Thermal Response of Additive Manufactured Aluminum

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Benefits Brought by 3D Printing

- Complexity free without additional cost
  - More degrees of freedom
  - Higher performance thermal management system
  - Higher fill factor
  - Higher power density
- Fast manufacture response time
  - Rapid prototyping
- More integrated functions and components
- Reduction in component count
  - Simplify the assemble process

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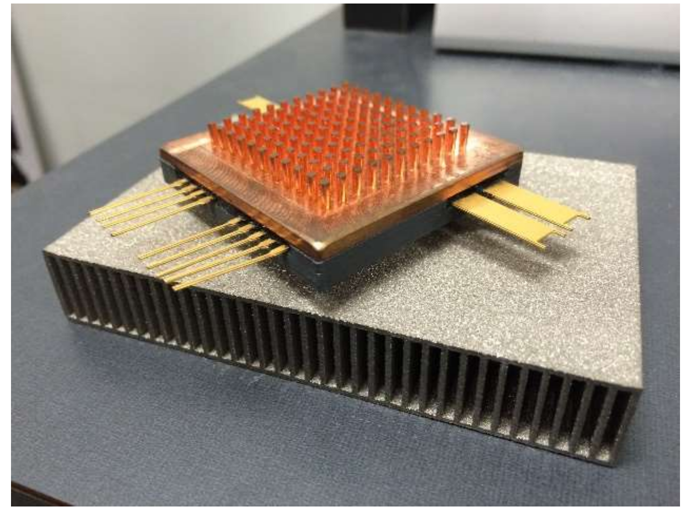
3D Printing in Power Electronics

- Polymers
- Metals
  - Titanium
  - Aluminum
  - Stainless Steel
  - Copper
  - Brass
  - others
- Ceramics

Aluminum Alloys

Conventional manufactured	3D printed
6xxx series(Al-Mg-Si)	AlSi10Mg
5xxx series(Al-Mg)	
3xxx series	
1xxx series	



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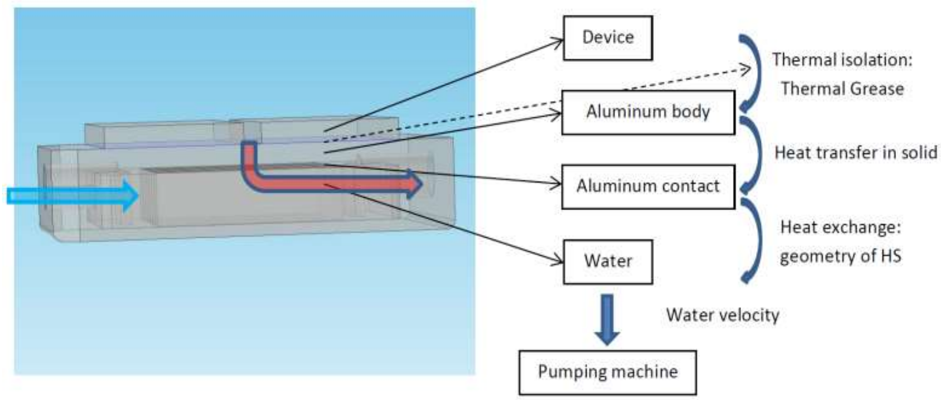
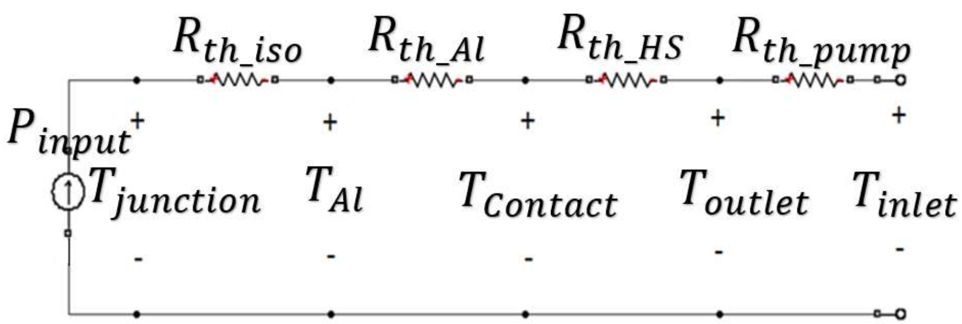
Conjugate Heat Transfer – Liquid cooled system





$$T_{outlet} = T_{inlet} + R_{th\,pump} \times P_{input}.$$

$$T_{junction} = T_{inlet} + (R_{th_{isolation}} + R_{th_{Aluminum}} + R_{th\,HE} + R_{th\,pump}) \times P_{input}$$

- A different heat dissipation.
- Changing $R_{th\,isolation}$ or even eliminating the thermal grease
- Changing $R_{th\,pump}$ by adjusting the liquid inlet speed
- Changing T_{inlet}, which will be again determined by the cooling costs.
- Varying $R_{th\,Aluminum}$, affected by the thermal conductivity of the material used

$$R = \frac{1}{\sigma} \cdot \frac{l}{A}$$

- Using a different heat sink geometry, which introduces different $R_{th\,HE}$ values.

