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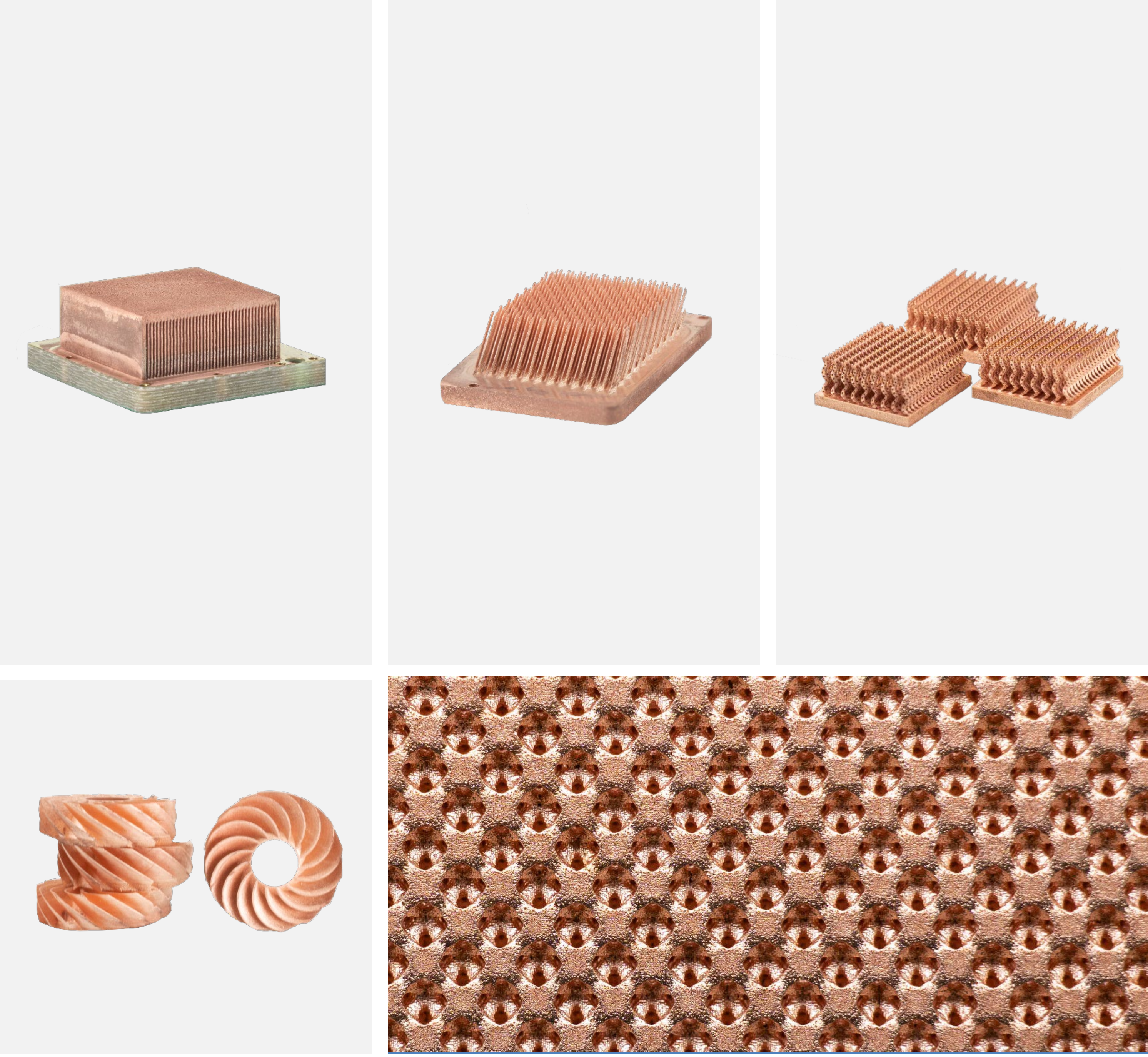
Electrochemical Additive Manufacturing (ECAM) For Cooling High Performance ICs



Hot Chips - 2023

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Overview

- Increased power dissipation requirements in high-performance computing applications are driving innovation in liquid cooling technologies to improve component and system-level heat extraction

- The current state of the art liquid cooling cold plate technology is based on microchannels – but these designs have limited performance

- A 35% improvement in thermal resistance was demonstrated by using a complex, 3D printed cold plate produced via Electrochemical Additive Manufacturing (ECAM)

- ECAM provides a solution for mass-manufacturing of application optimized thermal management products that employ geometrically graded structures and generative AI-based designs

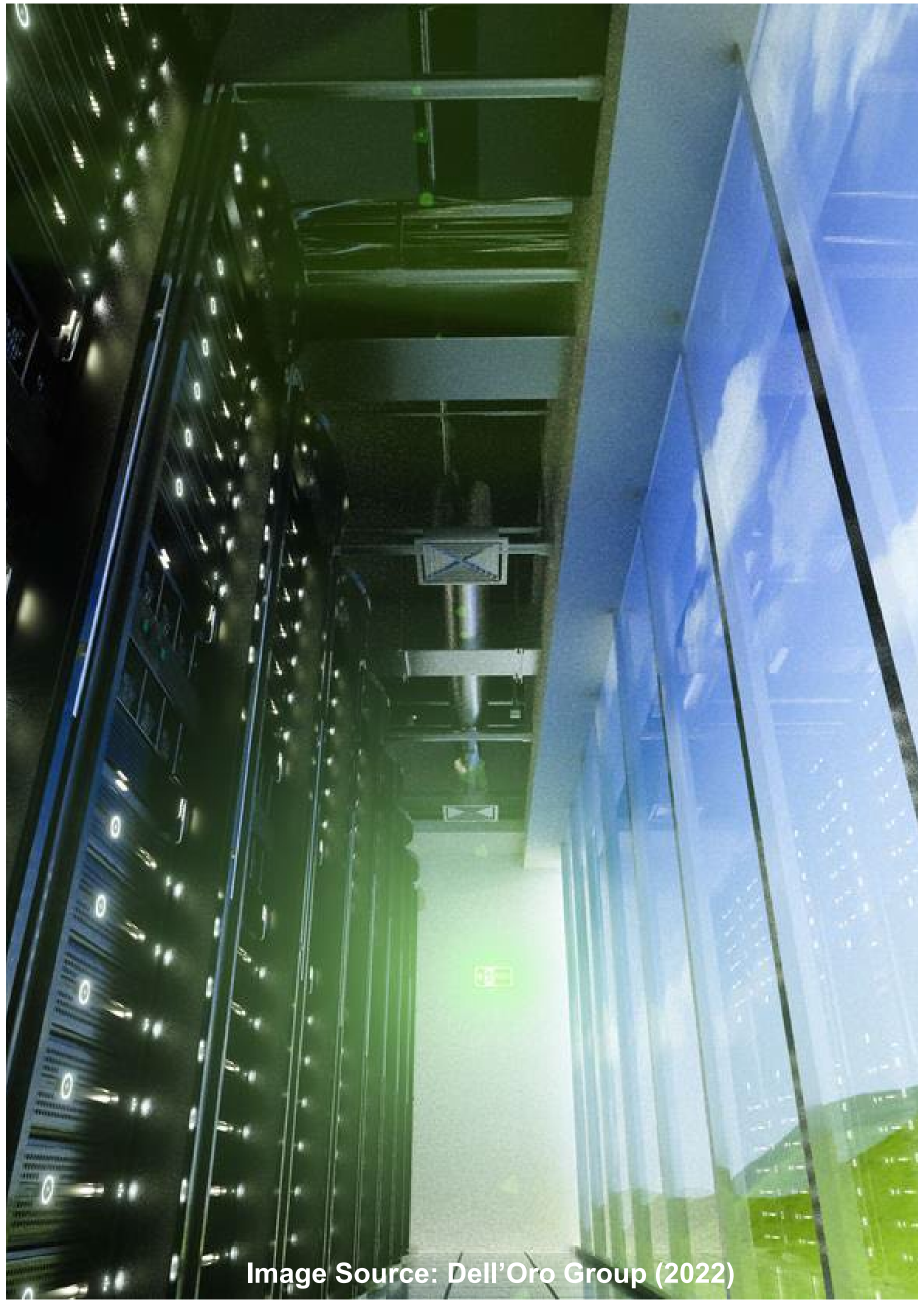
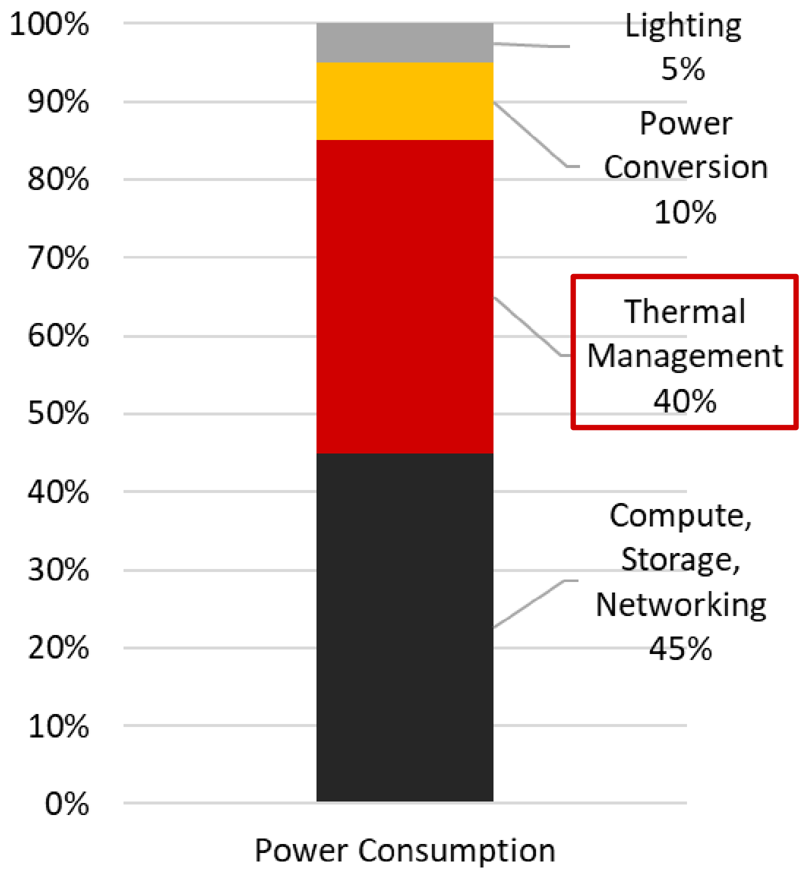


