperature. The effects of the surface texture were examined with MTS, MRS, and PS as test surfaces. LFTs on the various surfaces were acquired at the maximum lifetimes of the droplets. The dynamics of the droplets were observed with a high-speed camera at approximately 5000 fps.

2.1. Surface preparation

MTS, MRS, and PS samples were prepared from zirconium. The sample surfaces had dimensions of $20 \text{ mm} \times 30 \text{ mm} \times 1 \text{ mm}$ (thickness). The surfaces were mechanically polished to remove impurities and to ensure surface uniformity. PS sample was polished using #2000 silicon carbide abrasive paper and MRS sample was polished using a #16 silicon carbide abrasive paper. Then, they were cleaned chemically using acetone, ethanol, and methanol and rinsed with deionized water. MTS sample was fabricated using anodic oxidation of PS sample [23] by following procedure. In the 0.5 wt.% hydrofluoric acid solution, which was maintained at a constant temperature of 10°C , the sample was anodized by applying a 20 V electric potential, with a distance of 50 mm between the anode and the cathode. The cathode material was graphite, and the anode material was a clean PS sample. The solution was stirred to ensure a uniform reaction. The reaction time was 10 min. After the reaction, the sample was rinsed with deionized water. All samples were maintained at 600°C for approximately one hour in a furnace to remove the residual fluorine and to avoid additional oxidation during the experiment.

2.2. Characteristics of the experimental surfaces

Fig. 1 shows scanning electron microscope (SEM) images of the test surfaces and the contact angles of water droplet on the surfaces. PS and MRS have low contact angles, of approximately 10° . MTS is super-hydrophilic, with a nearly 0° contact angle.

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