MARMARA UNIVERSITY

FACULTY OF ENGINEERING

Development of Novel Heat Sink with Additive Manufacturing Method

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GRADUATION PROJECT REPORT

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ISTANBUL, 2024

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by

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June, 2024, Istanbul

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF SCIENCE AT MARMARA UNIVERSITY

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ACKNOWLEDGEMENT

First of all, We would like to thank our supervisor Assoc.Prof.Dr. Mehmet Rafet Özdemir for the valuable guidance and advice on preparing this thesis and giving me moral and material support.

June, 2024

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ABSTRACT

Heat sinks are indispensable elements in a computer system that are used to cool the CPU and GPU and operate them at optimum temperature. It is mounted by positioning it on the CPU and GPU. Heat sinks come into contact with the CPU and GPU, absorbing their heat and thus cooling them. For this reason, it is produced using materials with high thermal conductivity.

In this thesis, it is aimed to produce more efficient heat sinks by analyzing the tendency of heat to spread on the heat sink instead of commercial heat sinks and by optimizing the topology. During the optimization phase, specific heat values of the materials (heat retention ability), thermal conductivity calculations, sensitivity values of the machines to be produced, and density of the materials were taken into consideration. Since the topology-optimized heat sink design has a detailed and complex geometry, it will be produced using the additive manufacturing method.

Finally, in this article, the produced topologic heat sink and commercial heat sink were subjected to calculations, tests and comparisons. And as a result of this thesis, it is concluded that the heat sink designed according to topology optimization and produced by the additive manufacturing method is more efficient than the commercial one.

SYMBOLS

- ρ_{solid} Density of solid
- ρ_{air} Density of air
- k_{solid} Solid material thermal conductivity
- k_{air} Air cooled thermal conductivity
- $C_{p_{solid}}$ Solid specific heat in constant pressure
- $C_{p_{air}}$ Air specific heat in constant pressure
- q Weighting between different objectives against each other
- p Penalization factor (It is used as 'n' in COMSOL.)
- $h_{\max\_solid}$ Maximal mesh element size
- $h_{\max\_design}$ Minimal mesh element size
- h_0 Parameter govering the size of details
- γ Solid fraction of the domain
- A Measured area
- k_{simp} Solid isentropic material with penalization thermal conductivity
- ρ_{simp} Solid isentropic material with penalization density
- $C_{p_{simp}}$ Solid isentropic material with penalization specific heat in constant pressure
- θ Weighting between different objectives
- R_{min} Filter radius
- P_0 Rate of heat
- Q_{cond} Conduction rate of heat
- k Thermal conductivity coefficient
- T_{CPU} Temperature of CPU
- T_{HS} Temperature of heat sink
- d Thin thermal paste layer thickness
- Q_{conv} Convection rate of heat
- h Heat transfer coefficient
- T_{air} Temperature of air

INTRODUCTION

Thermal management is a crucial aspect of the electronics industry, particularly within the setting of creating more compact devices with expanded execution and control necessities. As electronic devices continue to undergo intensifying miniaturization, power densities persist in being on a rising trend. (1) Rising client requests for increased computational execution and functionalities has been fueling the improvement of high-power chips. Operation devices at intemperate temperatures impedes device performance and reliability and ultimately causes their failure. For example, thermal stresses occur due to the differences in thermal expansion coefficients of the materials in printed circuit boards. (2) Current designs aim to limit maximum temperatures between 40 and 45 °C as well as to realize the highest possible temperature uniformity. (3) In this manner, there is a require for innovative cooling arrangements that cater to the transitory thermal administration prerequisites of electronic devices and it is basic to create compact thermal management arrangements that can keep up ideal temperatures for electronic devices to guarantee their execution unwavering.

There are two primary categories of cooling techniques: passive cooling and active cooling. Passive cooling utilizes natural conduction, convection and radiation to cool a component, while active cooling requires the use of energy specifically dedicated to cooling component. Current research and development of these technologies are focused on: microchannels, heat pipes, heat pumps, spray cooling, phase change materials, free cooling and thermoelectric cooling. (4) Heat sinks are a common solution for transferring heat in electronic devices through convection. They are passive cooling devices that transfer heat from the electronic device to the surrounding environment. Heat sinks are widely used because of their cost-effectiveness and ease of implementation.

The design and optimization of heat sinks has been a topic of interest for many years. Traditional design methods have relied on trial and error, experimental studies and intuition to create effective heat sinks. However, these methods have limitations, such as assuming simple geometries, which can lead to suboptimal designs. Optimization studies have emerged as an alternative approach to enhance heat sink performance. Bejan proposed an alternative approach for optimizing heat conduction point to volume problems based on constructable theory. (5) This method allows designing optimized high thermal conductivity paths by sequentially assembling blocks of a high conductivity material to minimize the maximum temperature of the domain. The amount of high conductivity material available as well as the total heat generation rate are fixed. As a result, tree-like configurations are obtained.

Topology optimization is a design approach that has been widely used in structural mechanics and more recently in various physics domains, including fluid mechanics and heat transfer. (6) The objective of topology optimization is to distribute material within a designated volume (design domain) to minimize a specified objective function while adhering to given design constraints. In the context of heat sink design, density-based topology optimization is a popular approach, where material distribution is represented as a binary field (void or solid) within the design domain. Specifically, 0 represents air and 1 represents the heat conducting material. This approach has been shown to be effective in optimizing the geometry of heat sinks to improve their thermal performance. However, the binary optimization problem can be computationally expensive and gradient-based optimization methods are not directly applicable.

Topology optimization is a design approach that has been widely used in thermal engineering, particularly in heat sink and heat exchanger design. (7-11) The application of topology optimization in thermal engineering can be traced back to its early use in 2D models for solving thermal diffusion problems. In recent years, topology optimization has progressed to more advanced 3D thermal diffusion models to heat sink design (12), and other technical applications (9,13). The utilize of thermofluidic topology optimization models postures a few challenges compared to easier thermal diffusion models. One of the most challenges is the expanded computational request related to thermofluidic models, especially at higher Reynolds numbers. The numerical stability of these models can moreover be an issue, as the optimization process can lead to the creation of complex geometries that are troublesome to simulate precisely. As a result, most of the investigation in this range has centered on laminar stream issues with low to direct Reynolds numbers.