Image Source: Dell'Oro Group (2022)

Demand for Liquid Cooling in Data Centers is Growing

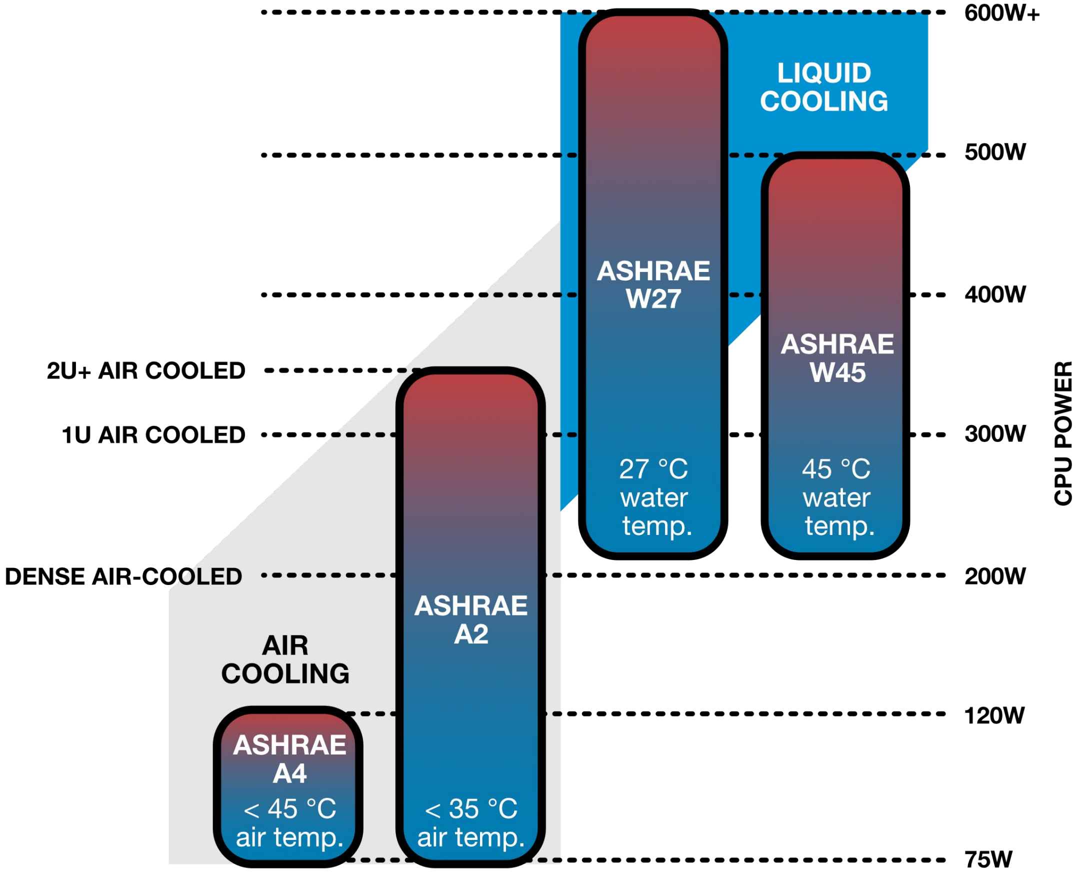
Thermal Management Drives 40% of Data Center Power Consumption



Total Cost of Ownership (TCO) is a key driver for thermal management opportunities

Reference: Data from Dell'Oro Group (2022)

Higher CPU/GPU Power Drives Liquid Cooling Requirement



Higher-power compute requires liquid cooling solutions (**ASHRAE** Tech Committee)

Reference: Image Adapted from ASHRAE Technical Committee 9.9, 2021

Liquid Cold Plate Performance has Been Limited by Straight Channels

Cold Plate Performance and Optimization

$$Performance \propto \frac{1}{Rth \, * \, P_{pump}}$$

- ⬇ Thermal Resistance (R_{th})
- ⬇ Pump Power (P_{pump}) ∝ Pressure Drop (Δp)
- ⬆ Temperature Uniformity, to manage non-uniform heat inputs

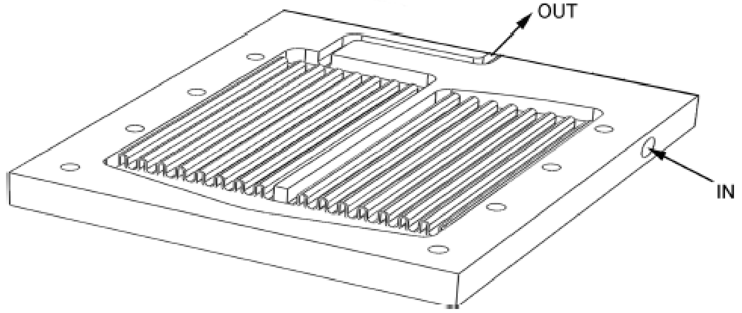


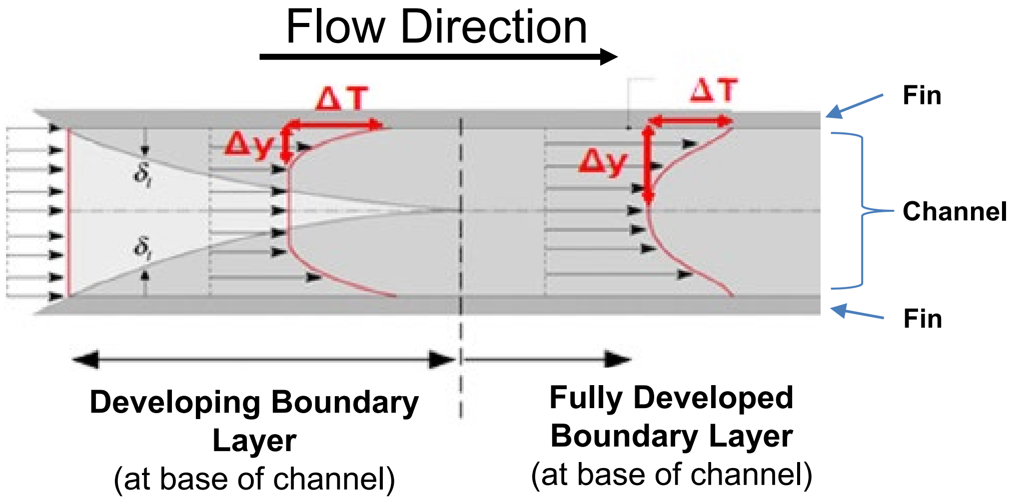
Image Reference:
Kandlikar, S. and Hayner, C., 2011

State of the Art: Microchannel Cold Plate

100 µm fin / channel

Image Reference:
Wieland Microcool

Straight Channels Have Limited Performance



***Convective heat transfer deteriorates** along the axial direction with the development of the boundary layer*

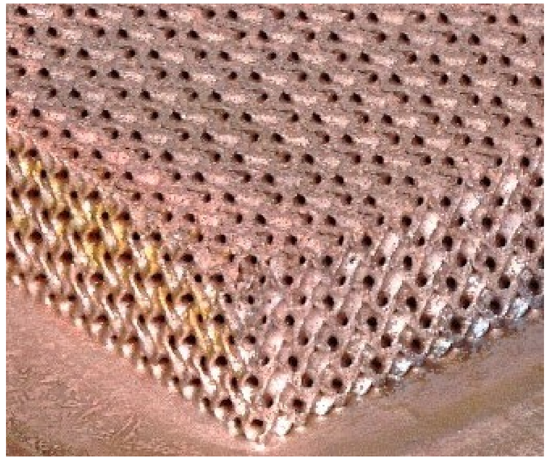
Reference:
Jin, L.W., et al, 2014

***Cannot simply increase flowrate** due to erosion limits of copper and tubing (~ 1.5 – 2 m/s)*

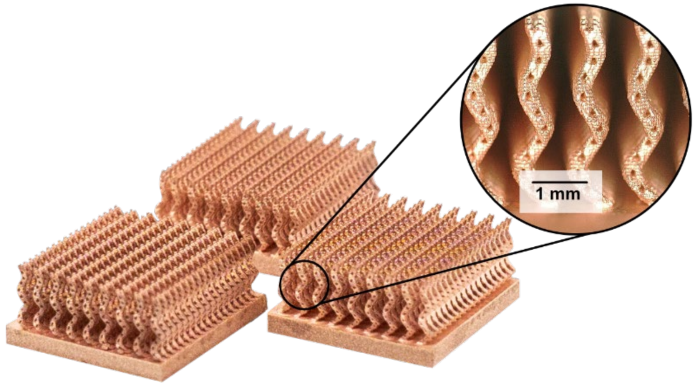
Reference:
Ortega, A,, et al., 2022

Additive Manufacturing (AM) Unlocks a New Wave of Thermal Products

Previously Impossible to Manufacture Designs to Maximize Conductive & Convective Heat Transfer

