IOP Conference Series: Earth and
Environmental Science

**PAPER** • **OPEN ACCESS**

# Experimental investigation of nucleate pool boiling heat transfer characteristics on modified copper surface via laser-structured microstructures

To cite this article: L Sugumaran *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1281** 012062

View the article online for updates and enhancements.

You may also like

- Optimization of SOFC Anode Microstructure for Performance and Highly Scalable Cells through Graded Porosity
  Yevgeniy Ostrovskiy, Muhammad Saqib, Jaewoon Hong et al.
- Development of PEFC Low Pt-Loading Graphene Catalyst Layer By Electrospray Method for Increasing Output Power
  Masaya Okano, Suguru Uemura and Yutaka Tabe
- An Examination of the Factors That Influence Primary Battery Longevity Performance Under Multiple-Cell Vs Single-Cell Testing Conditions
  Jessica Joubert and Ray Iveson


PRIME PACIFIC RIM MEETING ON ELECTROCHEMICAL AND SOLID STATE SCIENCE
HONOLULU,HI
October 6-11, 2024
Joint International Meeting of
The Electrochemical Society of Japan (ECSJ)
The Korean Electrochemical Society (KECS)
The Electrochemical Society (ECS)
Early Registration Deadline:
September 3, 2024
MAKE YOUR PLANS
NOW!

This content was downloaded from IP address 103.53.32.15 on 12/07/2024 at 09:02

# Experimental investigation of nucleate pool boiling heat transfer characteristics on modified copper surface via laser-structured microstructures

**L Sugumaran[1], M N M Zubir[1], K M S Newaz[1], T Z T Zahari[1], S M Aznam[2] and A M Halil[3]**

[1] Department of Mechanical Engineering, Faculty of Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia
[2] Kulliyyah of Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia
[3] Faculty of Mechanical & Automotive Engineering Technology Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

E-mail: nashrul@um.edu.my

**Abstract**. This study aims to evaluate the performance of pool boiling heat transfer on a structured surface subjected to constant heat flux. A nanosecond laser ablation was used to create different surface profiles on copper samples. Specifically, a series of step-like microstructured surfaces with varying secondary groove widths were fabricated to investigate their effect on pool boiling heat transfer performance of distilled water. The results indicated a significant enhancement in heat transfer performance for the laser-structured surfaces compared to the smooth surface at low heat flux. This improvement was attributed to the increased surface area, nucleation frequency, and nucleation site density. However, at higher heat flux, the surface with a smaller secondary groove width (LS 2) exhibited a decline in heat transfer performance, which was likely due to larger bubble escaping resistance. In contrast, the surface with a larger secondary groove width (LS 1) demonstrated the best heat transfer performance. The current work would help in finding an optimum surface structuring design for gaining higher boiling heat transfer performance which benefits industries dealing with thermal management processes.

## 1. Introduction

Pool boiling, which is a phase change heat transfer technique, offers a highly effective means of achieving significant heat exchange even with minimal temperature differences, and it has diverse applications in high heat flux density scenarios. There are two ways to improve boiling heat transfer on a surface, either by passive or active methods. The presence of microstructures [1]-[2], porous surfaces [3]-[4], protrusions, and crevices on a surface can affect the pool boiling characteristics. The modification of heating surfaces has led to a substantial improvement in boiling heat transfer performance, known as heat transfer coefficient (HTC).

For the surface modification technique to be widely applicable, the procedures must be reliable, environmentally friendly technology, adaptable, mechanically stable, and durable for long-term use, and economical. There are various surface modifications that have been used to fabricate microstructured surfaces such as micromachining [5], chemical vapor deposition, nanoparticle coating [6]-[7], chemical

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

etching [8]-[9] etc. Recently, laser fabrication method has gained traction as an alternative surface modification technique for improving heat transmission during pool boiling process. In particular, laser ablation has been adopted for surface texturing in a variety of investigations, demonstrating its significant potential to enhance heat transfer during pool boiling [10]. This technique allows for faster fabrication of a variety of micro-scale structured geometry [11].

