



ADDITIVE MANUFACTURING FOR MICROSCALE HEAT EXCHANGERS OPERATING IN FLOW BOILING

Enes Bekir¹, Alexandros Askounis², Tassos G. Karayiannis^{1*}

¹Department of Engineering, Brunel University of London, Middlesex UB8 3PH, United Kingdom

²School of Architecture, Computing and Engineering, University of Wolverhampton, Wolverhampton WV1 1LY, United Kingdom

ABSTRACT

Micro scale heatsinks provide a promising thermal solution for high-power electronic components. However, the capabilities of current top-to-bottom subtractive manufacturing techniques are constraining the production of complex geometric features required for optimised micro-scale heatsink designs. Thus, additive manufactured heatsinks are introduced as a bottom-up alternative for producing complex surface geometries. The effect of these two different manufacturing techniques, particularly surface characteristics and their effect on heatsink performance, should be evaluated.

1. INTRODUCTION

In the 1970s, advancements in silicon semiconductor technology caused an increase in the number of transistors, which resulted in higher power consumption per unit area [1]. Tuckerman and Pease [2] introduced the first silicon micro-channel heatsink manufactured by potassium hydroxide anisotropic etching achieving a heat flux rate of 790 W/cm². Flow boiling was introduced to enhance micro-channel cooling due to temperature gradient issues in the substrate (electronic component to be cooled) in single-phase flow [3]. With the introduction of two-phase flow, the maximum possible heat flux, i.e. the critical heat flux (CHF) became the major performance factor for flow experiments. Micro pin-fin structures evaluated as an alternative to micro-channel heatsinks and demonstrated a significant heat transfer enhancement in flow boiling. Recently, Al-Zaidi and Karayiannis [4] suggested further investigation into additive manufactured heatsinks, which could optimise the geometry and enhance the nucleation. Early studies [5] showed significant increase in heat transfer performance when using additive manufactured heatsinks with high pressure drops. Thus, the process of manufacturing needs to be fully understood to examine the benefits of the additive manufacturing technique.

3. IMPORTANCE OF MANUFACTURING PROCESS AND SURFACE CHARACTERISTICS

Most micro pin-fin structures were manufactured by highly precise micro-milling manufacturing techniques. In 2026 Al-Zaidi and Karayiannis [4] achieved a surface roughness (Ra) of 0.15µm using micro-milling

*Corresponding Author: Tassos.Karayiannis@brunel.ac.uk

machining, where strictly controlled tolerances were established as key parameters affecting single and two-phase experiments. However, the machined surfaces appeared polished-like and often suffered from lack of micro cavities, which can result in reduced vapour trapping, which in turn can the onset of boiling thus, hindering heat transfer performance. On the other hand, additive manufacturing was found to inherently increase surface roughness, enhancing the number of cavities. In 2024, Inanlu et al. [6] showed that the roughness and microstructures increase the heat transfer enhancement by reducing the wall superheat at a given heat flux to much lower values than those that prevail in smooth surfaces. However, this could also introduce flow instabilities, which could counter the benefits of roughened surfaces.

Another important factor for additive manufacturing emphasised in 2025 by Altland et al. [7] is the direction of the build, which affects different regions of the manufactured parts. Major surface differences are present between the upskin (print over sintered layer) and downskin (print over unsintered powder). The downskin presents higher average roughness due to the melted powder particles attaching to the surface. These manufacturing and surface considerations highlight the need to balance roughness benefits against potential flow instabilities, particularly when selecting between micro-milling and additive approaches for micro-channel design.

4. MANUFACTURING PROCESS

4.1 Subtractive manufacturing

Computer numerical control (CNC) machining is a widely established subtractive manufacturing process, where the material is removed from the workpiece using cutting tools. Machining produces fully dense components with tight tolerances. While 5-axis machining enables the manufacturing of complex geometries within a single setup, the machining of pure copper presents several well-documented challenges. Its high ductility and thermal conductivity impose stringent requirements on tool geometry and cutting parameters. Furthermore, CNC machining is limited by tool accessibility, meaning that intricate internal features and fine-scale details within heatsinks may be inaccessible to conventional machining operations [8]. At the microscale, machining capability is further restricted by limited tool availability, burr formation, rapid tool wear, and the difficulty of achieving high aspect ratios while maintaining the required dimensional accuracy and surface finish [9].

