Additive Manufacturing for Cost Efficient Production of Compact Ceramic Heat Exchangers and Recuperators

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Outline

I. Project Overview
II. Material Selection
III. Characterization
IV. Prototype Fabrication
V. Summary

Project Overview

Objective: design and build a prototype compact high-temperature ceramic heat exchanger as a key component for high efficiency advanced power generation systems

Strategy: Leveraging materials, modeling, and additive manufacturing technologies to solve fabrication and system integration challenges

Target:

- Operation > 1500 °F (816 °C)
- 25% microturbine thermal cycle efficiency improvement
- 60% weight to volume reduction compared to metal HEX
- Scalable fabrication for implementation

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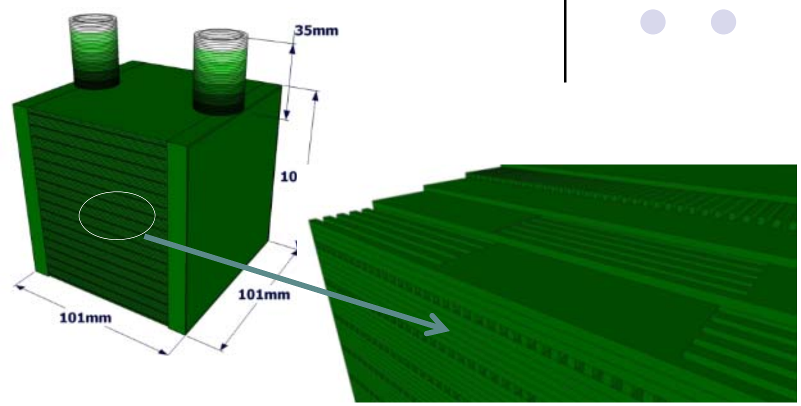
Project Overview:
Tasks



Project management – Ceralink

Manage and direct project management plan

Update PMP as necessary

HEX modeling & optimization – UTRC

Thermo-fluid Modeling

Thermal Stress Model Development

Design Optimization for Prototype Fabrication

Fabricate HEX prototypes – Ceralink

Materials Selection and Tape Fabrication

Build Sub-Scale Prototypes via Additive Manufacturing

Property and Performance Characterization

Fabricate Full-Scale Prototypes via Additive Manufacturing

Investigate system level challenges – Ceralink

Sealing of Heat Exchangers for Testing

Cost Projections

HEX performance validation – UTRC

Commission high temp test rig → measure and validate performance of prototypes

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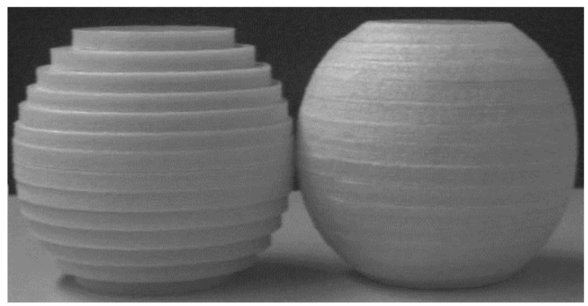
Additive Manufacturing