Grabas conducted a study on heat transfer enhancement of flat steel workpieces using vibration-assisted laser processing. The results exhibited that the HTC on the textured surfaces increased by more than four times. Moreover, the maximum critical heat flux (CHF) enhancement is attained on the surface with higher roughness [12]. Kurse et al. performed a study on the heat transfer during pool boiling of deionized water on metallic surfaces that were functionalized at both the micro and nano scale. They found that the surfaces treated with femtosecond laser exhibited significantly improved both the HTC and CHF to the smooth sample [13]. Može et al. employed laser texturing to boost the boiling heat transfer performance on copper surfaces. The method involved producing microcavities that acted as favoured nucleation sites for boiling. The outcomes indicated a substantial improvement in both CHF and HTC [14]. Liu et al. conducted the experiments on hierarchical micro/nano structured surfaces which were modified by femtosecond laser processing in FC-72 boiling liquid. They have found that surfaces with wider separations showed improved CHF and HTC, while surfaces with closely spaced structures only showed improved HTC. Their study suggests that the spacing of micro/nano structures on surfaces can have an outstanding impact on HTC and CHF [15].

The literature suggests that laser ablation can enhance pool boiling performance by creating structured surfaces for heat exchange. This study introduces a novel approach for the pool boiling heat transfer enhancement by utilizing stepped microchannels of varying widths developed using nanosecond laser surface processing. It is anticipated that different step configurations would affect the bubble dynamics leading to increasing and deteriorating boiling heat transfer performance.

## 2. Methodology

### *2.1. Surface processing and characterization*

Three copper samples (99.964% Cu) were machined as illustrated in figure 1. Each sample contained three 1 mm diameter holes that were drilled to a depth of 6 mm. Three type K thermocouples were then installed into the holes to measure the temperature of the samples. To ensure uniform surface roughness across all samples, the surfaces were finely ground with P1000 grit sandpaper. A laser machine-(Herolaser ML-MF-A01) was used to fabricate the stepped microstructure on copper samples. This machine is an optical fiber laser marking machine that is engineered for use on metal materials. This machine features a 30 W IPG laser that generates a 1064 nm wavelength beam capable of producing accurate and intricate marks and engravings on metal surfaces. Two samples, marked as LS 1 and LS 2, were fabricated with stepped microchannels having varying groove widths, as shown in table 1 and figure 2, using a laser speed of 500 mm/s, a frequency of 20 KHz, and 80% power.

**Table 1.** Geometric parameters of the copper sample.

| Sample | Groove Width / μm | | | Groove Depth / μm | | |
|---|---|---|---|---|---|---|
| | Primary (a) | Secondary (b) | Ratio (a/b) | Primary (c) | Secondary (d) | Ratio of (c/d) |
| SS (Smooth surface) | - | - | - | - | - | - |
| LS 1 (Laser Structured Surface 1) | 226.50 | 126.55 | 1.8 | 100.52 | 85.11 | 1.2 |
| LS 2 (Laser Structured Surface 2) | 221.96 | 38.52 | 5.8 | 87.59 | 67.43 | 1.3 |