Despite the substantial body of literature on topology optimization in the design of thermal systems (14), there has been relatively limited attention given to the fabrication and experimental validation of topology-optimized designs for thermal applications. The additive manufacturing and experimental testing of an air-cooled heat sink designed using a thermal diffusion optimization model are presented in (12). Soprani et al. (13) use a thermal diffusion model to optimize the thermal integration of a thermoelectric cooler into a robotic tool and subsequently fabricate and test an optimized prototype.

The mentioned topology optimization studies include experimental validation for optimized structures. This work aims to utilize topology optimization techniques to improve the thermal management of a computer. In this device, the thermal load may be referred to as processor thermal load. While the studies focused on two components (CPU and GPU), a Central Processing Unit focused study was continued in this research. By placing the designed topology optimized heat sink on the processor used, the heat sink absorbs the heat and convection transmission is provided with the fan. This research uses a density based thermal topology optimization model to design the heat sink to reduce the computer's possible maximum temperature according to the repeated experiment procedure.

GENERAL INFORMATION ABOUT HEAT SINKS

Heat sinks are essential components in modern electronics, designed to manage and dissipate heat generated by electronic devices. As electronic devices become more powerful and compact, efficient thermal management becomes critical to ensure their reliability and performance.

Principle of Heat Sinks

Heat sinks operate based on the principle of thermal conduction and convection. Thermal conduction is the process of heat transfer through a material, while convection involves the transfer of heat from a surface to a fluid (usually air or liquid) moving over it. A heat sink enhances the surface area in contact with the cooling medium, facilitating the dissipation of heat away from the electronic component.

The efficiency of a heat sink is measured by its thermal resistance, which indicates the temperature difference between the heat source and the cooling medium per unit power dissipated. A lower thermal resistance signifies a more effective heat sink.

Design Considerations

The design of a heat sink is influenced by several factors, including the amount of heat to be dissipated, the available space, and the cooling medium. Key parameters in heat sink design include surface area, material, fin design, and attachment method. Increasing the surface area of the heat sink allows more heat to be transferred to the cooling medium, often achieved through the use of fins or pins. The material of the heat sink significantly impacts its thermal conductivity; common materials include aluminum, known for its lightweight and good thermal conductivity, and copper, which has superior thermal conductivity but is heavier and more expensive. The shape, size, and orientation of fins affect the airflow and heat dissipation, with various designs like straight, flared, or pinned fins offering different thermal performance characteristics. The method of attaching the heat sink to the electronic component (e.g., thermal adhesive, mechanical clips, or screws) affects the thermal interface resistance. A good thermal interface material (TIM) is essential to minimize resistance and improve heat transfer.

Types of Heat Sinks

Heat sinks come in various types, tailored for specific applications and environments. The main types include passive heat sinks, active heat sinks, liquid-cooled heat sinks, and heat pipe heat sinks. Passive heat sinks rely solely on natural convection and radiation to dissipate heat. They are simpler, more reliable, and quieter but may not be sufficient for high-power applications. Active heat sinks use forced convection, typically through a fan, to enhance heat dissipation. Active heat sinks are more effective for high-power devices but introduce noise and additional power consumption. Liquid-cooled heat sinks involve a liquid coolant circulating through a heat exchanger to remove heat and are used in high-performance applications where air cooling is insufficient. Heat pipe heat sinks use heat pipes to transfer heat from the source to the heat sink more efficiently and are often combined with other types of heat sinks to enhance performance.

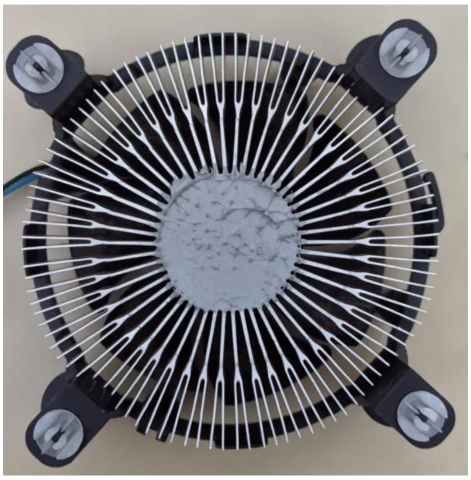

Figure 1 – A6063 Aluminum Heat Sink - Commercial Design

Applications

Heat sinks are ubiquitous in electronics, ranging from everyday consumer devices to high-performance computing systems. Common applications include computers and servers, LED lighting, power electronics, and automotive electronics. In computers and servers, CPUs and GPUs generate significant heat and rely on advanced heat sink designs for thermal management. High-power LEDs produce considerable heat, and efficient heat sinks are critical to maintain their performance and longevity. Power electronics, such as power transistors and rectifiers, use heat sinks to handle high power levels and prevent overheating. Automotive electronics employ heat sinks in control units, inverters, and other components to ensure reliability under varying temperature conditions.

MATERIAL SELECTION

With the development of the manufacturing industry, 3D metal printing offers innovative solutions. Due to the rapid and precise production of complex parts, it was decided to manufacture them with a heat sink 3D metal printing machine with topology optimization in this project. Leveraging the advantages of additive manufacturing method can lead to the production of more effective and efficient heat sinks. In our material selection, we considered the fact that this material is frequently preferred in SLM 3D printing applications.

Upon the identification of materials compatible with SLM 3D printing within the material selection process, an exploration of the specific considerations guiding this selection is undertaken. An analysis of material properties that augment product performance and those characteristics that were avoided is provided.

EOS Aluminum AlSi10Mg, its exceptional thermal conductivity facilities the removal of heat from the heat source, while its impressive strength and rigidity ensure structure integrity under demanding thermal loads. Additionally, its superior corrosion resistance safeguards the heat sink against environmental degradation, ensuring long-lasting performance. Furthermore, the materials lightweight nature contributes to weight optimization, a crucial factor in various applications. Notably, properties can be modified with heat treatments to

Main characteristics of EOS Aluminum AlSi10Mg are good strength, hardness and dynamic properties, High corrosion resistance, Good thermal and electrical conductivity, Properties can be modified with heat treatments, enabling customization to meet specific heat sink requirements.

Thermal conductivity

Thermal conductivity determines how well a material conducts heat. Materials with high thermal conductivity increase the performance of the heat sink by dissipating heat efficiently and quickly. Therefore, it is the most crucial feature.