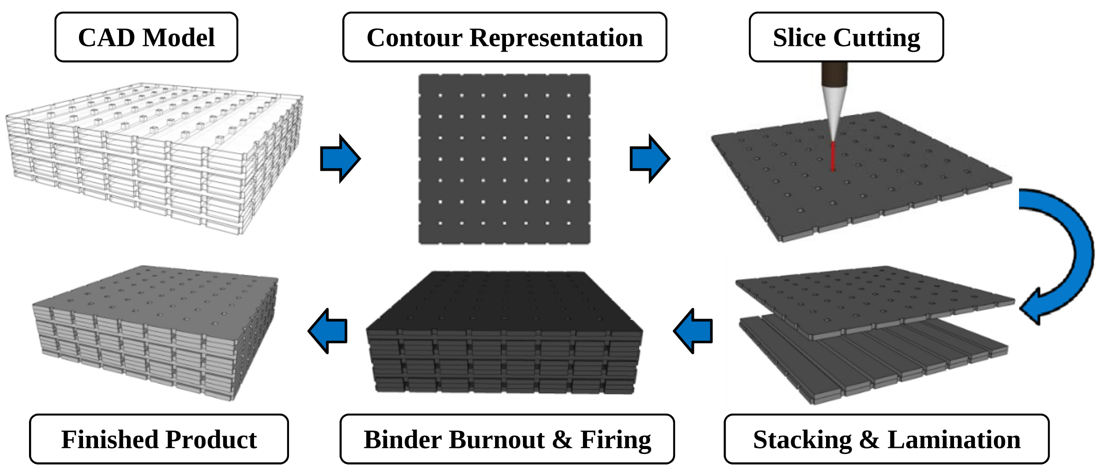
Laminated Object Manufacturing

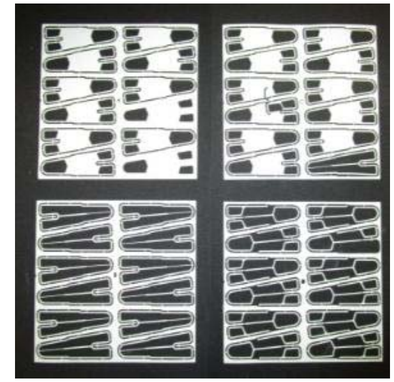
***See Dr. Shulman's article Ceramic Industry Magazine Dec 2012**

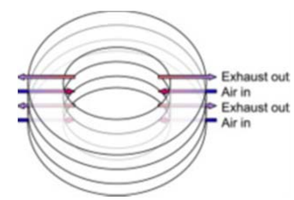
- LOM builds 3D parts from 2D ceramic tapes
- Precision cut with laser, tangential smoothing, precision stack
- Functional grading by changing tape composition

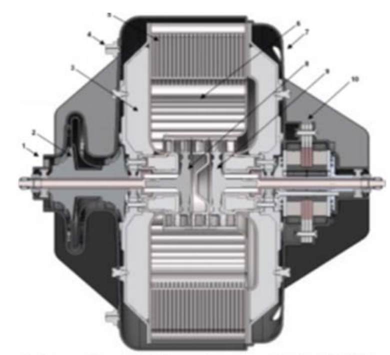
CAM-LEM









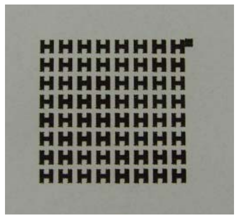


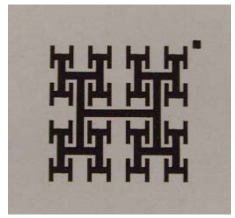
J. Eng. Gas Turbines Power. 2010;132(9):

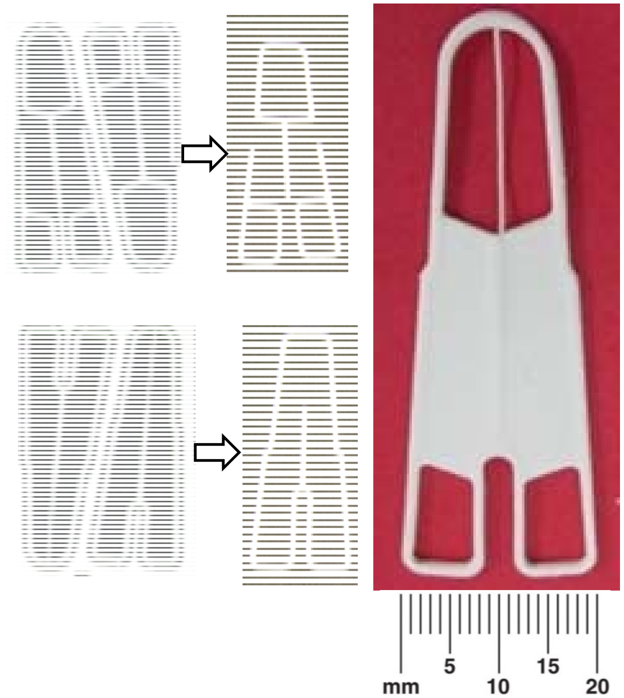
Naval Research Lab compact ceramic recuperator