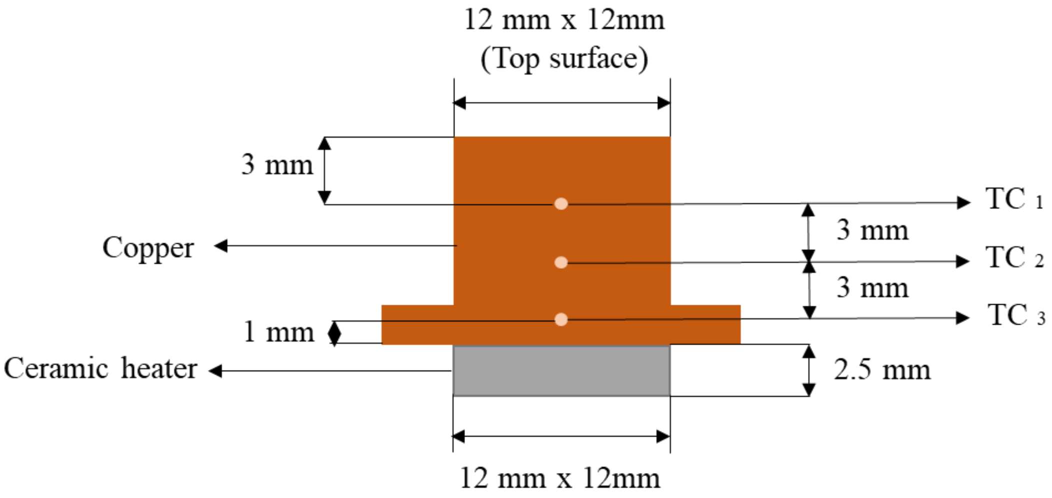
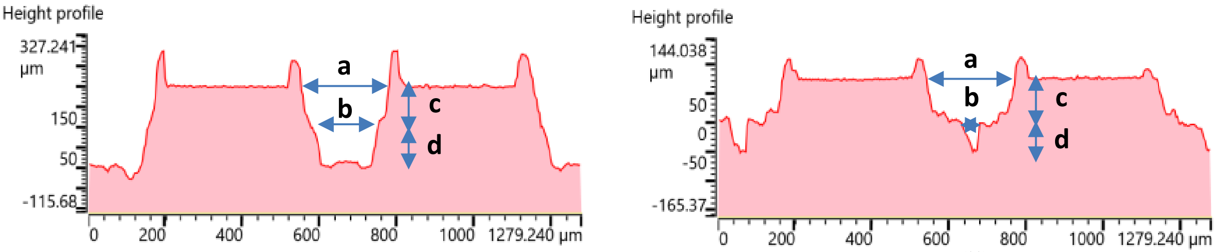


**Figure 1.** Schematic diagram of copper sample



(i) (ii)

**Figure 2.** 2-D profile of laser structured microstructured surfaces: (i) LS 1, (ii) LS 2

### *2.2. Pool boiling experimental setup and procedure*

Figure 3 illustrates the experimental setup used in this pool boiling study. The setup consists of a heating system, boiling chamber, visualization system, data acquisition system, and cooling water bath. The boiling chamber is constructed from aluminum plates with Pyrex glass windows for visualization purposes. Two 1000 W cartridge heaters were installed within the boiling chamber to ensure the distilled water remained at saturation temperature during the experiment. A glass condenser was also affixed to the top aluminum cover to condense and recycle vapor initiated during the pool boiling process.

The copper samples underwent a cleaning process with acetone and ethanol in an ultrasonic cleaner, lasting for 5 minutes each. Subsequently, the copper sample was affixed to a polycarbonate holder with Permatex Ultra copper gasket maker. A Watlow Ultramic 600 Advance ceramic heater was employed to heat the copper sample, while the K-type thermocouples were inserted into the side holes of the copper sample to measure its internal temperature. These thermocouples were linked to the data acquisition system, which enabled the calculation of wall temperature and heat flux according to Fourier's law of heat conduction.

The distilled water inside the testing chamber was heated towards reaching its saturation temperature. Then the ceramic heater was turned on to heat the sample with a specified power until the steady state condition is attained (when the average temperature remains stable within a rate of change of 0.5 °C over a period of three minutes), followed by measurements of ceramic heater temperature, bulk temperature, reading from the three thermocouples ($TC_1$, $TC_2$ and $TC_3$), input electrical power were taken and recorded. The data were taken at an increment of approximately 0.01 MW/m$^2$ at the incipience and 0.05-0.07 MW/m$^2$ after bubble nucleation [16].