Table 1 - Material Selection - Thermal Conductivity of EOS AlSi10Mg

Thermal Conductivity (ISO 22007-2:2015)			
Typical Values	As Manufactured	EOS T6 [W/m*K]	Stress-Relieved [W/m*K]
Vertical	100	165	160
Horizontal	110	155	165

Above is the table of thermal conductivity values of the EOS Aluminum AlSi10Mg material. These values are sufficient for an ideal heat sink production. (15)

Coefficient of thermal expansion

Thermal expansion coefficient determines how much material expands when exposed to heat. A low coefficient of thermal expansion reduces thermal stress and deformation, ensuring the long life of the material.

Table 2 - Material Selection - Coefficient of Thermal Expansion of EOS AlSi10Mg

Coefficient of Thermal Expansion			
Standard ASTM E228			
Temperature	25-100 (°C)	25-100 (°C)	25-300 (°C)
CTE	0.00002/K	0.000022/K	0.000027/K

Above is the table of coefficient of thermal expansion values of the EOS Aluminum AlSi10Mg material. These values show that coefficient of thermal expansion value of material is not problem for an ideal heat sink production. (15)

Density

The low weight of the heat sink is only possible if the density of the material is low. Low-density materials reduce the overall weight of the device, making it more user-friendly. Especially in portable devices, the weight of the device is very important.

According to research density of the EOS Aluminum AlSi10Mg is 2.67 g/cm^3. The value of the density of material is It will not create a handicap in terms of weight.

Corrosion Resistance

- EOS Aluminum AlSi10Mg generally demonstrates better, or comparable corrosion resistance compared to traditional aluminum alloys such as 5083, 1050, 3003, 6082, and A356. This is likely due to the microstructural advantages provided by additive manufacturing.
- Stress relief treated AM (Additive Manufacturing) AlSi10Mg performs better than cast and wrought traditional alloys, indicating its superior performance. (16)

Mechanical Strength

The durability and structural integrity of the material is important. The heat sink must be able to withstand mechanical stresses that may occur during assembly and use.

Table 3 - Material Selection - Mechanical Properties of EOS AlSi10Mg

Mechanical Properties (As Manufactured State)			
	Yield Strength [MPa]	Tensile Strength [MPa]	Elongation at Break
Vertical	230	460	6.3%
Horizontal	270	450	10.2%

Aluminum AlSi10Mg material is a material with sufficient strength for the heat sink. Mechanical strength values are given in the table above. (15)

TOPOLOGY OPTIMIZATION METHODOLOGY

Topology optimization is a computational method used in engineering design to determine the optimal material layout within a given design space based on specific performance criteria. The goal is to maximize or minimize an objective function, such as structural stiffness, weight, or thermal performance, while satisfying various constraints. For this purpose, a design variable known as design density is established, which ranges from 0 (representing no material or fluid) to 1 (representing solid material) for each finite element. A penalization scheme is employed to adjust the material distribution, discouraging intermediate values and ensuring a well-defined material layout.

In this topology optimization methodology, stationary study was used as the field variables do not change over time. The dependent variable was temperature. The main subject of this study was carried out on heat transfer in solids and COMSOL Multiphysics was used.

It is important to initially assign the parameters of the materials. (A360.0 and Air)

$$\rho_{solid} = 2670\ [kg/m^3]$$

$$\rho_{air} = 1.205\ [kg/m^3]$$

$$k_{solid} = 160\ [W/(m*K)]$$

$$k_{air} = 0.1\ [W/(m*K)]$$

$$C_{p_{solid}} = 870\ [J/(kg*K)]$$

$$C_{p_{air}} = 0.1\ [J/(kg*K)]$$

Then mesh and optimization parameters are determined. The penalty factor p diminishes the contribution of elements with intermediate densities (gray elements) to the total stiffness. The penalty factor steers the optimization solution to elements that are either solid black (ρ_{design} = 1) or void white (ρ_{design}= ρ_{min}). Numerical experiments indicate that a penalty factor value of p = 3 is suitable. (16)

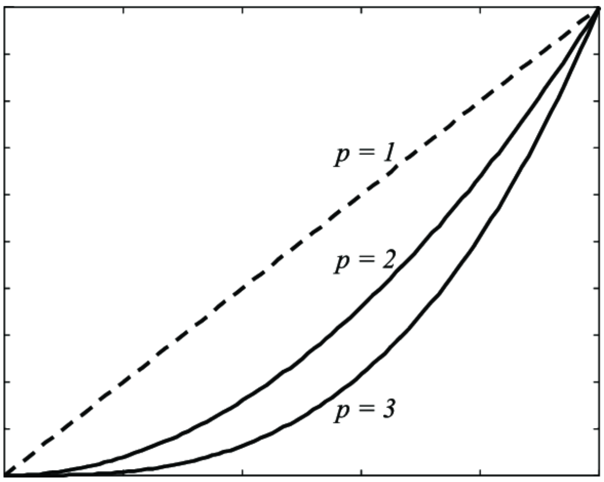

Figure 2 - Penalizations of the intermediate densities in the SIMP (Solid Isentropic Material with Penalization) model. (17)

Weighting between different objectives against each other;

$$q = 0.5$$

Penalization factor (It is used as 'n' in COMSOL.);

$$p = 3$$

Maximal mesh element size;

$$h_{\max\_solid} = 0.0002\ [m]$$

Minimal mesh element size;

$$h_{\max\_design} = 0.0001\ [m]$$

Parameter governing the size of details

$$h_0 = 0.000004\ [m]$$

Solid fraction of the domain;

$$\gamma = 0.67$$

Measured area;

$$A = 0.072666666402\ [m^2]$$

Geometry features and dimensions are determined. The circle to be used in this project has a radius of 44.925 mm and the center radius is 20 mm.

Figure 3 Designing the surface

Solid Isentropic Material with Penalization (SIMP) method is a method used in structural optimization problems. This method is often applied in topology optimization and aims to achieve the highest performance under a certain volume or weight limit by optimizing material distribution.