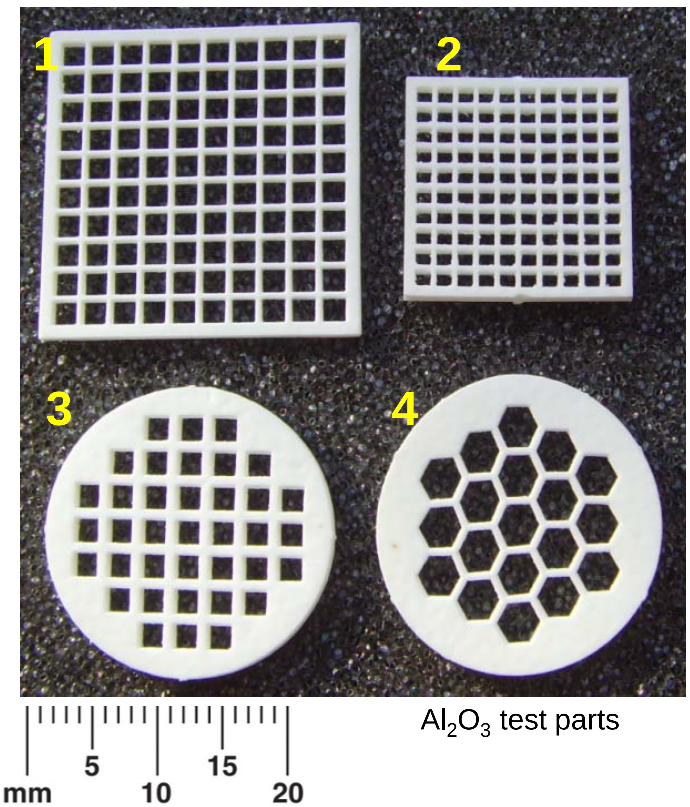
Prototype Fabrication

CAM-LEM Capabilities





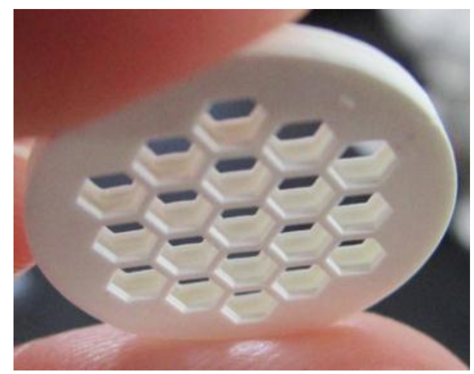




Al_2O_3 test parts

Demonstrated capabilities

	Channel Wall Width (µm)	Height (µm)
1	500	1000
2	400	1700
3	800	1500
4	600	1600



ZTM test part

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Materials Selection

Considerations

- Materials properties
  - Thermal conductivity, strength, toughness, thermal expansion
- Attaching ceramics to metal
  - Thermal expansion mismatch
- Ease of fabrication
- Candidates:
  - Aluminum Nitride
  - Zirconia toughened mullite

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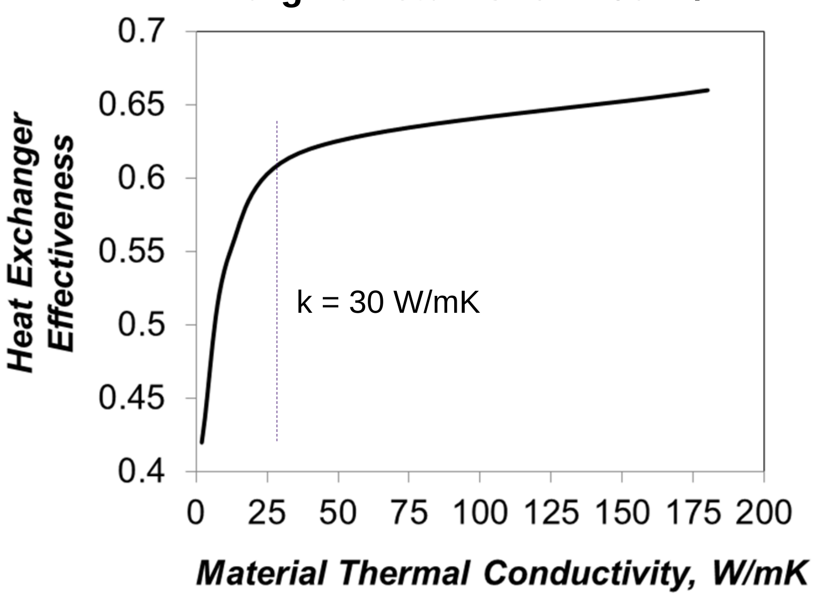
Material Selection:
Design Trade-Off Study

