

An investigation into the influence of micro structures on nucleate boiling processes

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Abstract

From the prior art it is known that a selective modification of heat transfer surfaces may lead to an improvement of heat transfer rates. For evaporation processes, often the heat transfer surfaces are roughened, coated with porous material or structured by electro-deposition. In this study micro structures are investigated to increase the heat transfer coefficient for heat transfer by nucleate boiling. Applying micro milling and sand-blasting, different micro structures are machined in aluminum plates. A specially developed test bench is used for measuring the heat transfer coefficients for different heat fluxes. The experimental setup and the experimental procedure are described in this paper. By comparing the measurement results it is analyzed as to which structures are most appropriate for heat transfer by nucleate boiling.

Keywords: nucleate boiling, heat transfer, micro structures, micro manufacturing technologies, experimental verification.

1 Introduction

Because of the rapid development in micro electronics with high heat flux dissipation, new cooling technologies become more and more important. The challenge is to remove large amounts of heat from small areas at moderately low wall superheats [1].

One promising technology is evaporative cooling, which is based on the principle of continuous boiling. For an effective heat transfer with reduced wall superheats several attempts were investigated over the last decades. It is



well known that a modification of the evaporation surfaces leads to an influence on heat transfer. The aim is to increase the number of active nucleation sites for bubble formation and the heat transfer efficiency.

A relatively simple and easy-to-implement method to improve heat transfer is roughening the heating surface [2–4]. Processes for roughening are, for example, sandblasting, grinding, rolling or turning.

Another way to achieve high nucleation site densities is coating the heating surface with porous material. Liter and Kaviany [5] showed, that with sintered copper structures the surface superheat to start nucleate boiling is about 2 to 2.5 times lower than that of a smooth surface.

Other research is dedicated to study the influence of defined micro structures, for example micro cavities or micro columns, on the heat transfer. Defined micro structures can be generated by depositing processes or direct structuring technologies. Ustinov [6] and Mitrovic [7] performed several experiments on nucleate boiling with electrodeposited micro pins made by copper. The results demonstrated that in selected cases the heat transfer coefficient is about 18 times higher in comparison to a smooth copper surface.

Shoji and Tagaki [8] have examined the influence of circular micro cavities on the formation of bubbles with distilled water. The measurement results showed a continuous bubble formation with low wall superheats for cylindrical and re-entrant cavities.

Chu *et al.* [9] investigated experimentally the influence of different cylindrical pin structures in silicon surfaces on the critical heat flux during boiling with high purity water. They found that an increase of the critical heat flux density up to 160% can be achieved, compared to an unstructured surface.

In this paper the influence of micro structures on nucleate boiling is analyzed. The micro structures are generated with micro milling and sand blasting. Using a special test bench the heat transfer coefficients are determined and compared with the characteristics of unstructured surfaces.

2 Modifying the heat transfer surfaces

As already mentioned, heat transfer with nucleate boiling can be influenced by micro structured surfaces. In this paper micro columns and roughened surfaces were selected, for the experimental studies.

Micro milling was applied to fabricate micro columns in aluminum. For this an end mill made of solid carbide with a diameter of 200 μm was used. First, lines in x-direction were processed with a center distance of 400 μm . Then the process was repeated in y-direction. The surface to be machined was 100 cm^2 .

In figure 1 the height profile of the milled micro columns is presented, measured with the 3D-laser scanning microscope Keyence VK-9700.

Shown is a section of the plate with four micro columns. The widths and the lengths of the micro columns are about 200 μm . The depths amount to 65 μm in the sections of the x-direction movement and about 90 μm in the sections of the y-direction movement. It can be seen in the height profile that the machined surfaces are very smooth. Only at the edges of the micro structures burrs appear.

In addition to the micro structures in itself, the burrs cause an enhancement in the effective heat transfer surface. It is expected, that the surface enlargement leads to an improvement in heat transfer. It is also possible that bubbles are formed preferred at the burrs. This can result in a further increase in heat transfer rates.

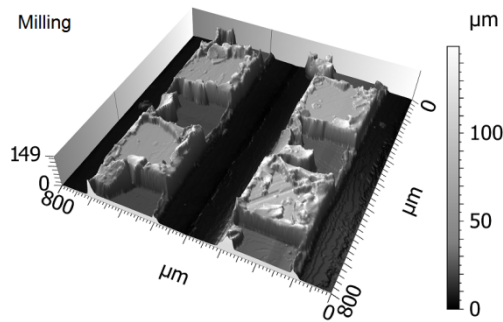


Figure 1: Height profile of the milled micro columns.