4.2 Subtractive manufacturing of samples

The samples were machined from oxygen-free copper (C101) stock using a five-axis Hurco VMX42SRTi machining centre. The surface microfeatures were produced using diamond-like carbon (DLC) coated solid carbide micro slot drills (Garant 201140) of 0.2 mm and 0.5 mm diameter. Thermocouple holes drilled by 0.6 mm diameter Mikron CrazyDrill Flexpilot solid carbide drill and samples were vapour-blasted to remove residual contamination. Scanning electron microscope images (SEM) were taken by JEOL JSM-IT 200. Figure 1 depicts a photograph of the machined heatsink alongside SEM images of the pin fins, taken at a 30° angle, and the top view of a single pin fin. Uniform fin walls and the consistent edges on the top surface verify the precision of the CNC machining.

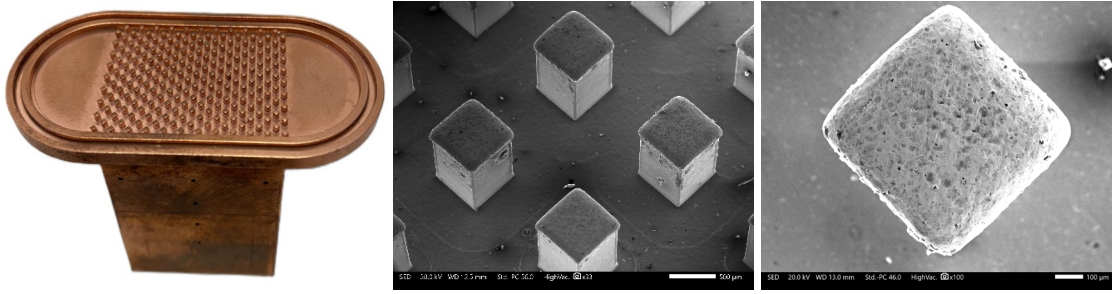


Fig 1. CNC machined oxygen-free copper samples.

4.3 Additive manufacturing (3D-printing)

Laser Powder Bed Fusion (L-PBF), high powered laser melts metal powder layer by layer, following pre-defined scan paths based on design data. Metal powder is then evenly recoated and heated on the previous layer to solidify. L-PBF offers a promising avenue for the development of advanced thermal management devices [10]. However, significant refinement of laser processing parameters is still required to yield high-performing parts and geometries.

4.4 Laser-assisted additive manufacturing of samples

Copper samples were manufactured using an industrial-grade EOS M90 L-PBF AM machine (400W laser, 100 µm spot size) in an argon environment (oxygen levels <0.1%). The setting used for the process are based on parameters used by authors [11]. These included a laser power of 370 W, a scanning speed of 400 mm s⁻¹, a layer thickness of 30 µm, and a hatch spacing of 0.14 mm. After printing, the samples were detached from the built plate using non-contact Electrical Discharge Machining (EDM). The photograph of the printed part is presented in Fig. 2 alongside SEM images of the pin fins, taken at a 30° angle, and the top view of a single pin fin. It is readily apparent that printing yielded rough, irregular fin walls and microcavities on the top surface with inconsistent edges.