Optimized HX performance for various material options

	Inconel	Aluminum Nitride	ZrO_2 (+Y_2O_3)	Stainless Steel
Thermal conductivity (W/mK)	12	180	2	40
Density (kg/m^3)	8190	3260	5900	7480
Weight (kg)	3.57	1.36	2.49	3.14
Effectiveness	0.55	0.66*	0.42	0.62
Heat transfer (kW)	32	39	24.5	36.5
*initial program target				

Marginal returns for > 30 W/mK



Sizing optimization for fixed:

- Fin design
- Inlet conditions
- Pressure drop constraints

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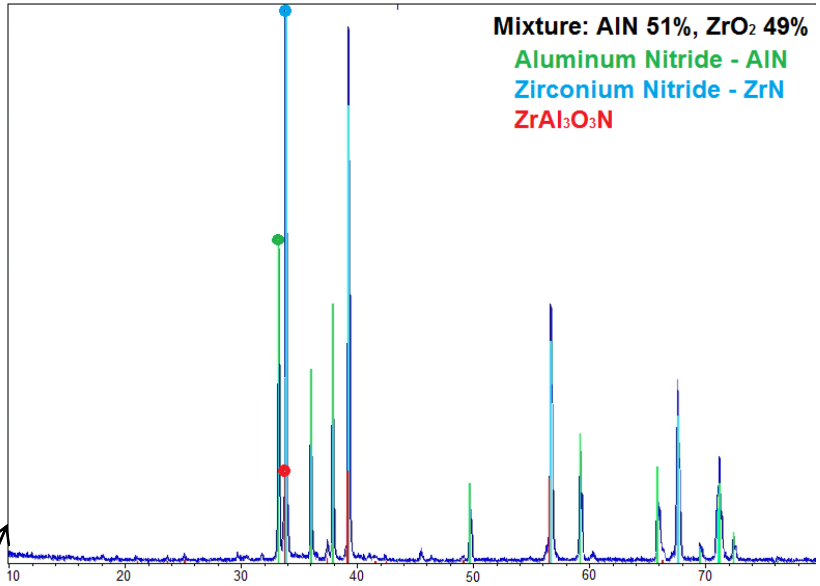
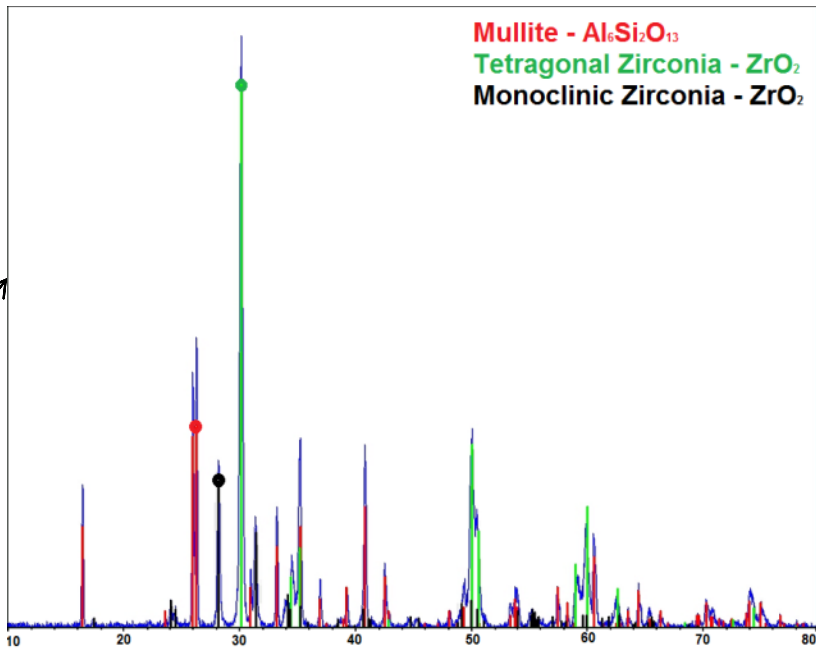
Material Selection