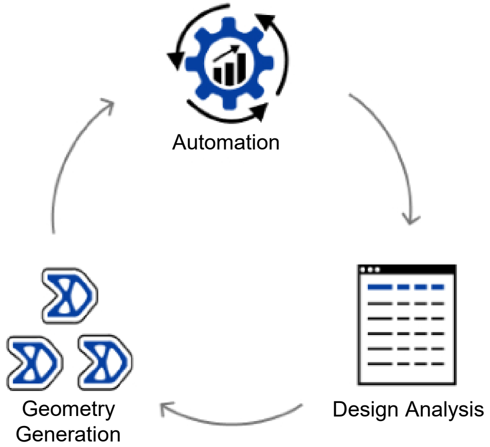


Triply Periodic Minimal Surface (TPMS) Structures

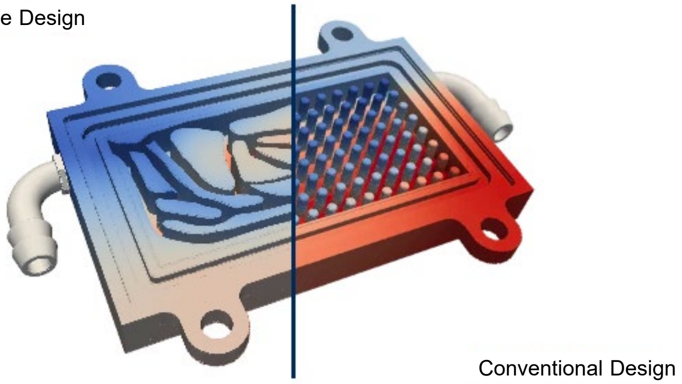


High Surface Area, Shape-Optimized Structures

Generatively Designed Solutions to Optimize for Thermal & Hydraulic Performance

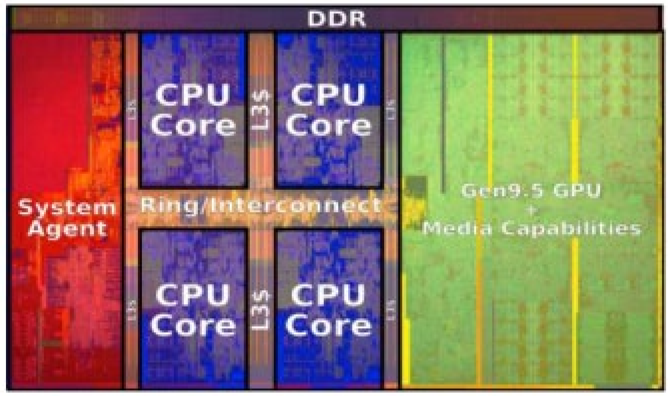


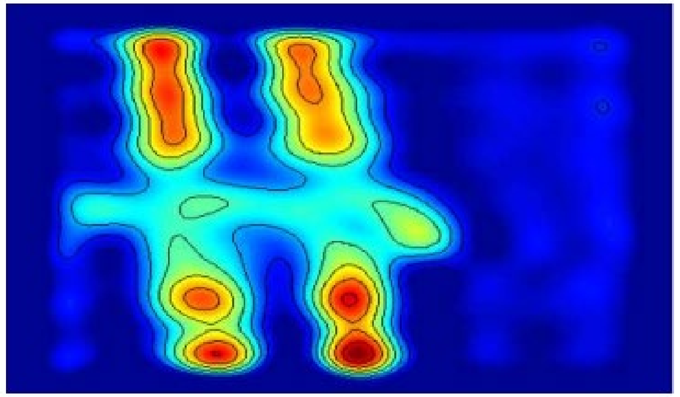
Reference:
nTopology



Reference:
Diabatix, Inc.

Application Specific Thermal Solutions to Address Non-Uniform Temperatures





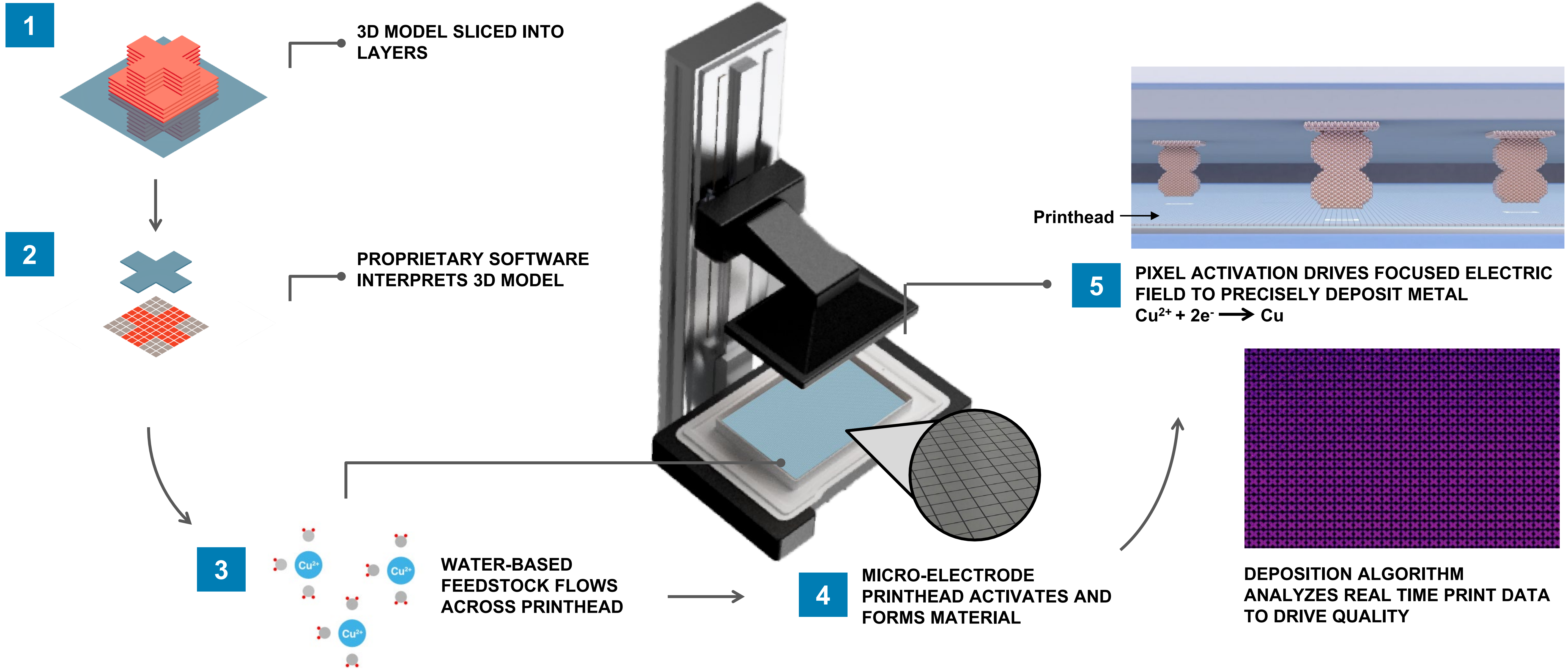
Reference:
Zhang, J. (2023)

A Novel AM Approach: Electrochemical Additive Manufacturing (ECAM)

ECAM Brings Additive Manufacturing Capability to the Electronics Value Chain

	Incumbent Additive Manufacturing (AM) Technologies		New AM Capability
	Binder Jetting	**Laser Powder Bed Fusion**	**Electrochemical Additive Manufacturing (ECAM)**
Feedstock	Med-Cost Metal Powder	High-Cost Metal Powder	**Low-Cost Metal Salts**
Metal Fusing Process	Sintering	Laser Melting	**Electrodeposition**
Post-Print Processing	Cure (Green Part), Depowdering, Sintering	Depowdering, Thermal Stress Relaxation, Support Removal	**Water Rinse**
End part cost, Copper ($/kg)	$$$	$$$$$	**$**
Minimum Feature Size	500 µm	150 µm	**50 µm**
Surface Roughness, Ra (micro-inches)	> 250	> 250	**< 50**
Conductivity (%IACS)	~ 90%	90 - 95%	**94 - 98%**

Process Overview: Electrochemical Additive Manufacturing (ECAM)