Material selection is determined by thermal conductivity, density and specific heat values. Variables 1;

$$k_{\text{simp}} = k_{\text{air}} + (k_{\text{solid}} - k_{\text{air}}) * dtopo1.\theta^{p}\ [W/(m * K)]$$

The purpose of this formula is to determine the effective thermal conductivity, which captures the effect of the material's topology and composition.

$$\rho_{\text{simp}} = \rho_{\text{air}} + (\rho_{\text{solid}} - \rho_{\text{air}}) * dtopo1.\theta^{p}\ [kg/m^{3}]$$

This formula is derived from similar principles used in the effective medium theory, which estimates the overall density of a composite or porous material by considering the densities of its constituent phases (air and solid).

$$Cp_{\text{simp}} = Cp_{\text{air}} + (Cp_{\text{solid}} - Cp_{\text{air}}) * dtopo1.\theta^{p}\ [J/(kg * K)]$$

The aim of this formula is to calculate the effective specific heat capacity of a material.

In the topology optimization, the density model and formulas created when using the density method are added to the COMSOL Multiphysics. These are the typical constraints used in many physical and mathematical models to describe a normalized variable or a fraction, a diffusion equation, and a parameterization equation that creates a new variable by adjusting the variable.

Density Model 1;

Name: dtopo1

$$0 \leq \theta_{c} \leq 1$$

$$\theta_{f} = \theta_{c} + R_{min}^{2}\nabla^{2}\theta_{f}$$

This formula resembles a diffusion equation, which describes the spatial rate of change.

$$\theta = \theta_{f}$$

$$\theta_{p} = \theta_{min} + (1 - \theta_{min})\theta^{p_{simp}}$$

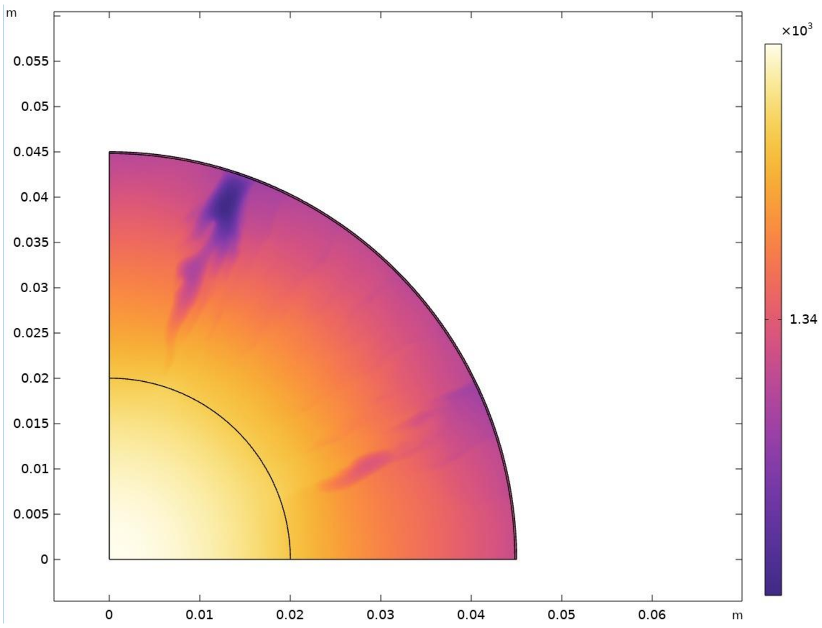

Figure 4 Heat Dissipation at 1/4 of the Heat Sink

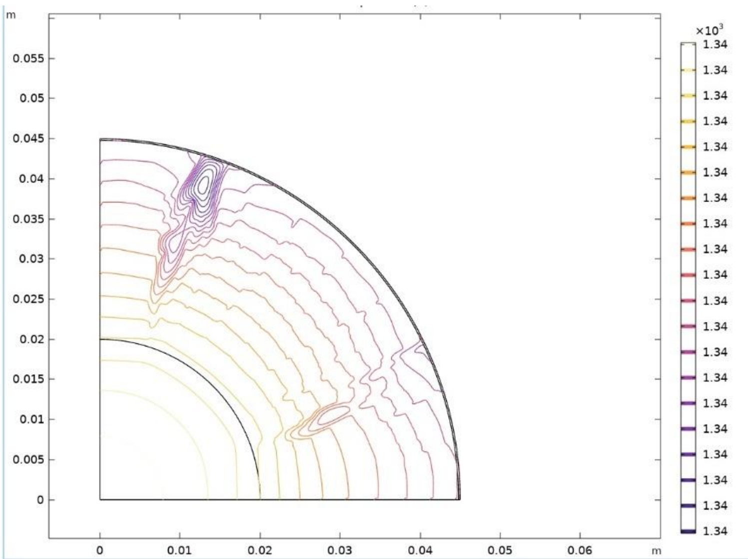

Figure 5 Isothermal Contours

This formula is a parameterization that adjusts the variable to create a new variable and a governed power law relationship.

Where the filter radius (R_{min}) is user defined. (h_0). Also, θ_{min} is user defined. (0.01)

The heat source is added to the system at the rate of heat. ($P_0 = 20W$) And the heat source is duplicated for the design area, it is called heat sink. (Here $P_0 = -10W$)

At this stage, heat flux definition should be made. In this report, the flux type is convective heat flux and convection type is external forced convection. Also, cylinder in cross flow is defined. (With 89 mm. diameter and 0.01 m/s velocity)

When meshing, user-controlled mesh is preferred, and element size is custom.

In this part, which is the last stage to show the optimization, topology optimization is selected from the study section, the method is selected, and the necessary information is processed.

Topology Optimization;

Method: MMA (Method of Moving Asymptotes)

MMA method is designed to handle large-scale structural optimization problems where other methods may struggle due to nonlinearity and complexity. This method is used to solve optimization problems where the objective is to minimize or maximize a function subject to a set of constraints. MMA combines the Navier-Stokes equations used for the motion of fluids with the energy equations used for heat transfer. This coupling brings together the momentum and energy transport processes, allowing the motion of fluids and heat transfer to be resolved together.

Optimality tolerance: 0.0001

Maximum number of iterations: 30

$$\begin{aligned}&\Big((1-q)*comp1.intop1\big(k_{\mathrm{simp}}*ht.gradTmag^2\big)+q*h_0*h_{\max\_design}\Big)\\&\qquad+0.000001/A\\&\qquad*comp1.intop1(sqrt\Big(0.001+d(comp1.dtopo1.\theta,x)^2\\&\qquad+\big(0.00001+d(comp1.dtopo1.\theta,y)\big)^2\Big)^2)\end{aligned}$$

This formulation aims to optimize thermal conductivity and temperature gradient distribution, ensures that a certain level of heat transfer performance or design specification is met, and adds a regulation to control the smoothness of the design variable.