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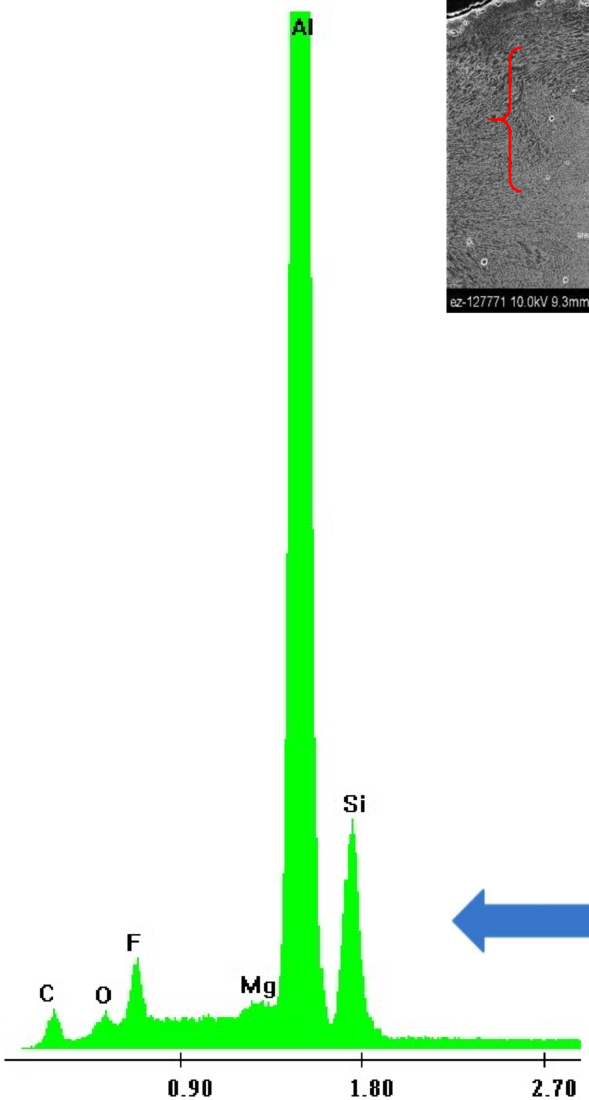
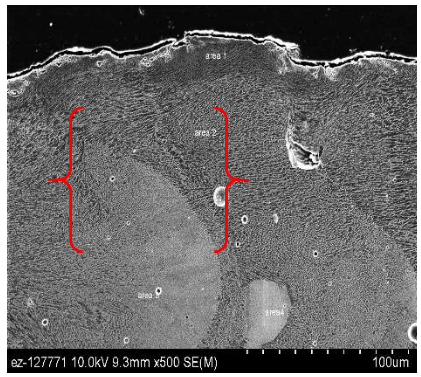
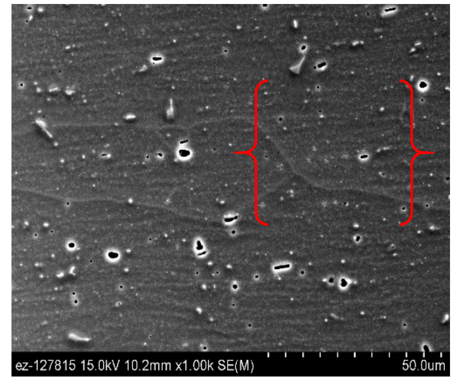
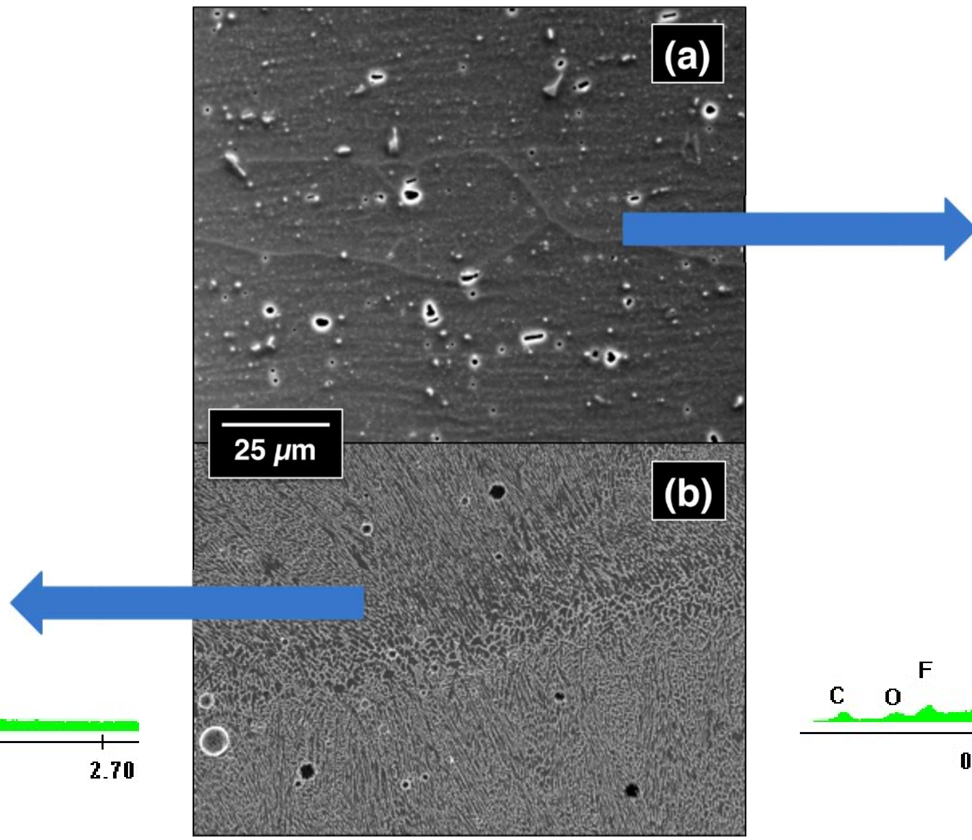
Material Composition