1 3D MODEL SLICED INTO LAYERS

2 PROPRIETARY SOFTWARE INTERPRETS 3D MODEL

3 WATER-BASED FEEDSTOCK FLOWS ACROSS PRINTHEAD

4 MICRO-ELECTRODE PRINTHEAD ACTIVATES AND FORMS MATERIAL

5 PIXEL ACTIVATION DRIVES FOCUSED ELECTRIC FIELD TO PRECISELY DEPOSIT METAL

$Cu^{2+} + 2e^- \longrightarrow Cu$

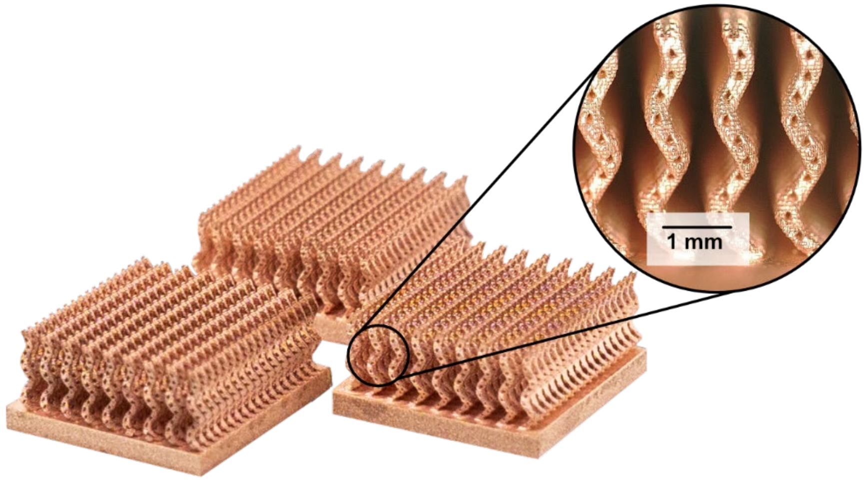
DEPOSITION ALGORITHM ANALYZES REAL TIME PRINT DATA TO DRIVE QUALITY

Room Temperature 3D Metal Printing - No Post-Processing Required - Massively Scalable

ECAM Enabled Thermal Management Products

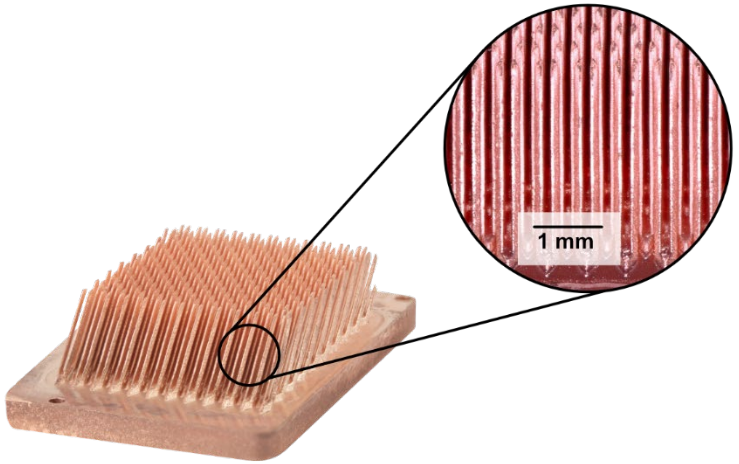
Additive Design Advantage

Micro scale feature resolution
Design freedom



High Thermal Conductivity

High purity copper
Dense structures as-printed



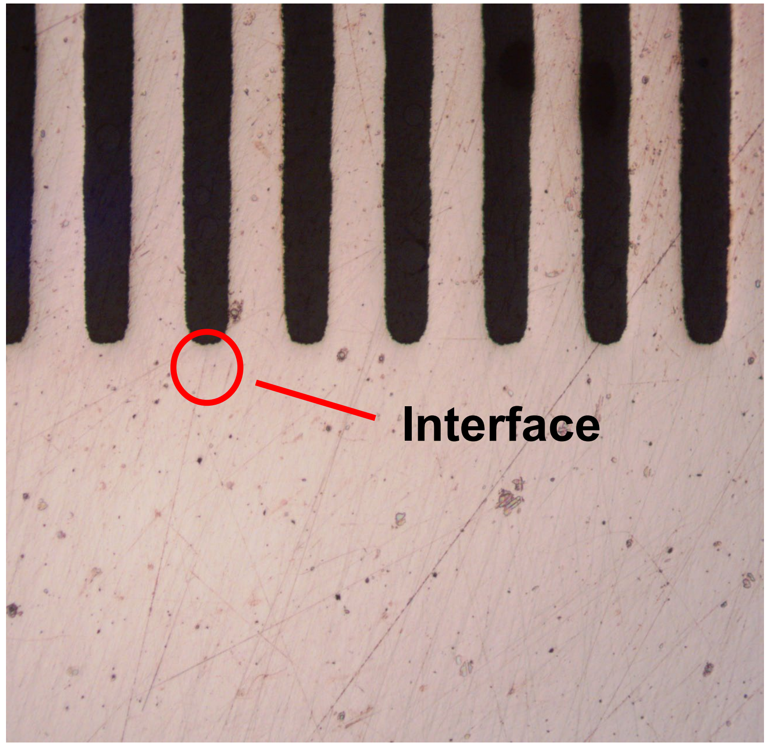
Competitive Economics

Low-cost feedstocks
Room temperature processing

ECAM produces high resolution, complex topological structures in high-purity copper enabling optimized thermal components at competitive economics.

Deep Dive – ECAM Printed Features on Copper Substrates

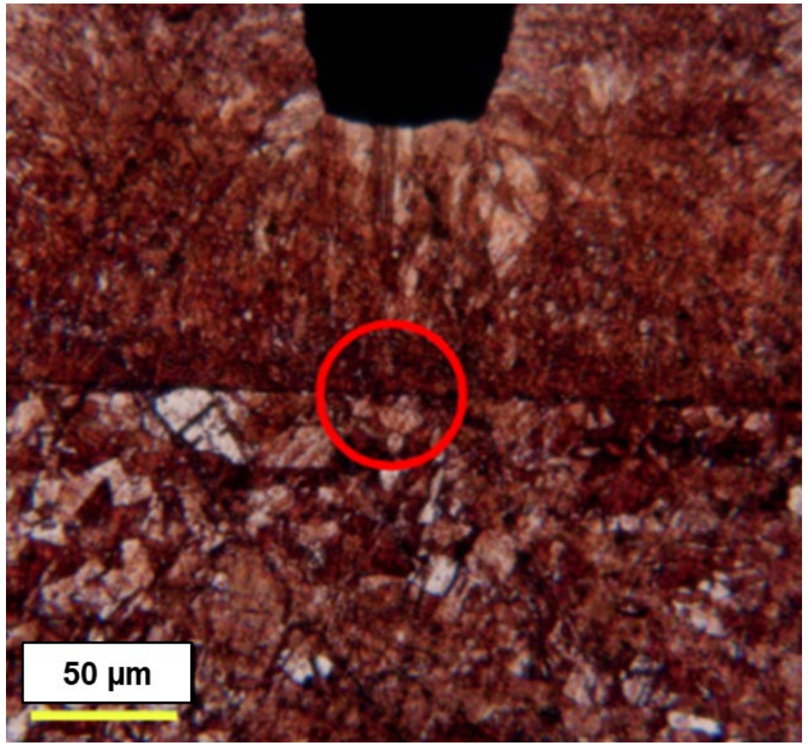
Mixed Manufacturing Method Enables Optimized Thermal Devices at Scale



Mount and mechanical polish optical inspection; no visible interface between substrate and printed structure

ECAM Printed Structure

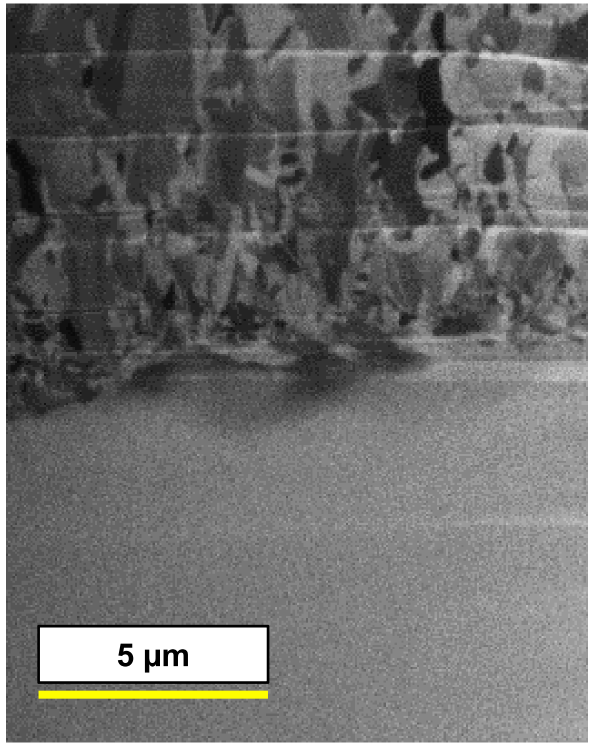
OFHC Substrate



Chemically etched surface to expose grain boundaries & interface (Etchant: $FeCl_3(H_2O)_x$+ HCl) 50x Magnification