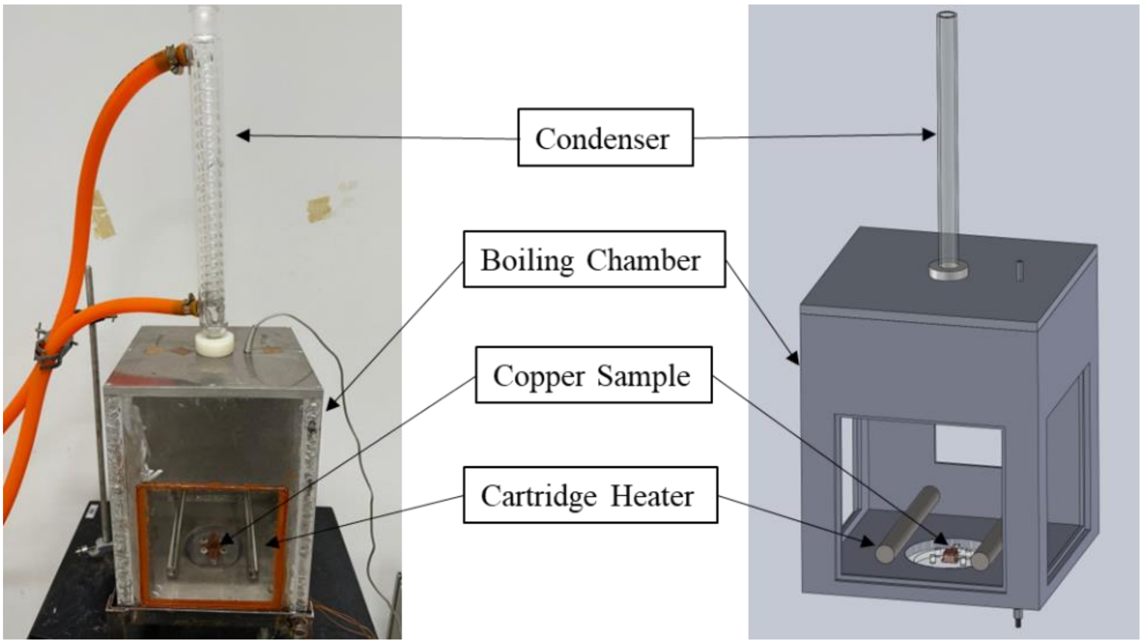


**Figure 3.** The experimental setup.

## 3. Results and discussion

Figures 4 and 5 depict the pool boiling heat transfer performance for the smooth surface and the laser-structured stepped microstructure surfaces. The laser-structured surfaces exhibit an earlier onset of nucleate boiling than the smooth surface due to their larger nucleation sites, which initiates nucleate boiling at a lower wall superheat temperature. Furthermore, the laser structured surface area is larger than the smooth surface, allowing more liquid to evaporate and thereby boosting the heat transfer performance. The structured surfaces also outperform the smooth surface in terms of heat transfer performance when the heat flux is below 100,000 W/m$^2$. This superiority is attributed to a combination of factors, including a high density of microscale cavities. When the heat flux is below 100000 W/m$^2$, this regime is considered as a lower heat flux regime. At this regime, isolated small bubbles are developed, and these small bubbles will evaporate quickly once they dispatch from the heated surface.

However, the heat transfer performance of LS 2 began to deteriorate when the heat flux increases above 100,000 W/m$^2$, entering a higher heat flux regime. In this regime, more nucleation sites were activated, resulting in bubbles forming at a greater rate. These bubbles quickly coalesce into larger bubbles, which cause difficulty escaping from smaller secondary grooves. As a result, the bubbles coalesced further and formed a vapor layer that blocked the liquid replenishment path, eventually leading to a decline in heat transfer performance.

The best heat transfer performance was attained for LS 1, exhibiting a significant improvement in heat transfer coefficient (HTC). The wider secondary grooves of LS 1 facilitate the escape of more bubbles, thereby reducing the resistance for bubble escaping and enhancing the heat transfer performance.