Additive-manufactured Aluminum alloy

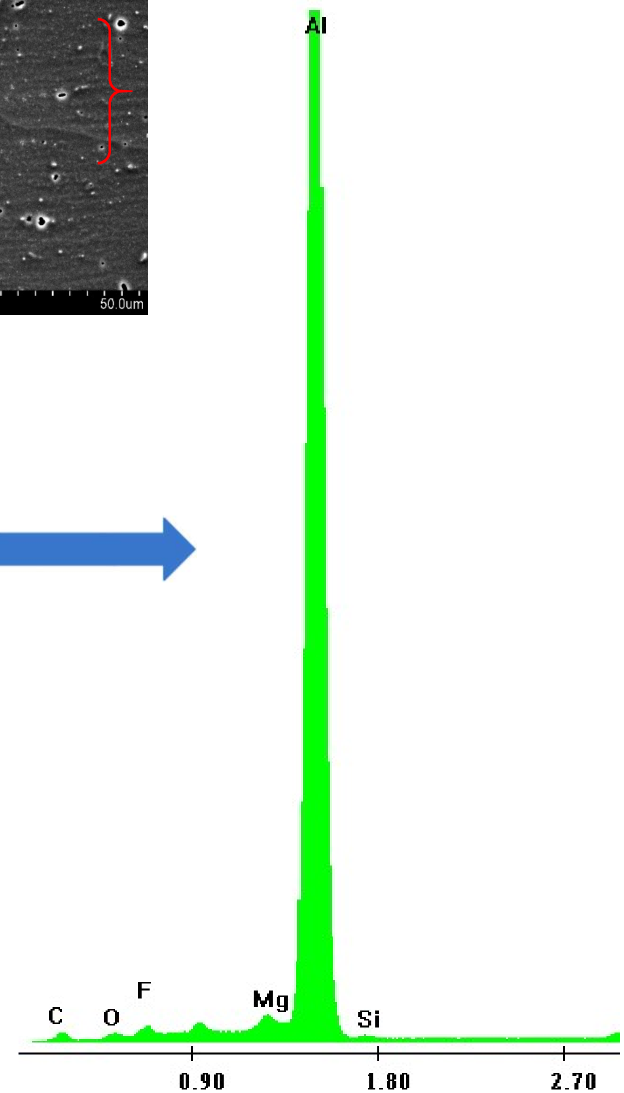




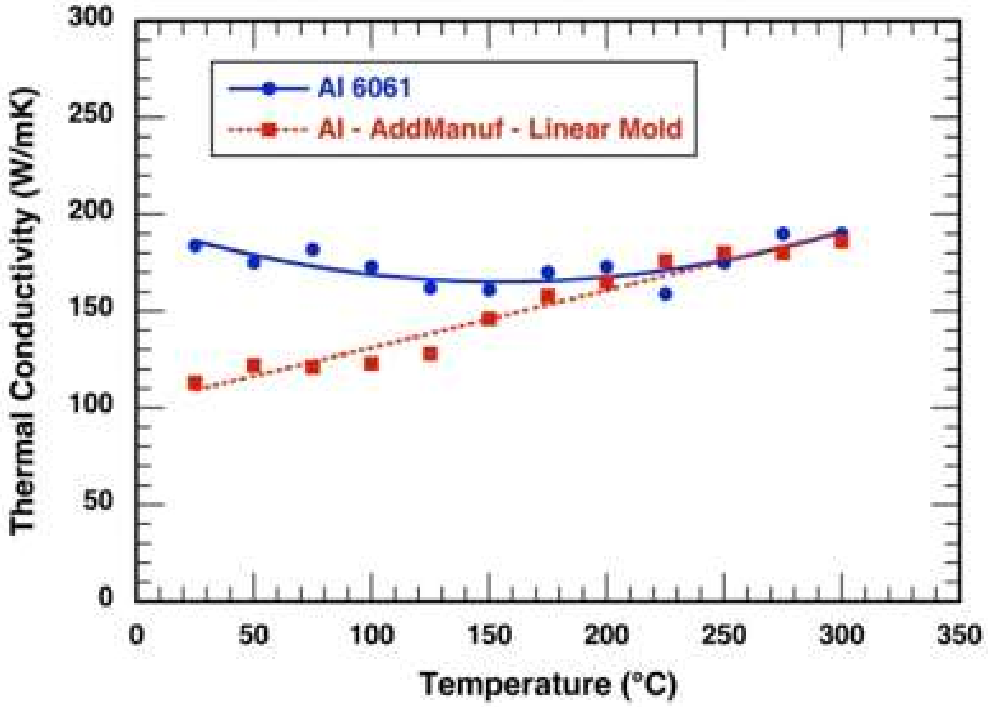




Aluminum 6061



Thermal Conductivity

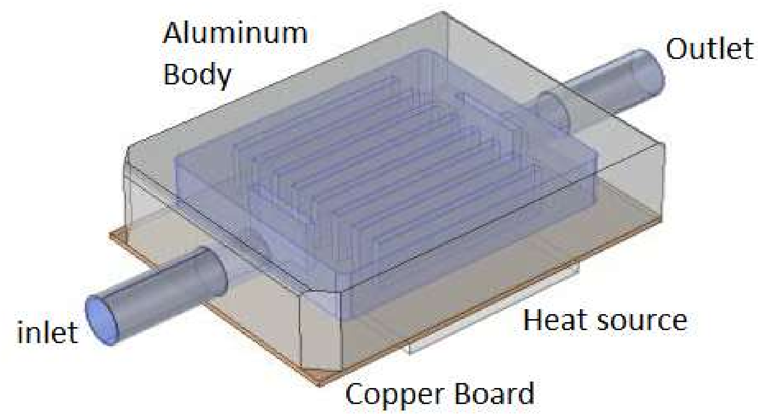


One-way test up to 350 ºC

Identical heat sinks

- 2 identical geometry Aluminum heatsinks
- Both contact surfaces are polished evenly
- Manufactured by conventional Aluminum 6061/ Additive manufactured Aluminum
- Size of the heatsink body is $4\ inch \times 3\ inch \times 1\ inch$

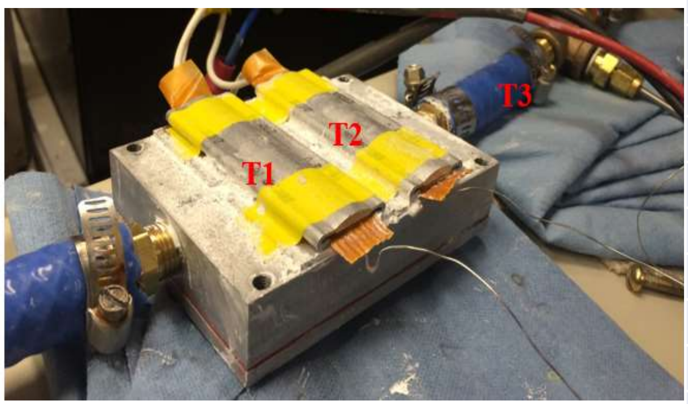
Heat sink manufactured for test



Heat sink model for FEA simulation

Experimental Setup

- Two series heat sources with cross voltage changes from 10V – 45V
- Thermal grease is used
- Thermal resistance cover is mounted
- Recycling loop pump provides inlet water speed 1.1 L/min at 20℃
- Three temperatures are measured
- K type Omega thermal couples with a precision of 0.1℃



Voltage(V)	Current(A)	Power(W)
10	1.08	10.8
20	2.45	49
24	3.145	75.48
28	4.04	113.12
32	5.23	167.36
36	6.89	248.04
40	9.1	364
43	10.525	452.575
45	11.27	507.15

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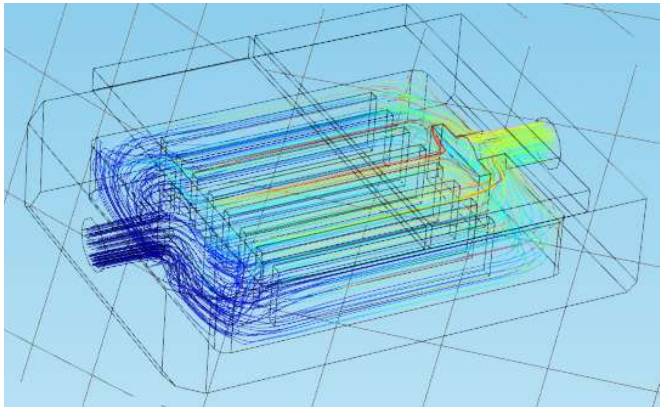
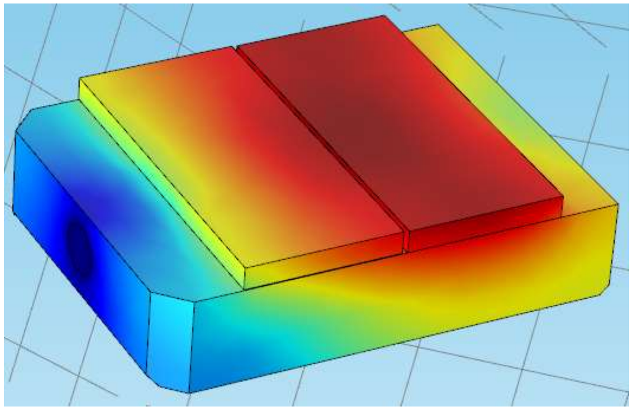
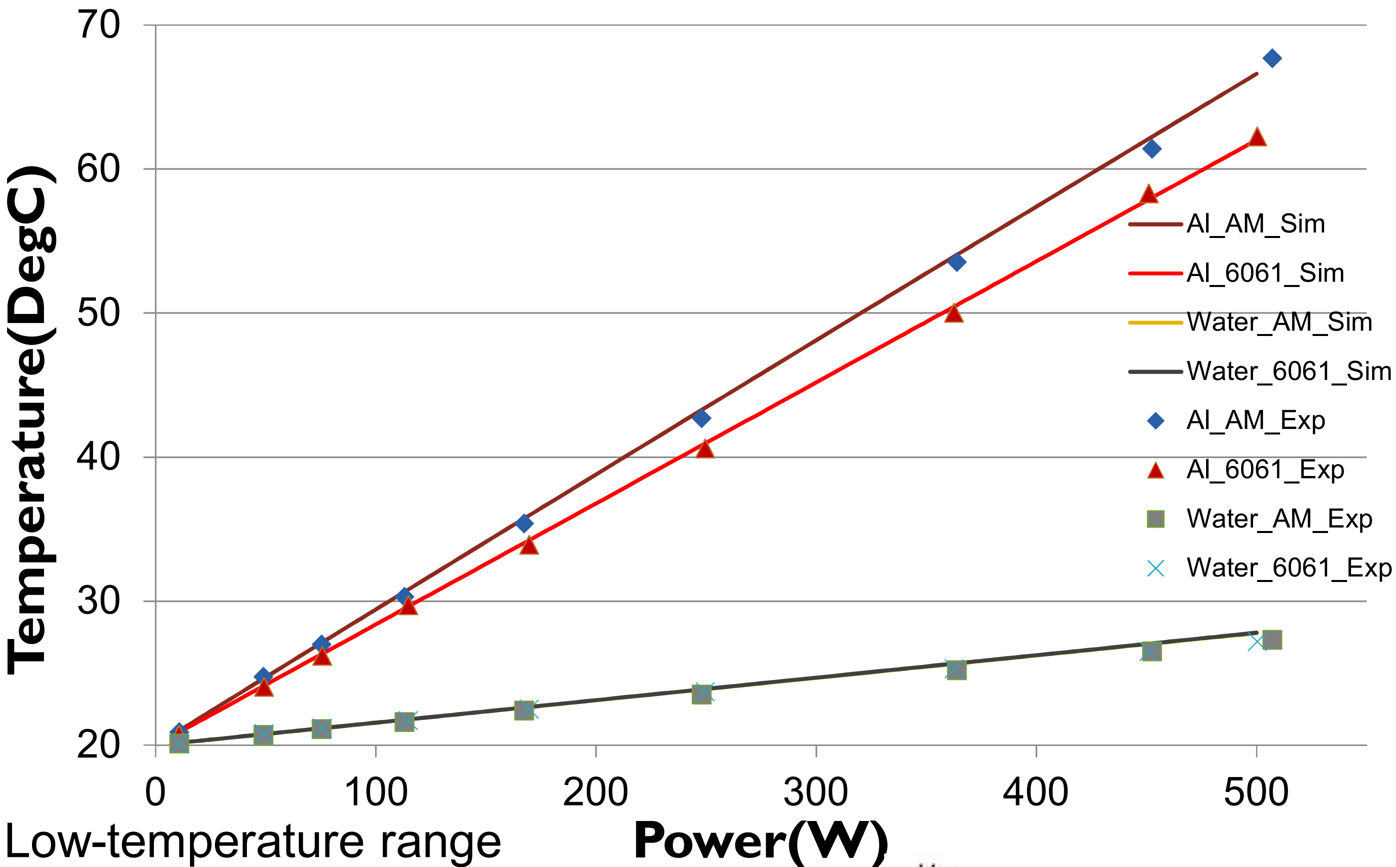
Simulation Setup

