Plasma deposition of hydrophobic coatings on structured surfaces for condensation and heat transfer applications

D. Gloess[1], P. Frach[1], M.Maicu[1], E. Holst[2], R. Schmittgens[2], G. Gerlach[2], C.H. Lu[4], T. Roch[3], M. Bieda[3], A. Lasagni[3], M. Beckmann[4]

[1] Fraunhofer-Institut für Elektronenstrahl und Plasmatechnik (FEP),Winterbergstraße 28, 01277 Dresden, Germany

[2] Technische Universität Dresden, Institut für Festkörperelektronik (IFE), 01062 Dresden, Germany

[3] Fraunhofer-Institut für Werkstoff und Strahltechnik (IWS),Winterbergstraße 28, 01277 Dresden, Germany

[4] Technische Universität Dresden, Institut für Energietechnik (IET), 01062 Dresden, Germany

Keywords:

condensation, plasma deposition, direct laser interference patterning, hydrophobic coating

1. Introduction

The control of vapor condensation processes by suitably prepared surfaces is a prominent research area with important applications in the industry. For example, it is well known that the efficiency of condensation heat exchangers can be significantly increased when the vapor condenses to form droplets on the surface, instead of a closed film which does not wet the surface [1, 2]. In the present work, hydrophobic thin films are deposited via plasma CVD processes on metallic surfaces to investigate the condensation of water vapor on these surfaces. The drop-wise condensation on the coated surfaces is analyzed by optical microscopy and the effect on the heat transfer is measured by heat flux measurements.

In order to show the potential of the deposition process for industrial applications and to investigate the effect of drop-wise condensation on heat transfer, copper (Cu) substrates were coated with a plasma polymer film using an organosilicon monomer (Hexamethyldisiloxane, HMDSO) as a precursor. In addition, the effect of surface roughness on the drop-wise condensation is presented because the static contact angle of water on hydrophobic surfaces depends strongly on surface topography.

2. Methodology, Results and Discussion

a) Plasma polymerization by PECVD

The plasma polymerization process is schematically shown in Fig.1. The PECVD unit consists of a RF capacitively coupled discharge, fed by a 60 MHz generator [3]. Beside the monomer HDMSO, Argon was used as inert gas. In the plasma region the monomer precursor is transformed into reactive species which polymerize as a thin film on the substrate. The film thickness was varied between 10 and 100 nm by adjusting pulse and deposition time.

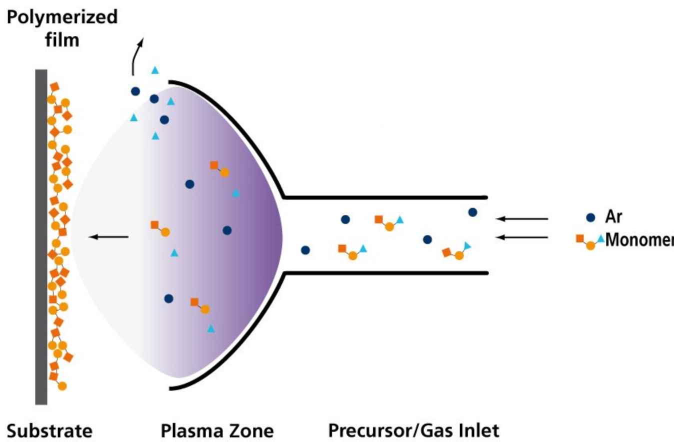

Fig.1. Scheme of the PECVD process for plasma polymerization.

b) Surface structuring by Direct Laser Interference Patterning (DLIP)

Patterning of surfaces and controlling the surface energy can be used to further enhance the efficiency of condensation heat exchangers, e.g. by defining droplet growth sites on the surface or by directing the drop movement. Direct Laser Interference Patterning (DLIP) is presented as an efficient structuring method for heat exchanger surfaces. Surface geometries for enhanced droplet removal are presented and the effect of the drop-wise condensation process is demonstrated.