In figure 2 the height profiles of the unstructured and the sand-blasted surface are shown.

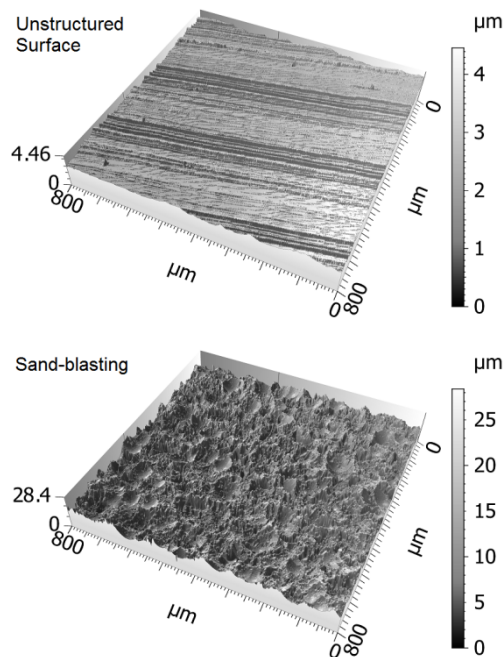


Figure 2: Height profiles of the unstructured and the sand-blasted surface.

Using face milling the unstructured surface was prepared. The arithmetical mean deviation of the profile R_a is about $0.5\ \mu\text{m}$ and the average surface roughness R_z amounts to approximately $7.4\ \mu\text{m}$.

For roughening by sand-blasting high-grade aluminum oxide with grain sizes of about $100\ \mu\text{m}$ was applied. The roughness R_a was increased to about $2.4\ \mu\text{m}$ and R_z to around $32.0\ \mu\text{m}$. With sand-blasting a rise in number of nucleation sites is expected, which leads to an enhancement in heat transfer rates.

3 Experimental setup

An experimental setup was developed, based on the principle of continuous evaporation and condensation of a refrigerant in a closed system, like illustrated in figure 3.

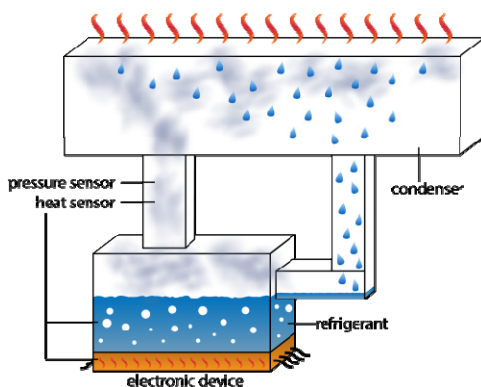


Figure 3: Scheme of the experimental setup with stationary nucleate boiling [10].

The power loss in form of heat of an electronic device is transferred to the evaporation plate by heat conduction. The evaporation plate is located in an evaporation module filled with refrigerant. If the heat flux is high enough, nucleate boiling occurs. The resulting vapor flows into a condenser, located above the module. The vapor is liquefied and flows back into the evaporation chamber. The setup corresponds to a thermosyphon, known from the literature [11].

In figure 4 a photo of the experimental setup is shown. Using an aluminum heating plate, consisting of 6 cartridge heaters, a defined heating power can be adjusted. The control of the heating elements is done by a temperature control device.

The experiments are performed with the refrigerant Solkatherm® SES36, as a non toxic and highly electrically insulating refrigerant. The filling capacity with the refrigerant was 360 ml for all experiments. Temperature sensors were applied to measure the temperatures of the heating plate ϑ_H , the evaporator plate ϑ_E , the

refrigerant ϑ_R and the vapor ϑ_V , at different heating powers. From the ratio between heating power \dot{Q} to surface superheat ΔT and projected heat transfer surface A , the heat transfer coefficient α can be calculated [12]:

$$\alpha = \frac{\dot{Q}}{\Delta T \cdot A} = \frac{Q}{\Delta T} \quad (1)$$

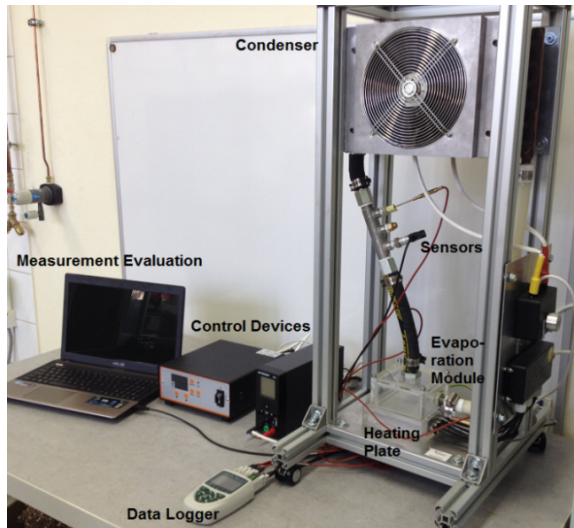


Figure 4: Photo of the experimental setup.

The projected heat transfer surface is 100 cm² in all cases. Q is the heat flux and the surface superheat is defined as the temperature difference between evaporator plate temperature and the temperature of the refrigerant. The heat transfer coefficient serves as an indicator for the efficiency of the micro structures.

Because of the strongly dependence of the thermal performance from internal pressure, a pressure sensor is placed on the vapor outlet for monitoring the pressure.

4 Experimental results

Experiments were performed with the different plates. In all experiments the starting internal pressure was 1 bar and the pressure was continuously monitored. The heating power was gradually increased until the heating plate temperature reach 80°C. At each adjusted power the temperatures of the heating plate, the evaporation plate, the refrigerant and the vapor were measured, after reaching stable temperature conditions defined in the following equation:

$$\Delta T_H + \Delta T_E + \Delta T_R + \Delta T_V < 0.5 \text{ K} \quad (2)$$

with:

$$\Delta T_{H,E;R;V} = \vartheta_{H,E;R;V}(t_n + 150 \text{ s}) - \vartheta_{H,E;R;V}(t_n) \quad (3)$$

t_n is the time of measuring. The equations (2) and (3) describe that as soon as the sum of all temperature differences over 150 seconds is less than 0.5 K, constant conditions dominate.

Then the measurements were done with decreasing heat powers in order to detect hysteresis effects. The experiments were repeated three times, and from the results, the mean values and the standard deviations were determined.

The experimental results for the unstructured plate are presented in figure 5 and figure 6. Figure 5 shows the relation between heat flux and surface superheat for increasing and decreasing heating power. At a maximum heat flux of 23 kW/m², the surface superheat amounts to approximately 16.8 K. It is also clear that in ascending and descending heat flux no clear hysteresis can be observed.

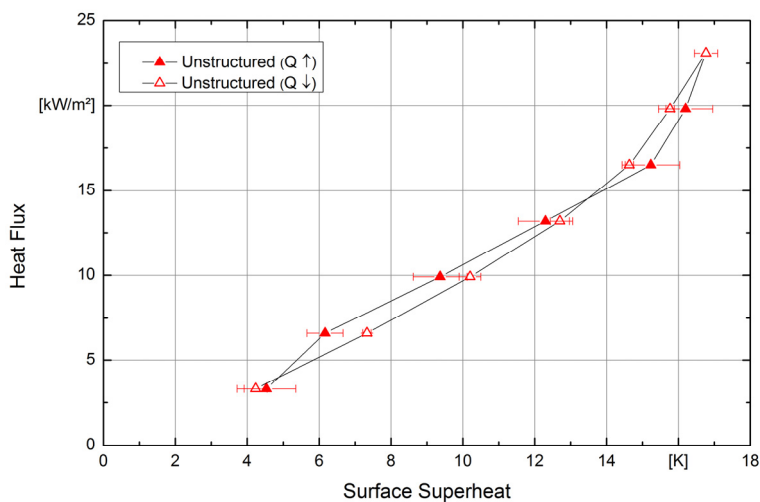


Figure 5: Surface superheat dependent to heat flux for unstructured plate.

In figure 6 the heat transfer coefficients dependent to the heat flux are presented. The maximum amount of the heat transfer coefficient is about 1380 W/m²K for a heat flux of 23 kW/m².

Following the experiments with unstructured plates, investigations on nucleate boiling with milled micro structures were performed under the same experimental regime. The surface superheat depending on the heat flux is illustrated in figure 7.