- Two heat sources provide power in total from 10W – 500W
- A thermal isolation layer is defined as thermal conductivity of 0.8W/(m·K) and thickness of 0.3 mm
- No natural convection heat exchange
- Inlet set as laminar flow rate of 1.1 L/min and temperature of 20℃
- Temperatures of three identical location as the experimental group are measured
- COMSOL is used as the FEA simulation software

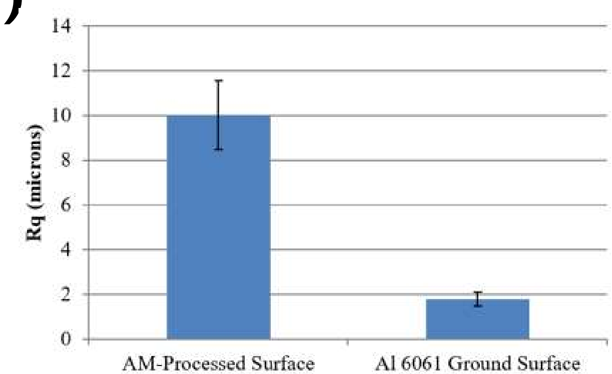




Results Comparison and Significance



- Low-temperature range
- 10% performance difference
- Outlet water temperature
- Mismatch in the AM group



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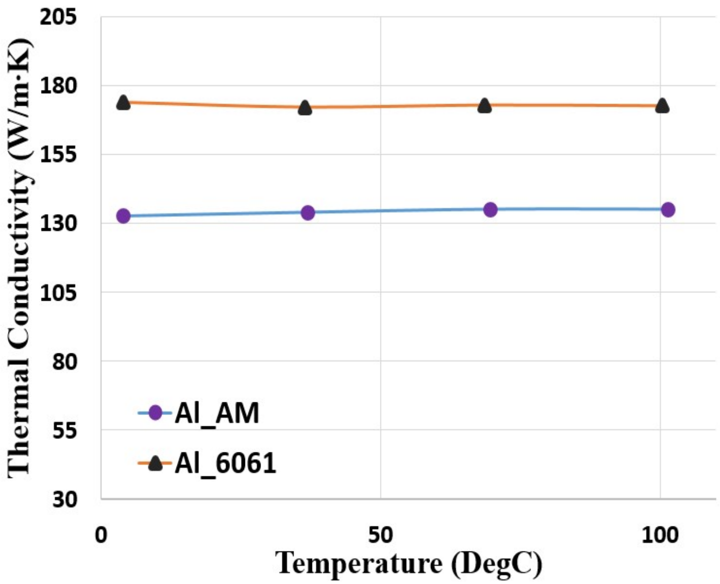
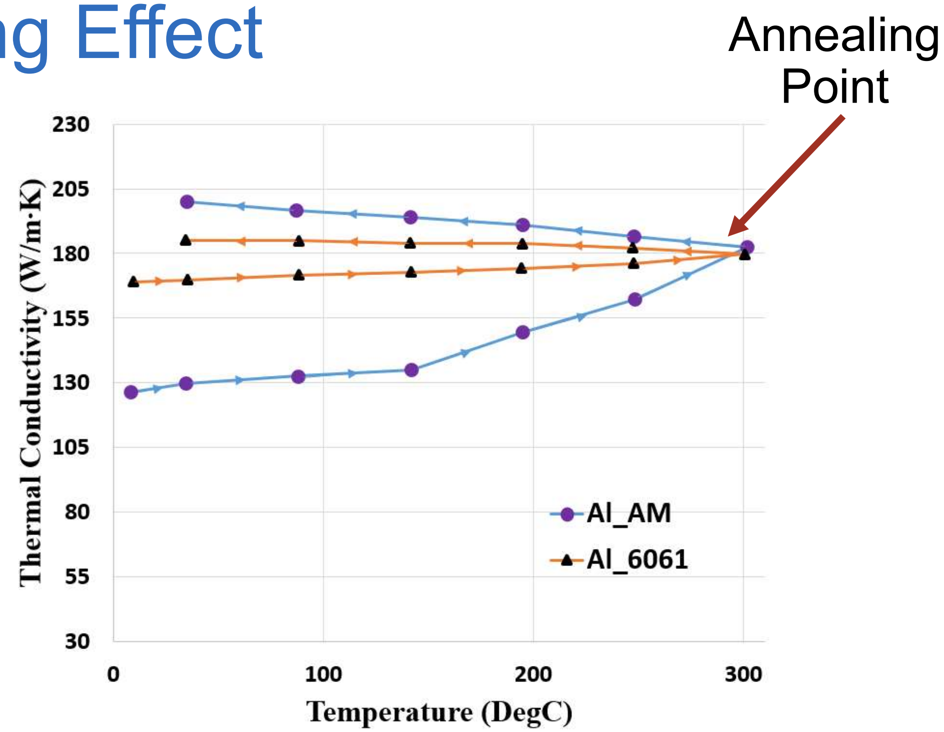
Post-processing