Material	Pressed		CIP Pellet		Temp (˚C)	Atm
	Linear Shrinkage	Theo. Density	Linear Shrinkage	Theo. Density		
AlN	3%	68%	2%	71%	1800, 1 hr	N_2
AlN + Y_2O_3	10%	81%	8%	~84%	1800, 1 hr	N_2
AlN/ZrO_2 (76/24)	12%	91%	10%	93%	1800, 1 hr	N_2
AlN/ZrO_2 (51/49)	16%	98%	14%	94%	1800, 1 hr	N_2
ZrO_2	22%	~99%	16%	~99%	1800, 1 hr	N_2
M2-ZTM	16%	93%			1550, 4 hr	Air
M3-ZTM (tape)	27%	98%			1550, 4 hr	Air
M3-ZTM (tape)	27%	100%			1570, 4 hr	Air

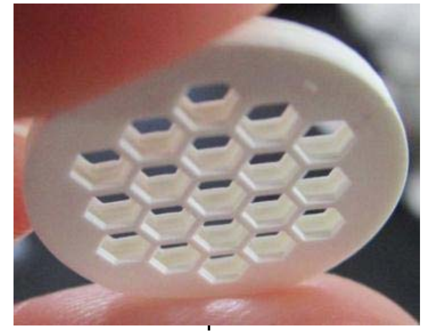




- **Zirconia toughened mullite (ZTM) selected for prototype fabrication**
  - Compatible with ZrO_2 firing, no side reactions

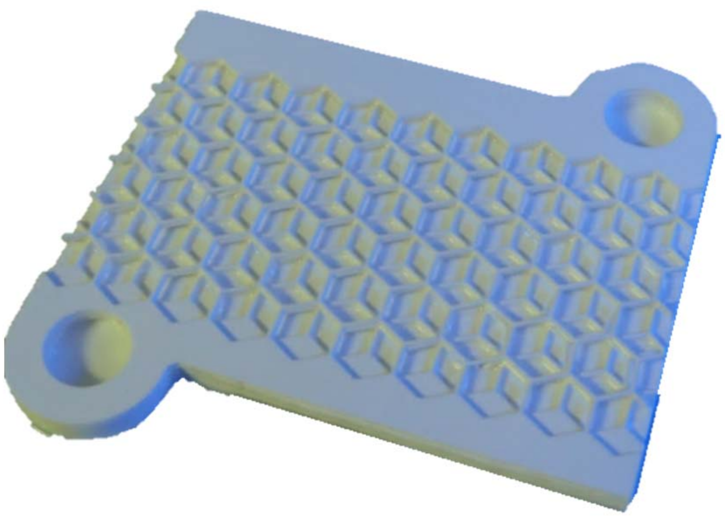
*Composition distribution by vol%

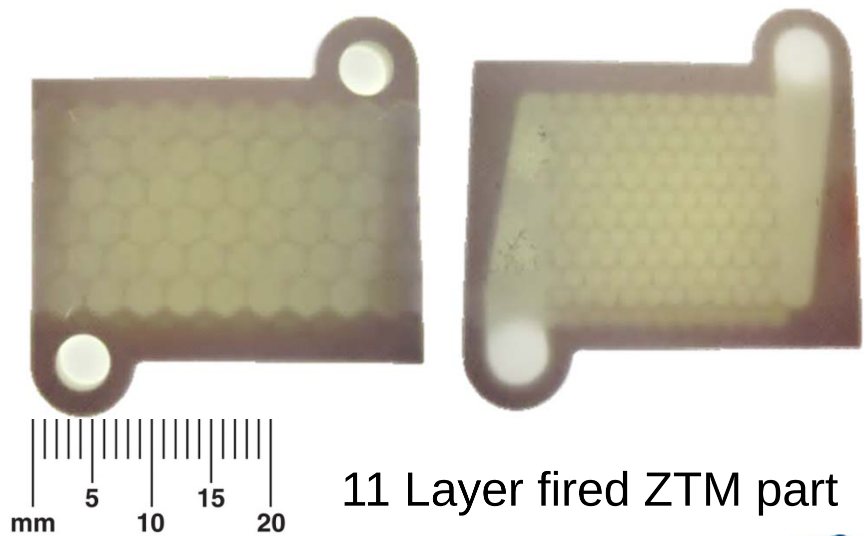
Prototype Fabrication
Sub-Scale Prototype