In order to fabricate the structures shown in Fig. 2, a q-switched Nd-YAG-Laser (pulse width: 10 ns, pulse repetition rate: 10 Hz) at 355 nm wavelength was used. The primary beam was split into two laser beams, which were then recombined to interfere on the substrate surface (Fig. 3). The pitch P is determined by the angle θ between the two beams and the laser wavelength λ:

$$P = \frac{\lambda}{2\sin\theta}.$$

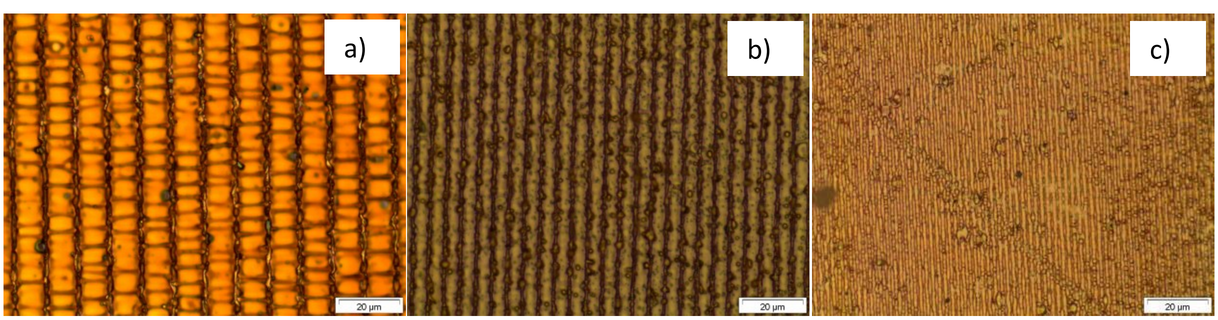

***Fig.2**.* Structured copper surfaces with different pitches: a) 10 µm, b) 5 µm, and c) 2 µm.

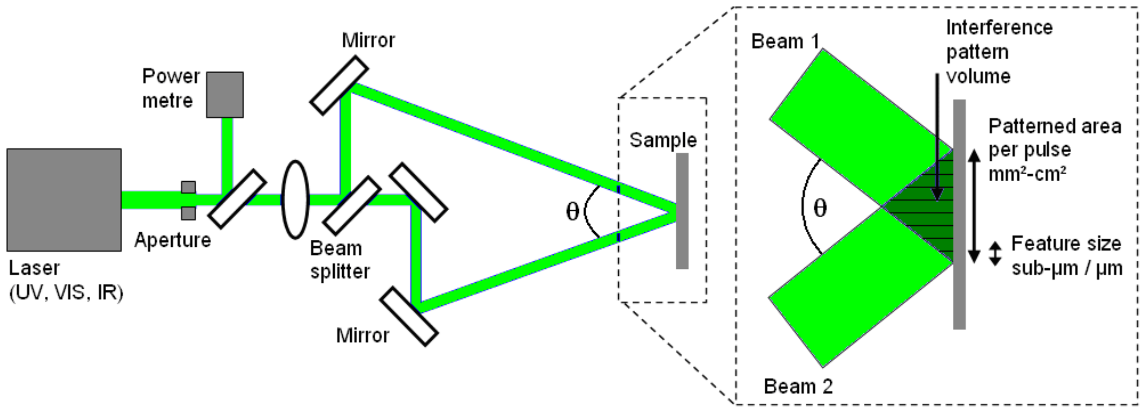

Fig.3. Scheme of the experimental setup for DLIP.

c) Heat transfer coefficient measurements

The extent of the condensation on structured and non-structured surfaces, as well as the influence of the hydrophobic coatings, was evaluated by calculating the heat transfer coefficient ***α*** (also ***h***) for all samples. The experiments are based on the measurement of the heat flow transfer through the sample. The heat flow was determined by monitoring the steam-to-metal surface temperature difference ΔT with thermocouples placed on both sides of the metallic samples [1].

The plots in Fig. 4 show the results of the heat flow transfer measurements, that were obtained for three different samples (substrate: Cu): (1) surface structured (P=2 µm)/coated with a hydrophobic film, (2) surface structured/uncoated, (3) surface unstructured/coated with a hydrophobic film. In addition, the theoretical curve based on the Nusselt theory for laminar films is included (4) to facilitate the comparison to samples (1) to (3). It is evident, that the laser structured Cu surface together with a post-deposited PECVD hydrophobic film result in higher values for α and an improved heat transfer.