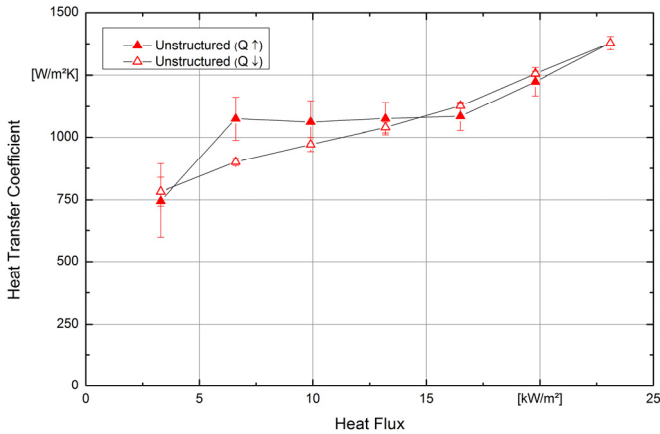


Figure 6: Heat transfer coefficient dependent to heat flux for unstructured plate.

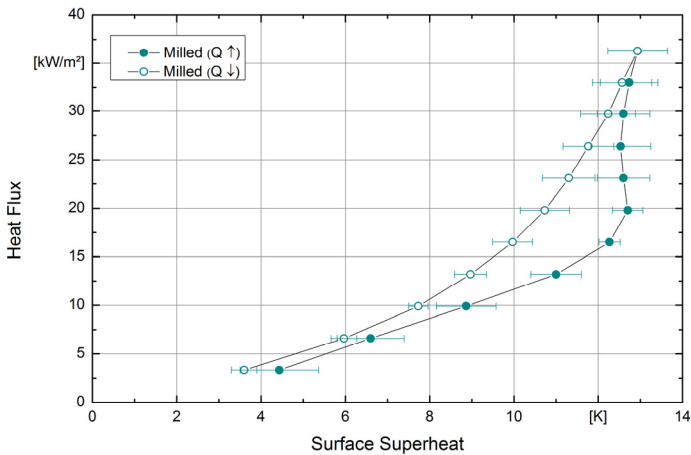


Figure 7: Surface superheat dependent to heat flux for milled micro structures.

In comparison to the unstructured surface, higher heat fluxes could be realized with the milled micro structured surface without exceeding a heating plate temperature above 80°C. The maximum superheat is approximately 12.9 K for a heat flux of 36 kW/m². Hysteresis was observed between ascending and descending heat fluxes. The surface superheats are lower for descending heat fluxes.

In figure 8 the heat transfer coefficients obtained with milled micro structures are shown.

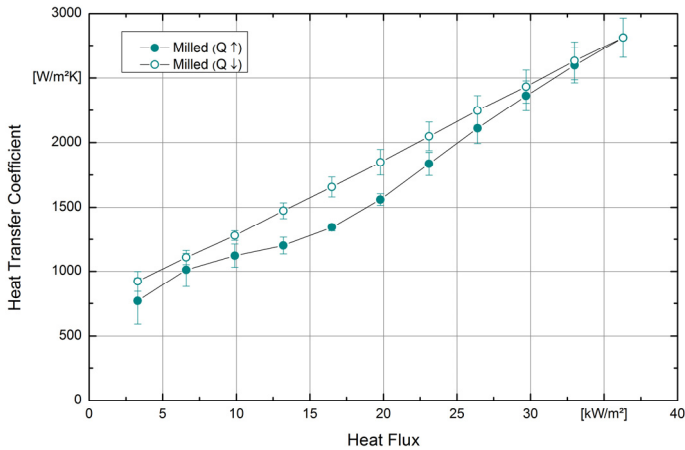


Figure 8: Heat transfer coefficient dependent to heat flux for milled surface.

The maximum heat transfer coefficient for a heat flux of 36 kW/m² is about 2810 W/m²K.

In addition to the unstructured and the milled surface the heat transfer with a sand-blasted surface was investigated. The results are presented in figure 9 and figure 10. Applying a maximum heat flux of about 40 kW/m², the surface superheat does not exceed 10 K, like illustrated in figure 9. As with the milled surface, a hysteresis could be observed for the sand-blasted surface. The surface superheat is lower with decreasing heat flux than with increasing the heat flux.