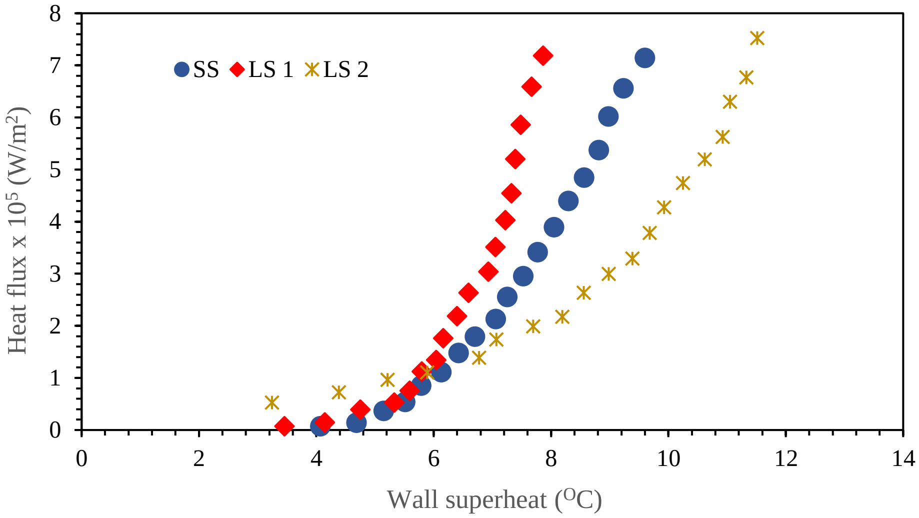


**Figure 4.** Comparison of heat flux versus wall superheat

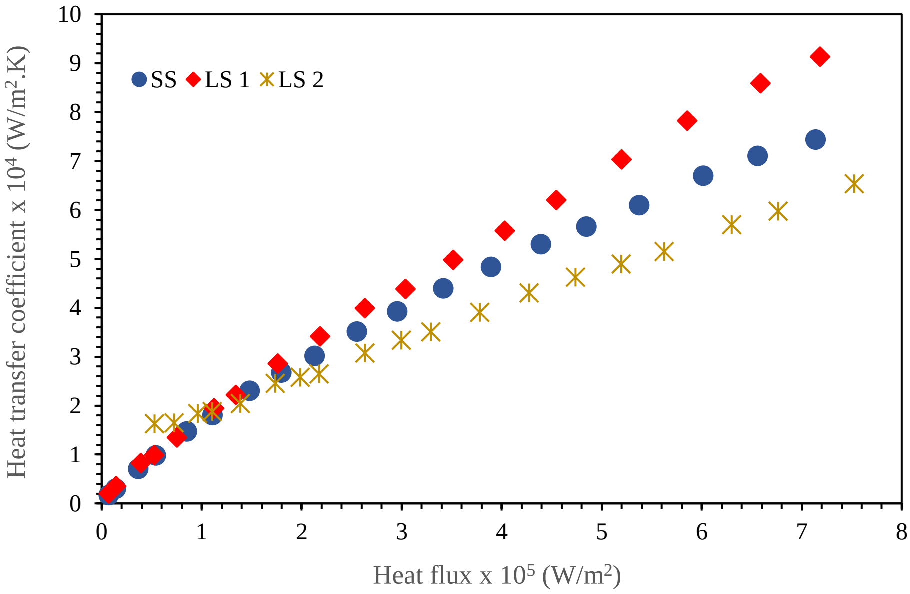


**Figure 5.** Comparison of heat transfer coefficient versus heat flux.

## 4. Conclusion

This study aimed to investigate the water pool boiling heat transfer performance of laser-structured stepped microstructure surfaces fabricated using nanosecond laser processing. The focus was on exploring the effect of the stepped groove width on the heat transfer performance. The results indicated that the laser-structured microstructure surfaces demonstrated superior heat transfer performance compared to the smooth surface at heat flux below 100,000 W/m$^2$. This was attributed to the higher nucleation sites and surface area of the laser-structured surfaces, which boosted the bubble formation and liquid replenishment rate. However, the heat transfer performance of the surface with a smaller secondary groove width (LS 2) experienced a declination trend as the heat flux increased. This was because, at lower heat fluxes, smaller isolated bubbles were produced at a lower rate. As the heat flux increased, these bubbles merged with adjacent bubbles to form larger bubbles, which encountered resistance when trying to escape, ultimately leading to a deterioration in heat transfer performance. In contrast, the sample with a larger secondary groove width (LS 1) demonstrated the best heat transfer performance, as wider grooves provided more channels for the bubbles to escape, thereby boosting the liquid replenishment process.