ECAM Printed Structure

OFHC Substrate

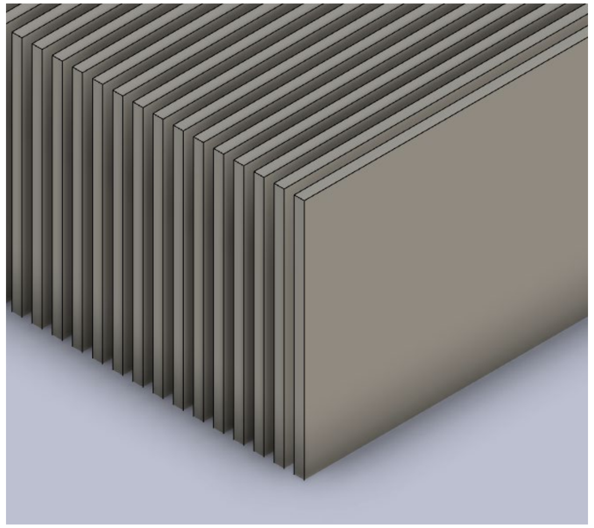


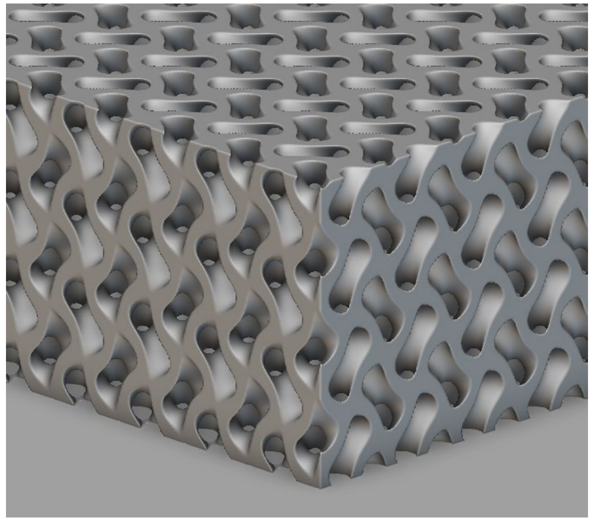
Focused ion beam cut + imaging

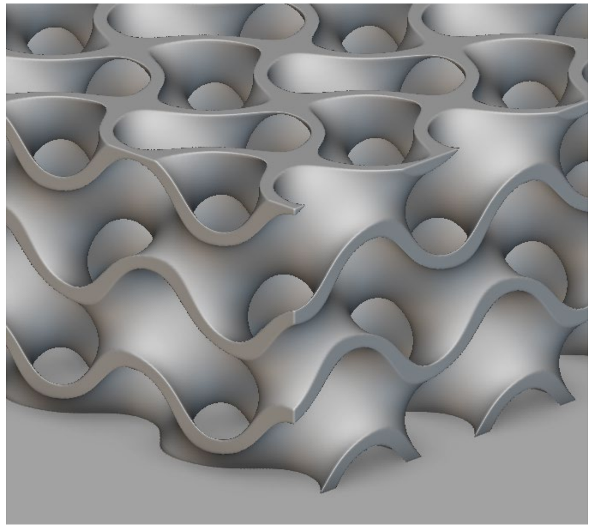
Metallurgically bonded, fine grained Cu microstructure.

Initial Structures Evaluated for Thermal Performance

Incumbent Microchannel vs. High-Resolution Gyroid Structures



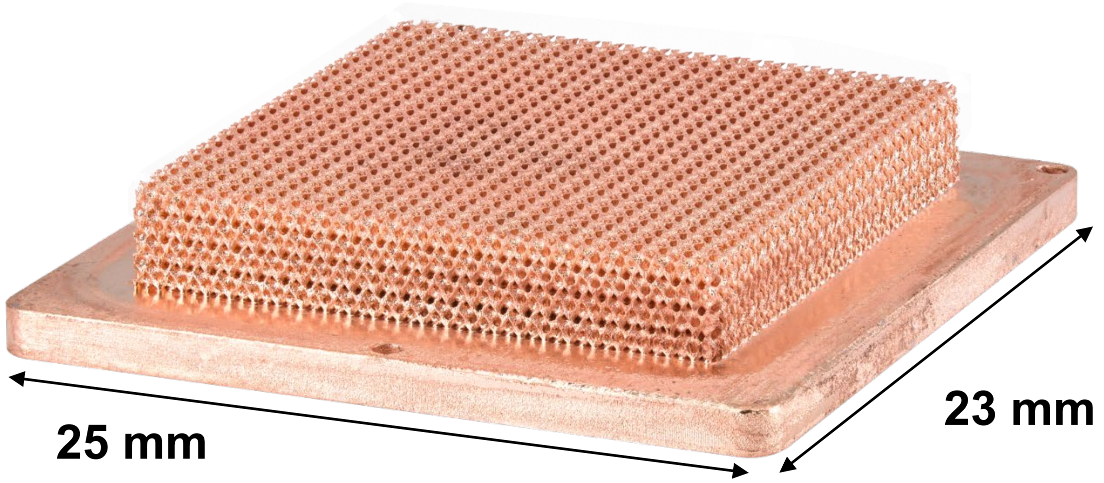


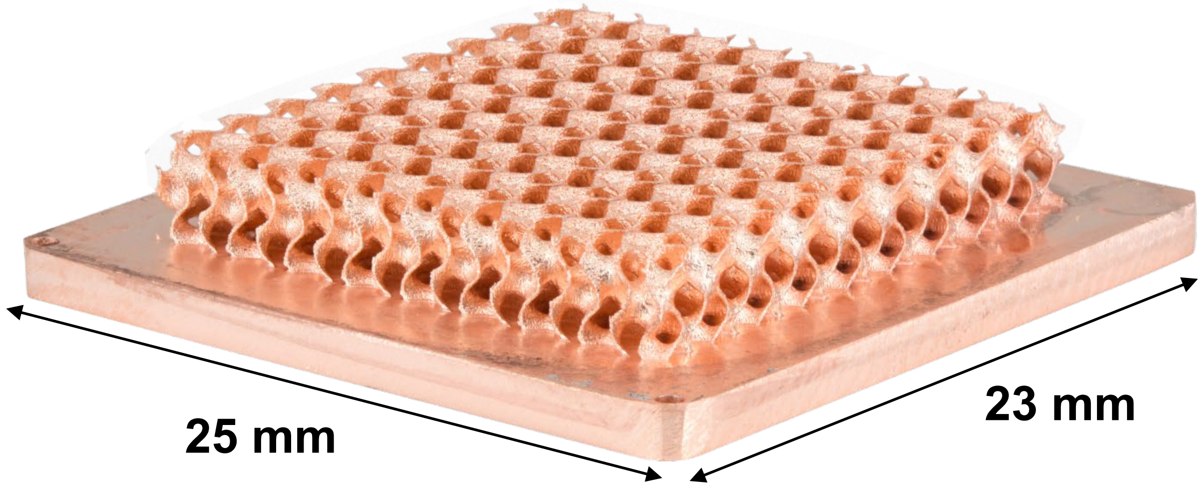


Design	**Incumbent Microchannel**	**Gyroid 50% Open**	**Gyroid 80% Open**
Wall Thickness, µm	100	100	133
Surface Area per Unit Volume (cm^2/cm^3)	108.6	74.4	31.5
Open Volume	49.2%	50.3%	80.2%

ECAM Printed Gyroid Structures

High-Resolution TPMS Structures Printed onto OFHC Copper Sheet Stock





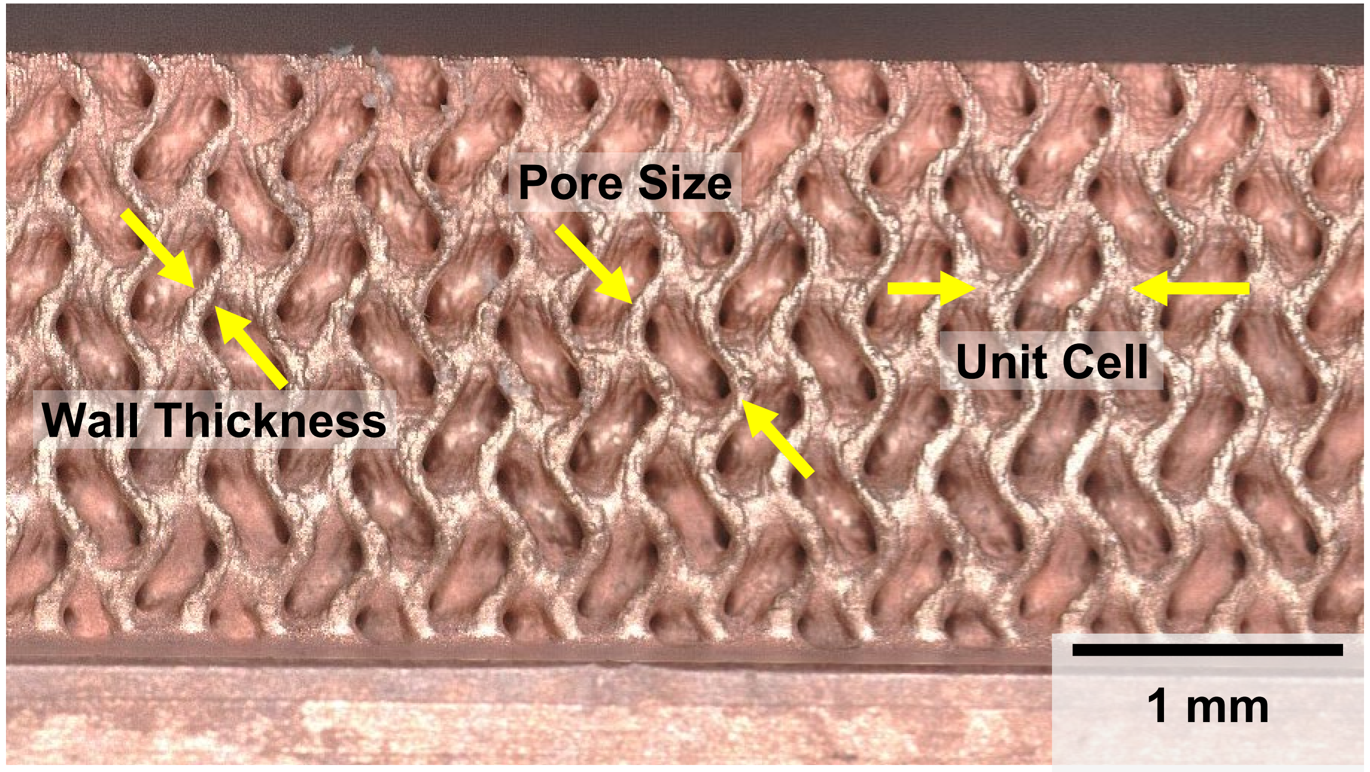
Gyroid, 50% Open Volume	
Wall Thickness, µm	100
Surface Area per Unit Volume (cm^2/cm^3)	74.4
Open Volume	50.3%