ZTM test part

- Laminated object manufacturing (LOM) → accurate fine features
- Robust nature inspired honeycomb design:
  - Explore materials handling challenges
  - High connectivity between fins → stability of individual layers
- Successfully fired to high density





11 Layer fired ZTM part

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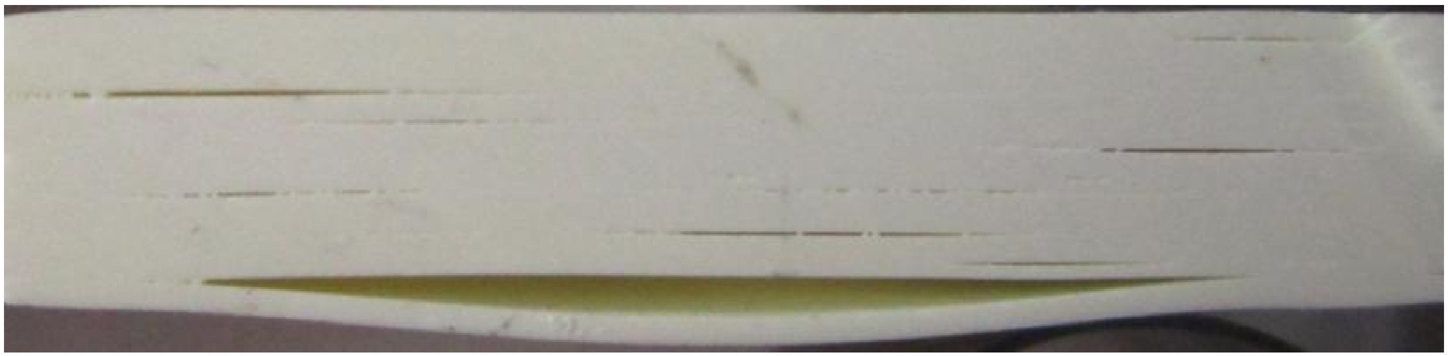
Characterization:
Macro Delamination