With the final stage, topology optimization was made for the designed heat sink.

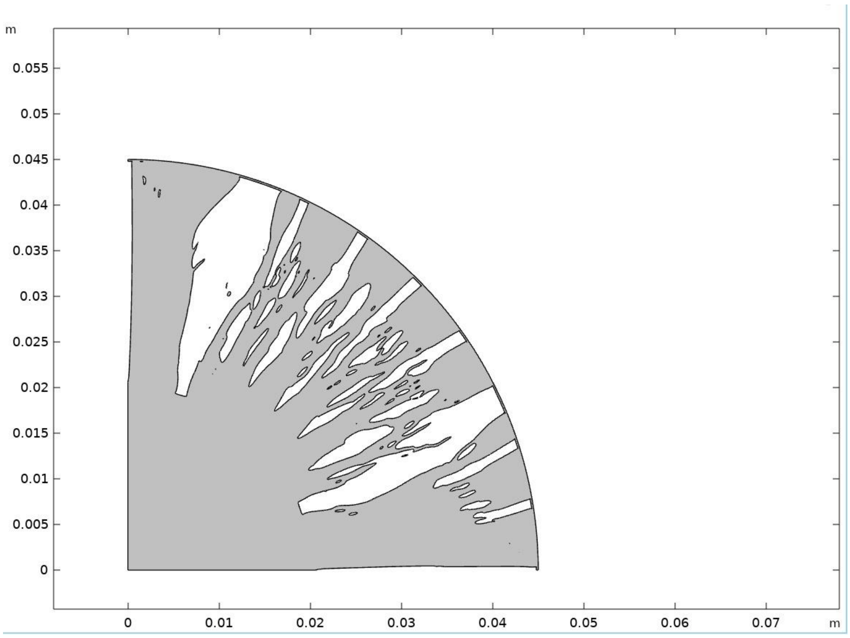

Figure 6 Topology Optimized 2D geometry

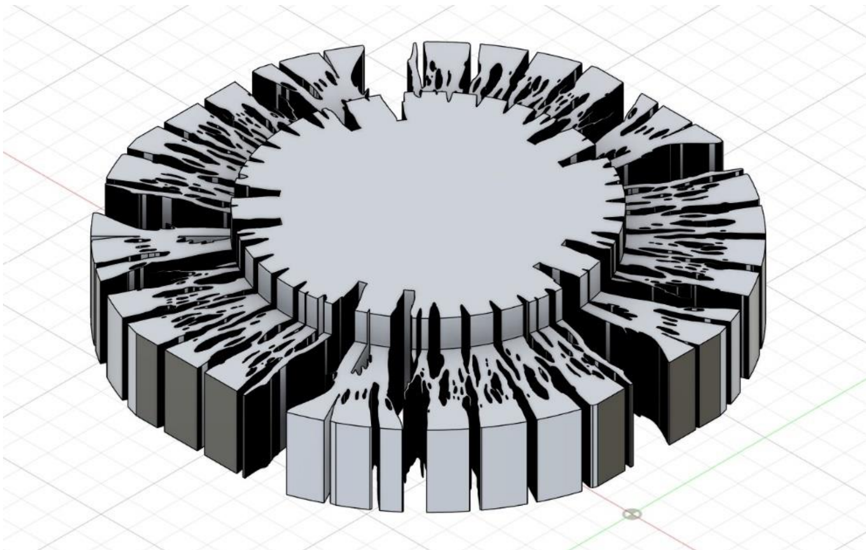

Figure 7 Topology Optimized Design of Heat Sink

CALCULATIONS

Commercial Heat Sink

Conduction Equation (Between CPU and Heat Sink)

$$Q_{cond} = \frac{k * A * (T_{CPU} - T_{HS})}{d}$$

$$k = 160\, W/m * K\ (Thermal\ conductivity\ coefficient\ for\ solid)$$

$$Q_{cond} = 32.409W$$

$$A = 0.00132012\ m^2$$

$$T_{CPU} = 59.0\ ℃$$

$$d = 0.001m\ (Thin\ thermal\ paste\ layer\ thickness)$$

$$T_{HS} = 58.846\ ℃$$

Forced Convection Equation (Heat Sink to Air)

$$Q_{conv} = h * A * (T_{HS} - T_{air})$$

$$h = 100\ W/m^2 * K\ (Heat\ transfer\ coefficient\ for\ air)$$

$$A = 0.07266665\ m^2\ \ (Surface\ Area\ of\ Commercial\ Heat\ Sink)$$

$$T_{air} = 25\ ℃\ (Assumed)$$

$$Q_{conv} = 245.9W$$

[DESKTOP-46TP43V] CPU [#0]: Intel Pentium G4560: Enhanced				
CPU Tümü	57.0 °C	29.0 °C	59.0 °C	53.4 °C
CPU IA Çekirdekleri	57.0 °C	28.0 °C	59.0 °C	53.4 °C
CPU GT Çekirdekleri (Grafik)	45.0 °C	28.0 °C	46.0 °C	42.5 °C
IA Gerilim Ofseti	0.000 V	0.000 V	0.000 V	0.000 V
GT (Slice) Gerilim Ofseti	0.000 V	0.000 V	0.000 V	0.000 V
CLR (CBo/LLC/Ring) Gerilim Ofseti	0.000 V	0.000 V	0.000 V	0.000 V
GT (Unslice) Gerilim Ofseti	0.000 V	0.000 V	0.000 V	0.000 V
Uncore/SA Gerilim Ofseti	0.000 V	0.000 V	0.000 V	0.000 V
VR VCC Akımı (SVID IOUT)	20.110 A	1.523 A	21.024 A	17.526 A
CPU Tüm Güç Tüketimi	31.663 W	5.679 W	32.409 W	27.373 W
IA Çekirdekleri Güç Tüketimi	19.839 W	1.088 W	20.666 W	17.088 W
Toplam DRAM Gücü	1.605 W	0.462 W	2.111 W	1.191 W
Geri Kalan Güç Tüketimi	11.852 W	4.017 W	11.903 W	10.315 W
PL1 Güç Sınırı (Static)	115.000 W	115.000 W	115.000 W	115.000 W
PL2 Güç Sınırı (Static)	130.000 W	130.000 W	130.000 W	130.000 W

