Pool boiling performance of laser-textured surfaces with time-dependent wettability

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Abstract. In last years, the direct laser texturing proved as environmentally friendly, scalable, flexible and efficient approach for surface functionalisation by creating appropriate surface features for enhanced boiling performance. When metal surface is laser-processed in open (oxygen-containing) atmosphere, it oxidizes and becomes (super)hydrophilic. However, it is well known that the wettability transition towards (super)hydrophobic state occurs, if such a surface is exposed to the presence of hydrophobic contaminants. When water is used as a working fluid, this wettability transition can have a significant effect on nucleate boiling performance, which is investigated in this work.

1. Introduction
Nucleate pool boiling is a process of heat transfer between a heated surface and a macroscopically stationary surrounding liquid in such a way that generation of vapor bubbles occurs. It is indispensable in many engineering applications as it allows extremely efficient dissipation of heat due to large enthalpy of vaporisation of the working fluids. Boiling itself is a complex phenomenon governed by a multitude of parameters, out of which the surface characteristics, including such as micro- and nanoroughness, wettability, surface chemistry, and porosity all have a strong effect on heat transfer performance. Consequently, surface functionalisation is the most commonly utilised passive approach to influence bubble dynamics, nucleation site density and therefore to enhance boiling heat transfer.

General aim of surface functionalisation is to develop surfaces that (i) provide earlier transition to nucleate boiling (i.e. lower temperatures at the onset of nucleate boiling), (ii) lower the surface temperature throughout the entire nucleate boiling regime (i.e. higher heat transfer coefficient - HTC), (iii) increase the density of active nucleation sites and bubble departure frequency and (iv) limit the bubble growth with enhanced rewetting of nucleation sites to delay the surface dry-out and therefore enhance the critical heat flux – CHF. Some of the developed surface modification methods [1] for boiling enhancement can be expensive, problematic for scale-up or questionable regarding the thermal, mechanical and temporal stability of the surfaces. Contrarily, the direct laser texturing has a potential to overcome these limitations at it allows chemical-free (i.e., environmentally friendly) and fast functionalisation of metals to achieve appropriate chemical and topographical modifications for enhanced and controlled nucleate boiling with various working fluids [2, 3].

When the metal surface is textured with laser pulse fluences well above the ablation threshold, this results in ablation and melting of the material, which can create channels, cavities and hierarchical structures due to oxidation and solidification of the molten material [4]. Immediately after the nanosecond laser texturing, the treated surface exhibits saturated Wenzel wetting regime with a contact angle $\theta = 0^\circ$ (i.e. superhydrophilic state). However, this state is not stable and tend to transition towards...
the (super)hydrophobic regime when exposed to atmospheric conditions [5-7]. Since the surface wettability plays an important role in boiling performance [8], the aim of this contribution is to evaluate how naturally-developed superhydrophobic laser-textured surfaces perform in pool boiling.

2. Methodology

2.1. Pool boiling experiments

Pool boiling experiments were performed with double-distilled water (Roth 3478.2) under saturated conditions at atmospheric pressure. The experimental setup (described in our previous study [9]) consists of a 170×100×100 mm³ glass boiling chamber, top-mounted condenser, immersed cartridge heater and the ceramic holder at the bottom serving as a heater unit with two electrical contacts to apply electrical power to the boiling surface. The boiling surface is a Joule-heated 25-µm thick stainless steel foil (AISI 316L) with an active boiling area of 27×17 mm². A borehole in the ceramic holder enables the observation of transient temperature fields on the foil’s underside (coated with high emissivity paint) with a high-speed IR camera at 1000 fps with a spatial resolution 125 µm/pixel. Expanded measurement uncertainty of IR measurements and the heat flux is 2 K and 0.5%, respectively.

2.2. Laser texturing and low-temperature annealing

In this study, one foil was kept untreated, while three other foils were textured by a nanosecond fibre laser (SPI Lasers, G4, SP-020P, λ = 1060 nm) using an F-Theta lens and a scanning head (Raylase, S5-1E1-10) to lead the beam across the surface at 150 mm/s. The pulse duration, repetition rate, pulse fluence and beam waist diameter equalled 28 ns (FWHM), 25 kHz, 8.5 J/cm² and 30 µm, respectively. The scanning line separation varied between 40 µm and 50 µm to create the multiscale µ-cavities with diameters ranging from 0.2 µm up to 10 µm (Figure 1). According to the nucleation criteria [10], such range of cavity diameters should provide active nucleation sites for wide range of fluids and enhance the pool boiling, which was experimentally confirmed in a previous study [11].