Gyroid, 80% Open Volume	
Wall Thickness, µm	133
Surface Area per Unit Volume (cm^2/cm^3)	31.5
Open Volume	80.2%

Nominal dimensions

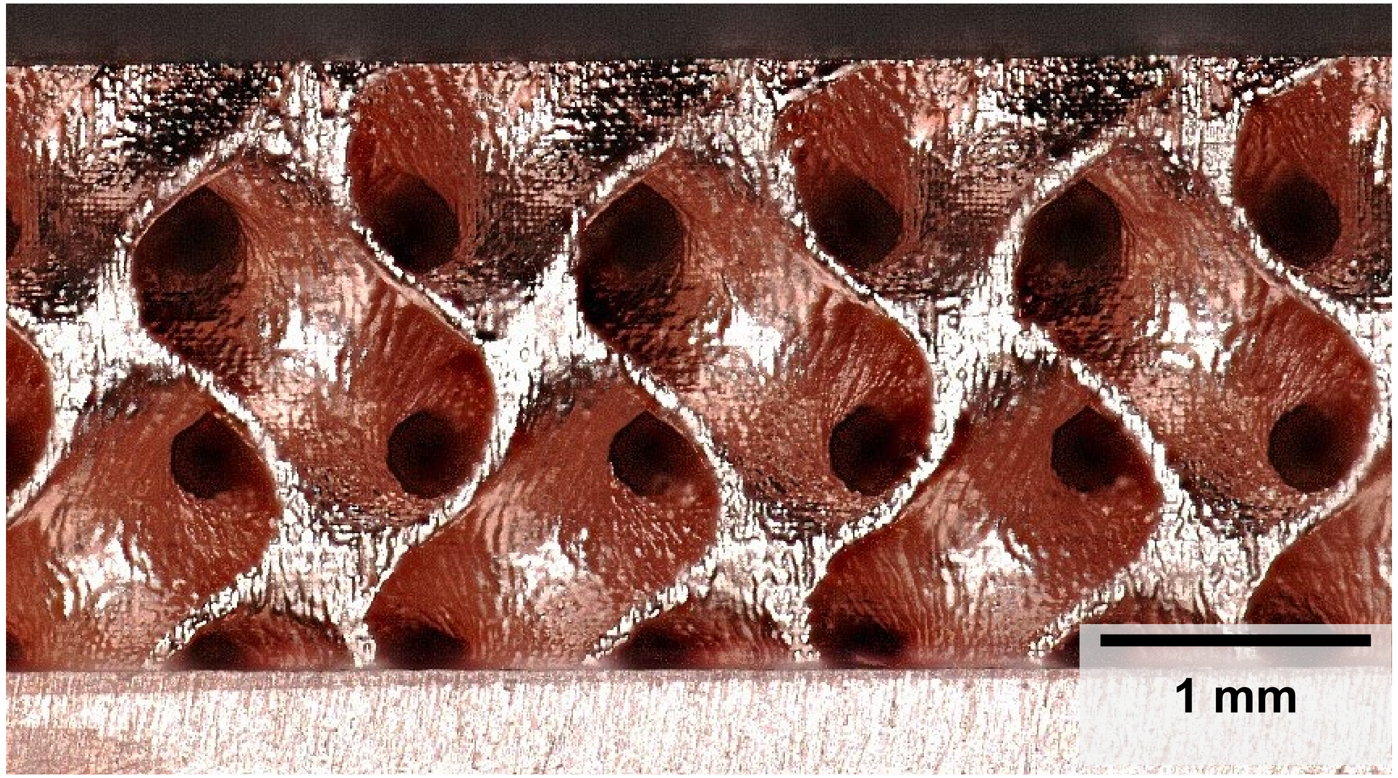
Gyroid Prints - Dimensional Inspection

High-resolution Gyroid Structures Printed with Excellent Feature Accuracy



Gyroid, 50% Open Volume

	Nominal	Measured	StDev
Wall Thickness, µm	100	107	11.4
Pore Size, µm	590	572	24.4
Unit Cell, µm	766	741	16.5

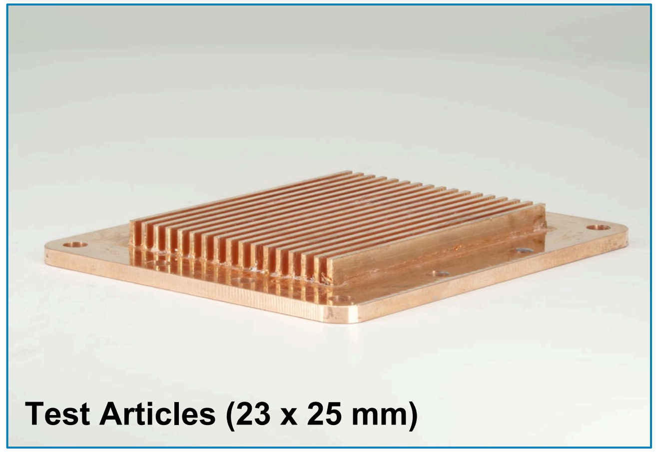


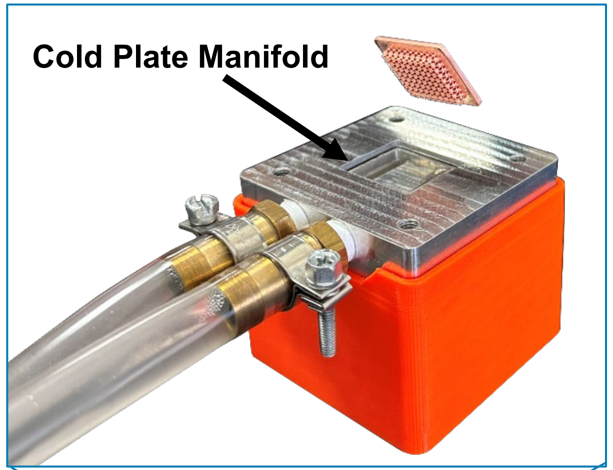
Gyroid, 80% Open Volume

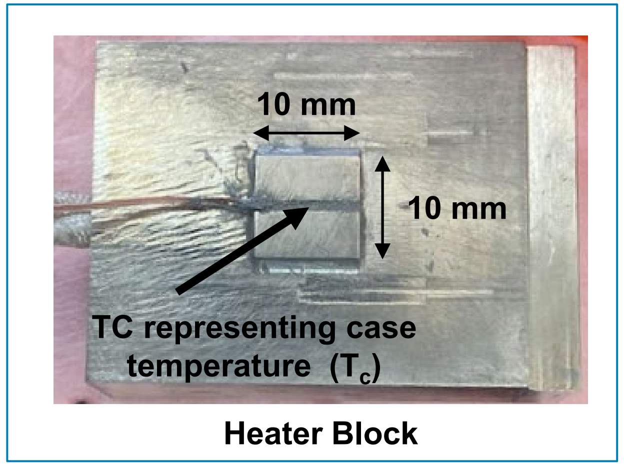
	Nominal	Measured	StDev
Wall Thickness, µm	133	113	11.0
Pore Size, µm	1840	1806	8.5
Unit Cell, µm	2045	2034	51.4

