The Future of Liquid Cooling

Novel Microgeometry Architecture for Lower Pressure Drop & Higher Thermal Performance

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The increasing demands of GPU-intensive AI workloads have rendered air cooling alone insufficient in modern data centers. Liquid cooling, specifically direct liquid cooling (DLC) systems, has become essential. However, conventional manufacturing techniques limit performance, add complexity, and restrict the design freedom needed for next-generation systems.

Alloy Enterprises', a Johnson Controls company, thermal solutions leverage our proven libraries of microgeometries and proprietary Stack Forging™ process to deliver advanced cooling performance. By enabling superior thermal performance and lower pressure drop compared to conventional cold plates, this technology enhances system reliability, reduces power costs, and supports higher compute density, providing data centers with a clear edge regarding ROI, performance, and sustainability.

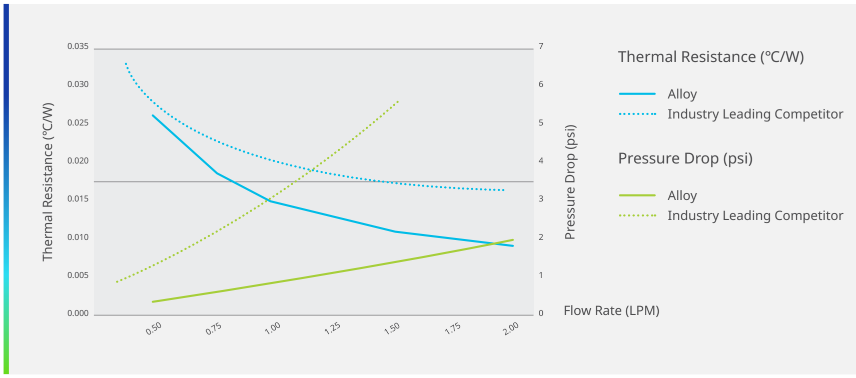


CHART compares thermal resistance and pressure drop between Alloy's DLC copper cold plate and an industry-leading skived-fin copper cold plate on an NVIDIA H100 GPU.

This white paper explores how Alloy is redefining what's possible in DLC thermal component design, delivering at scale, customizable liquid cooling solutions built for the future of high-performance computing.

Cooling Data Centers In the AI Era

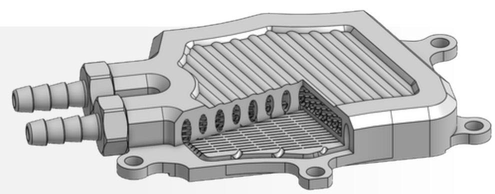
With computing density skyrocketing—driven by AI, high-performance computing, and cloud-based applications—traditional cooling methods are struggling to keep up. **Efficient thermal management is no longer just a technical issue; it's a business imperative, with insufficient cooling leading to fewer AI tokens sold, higher costs, greater power consumption, and potential downtime.** With data center infrastructure investments expected to surpass $250 billion by 2030, the industry faces mounting pressure to adopt more effective cooling solutions, especially in light of NVIDIA CEO Jensen Huang announcing that 600 kW per rack is imminent. DLC offers a path forward, enhancing thermal performance, reducing power consumption, and supporting sustainability goals in an era of unprecedented demand.

Direct Liquid Cooling

A Powerful Solution

The fundamental limits of air's heat capacity and thermal conductivity mean that adding more fans or increasing air flow simply cannot keep up with the heat generated by modern computer hardware. DLC addresses this challenge by circulating liquid through cold plates directly attached to high-performance server components, such as CPUs and GPUs. These cold plates feature embedded thermal geometries that maximize surface area for heat exchange, allowing heat to be efficiently transferred away from the chip to an external cooling system. This direct heat removal approach enables precise temperature control and supports higher-density server configurations.

CAD RENDERING of Alloy's DLC cold plate for an AMD MI-300 GPU showing internal microcapillary™ architecture that can only be manufactured via the Stack Forging™ process.



However, DLC cooling is not without its challenges. For example, brazing and other sealing methods can be unreliable, sometimes causing leaks that put sensitive electronics at risk. Some cooling materials, like thermal interfaces and fluids, have used polyfluoroalkyl substances (PFAS), chemicals now under scrutiny for environmental and health hazards. Furthermore, reducing the number of parts and simplifying the system design will be required to achieve higher rack densities.

Despite these challenges, DLC is an essential step forward in thermal management; legacy manufacturing limitations shape its current implementation. Unlocking its full potential requires new design freedoms, allowing high-performance microgeometries without increasing part count or compromising reliability. Achieving this level of optimization requires a fundamentally different approach to designing and manufacturing thermal components. Enter Alloy Enterprises.