Annealing Effect



Round-trip test up to 100 ºC

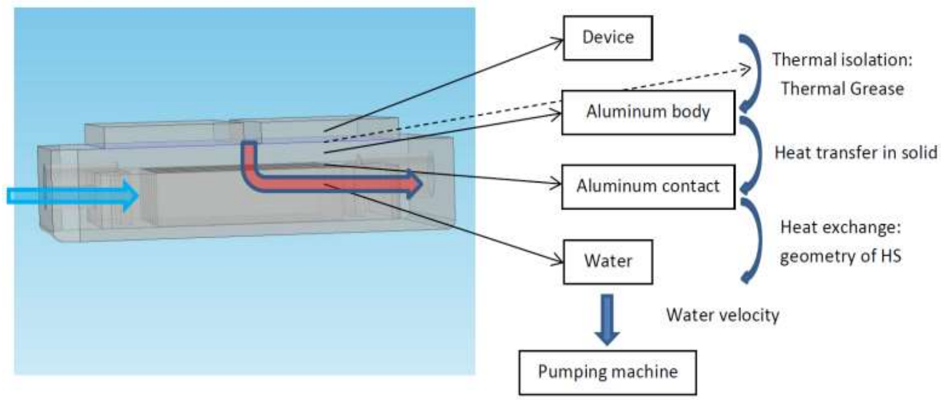


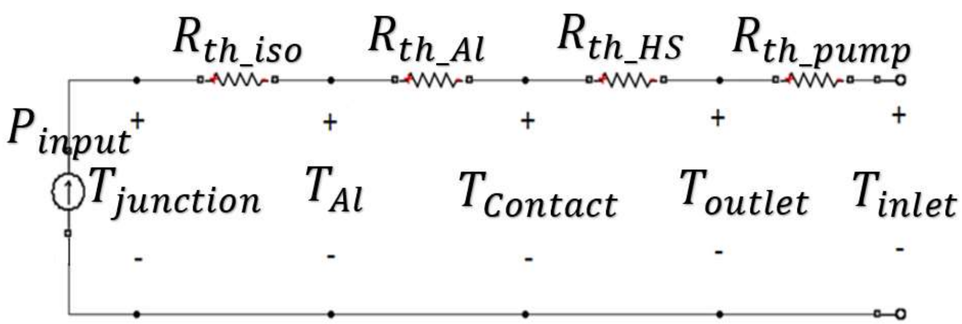
Round-trip test up to 300 ºC

Over the annealing point, the thermal property of the Al_AM will permanently change, and the gap of material properties is erased.

One possible solution!

Conjugate Heat Transfer – Liquid cooled system





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- Using a different heat sink geometry, which introduces different $R_{th\,HE}$ values.

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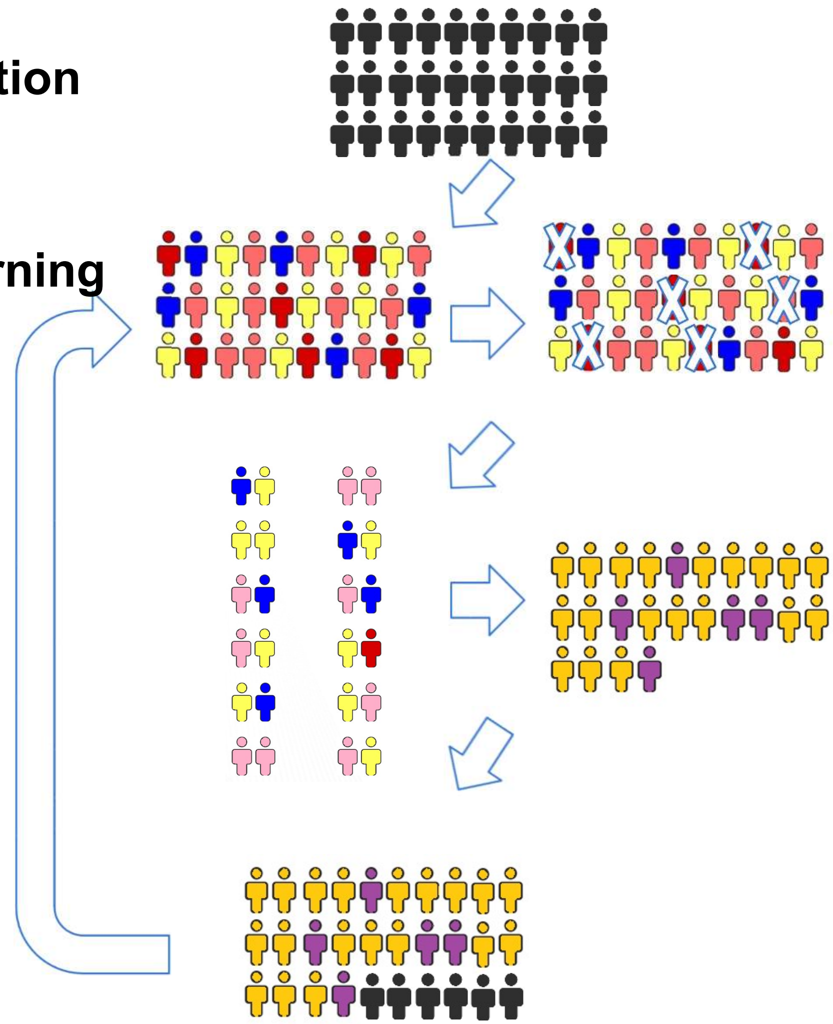
Genetic Algorithms Approach

- **Solution space searching algorithm**
- **Imitates the process of natural evolution**
- **"Survival of the fittest"**
- **Evolves automatically – Machine learning**
  - Initialize Population
  - Evaluation and Selection
  - Crossover and Mutation
  - Reproduction