20 samples for each feature measurement

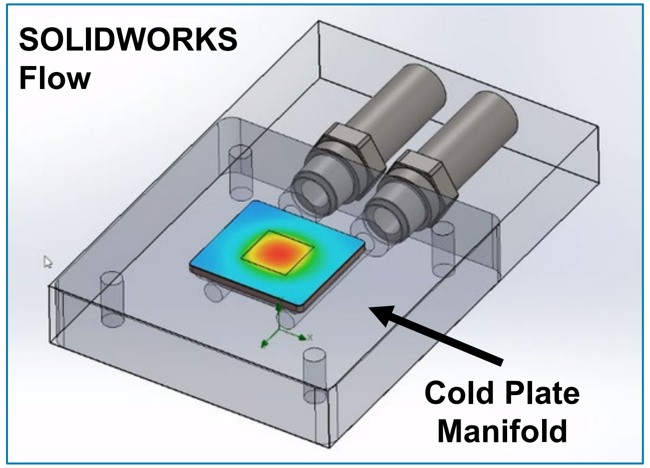
Cold Plate Test Setup and Simulation

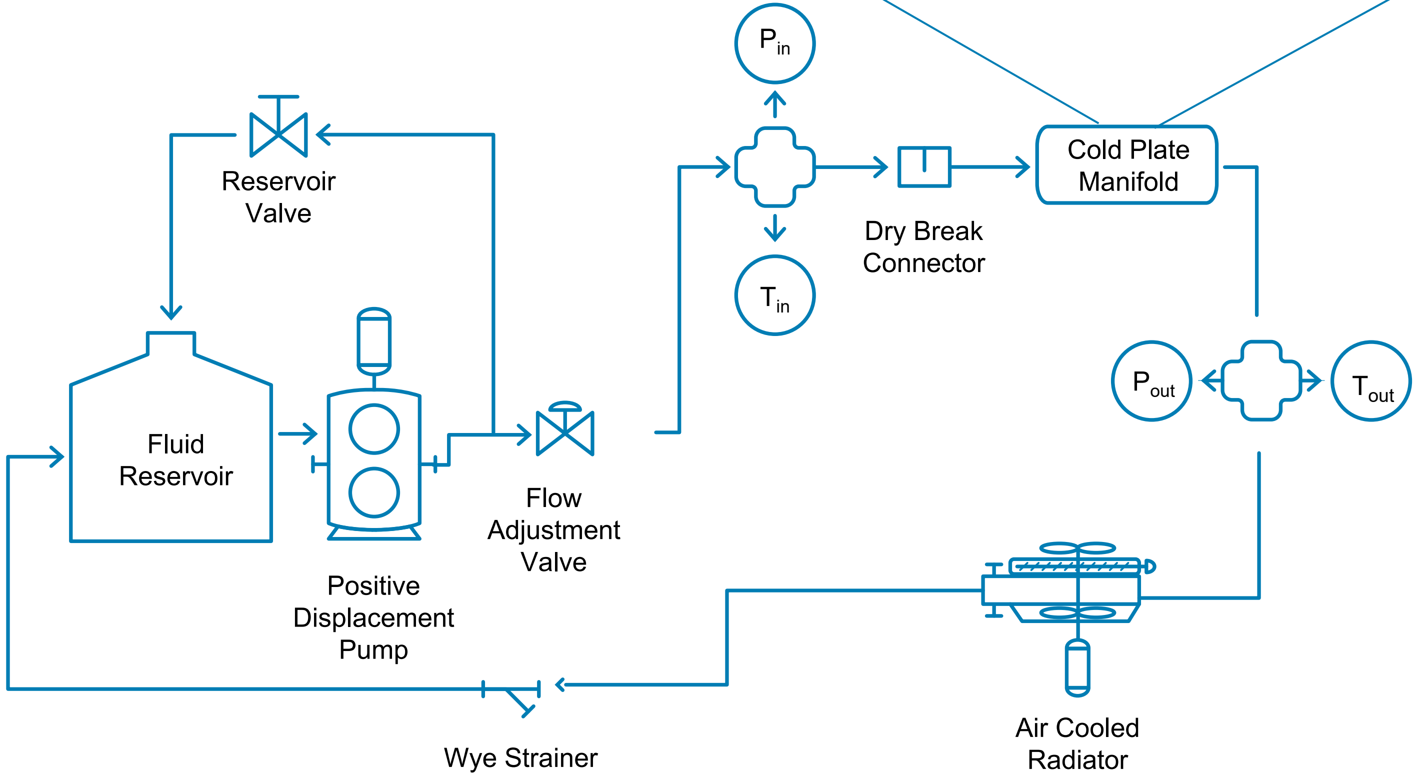

Test Articles (23 x 25 mm)





Heater Block



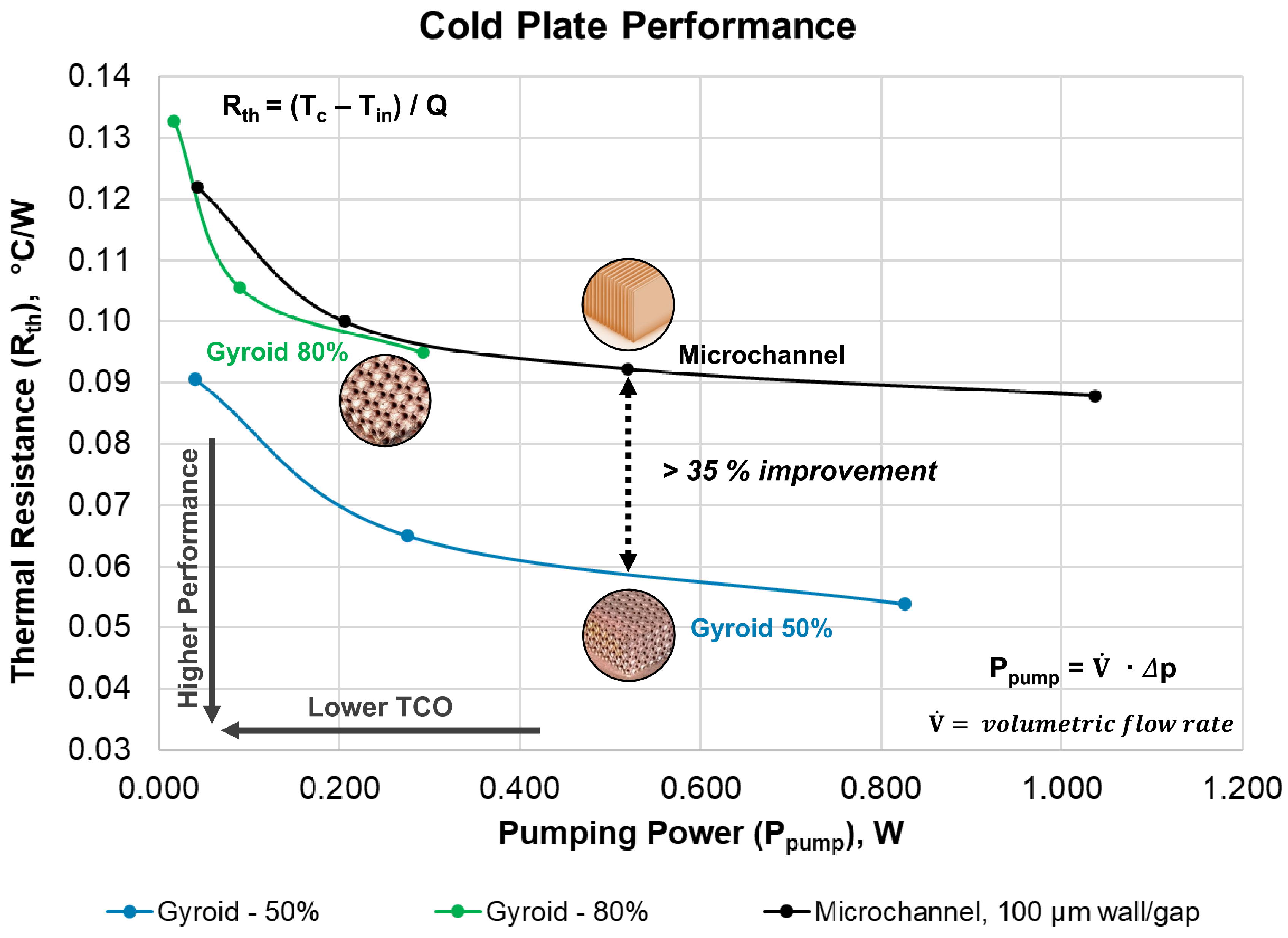


TEST SETUP OVERVIEW:

- “Cold plate manifold” was designed and manufactured (shown left) to receive various cold plate test articles
- Cross-flow setup, flow-rate controlled, pressure measured at inlet (P_{in}) and outlet (P_{out}) to determine Δp
- Heater block, 10 x 10 mm, heat input (Q) range 100 - 1,000W
- Temperature collected at the center of the cold plate base (T_c), as well as the fluid inlet (T_{in}) and outlet (T_{out})
- Heat removed from test system via a radiator
- Thermal resistance determined by $R_{th} = (T_c – T_{in})/Q$