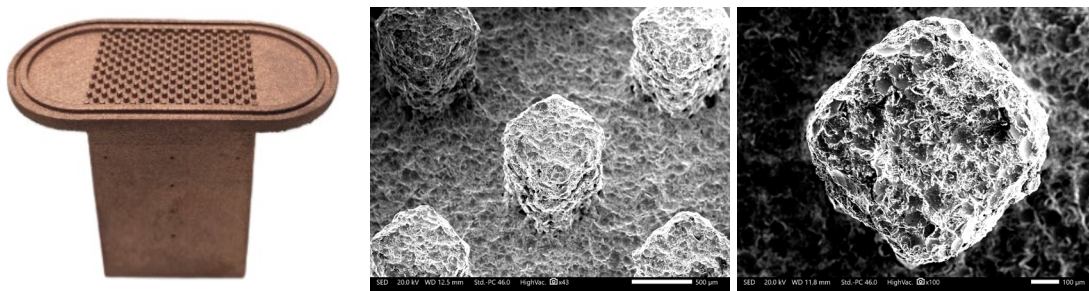


Fig 2. L-PBF printed samples.

5. CONCLUSION

Additive manufacturing offers the potential to produce complex micro heatsinks designs, otherwise impossible with conventional techniques. Future work will focus on establishing the relationship between manufacturing-induced surface characteristics and thermal as well as pressure drop performance of micro pin-fin heatsinks. Thermal hydraulic performance will be assessed under both single and flow boiling conditions.

References

- [1] D.B Tuckerman et al, "Microchannel heat transfer: Early history, commercial applications, and emerging opportunities." *Proceedings of the ASME 2011 9th International Conference on Nanochannels, Microchannels, and Minichannels*, " Alberta, Canada, 2011.
- [2] D.B. Tuckerman and R.F.W. Pease, "High-Performance Heat Sinking for VLSI," *IEEE Electron Device Letters*, vol. 2, (5), pp. 126–129, 1981.
- [3] M. B. Bowers and I. Mudawar, "Two-Phase Electronic Cooling Using Mini-Channel and Micro-Channel Heat Sinks: Part 1 -Design Criteria and Heat Diffusion Constraints," *Journal of Electronics Packaging*, 1994.
- [4] A.H. Al-Zaidi and T.G. Karayiannis, "Flow boiling in micro-pin fin heat exchangers and comparison with correlations," *Applied Thermal Engineering*, vol. 283, 2026. DOI: 10.1016/j.applthermaleng.2025.129008.
- [5] K.I. Kirsch and K.A. Thole, "Pressure loss and heat transfer performance for additively and conventionally manufactured pin fin arrays," *International Journal of Heat and Mass Transfer*, vol. 108, pp. 2502, 2017. DOI: 10.1016/j.ijheatmasstransfer.2017.01.095.
- [6] M.J. Inanlu et al., "Unveiling the fundamentals of flow boiling heat transfer enhancement on structured surfaces," *Science Advances*, 2024.
- [7] A. Y. Altland, T. M. Corbett and K. A. Thole, "Impacts of Material and Machine on the Variation of Additively Manufactured Cooling Channels," 2025. DOI: 10.1115/1.4066580].
- [8] I. Kaur and P. Singh, "State-of-the-art in heat exchanger additive manufacturing," *International Journal of Heat and Mass Transfer*, vol. 178, 2021. DOI: 10.1016/j.ijheatmasstransfer.2021.121600.
- [9] B. Z. Balázs et al, "A review on micro-milling: recent advances and future trends," *The International Journal of Advanced Manufacturing Technology*, vol. 112, (3-4), 2021. DOI: 10.1007/s00170-020-06445-w.
- [10] W. W. Wits and D. Jafari, "Experimental Performance of a 3D-Printed Hybrid Heat Pipe-Thermosyphon for Cooling of Power Electronics," *THERMINIC 2018 - 24th International Workshop on Thermal Investigations of ICs and Systems, Proceedings*, "Stockholm, Sweden, 2018.
- [11] T. Bregar, A. Hadzic, J. Robinson, A. Askounis, M. Zupancic, I. Golobic, "Additively manufactured copper surfaces with porous microfeatures for enhanced pool boiling performance," *International Journal of Thermal Sciences*, vol. 220, 2025. DOI: 10.1016/j.ijthermalsci.2025.110325.