$Fitness = \Delta T + P_{drop}/2^{\gamma}$

$(Rank(i)/Sum(rank))^{\alpha}$

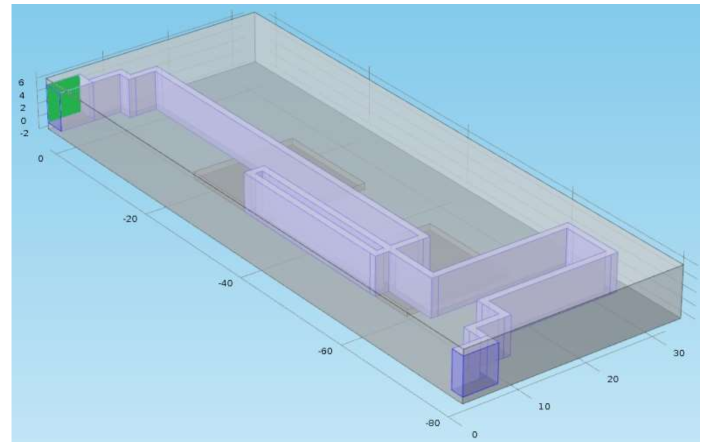


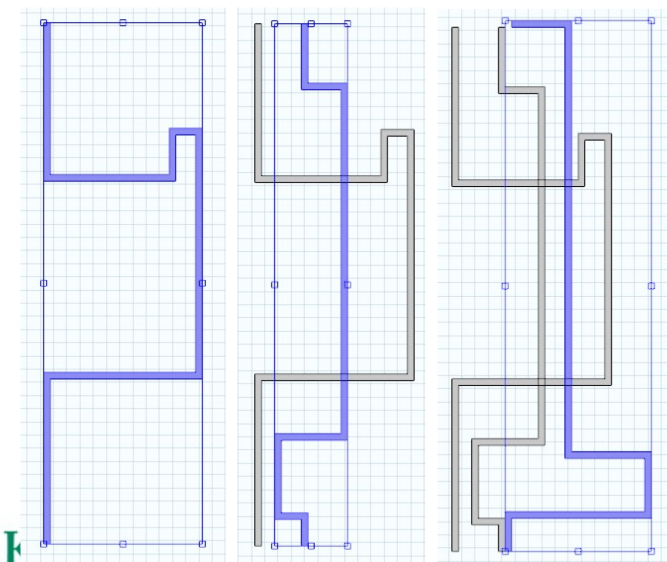
T. Wu, B. Ozpineci, and C. Ayers, "Genetic algorithm design of a 3D printed heat sink," *2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Mar. 2016.* pp. 3529 – 3536.

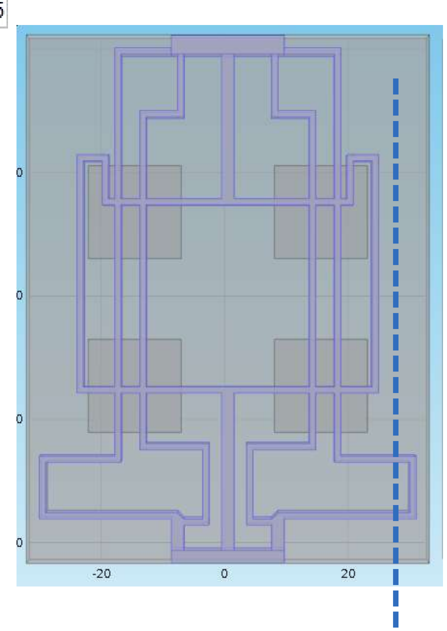
Random Walking Process

'Start from(1,1)'	'Start from(1,2)'	'Start from(1,3)'	'Start from(1,4)'	'Start from(1,5)'	'Start from(1,6)'	'Start from(1,7)'	'Start from(1,8)'	'Start from(1,9)'	'Start from(1,10)'
24x2 double	[1,2;1,1;31,1;31...	7x2 double	[]	27x2 double	27x2 double	7x2 double	8x2 double	27x2 double	12x2 double
[]	[]	[]	6x2 double	17x2 double	[]	[]	[]	[]	[]
12x2 double	[]	14x2 double	7x2 double	[]	[]	18x2 double	[1,8;1,1;78,1;78...	[]	7x2 double
[]	[]	[]	[]	14x2 double	[]	[]	[]	[1,9;79,9;80,9]	[]
[1,1;1,29;77,29;...	[]	7x2 double	[]	[]	[]	[]	8x2 double	23x2 double	[]
9x2 double	7x2 double	7x2 double	13x2 double	8x2 double	60x2 double	10x2 double	7x2 double	9x2 double	11x2 double
[]	[]	[]	[]	[]	[]	21x2 double	9x2 double	23x2 double	11x2 double
[]	[]	[]	[]	[1,5;77,5;80,5]	[]	21x2 double	[]	[]	11x2 double
[]	33x2 double	[]	[]	27x2 double	[]	15x2 double	12x2 double	[]	[1,10;1,30;21,30...
29x2 double	7x2 double	16x2 double	7x2 double	9x2 double	[1,6;1,1;45,1;45...	[]	[]	[]	14x2 double
33x2 double	10x2 double	37x2 double	9x2 double	[1,5;1,9;39,9;39...	7x2 double	36x2 double	7x2 double	37x2 double	[1,10;1,27;78,27...
12x2 double	[1,2;79,2;80,2]	10x2 double	26x2 double	11x2 double	11x2 double	6x2 double	12x2 double	[1,9;1,28;25,28;...	11x2 double
37x2 double	14x2 double	[]	[]	33x2 double	[1,6;1,3;71,3;71...	7x2 double	7x2 double	[1,9;1,7;63,7;63...	9x2 double
[]	20x2 double	[1,3;1,27;6,27;6...	[]	[]	[]	10x2 double	[]	15x2 double	[]
[1,1;79,1;80,1]	35x2 double	[]	[1,4;1,23;19,23;...	[]	[]	10x2 double	[]	[]	31x2 double

	1	2
1	1	5
2	1	10
3	3	10
4	3	14
5	58	14
6	58	7
7	33	7
8	33	9
9	66	9
10	66	29
11	74	29
12	74	10
13	78	10
14	78	5
15	80	5







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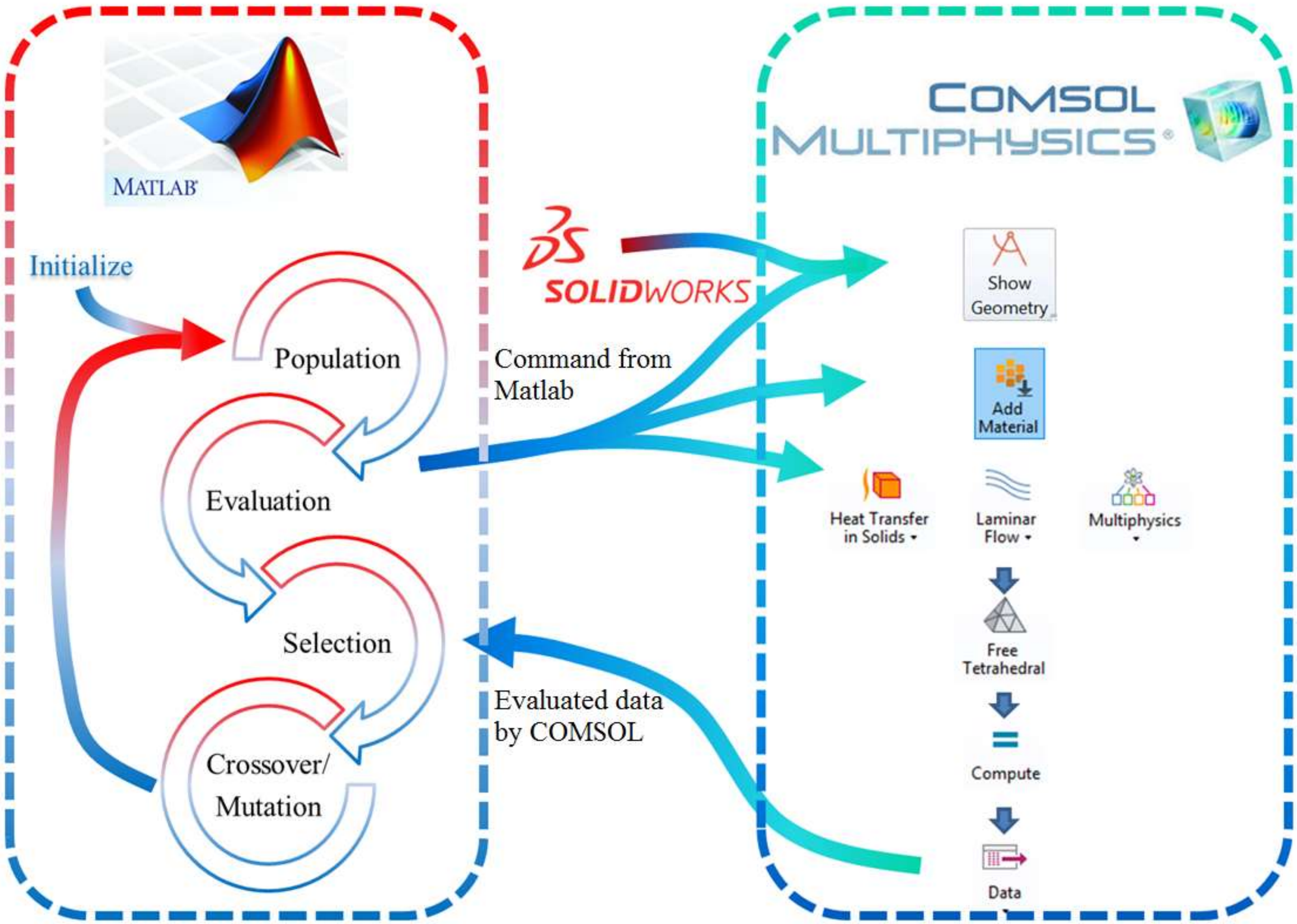
Machine Learning Optimization