Delamination caused by binder burnout



0 1 mm

Macro-defects eliminated with slow binder removal step

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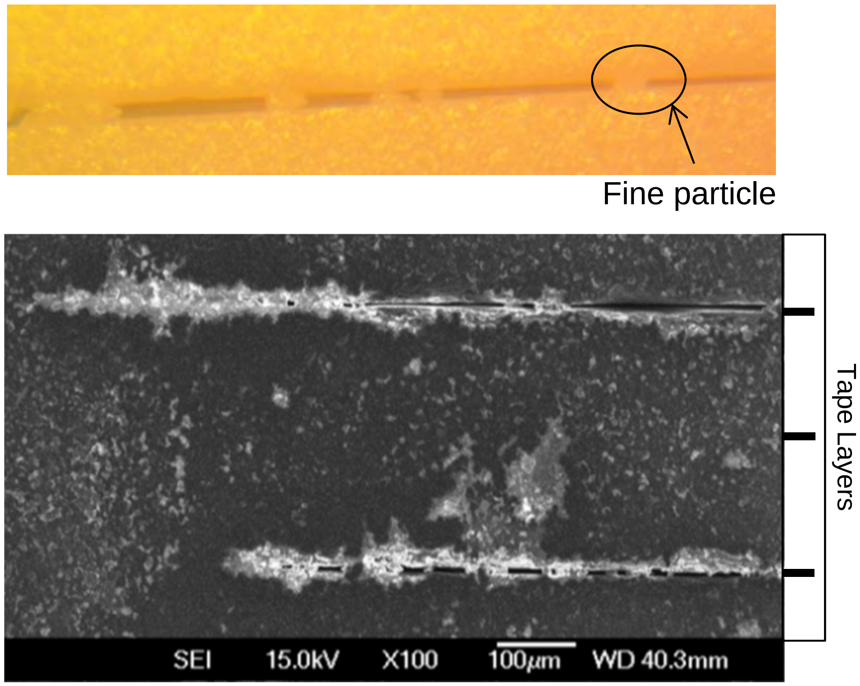
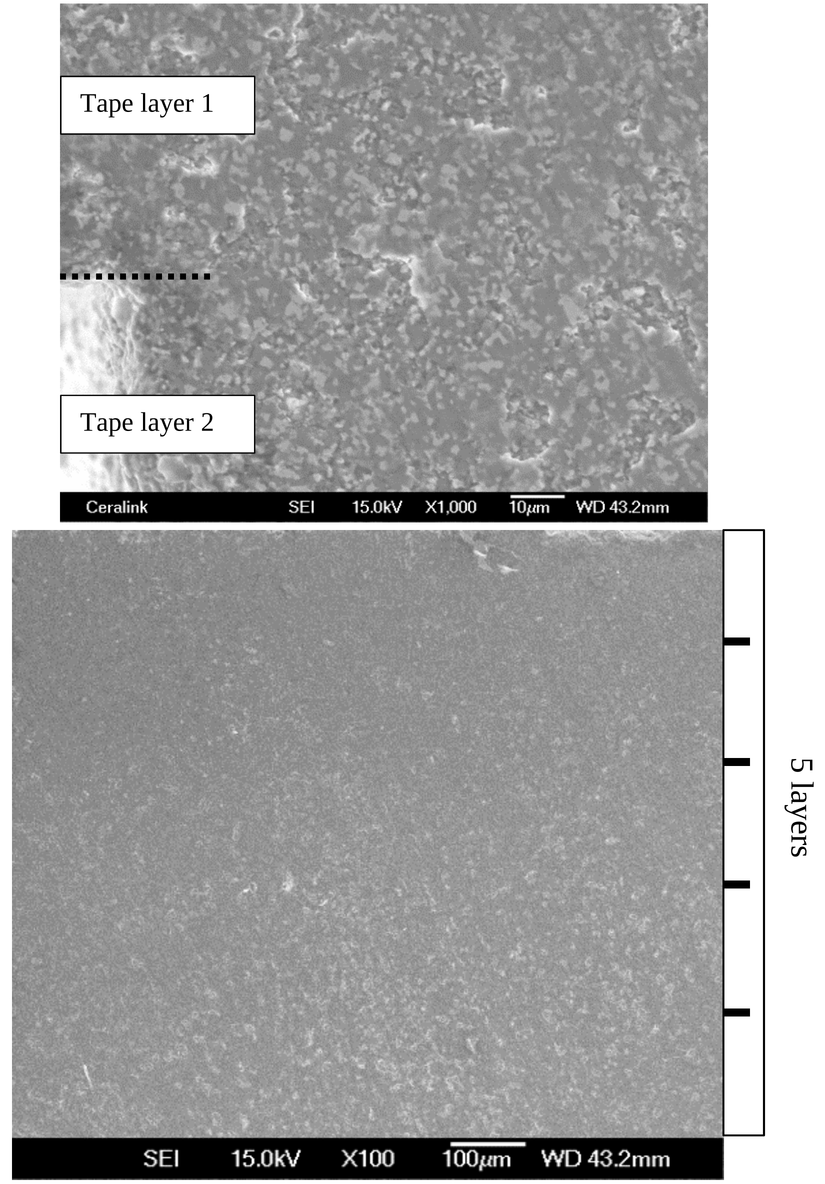
Characterization:
Micro Delamination