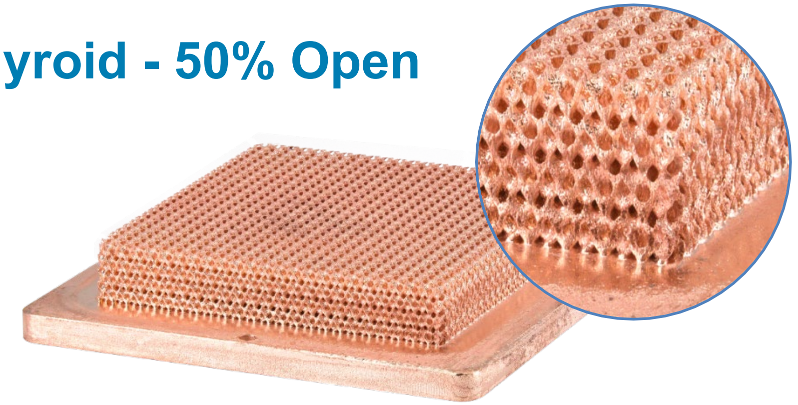
Thermal Performance Results

ECAM Enabled Structures Significantly Outperform Incumbent Microchannel

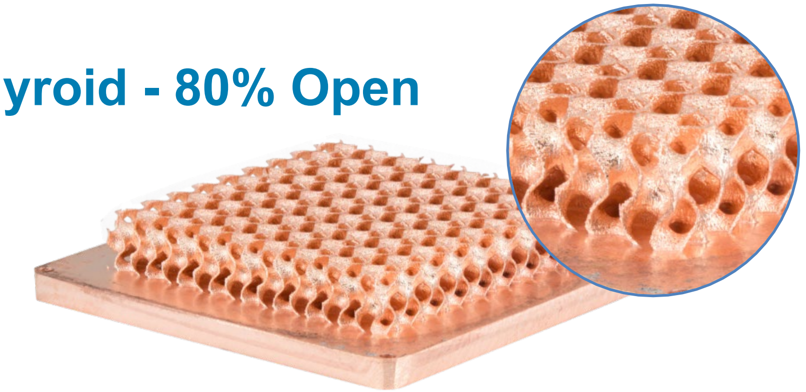


50% Gyroid Structure showed **> 35% improvement in thermal performance** at equivalent pumping power vs. incumbent microchannel

Gyroid - 50% Open



Gyroid - 80% Open



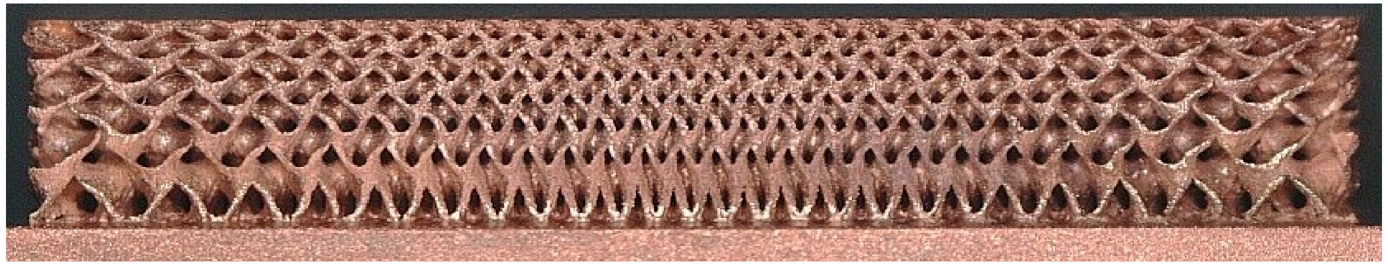
Conclusions and Future Work

Electrochemical Additive Manufacturing (ECAM) was shown to be capable of producing high-performance thermal management devices with greater than 35% better performance than incumbent technologies.

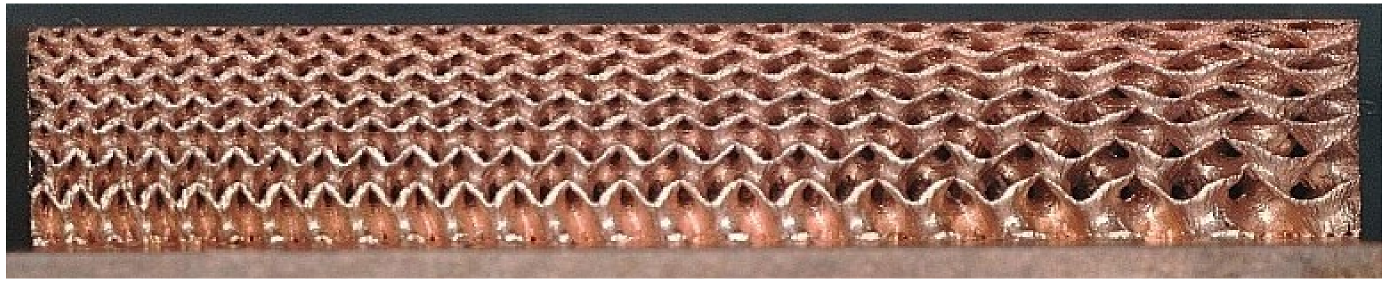
Application specific cooling structures that leverage complex and customized designs in conjunction with ECAM's unique capabilities have great potential to realize optimized cooling performance.

Future Work

Optimizing via Graded Structures



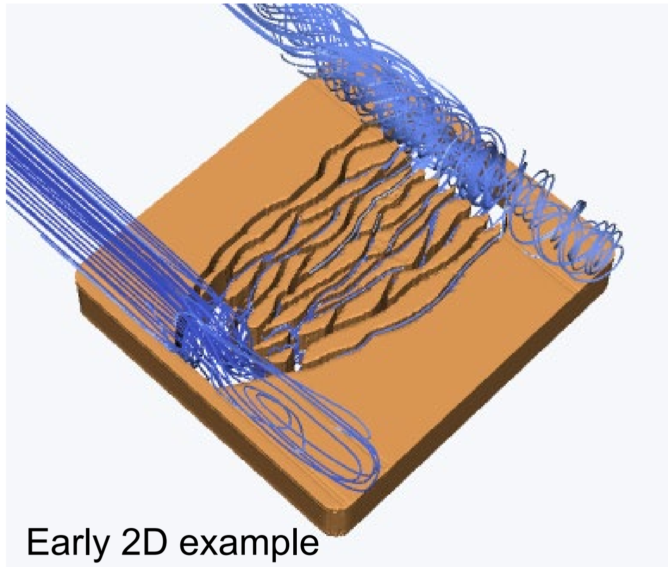
Flow Inlet View



Side View (flow left to right)

Developing design-analysis-test capability

Optimizing via Generative AI



Early 2D example

Developing partnerships and tools that align with ECAM capabilities

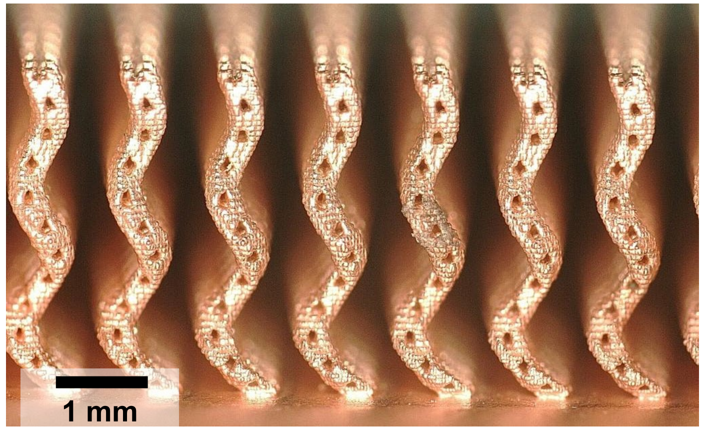
Summary

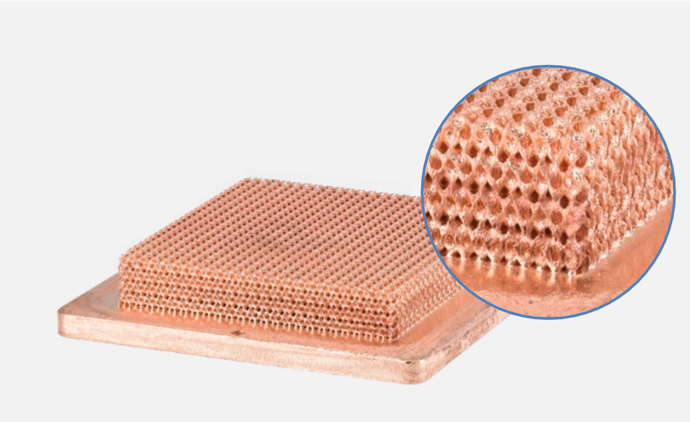
- Increased power dissipation requirements in high-performance computing applications are driving innovation in liquid cooling technologies to improve component and system-level heat extraction

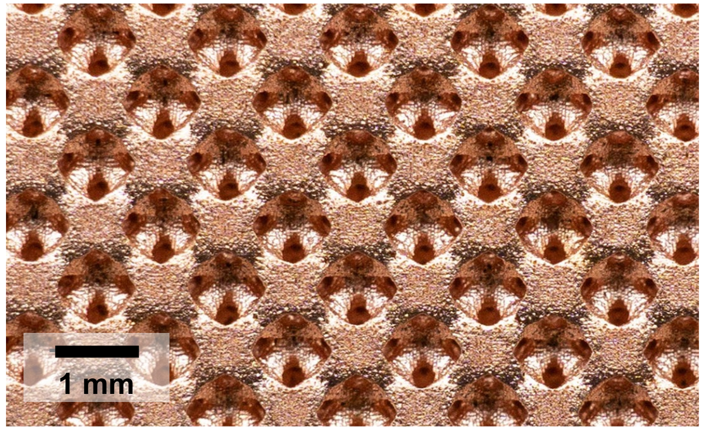
- The current state of the art liquid cooling cold plate technology is based on microchannels – but these designs have limited performance

- A 35% improvement in thermal resistance was demonstrated by using a complex, 3D printed cold plate produced via Electrochemical Additive Manufacturing (ECAM).

- ECAM provides a solution for mass-manufacturing of application optimized thermal management products that employ geometrically graded structures and generative AI-based designs







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