Figure 8 - Thermal Test Results of A6063 - Commercial Heat Sink

Topological Heat Sink

Conduction Equation (Between CPU and Heat Sink)

$$Q_{cond} = \frac{k * A * (T_{CPU} - T_{HS})}{d}$$

$$k = 160\ W/m * K\ (Thermal\ conductivity\ coefficient\ for\ solid)$$

$$Q_{cond}$$

$$A = 0.00132012\ m^2$$

$$T_{CPU}$$

$$d = 0.001m\ (Thin\ thermal\ paste\ layer\ thickness)$$

$$T_{HS}$$

Forced Convection Equation (Heat Sink to Air)

$$Q_{conv} = h * A * (T_{HS} - T_{air})$$

$$h = 100\ W/m^2 * K\ (Heat\ transfer\ coefficient\ for\ air)$$

$$A = 0.06031809\ m^2\ (Surface\ Area\ of\ Topological\ Design)$$

$$T_{air} = 25\ ℃\ (Assumed)$$

$$Q_{conv}$$

Since the topological design could not be produced at this stage, testing could not be done. Maximum temperature value and CPU power consumption values could not be determined. If the production yielded positive results, we would apply the steps we applied in the commercial heat sink to the topological design.

MANUFACTURING

When using topology optimization for designing heat sinks, we faced with very hard geometries. To be able to manufacture these geometries, additive manufacturing is very useful because of its abilities.

In the designing phase, after the topology optimization is done, 3D CAD file should be prepared. A detailed 3D CAD model of the heat sink is created, including optimized fin structures, mounting features, and any channels for enhanced airflow or liquid cooling. After CAD files are ready, files must be saved with ".stl" extension. After the extension of the file is ready, the slicer programs can be used. These slicer programs turn 3D CAD files into the hundreds of layers. When slicing or layering process is done, the file for the additive manufacturing should be ready with the ".gcode" extension.

Direct Laser Metal Sintering (DLMS), also known as Direct Metal Laser Sintering (DMLS), is an additive manufacturing technique used for creating complex and high-performance metal parts directly from digital models. Which is the best way to use for this project.

DLMS allows the production of intricate and optimized geometries that are difficult or impossible to achieve with traditional manufacturing methods. This is particularly beneficial for heat sinks, where complex fin designs can enhance thermal performance. The process minimizes material waste since it involves adding material layer by layer only where needed, contrasting with subtractive methods like milling, which remove material from a larger block. Additionally, the digital nature of DLMS allows for easy customization and rapid prototyping, enabling each heat sink to be tailored to specific thermal requirements and physical constraints. The resulting parts have excellent mechanical properties, often comparable to those made by conventional methods, making the heat sinks strong, durable, and capable of withstanding high thermal and mechanical stresses.

In DLMS machines, lots of different materials can be used. For example, AlSi10Mg is one of the materials that can be used for heat sink production because of its thermal conductivity and specific heat properties.

If the material selection is ABS plastic instead of metal alloy for some reasons, FDM additive manufacturing devices can be used.

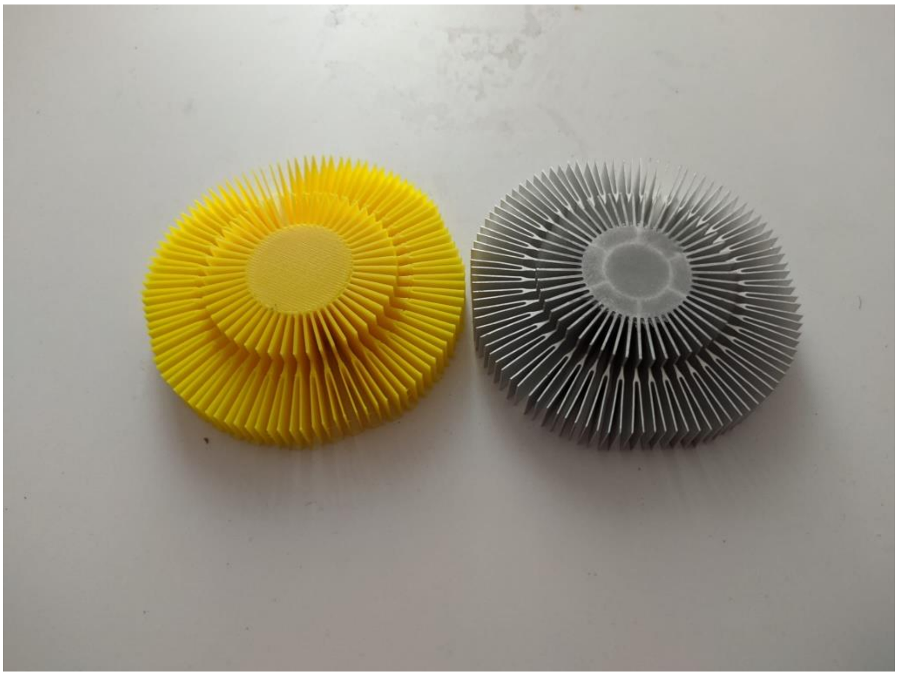

Figure 9 ABS commercial and Aluminum Commercial Heat Sinks

TEST PROCEDURE

Equipment list

- Intel G4560 CPU
- Intel 57A01B1 Fan
- Cooler Master E1 Thermal Paste
- LED Monitor
- Fakir VC 20 S 50 Hz 55-Watt External Fan
- H110M pro Motherboard
- Commercial Heat Sink manufactured with ABS
- Topology Optimized Heat Sink manufactured with ABS

Preparation Phase

1. Inspection and Cleaning of the Heat Sink: Inspect the heat sink for any physical damage or manufacturing defects.
2. Clean the surface of any dirt, oil, or dust. Use isopropyl alcohol and a microfiber cloth to wipe the surface.
3. Preparation of the CPU and Motherboard: Mount the CPU onto the motherboard.
4. Clean the surface of the CPU. Remove any residual thermal paste using isopropyl alcohol and a microfiber cloth.

Mounting the Heat Sink

1. Application of Thermal Paste: Apply a small, pea-sized amount of thermal paste to the center of the CPU.
2. Spread the thermal paste evenly across the CPU surface using a plastic spreader or by placing the heat sink and allowing the pressure to spread the paste.

