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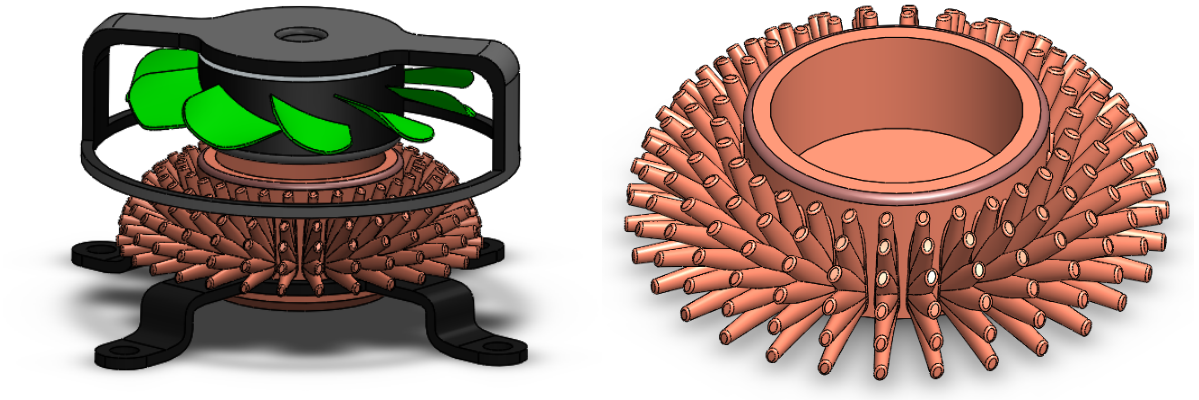
The Copper Cooler: Heat Sink for CPUs

Implementation of Binder Jetting Additive Manufacturing for production of porous copper heat sinks to cool Central Processing Units



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1 Problem Statement and Project Focus

This project investigates the redesign of a heat sink for cooling central processing units (CPUs).

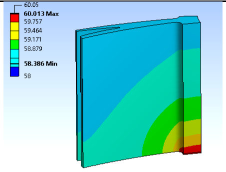
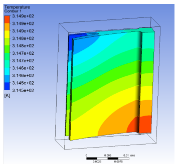
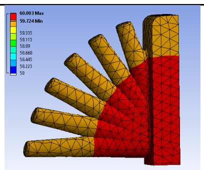
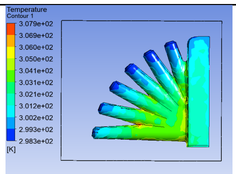
Heat dissipation is one of the most critical aspects to be considered when designing any electronic device. Whenever current flows through a resistive element, heat is generated [1]. Heat must be removed in order to maintain the continuous operation and proper function of the electronic device [2]. Heat sinks are devices that enhance heat dissipation from a hot surface, usually that of a heat generating component, to a cooler ambient, usually air. A more efficient heat sink would lower the device operating temperature (thus improving its performance) and/or allow for the usage of faster and more powerful CPUs.

2 Functionality and Durability

The new heat sink features an organic, branched fin design revolved around a circular base which is situated on top of the CPU. It will be part of an assembly with a fan mounted above the heat sink to facilitate forced convection, making it an active heat sink system.

The main functional requirements of the heat sink are to efficiently conduct heat through the fin, cool the fin through convective heat transfer, and ultimately prevent the CPU from overheating. Finite element analysis was performed using ANSYS in order to compare the thermal performance of the new copper heat sink fin design to the original aluminum fin design (which was retrieved from the GrabCAD library [3]). Table 1 shows a summary of the results.

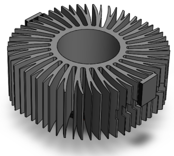
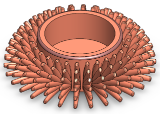
Table 1: Finite element analysis for single fin of heat sink

	Heat Conduction **Steady state thermal analysis** Temperature at CPU = 60 °C, CPU heat generation Q = 8488300 W/m^3	**Heat Convection** **Transient thermal analysis** T_{fin} = 333 K, T_{air} = 298 K, Air speed = 0.75 m/s, CPU Q = 8488300 W/m^3
Aluminum fin (benchmark)	 $T_{Min.}$ = 58.39 °C	 $T_{Max.}$ = 314.9 K $T_{@CPU}$ = 314.9 K
Copper fin (new design)	 $T_{Min.}$ = 59.72 °C	 $T_{Max.}$ = 307.9 K $T_{@CPU}$ =303 K

The fin is most efficient when $T_{tip} = T_{base}$ (meaning there is no excess material that is unheated). The steady-state thermal analysis revealed that the new fin had a more uniform temperature distribution and a higher minimum temperature, meaning that the entire fin geometry is in use and no material is wasted. The transient thermal analysis for the convective cooling regime resulted in a lowered maximum temperature for the new fin design, which was also well within CPU manufacturer's recommended operating temperatures [4].