## 5. References

[1] Chang H, Liu B, Li Q, Yang X and Zhou P 2023 Effects of electric field on pool boiling heat transfer over composite microstructured surfaces with microcavities on micro-pin-fins *Int. J. Heat Mass Transf.* **205** 123893
[2] Liu B, Garivalis A I, Cao Z, Zhang Y, Wei J and Marco P Di 2022 Effects of electric field on pool boiling heat transfer over microstructured surfaces under different liquid subcoolings *Int. J. Heat Mass Transf.* **183** 122154
[3] Lv Z, An Y and Huang C 2023 Enhanced pool boiling heat transfer by adding metalized diamond in copper porous materials *Appl. Therm. Eng.* **226** 120288
[4] Zhang K, Bai L, Yao G and Wen D 2023 Influence of pore size distribution on pool boiling heat transfer in porous artery structure *Int. J. Heat Mass Transf.* **209** 124116
[5] Long J, Liu Z, Lin H, Li Y, Cao Z, Zhang Z and Xie X 2022 Pool boiling heat transfer and bubble dynamics over V-shaped microchannels and micropyramids: Does high aspect ratio always benefit boiling? *Appl. Therm. Eng.* **201** 117796
[6] Chen Y, Fu R and Yan Y 2022 Enhanced pool boiling heat transfer on grooved surfaces by wettability modification with nanoparticle coatings *Int. Commun. Heat Mass Transf.* **137** 106298
[7] Zhong Z, Huang C and Wang X 2023 Enhanced pool boiling heat transfer of multilayer copper -nanoparticle-packed beds by copper mesh coating *Int. J. Therm. Sci.* **184** 107965
[8] Kalita S, Sen D, Sen P, Das S and Saha B B 2023 Pool boiling heat transfer enhancement and bubble visualization on a microporous copper over CuO filmed surface through combination of chemical etching and electrochemical deposition *Int. Commun. Heat Mass Transf.* **144** 106740
[9] Kalita S, Sen P, Sen D, Das S, Das A K and Saha B B 2021 Experimental study of nucleate pool boiling heat transfer on microporous structured by chemical etching method *Therm. Sci. Eng. Prog.* **26** 101114
[10] Serdyukov V, Starinskiy S, Malakhov I, Safonov A and Surtaev A 2021 Laser texturing of silicon surface to enhance nucleate pool boiling heat transfer *Appl. Therm. Eng.* **194** 117102
[11] Siti Faqihah R 2020 Effect of LST parameter on surface morphology of modified copper substrates
[12] Grabas B 2015 Vibration-assisted laser surface texturing of metals as a passive method for heat transfer enhancement *Exp. Therm. Fluid Sci.* **68** 499–508
[13] Kruse C M, Anderson T, Wilson C, Zuhlke C, Alexander D, Gogos G and Ndao S 2015 Enhanced pool-boiling heat transfer and critical heat flux on femtosecond laser processed stainless steel surfaces *Int. J. Heat Mass Transf.* **82** 109–16
[14] Može M, Zupančič M, Hočevar M, Golobič I and Gregorčič P 2019 Surface chemistry and morphology transition induced by critical heat flux incipience on laser-textured copper surfaces *Appl. Surf. Sci.* **490** 220–30
[15] Liu B, Liu J, Zhang Y, Wei J and Wang W 2019 Experimental and theoretical study of pool boiling heat transfer and its CHF mechanism on femtosecond laser processed surfaces *Int. J. Heat Mass Transf.* **132** 259–70
[16] Liu X, Chang Y, Zhang X and Yu Z 2022 Experimental study of pool boiling heat transfer under rolling condition *Exp. Therm. Fluid Sci.* **139** 110741

## Acknowledgement

The financial support from the University of Malaya MoE (Fundamental Research Grant Scheme) grant reference No: FP097-2018A (FRGS/1/2018/TK03/UM/02/1) is acknowledged.