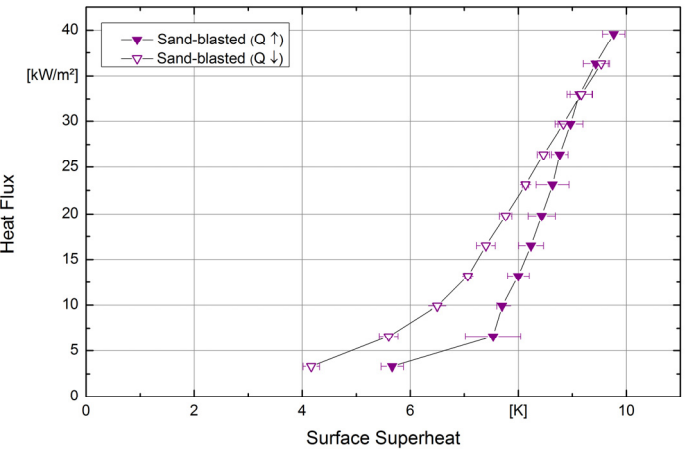


Figure 9: Surface superheat dependent to heat flux for sand-blasted surface.



In figure 10 the heat transfer coefficients for the sand-blasted surface are shown.

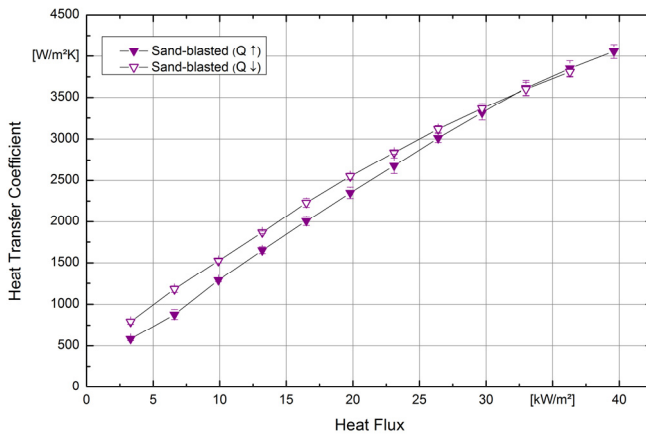


Figure 10: Heat transfer coefficient dependent to heat flux for sand-blasted surface.

A maximum heat transfer coefficient of approximately 4060 W/m²K for a heat flux of about 40 kW/m² was achieved.

The experimental results are compared in figure 11 to figure 14, for a better illustration of the effects of surface modification on nucleate boiling.

In figure 11 the superheats applying the different surfaces for an increasing heat flux are presented. It is obvious that with a modification of the surface the superheats can be significantly reduced.

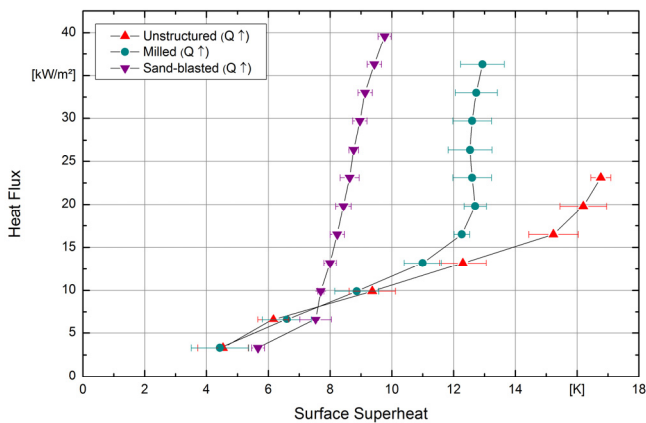


Figure 11: Surface superheat dependent to ascending heat flux for different surface properties.

The best results were obtained with the sand-blasted plate, followed by the milled surface. As an example, the values for 23 kW/m^2 are compared. While the superheat for the unstructured plate amounts to approximately 16.8 K , the superheat for the milled surface is about 12.6 K and for the sand-blasted only 8.6 K . This enormous effect was also found in the descending heat fluxes, like illustrated in figure 12. In this case, the surface superheat for a heat flux of 23 kW/m^2 could be reduced from 16.8 K for the unstructured surface to about 11.3 K with the milled micro structures and to about 8.1 K with the sand-blasted surface. This represents a reduction by 33% and 52% respectively.

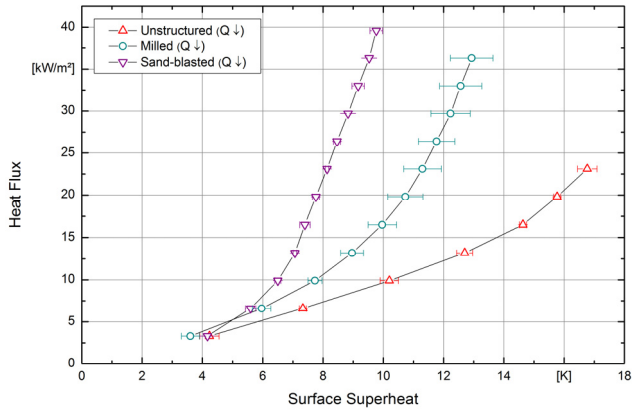


Figure 12: Surface superheat dependent to descending heat flux for different surface properties.