By leveraging the benefits of the more efficient heat transfer functionality, the new heat sink was also designed to be smaller and lighter than the original, with a larger surface area to volume ratio. Table 2 shows the comparison.

Table 2: Geometry and weight comparison between the original and new design

Component		
Dimensions (cm)	d=7.47, h=2.7	d=6.2, h=1.6
Volume (cm^3)	41.5	12.2
Mass (g)	112.1	109.3
Surface Area (cm^2)	533.6	191.1
SA:V ratio	12.9	15.7

3 *Material Selection: Aluminum vs Copper*

Metals with high thermal conductivity and relatively low cost are preferred materials to be used. Commonly used materials for heat sinks are aluminum and copper. Due to its higher thermal conductivity and volumetric heat capacity, copper would seem to have the superior thermal performance. However, aluminium is the most prominently used heat sink material because of its lower cost. Clearly the main reason for not using all-copper heat sinks is the high density which leads to increased weight, and high cost. This project proposes the use of all-copper heat sinks because of its stellar thermal properties. However, this all-copper heat sink design will be an optimized design and the main aim of this heat sink will be light-weighting. Binder jetting additive manufacturing is readily adaptable to a wide-range of materials [5], and copper parts have successfully been printed by Bai et al [6].

4 *Method of Manufacturing: DDM using binder jetting*

Binder Jetting is a direct digital manufacturing process in which a liquid binding agent is selectively deposited to join powder materials and form a part layer-by-layer [7]. The printed parts are then sintered to fuse the particles together through atomic diffusion and to obtain the final part density and strength. The binder jetting process offers the utmost design freedom in the realization of complex geometries. Unlike other powder-bed technologies, it does not require the use of support structures for part anchoring or heat dissipation purposes. The organic, branched heat sink fin can be easily produced with the powder bed acting as support for the overhanging segments.

The minimum feature size on the fin is an ellipse with a minor dimension of 1.3 mm. A certain scaling factor is required to account for part shrinkage during the sintering step. With an assumed scaling factor of 1.5x, the minimum feature size meets the design guideline for binder jetting (thin wall > 2mm). Since this has not been experimentally determined, it is possible that the assumed scaling factor will be too large. However, binder jetting is known to build parts with some level of porosity, so if the part must be built larger, it will still be lightweight since the lowered density will allow for a greater volume without increasing the mass as much as a fully dense part.

5 Design Integration and Innovation

Traditionally, copper heat sinks are die-cast and bound together in plates. Binder jetting DDM has the benefit of directly printing the metal without the need for additional tooling / fabrication of casting molds. This results in faster lead times, faster prototype production and shorter product design cycles. It may result in reduced material waste, since only the required material is printed and unused powder can be recycled. The energy cost is also lower since sintering particles requires less energy than fully melting (as required in casting).

An alternative to all-aluminium heat sinks is the joining of aluminium fins to a copper base in order to combine the benefits of lightweight aluminum with the heat transfer properties of copper. The new all-copper heat sink design is also small and lightweight, but is easier to manufacture because it has fewer assembly components and fewer materials required for supply chain logistics.

6 Cost-benefit / Value Analysis

Binder jetting can effectively reduce the cost per part by having a huge build where multiple heat sinks are manufactured with the help of stacking and clustering in the build box. The process does not require an enclosed chamber or use expensive energy sources, so the technology is inherently scalable. Commercial systems can offer high build volumes and have a relatively high throughput: a 100 nozzle printhead can create parts at up to ~200 /min [6]. However, determination of cost per part is based on the copper powder (this includes size of powder particles, location of vendors, powder type, amount of powder) that is purchased, and is estimated to be around $11.75 per part.

Secondary costs (post-manufacturing, during and after delivery to the consumer) may also be reduced due to the added value of the new design. The smaller dimensions and reduced mass mean that moving the product would have a smaller economic and environmental footprint. The improved functional performance could lead to lower energy costs associated with consumer electronic usage.

7 Marketing

The reliability and performance of all electronic devices are temperature dependent. However, nowadays as devices become smaller and more powerful, they need more sophisticated systems to cope with heat. There is a huge market for consumer electronics and many people in North America own or operate a computer every day. The highly efficient heat sink can be viewed as a disruptive platform technology enabling faster and more powerful CPUs within more compact and elegant packaging, all of which being highly appealing to both the design engineer and consumer.

8 Social and Environmental Impact

The small, lightweight design enables efficient delivery transportation and a small environmental footprint. The lower volume of material required is more sustainable since less raw material will be consumed in its production. Binder jetting DDM also has low material waste since unused powder can be reused in future prints.

Socially, the new heat sink design could improve global connectivity by providing efficient thermal management for servers and cores, ultimately reducing their energy footprint. This would have a large impact on high performance computing industries and may help provide the computational resources needed for new innovation. The proposed organic fin design for heat sinks can also be scaled up for other heat sink applications apart from CPUs.

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