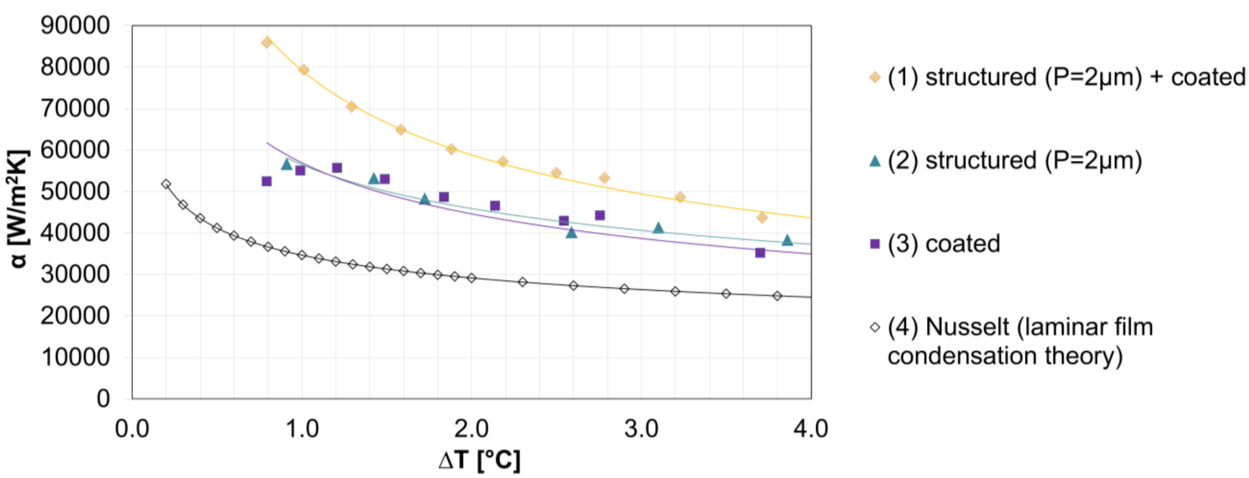

Fig.4. Heat transfer coefficients α versus the subcooling temperature ΔT measured for Cu samples with and without plasma polymer coating and laser patterns.

Moreover, water contact angles measurements show increasing values in the order: uncoated (~90°) < coated (~105°) < structured and coated (119...130° for P=2...5 μm) Cu substrates. No drifts in the contact angles were observed for all samples even after boiling tests (Fig. 5), which proves the high stability and durability of the films to some extreme conditions under those commercial condensation heat exchangers would run.

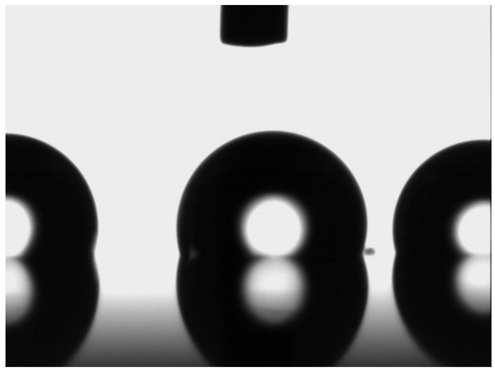

Fig.5. Image of the contact angle measurement for a Cu sample coated with a plasma polymer film and submitted to boiling test.

3. Conclusions

The potential of a PECVD deposition process to create hydrophobic films based on organosilicon monomers has been successfully proven. The plasma polymer coated surfaces yielded higher contact angles than uncoated surfaces and are also characterized by a higher heat transfer coefficient ***α*** (***h***). Furthermore, structuring the Cu surface by Direct Laser Interference Patterning before the film deposition proved to be an effective method to enhance the drop-wise condensation and consequently improve the heat transfer. The combination of both technologies to modify surfaces and consequently enhance the efficiency of condensation heat exchangers shows a great potential for industrial applications.

Acknowledgement

This work has been partially supported by a Grant-in-Aid for Technology Funding by the European Regional Development Fund (ERDF) and the State of Saxony (Grant no. 14256/2423).

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