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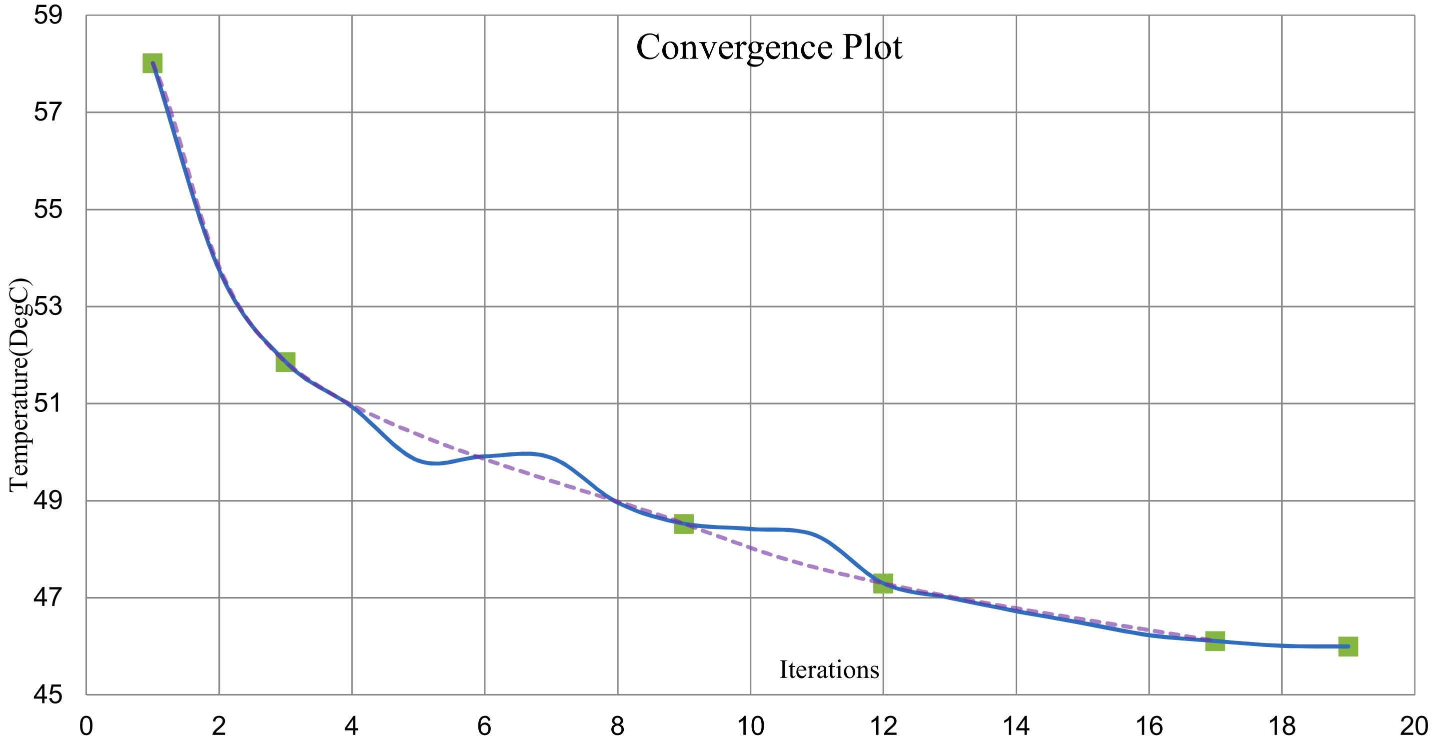
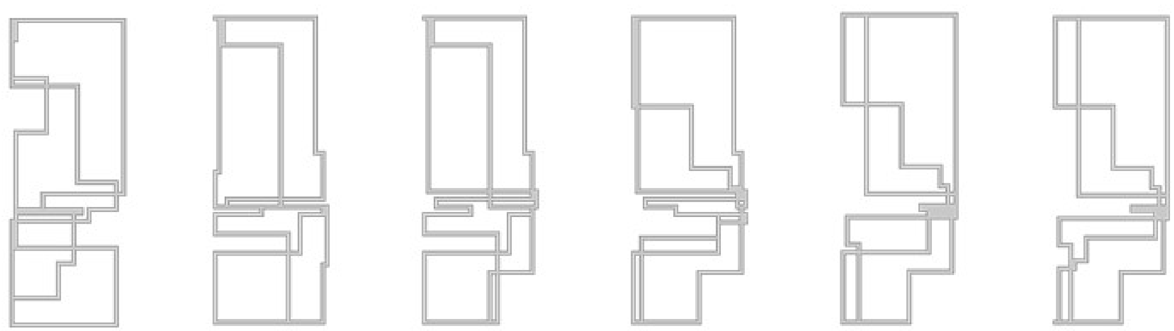
Convergence





Step 1	Step 3	Step 9	Step 12	Step 17	Step 19
58.016°C	51.858°C	48.526°C	47.297°C	46.110°C	45.998°C