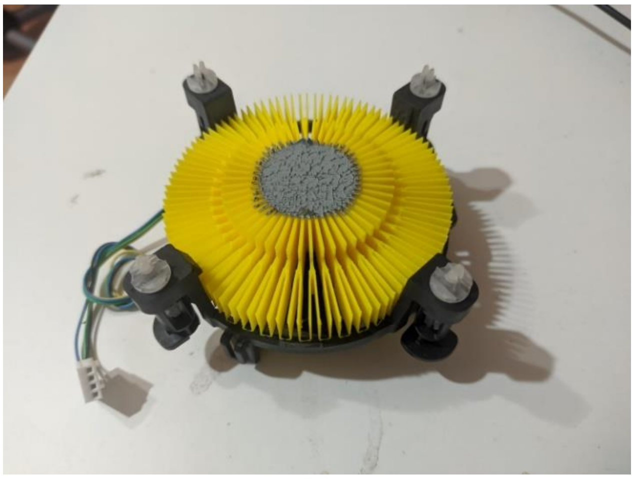

Figure 10 Thermal Paste Applied Commercial ABS Heat Sink

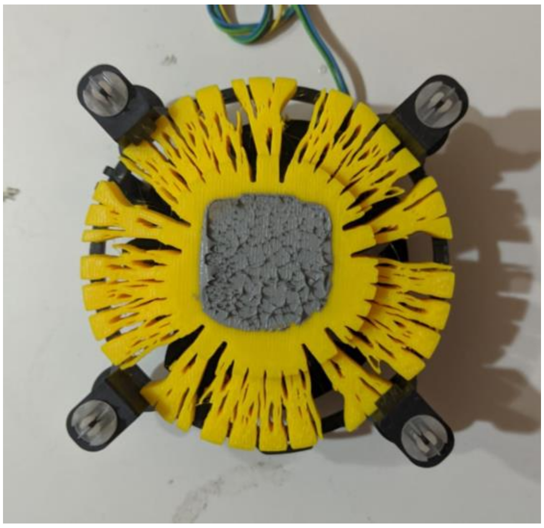

Figure 11 FDM Manufactured Toplogy Optimized Heat Sink

Attaching the Heat Sink

1. Place the heat sink onto the CPU with Intel 57A01B1 Fan, ensuring it is properly aligned.
2. Secure the fan screws with turning them counterclockwise after plugging them into the motherboard.
3. Ensure even pressure is applied across the heat sink to avoid air gaps.
4. If the heat sink is manufactured from ABS material, An external Fan (Fakir VC 20 S 50 Hz 55-Watt External Fan) have to be used to be able to complete the test before CPU gets overheated and system shut down.

Figure 12 Topologic Heat Sink Mounted on the CPU

Testing Phase

1. Initial Power-On and System Stability Check: Power on the system and enter the BIOS/UEFI to monitor initial CPU temperatures.
2. Check for any immediate overheating or improper contact between the heat sink and CPU.

Temperature Measurement

1. Boot into the operating system and let the system idle for at least a couple of minutes.
2. Open task manager, searching motor and temperature monitoring software to be able to see the temperature values of the system simultaneously.
3. As temperature monitoring software HWMonitor can used to record the temperatures of the CPU.

Load Temperature Measurement

1. Run a CPU stress test using software like Prime95, AIDA64, or similar tools for a duration of 30 minutes. However, if ABS made heat sink is used, only task manager, searching motor and temperature monitoring software will be enough to overheat the CPU because of lower thermal conductivity of the ABS material.
2. Monitor and record the CPU temperatures throughout the stress test.

Analysis of Results

1. Compare the recorded temperatures with the CPU’s maximum operating temperature specifications.
2. Evaluate the performance of the heat sink based on the temperature data collected.

Inspection After Testing

1. Power off the system and remove the heat sink.
2. Inspect the thermal paste spread and contact area between the heat sink and CPU.
3. Check for any signs of overheating or physical damage.

COST ANALYSIS

This cost analysis aims to provide a comprehensive overview of the expenses involved in the topological design and production of aluminum heat sinks using additive manufacturing methods. The analysis will include software costs for topology optimization, production quotes from regional companies, and material costs for FDM printing. The data is organized in three tables. The first table presents the annual fees of various topological optimization software. The second shows price quotes received from two regional companies for the production of aluminum heat sinks. The last table details the production costs of heat reducers of different weights and the cost per kilogram of raw material.

Table 4 - Cost Analysis - Software and Annual License Fees

Software	Price
ANSYS	$3,000 - $10,000
Altair OptStruct	$2,000 - $7,000
COMSOL Multiphysics	$600 - $4,000
Siemens NX	$3,000 - $8,000
Abaqus	$3,000 - $8,000

The data in the table consists of approximate values.

The table lists annual subscription fees for various topology optimization software options. Among these, COMSOL Multiphysics stands out as a cost-effective choice with a price range of $ 600 to $ 4,000. COMSOL is the primary choice with its more affordable price and comprehensive features in multi-physics simulation. We used the COMSOL Multiphysics program for the thermal and structural analysis needed in this project.

Table 6 - Cost Analysis - Producing Companies and Their Quotes

Producing Company	Quote
PLG Lab	€ 384
Xometry TR	€ 404

This table shows offers from two regional companies, PLG Lab and Xometry TR, for the production of aluminum heatsinks using additive manufacturing. PLG Lab offers a lower price of € 384 compared to Xometry TR's offer of € 404. This comparison shows that, assuming both companies have a similar structure, choosing PLG Lab can save costs while ensuring the same product quality. However, when evaluated for the cost of a single product of these sizes, it is observed that the prices are high.

Table 8 - Cost Analysis - Raw Material Cost of Two Different Designs

A kilogram of ESUN ABS+ Filament cost: ₺ 550	
Topological Design (67gr)	Commercial Design (32gr)
₺ 36.85	₺ 17.6

The above summarizes the production costs of two different weights of heat sinks using FDM printers. The price per kilogram of ESUN ABS+ filament is ₺ 550. In this regard, the cost of producing a 67-gram topological design is ₺ 36.85, and the cost of a 32-gram commercial design is ₺ 17.6. In order to obtain the full production cost, hourly electricity and waste material costs, as well as machine wear and tear costs, must be added to these material costs. Since the costs to be added for these designs, whose production times are around 5 hours, will be low, raw material costs are sufficient for comparison.