Alloy has developed the Stack Forging manufacturing process, which addresses these concerns and enables the production of next-generation DLC components. This solid-state metal manufacturing method eliminates the limitations of traditional part production, allowing the creation of unique three-dimensional internal structures, including microcapillary™ architecture, within a fully dense, leak-tight aluminum or copper part. These microcapillary architectures provide exceptionally low pressure drop and thermal performance while remaining fully customizable. Unlike conventional techniques that require expensive and time-consuming tooling, Alloy's components, manufactured with the Stack Forging process, can be rapidly tuned to meet specific geometric and performance needs.

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How the Stack Forging™ Process Works

ALLOY'S Stack Forging Process Steps and Equipment.

The Stack Forging process follows a precise, scalable approach:

1. **Material Selection –** Aluminum or copper feedstock is available for their optimal thermal and mechanical properties.
2. **Digital Slicing** – Slice the 3D model into discrete layers via our proprietary slicing software.
3. **Cutting & Inhibition** – Laser-cut the design into sheets of custom feedstock and apply an inhibition layer in the designated areas of the design.
4. **Stacking & Bonding** – The metal sheets are stacked and metal-to-metal diffusion-bonded to form a single block, minus any internal channels or voids.
5. **Heat Treatment** – Once the block is formed, the support material is removed, and the aluminum components are heat-treated to achieve strength and hardness. Copper does not require heat treatment.
6. **Quality Control & Testing** – Alloy's comprehensive quality management system(ISO 9001:2015 certified) and testing capabilities ensure our parts meet all customer dimensional and performance requirements.

The Stack Forging process has been designed from the ground up with scalability in mind, creating a clear path to providing thermal management solutions to even the largest hyperscalers. Unlike traditional metal additive manufacturing processes, the steps in the Stack Forging process can be easily parallelized and split across multiple machines enabling a level of production throughput that is not attainable with traditional metal additive technologies.

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Cooling Architectures Enabled by Stack Forging Technology

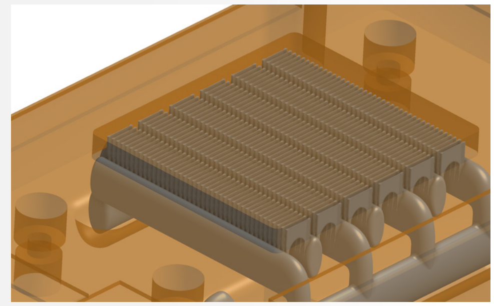
The true value of the Stack Forging process lies in the library of microgeometries it enables. These microgeometries create microcapillary architecture that target heat directly at its source. They provide superior cooling, improved system reliability, lower power costs, and support for higher compute density. Because the process builds metal structures layer by layer, internal geometries are no longer limited by tool access or cutter radius, allowing for designs previously impossible to manufacture, with optimized thermal and fluidic behavior tailored to the demands of next-generation compute environments. The Stack Forging process involves no powder and no melting of the stock material, enabling precise geometries without the risk of powder clogs or the wicking of molten metal into channels due to capillary action.

Microcapillary™ Architecture

The Stack Forging process allows for tightly packed, high-aspect-ratio passages fully supported by a three-dimensional structure, which Alloy has termed microcapillary architecture. These features greatly increase the surface area, which maximizes the component's heat transfer. Microcapillary architecture allows for significant design freedom beyond typical passageways. A balanced flow distribution is ensured across the entire contact area by arranging them in parallel arrays and designing inlet and outlet channels across multiple length scales throughout the part. The result is a DLC component that maintains low thermal resistance while minimizing pressure drop, even at high flow rates.

LEFT: Top of the Alloy DLC plate for MI325X GPU.

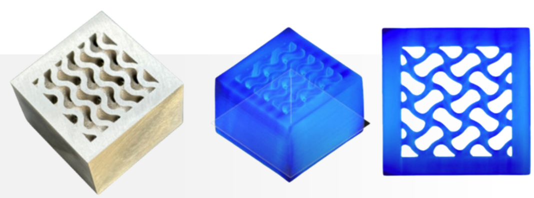
RIGHT: Transparent rendering of internal microcapillary architecture of the Alloy DLC cold plate for MI325X GPU, only manufacturable via the Stack Forging process.