![Figure 1. Laser texturing of stainless steel foils with SEM image showing the region of µ-cavities formed in between laser scanning lines.](image)

Immediately after the laser texturing, all three laser-textured foils were superhydrophilic. When exposed to various conditions they became either hydrophilic (sample HPI) or superhydrophobic (samples SHPO and SHPO-RT) before the boiling performance evaluation. Sample HPI was kept in a contaminated furnace (Kambič, model VS-50 SC) under the same conditions as in ref. [12] at 100 °C for 2.5 h. Its apparent static contact angle (CA) equaled 34°, while the SHPO sample was annealed for 17 h to reach a CA of 154°. The sample SHPO-RT, was exposed to the normal open atmosphere at room temperature (~25 °C and RH ~55%) for 82 days and became superhydrophobic with CA of 158°. In this context, the terms ‘contaminated furnace’ and ‘normal open atmosphere’ are used arbitrarily, since the underlying mechanism responsible for the wettability transition is still under debate [13]. Initial (super)hydrophilic properties of laser-textured surfaces can be attributed to increased surface micro/nano-roughness and formation of an intrinsically hydrophilic oxide layer with high surface energy [14]. Different authors showed [5-7] that contaminants from the atmosphere are attracted by hydrophilic surfaces leading to the formation of a thin layer of contaminants responsible for hydrophobicity.
3. Findings
Each laser-textured sample was used in two consecutive boiling experiments whereas the pool of water was emptied between both runs. The CA was measured with custom-developed goniometer (the drop size equaled 5µl) prior to the first (up to 500 kW/m²) and the second (up to the burnout point) boiling run as shown in Figure 2b. Both SHPO samples exhibited virtually the same boiling behaviour. During the first run (Figure 2a), the boiling onset was reached at about 3 K of superheat (< 25kW/m²) and a significant HTC enhancement compared to the untreated sample was noticeable. However, in the second run, the onset of boiling was increased to about 9 K, but both samples still showed remarkable enhancement compared to the untreated surface and reached the burnout at ~1300 kW/m². The HPI sample exhibited similar performance during both runs and showed more than 20% lower HTC and CHF than SHPO samples.

![Figure 2](image)

Figure 2. (a) Pool boiling curves for saturated boiling of water on superhydrophobic and hydrophilic laser-textured surfaces in comparison with untreated stainless steel. (b) Sessile drop of water on SHPO sample prior and after 1st boiling run.

![Figure 3](image)

Figure 3. (a) Selected temperature fields of the SHPO-RT sample during 1st and 2nd boiling run at 200 kW/m² and (b) corresponding wall temperature fluctuations underneath single nucleation site. (c) Average bubble footprint diameters (prior to departure) where the shaded areas represent the standard deviation above and below the average value.
It was observed that all surfaces exhibited a static CA in the range of 23–27° after the first boiling run, which shows that developed superhydrophobic properties cannot completely survive exposure to boiling of water. To further elucidate the performance differences, we processed the recordings taken by the high-speed IR camera (Figure 3). The two initially superhydrophobic samples (SHPO and SHPO-RT) provided extremely small bubble footprints during the first run and more than two times higher nucleation frequencies compared to the second run. This may have happened due to entrapment of non-condensable gasses (air) in µ-cavities. Air entrapment inside hydrophobic structures can even survive extensive boiling degassing (as performed in our experiments) and in turn result in low bubble activation temperatures and completely different bubble dynamics compared to a fully degassed surface [15].

Superhydrophobic surface properties in combination with air (or vapor) entrapment usually result in the so-called Cassie-Baxter boiling regime [16], which causes early spreading of the vapor and therefore extremely low CHF values. However, when we increased the heat flux over 200 kW m⁻² on SHPO and SHPO-RT samples during the first run (Figure 3c), bubble footprints gradually approached the values that were later observed during the second boiling run. There is no evidence of vapor spreading and we believe that initial superhydrophobic properties were lost at this stage.

4. Conclusions

The transition of laser-textured surfaces from a (super)hydrophilic to a (super)hydrophobic wetting state should be rigorously examined prior to the integration of such surfaces in boiling heat transfer applications, since the wettability alteration can have negative or positive consequences on boiling performance. As shown here, laser-textured surfaces can enhance boiling performance of water despite their time-dependent wetting behaviour. Static contact angles of initially superhydrophobic surfaces decreased to ~25° after the first boiling run, which confirms that hydrophobic species (mostly PDMS in our case [12]) cannot completely survive boiling. However, these surfaces still outperformed the initially hydrophilic surfaces (with the same surface topography) in terms of the nucleation site density, nucleation frequency and bubble activation temperatures. This shows that (super)hydrophobicity might still be locally present even after the boiling, which requires a further analytical confirmation.

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