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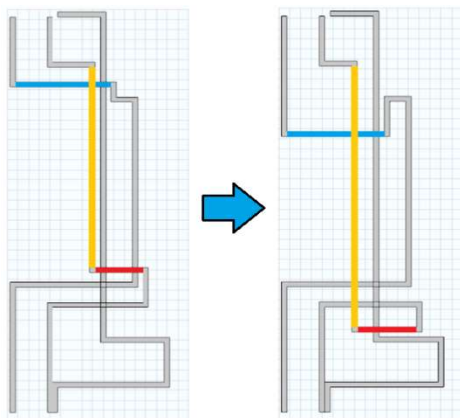
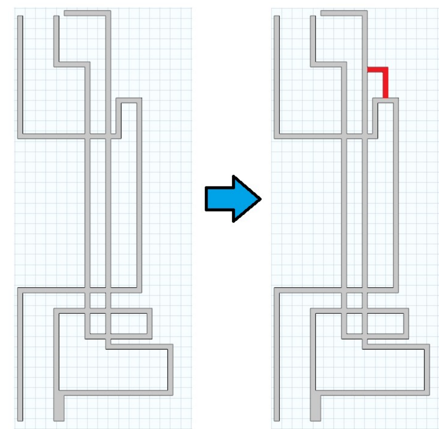
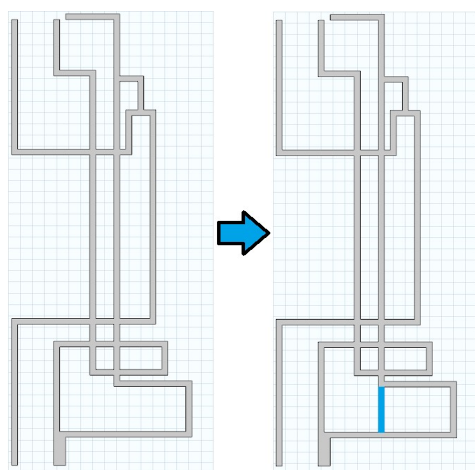
Second stage genetic algorithm approach



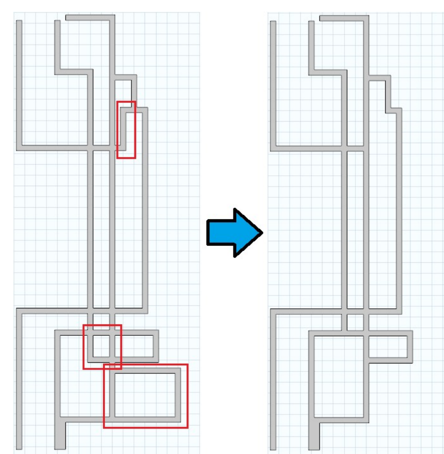
Translation



Creation



Connection



Deletion

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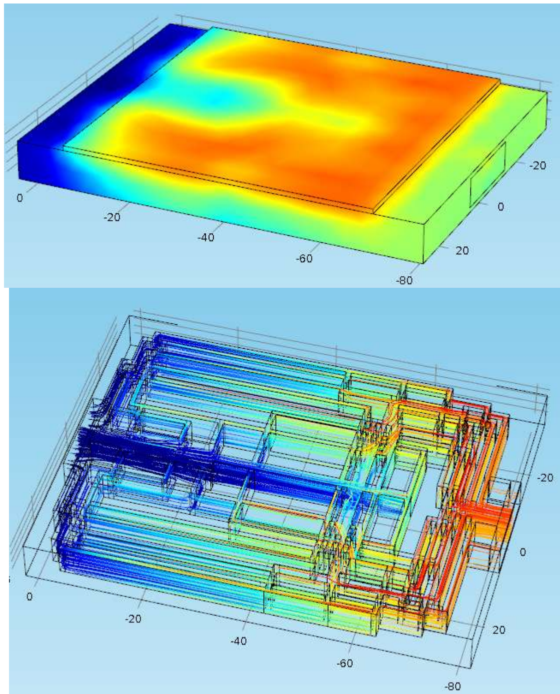
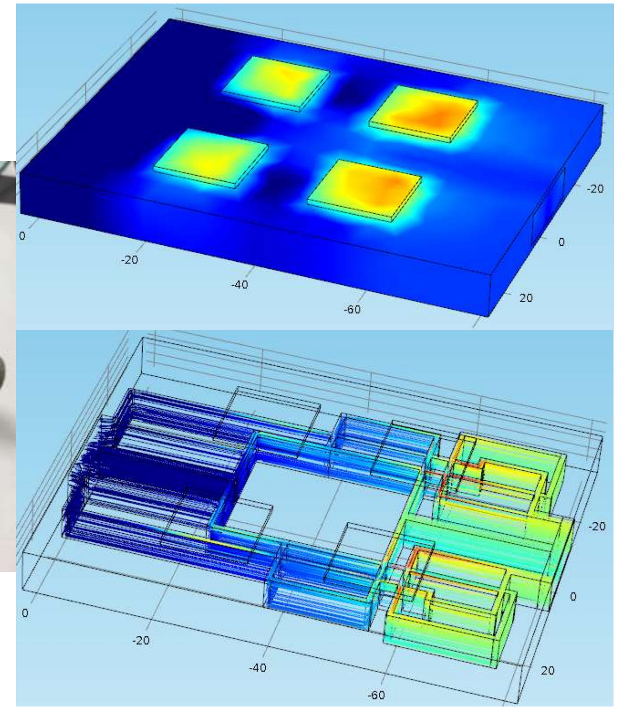
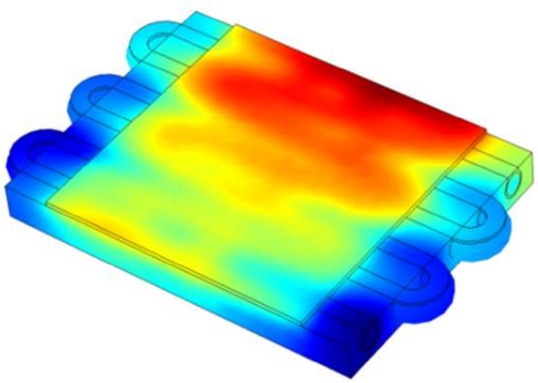
Optimization Results

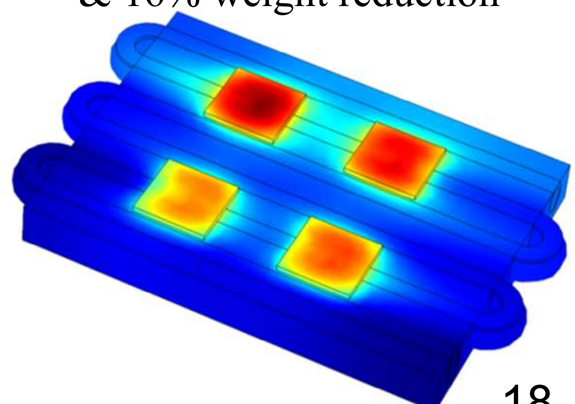




17.1% junction temperature reduction
& 33% weight reduction

22.8% junction temperature reduction
& 16% weight reduction





Conclusion

- In this paper, both experimental and simulation comparisons between additive manufactured Aluminum heat sink and the conventional heat sink, have been studied and obvious differences are shown.
- A post-processing is proposed to modify the degraded performance.
- Genetic algorithm combining with the machine learning process is developed to realize automatically evolve and eventually can be used to to optimize a better and unique printed heat sink based on the given heat dissipation, distribution and the allowed volume.

Questions

Thank you!