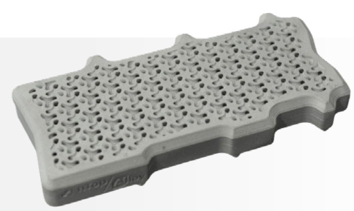
Volumetric Infill Structures (e.g. Gyroids)

Where traditional DLC components are limited to planar channels, the Stack Forging process supports fully three-dimensional infill geometries such as gyroids and other triply periodic minimal surfaces (TPMS). These structures optimize the heat transfer area within a given volume while promoting turbulence, thereby increasing local heat transfer coefficients and enabling better thermal uniformity across the plate. Because the infill is fully enclosed within a solid metal block, there is no need for internal supports, inserts, or secondary bonding.

EXAMPLES of gyroids manufactured via the Stack Forging process.

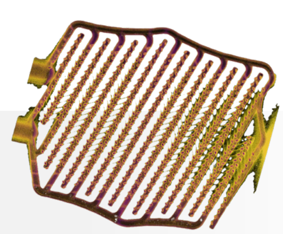


DIRECT LIQUID COOLING COLD PLATE for NVIDIA H100 PCIe designed using nTop, manufactured via the Stack Forging process. Source: nTop



Massive Parallelization

In traditional manufacturing, increasing the number of channels often leads to diminishing returns, as features lose structural rigidity. The Stack Forging process changes this dynamic. It supports hundreds of flow paths operating in parallel, each with optimized geometry, all integrated into a single monolithic structure. This approach offers two benefits: a very low pressure drop and an even distribution of cold fluid over the DLC component surface. These channels also easily scale from small to large chips, enabling their use across various-sized components.



CT SCAN showing parallel microcapillary architecture in the Alloy DLC cold plate for AMD MI300 GPU.

Integrated Flow Control Features

Cold plates manufactured via the Stack Forging process can include embedded bifurcations, impingement jets, swirl inducers, and other fluid dynamic features directly within the internal structure. These elements are not added as discrete parts but are designed into the metal itself reducing system complexity and eliminating the reliability concerns associated with gaskets, seals, or inserts.

Design Customization and Form Factor Flexibility

Because no expensive, long-lead tooling is required, each Alloy component can be customized to match the chip layout, board footprint, packaging stack up, or desiredfluid routing. This flexibility is essential for AI server blades, where densely packed systems—including GPUs, DIMMs, SIMs, and NICs—require comprehensive liquid cooling. These tight layouts demand complex, highly adaptable cooling component designs. Whether accommodating non-uniform die maps, aligning with facility loop routing, or co-optimizing for pressure drop and heat flux density, our library of microgeometries and the Stack Forging process make tailored solutions practical at production scale.

These architectural possibilities enable engineers to design DLC solutions that match the physics of the problem, and not the limitations of the machine shop. The results are not only more thermally efficient but also more reliable, compact, and integration-friendly. Visual examples throughout this section demonstrate the range of geometries that can be manufactured using the Stack Forging process, including high-resolution renders, CT scans, and performance test prototypes.

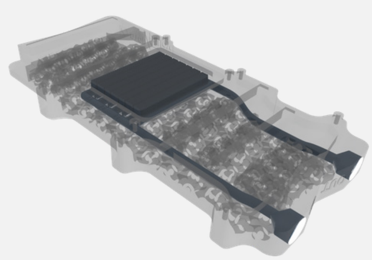
Design Examples and Performance Results

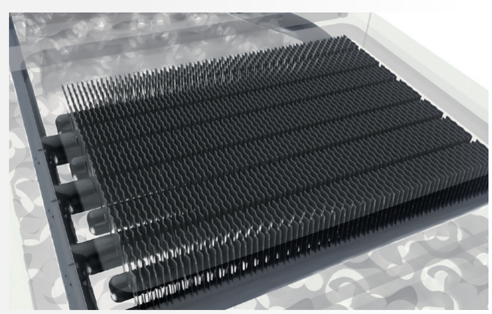
Alloy's components are already deployed in some of the most demanding thermal environments, delivering superior performance across multiple processor types and configurations. Below are representative design examples and benchmarked performance results that illustrate the tangible benefits of this technology across real-world use cases.

GPU Direct Liquid Cooling Cold Plate: NVIDIA H100

LEFT: Transparent rendering showing the internal geometry of the Alloy DLC cold plate for the NVIDIA H100 GPU.

RIGHT: Transparent close-up rendering showing the microcapillary architecture of the Alloy DLC cold plate for the NVIDIA H100 GPU.





Designed using Alloy’s proprietary Stack Forging process, the H100 cold plate leverages tightly packed microcapillaries to optimize surface area for convective heat transfer while dramatically reducing flow resistance. In benchmarking tests, Alloy’s cold plate outperformed a leading skived copper cold plate, an industry standard, by achieving:

- 11X lower pressure drop at the same flow rate
- Enhanced thermal performance due to better flow distribution and higher internal surface area
- Full compatibility with 44 °C inlet water and dry chiller systems, maintaining thermal headroom under elevated ambient conditions

These capabilities directly enable more energy-efficient cooling infrastructure, lower pump power requirements, and support for denser rack configurations.