In figure 13 the heat transfer coefficients for the different surface properties with increasing heat flux are shown.

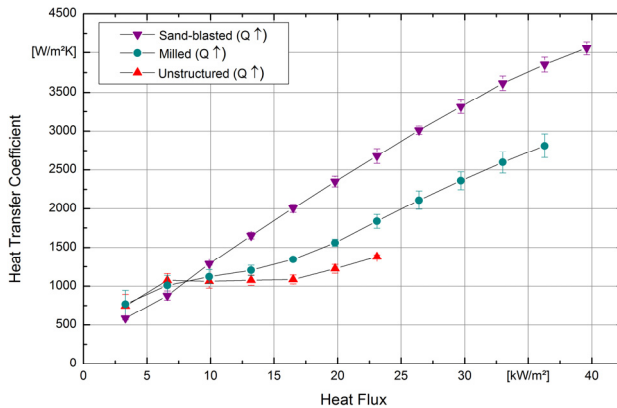


Figure 13: Heat transfer coefficient dependent to ascending heat flux for different surface properties.

The highest heat transfer coefficients were obtained with the sand-blasted surface, followed by the milled micro structures. For a heat flux of 23 kW/m^2 the heat transfer coefficients are about $2680 \text{ W/m}^2\text{K}$ for the sand-blasted surface, $1840 \text{ W/m}^2\text{K}$ for the milled micro structures and $1380 \text{ W/m}^2\text{K}$ for the unstructured surface. This is equivalent to a maximum increase of the heat transfer coefficient of about 1.96 times applying a sand-blasted surface instead of an unstructured one. Even at higher heat fluxes the sand-blasted plate is characterized by the most effective heat transfer. For example, the heat transfer coefficient for the milled micro structures at 36 kW/m^2 is about $2810 \text{ W/m}^2\text{K}$. With the sand-blasted surface the heat transfer coefficient achieves an about 1.37 times higher value of approximately $3850 \text{ W/m}^2\text{K}$.

In figure 14 the heat transfer coefficients with decreasing heat flux are presented. Also in this diagram, the effect of surface modification to increase heat transfer rates in nucleate boiling is confirmed. For a heat flux of 23 kW/m^2 an improvement in heat transfer coefficient by a factor of 1.49 for the milled surface and 2.06 for the sand-blasted plate was realized, in comparison to the unstructured surface.

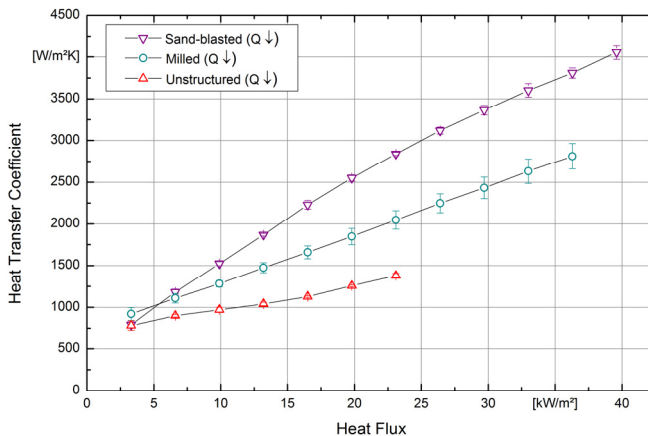


Figure 14: Heat transfer coefficient dependent to descending heat flux for different surface properties.

5 Conclusion

In this paper the influence of micro columns and sand-blasted surfaces on heat transfer rates in nucleate boiling was analyzed and compared with an unstructured surface. For this, an experimental setup was developed. Due to modifying the heat transfer surface, higher heat transfer coefficients and lower surface superheats were realized. Especially the sand-blasted surface showed promising heat transfer characteristics. In comparison to the unstructured surface about two times higher heat transfer coefficients were obtained. Furthermore it

was found, that hysteresis effects between ascending and descending heat flux occur for the milled and the sand-blasted micro structures.

In further research, the impact of other micro structures on heat transfer with nucleate boiling will be examined.

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