In summary, this cost analysis provides a detailed view of the expenses associated with the topological design and fabrication of heat sinks. Overall, the analysis highlights the selection of COMSOL Multiphysics due to its cost effectiveness and capability, comparison of manufacturing quotes from PLG Lab and Xometry TR, and calculation of material costs for FDM printing. Assuming that an agreement is made with PLG Lab to produce the output in aluminum, the topological design of which is carried out by choosing COMSOL, the total cost is on average 1635 dollars. When plastic production is carried out, the total cost is 1225 dollars.

RESULTS

When we complete the experiment as the way that we explained in the Test Procedure, we collected the data for each heatsink design. In the first experiment, we applied thermal paste to the commercial heat sink design and complete the assembly on the motherboard with Intel 57A01B1 fan. The 10-minute test, with only three programs opened which are the command center, search motor and HWInfo, completed and data is shown below.

CPU Tümü	91 °C	59 °C	94 °C	74 °C
CPU IA Çekirdekleri	91 °C	59 °C	94 °C	74 °C
CPU GT Çekirdekleri (Grafik)	77 °C	59 °C	80 °C	70 °C
Gerilim Ofsetleri		0.000 V	0.000 V	
VR VCC Akımı (SVID IOUT)	17.063 A	2.438 A	18.586 A	9.871 A
CPU Tüm Güç Tüketimi	14.179 W	5.700 W	28.233 W	16.621 W

Figure 13 - Thermal Test Result of ABS Heat Sink - Commercial Design

The maximum temperature that CPU undergoes is 94 ^{O}C with the commercial heat sink design manufactured with ABS plastic. And the average temperature during the 10 minutes test interval is 74 ^{o}C.

When we dismantled the Commercial Heat sink and change it with the Topologically Designed Heat Sink, we implemented the same test procedure. The results of the test for Topologically Designed Heat Sink are shown below.

CPU Tümü	84 °C	60 °C	89 °C	71 °C
CPU IA Çekirdekleri	84 °C	60 °C	89 °C	71 °C
CPU GT Çekirdekleri (Grafik)	70 °C	56 °C	77 °C	66 °C
Gerilim Ofsetleri		0.000 V	0.000 V	
VR VCC Akımı (SVID IOUT)	16.758 A	2.438 A	18.586 A	9.491 A
CPU Tüm Güç Tüketimi	11.461 W	6.335 W	27.464 W	16.032 W

Figure 14 - Thermal Test Result of ABS Heat Sink - Topologic Design

The results of the Topology Optimized Heat Sink experiment with the same fan and the same conditions shows that, the maximum temperature that CPU undergoes during the test is 89^{o}C and the average temperature during the 10-minute test is 71^{o}C.

So, the topology optimized design is cooling 5.32% more when we compare it with the commercial heat sink design. Also, the average temperature is decreased by 3^{o}C.

DISCUSSION

In this project, it is aimed to produce a topology-optimized heat sink with the additive manufacturing method and to compare it with a traditional heat sink. However, throughout the project, some problems were encountered during the production and topology optimization phases. Because of the lack of information on the web, our topology optimization process took too much time and effort for our project team. When 2D design completed, we created 3D CAD design with SolidWorks and Fusion360, we used 72 degrees of our 90-degree design part and rotate the 72 degree part 5 times. Which created our 3D Design.

We researched and contacted many companies to complete the additive manufacturing phase. We tried to get an affordable price for our manufacturing. But as shown in the cost analysis part, most of the companies did not return to our mails and others gave expensive prices. As a result, we decided to continue with Polygon Engineering to produce our topology-optimized heat sink. When we contacted the company officials, they want to move our project to the production phase immediately and we planned in line with the feedback they gave. However, this process took too long due to the company's ongoing productions and the holiday break also the company told us that they could not complete the production until the 22.06.2024.

Because of the geometries on the topology optimized heat sink, every step that we are trying to complete took too much time. Even deleting one point on the 2D design took 20-30 minutes for our computers. Moreover, the price offer, we received from the company exceeded our budget, we could not produce it with EOS Aluminum AlSi10Mg material. So, we tried to complete the manufacturing phase with our own methods which is FDM 3D printing, using ABS material, to continue the project. The reason that we choose the ABS is, ABS is the most thermally conductive plastic that we can produce from our FDM 3D printing machines. (19). We decided to produce the heat sink designs, both Commercial one and topology optimized one with our Creality K1 brand 3D printer and then compare it and successfully complete the project.

To be able to complete the thermal tests, we needed extra external cooling. Because computer was reaching the critical temperatures and immediately shutdowns itself. And as a result, and thanks to the external fan, we successfully completed the thermal test and compared the cooling performances of two different geometries which are produced from the same material and experienced same test procedure.

CONCLUSION

In this project, we aimed to explore the feasibility of producing a heat sink using Direct Laser Metal Sintering (DLMS) but shifted to ABS plastic due to problems encountered in metal manufacturing. Despite this deviation from the original metal design, we successfully demonstrated the significance of topology optimization in achieving targeted thermal efficiency. The efficiency we achieved with the difference between the heat sink we designed with topology optimization and the commercial heat sink used was revealed in the presence of topology optimization.

Topology optimization allowed us to refine the heat sink design by systematically redistributing material within the constraints of ABS plastic manufacturing. By leveraging advanced computational algorithms, we optimized the structure to enhance heat dissipation while maintaining structural integrity. This approach not only aligned with our thermal performance goals but also underscored the versatility of topology optimization in adapting designs across different manufacturing processes.

Comparing the ABS plastic heat sink with the originally intended metal design provided valuable insights. While the thermal conductivity of ABS plastic is lower than metals, our optimized topology effectively compensated for this limitation. Through thermal testing and analysis, we confirmed that the optimized design achieved the desired thermal efficiency, showcasing the practical benefits of topology optimization in overcoming material constraints. In addition, the cost analysis we worked on, the results obtained and the comparisons we were able to make enabled us to obtain new information in heat sink design in terms of manufacturability.

Moving forward, the success of this project highlights the importance of embracing adaptive design methodologies like topology optimization. By focusing on functional performance rather than material specificity, engineers can innovate more flexibly and efficiently, particularly in contexts where material choices are restricted. This project not only validated our approach to heat sink design, but also enabled the investigation of hybrid manufacturing strategies that blend optimized designs with appropriate materials and maximize performance in spread applications.

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