Direct Liquid Cooling Cold Plate for SP5 CPU

Alloy’s solution integrates microcapillary channels tailored to the thermal needs and optimized for parallel flow, resulting in:

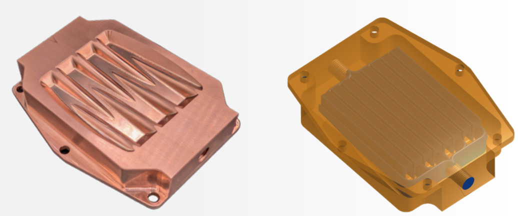
- Significant reduction in pressure drop compared to an industry-leading cold plate
- Lower junction temperatures, reducing the risk of thermal throttling or failure
- Elimination of complexity associated with discrete nozzles, seals, and inserts

The lower pressure drop improves system reliability and pump efficiency, enabling the broader adoption of DLC systems across existing facility loops.

These results underscore that the Stack Forging process and microcapillary architecture deliver measurable improvements in thermal and hydraulic performance. By unlocking new design freedoms and eliminating traditional manufacturing constraints, Alloy enables the development of cold plates that are higher-performing, more scalable, reliable, and integration-ready.

LEFT: Alloy DLC copper cold plate for the SP5 CPU manufactured via the Stack Forging process.

RIGHT: Transparent rendering of the internal geometry of the Alloy DLC cold plate for the SP5 CPU.



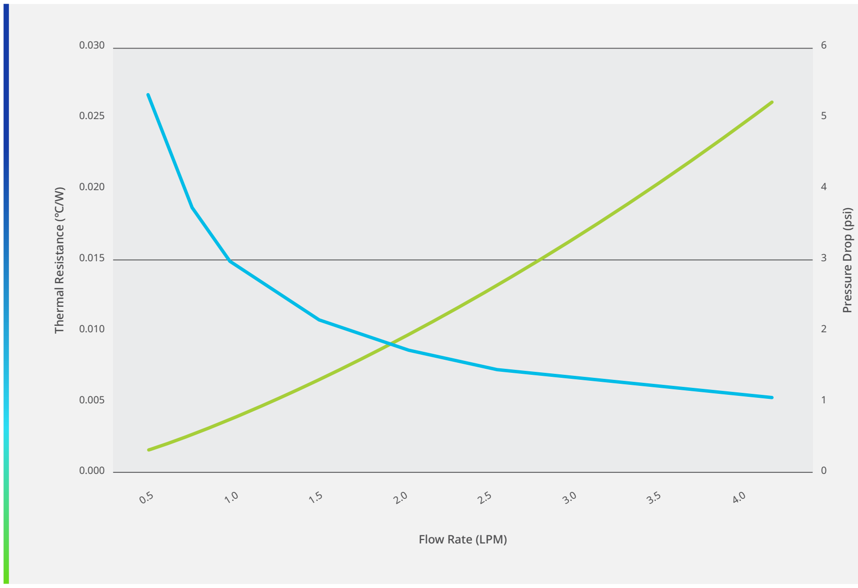


CHART shows thermal resistance and pressure drop of Alloy's DLC copper cold plate for the SP5 CPU.

Conclusion

Thermal management is emerging as a key enabling technology as data centers race to meet the demands of AI, high-performance computing, and escalating rack power densities. Traditional manufacturing methods impose design and performance limitations and struggle to scale alongside modern compute requirements.

Alloy Enterprises' Stack Forging process offers a fundamentally new path forward. By eliminating legacy design constraints and enabling ultra-fine, fully dense metal microcapillary architecture, the Stack Forging process delivers complete thermal management packages that are more thermally efficient, compact, robust, and reliable, without increasing system complexity. These innovations directly translate into lower power use, higher compute density, reduced total cost of ownership, and ultimately, increased revenue.

Our technology is built for performance and production. With a scalable, tool-free manufacturing approach, the Stack Forging process supports rapid customization and high-volume deployment, making it ideal for hyperscalers, OEMs, and enterprises alike.

As the industry moves towards 600 kW racks and likely beyond, the ability to manage heat precisely at the microscale level will define the next generation of infrastructure. Alloy's Stack Forging process doesn't just keep up—it leads the way.

To learn how Alloy Enterprises can help you solve your most critical thermal challenges, contact us at **info@alloyenterprises.co.**