Solved by cleaning step

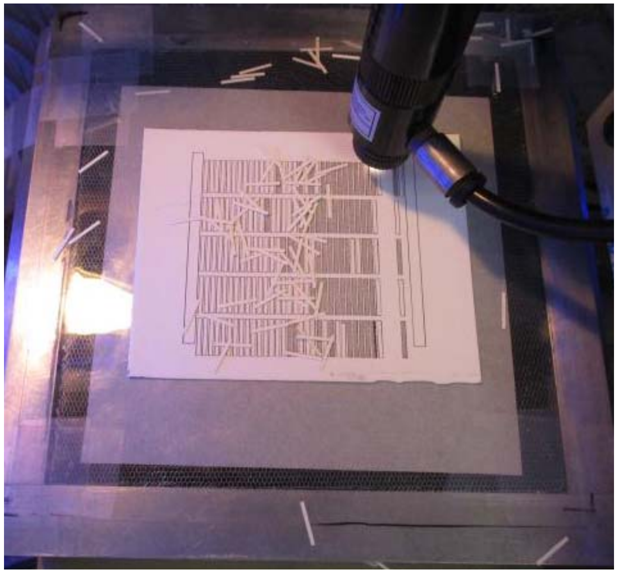




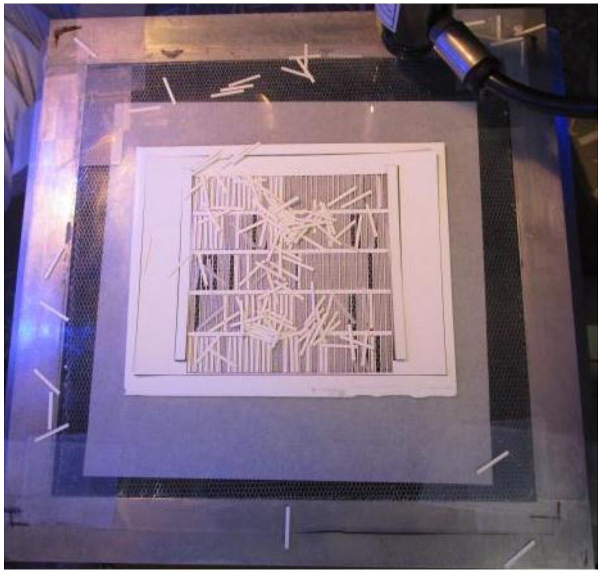
- ➢Particulate in delamination defects
- ➢No differentiation between layers

Prototype Fabrication
Cleaning step

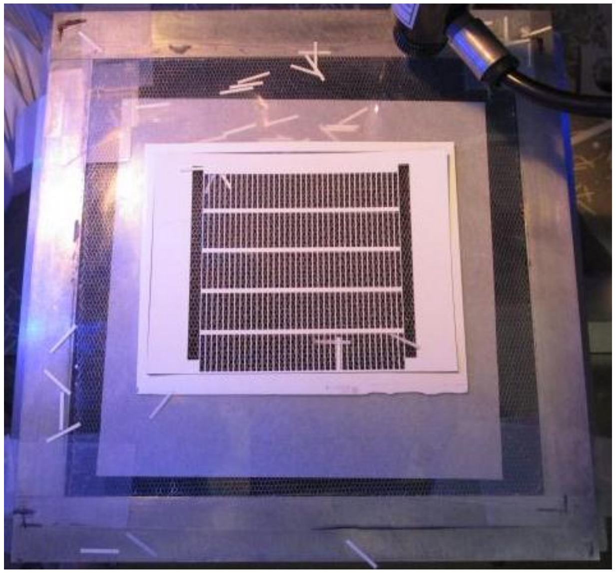
Cutting process



Cut part with debris



After cleaning



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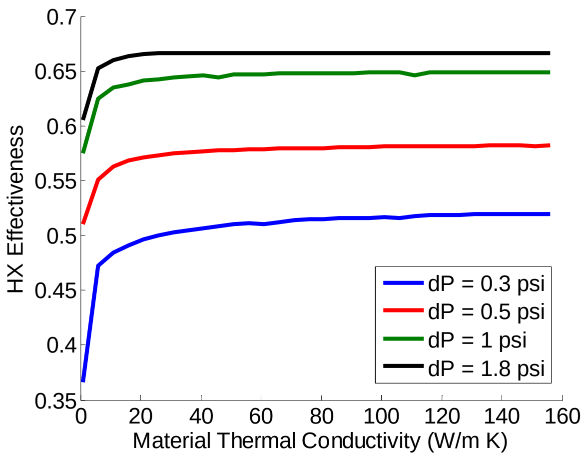
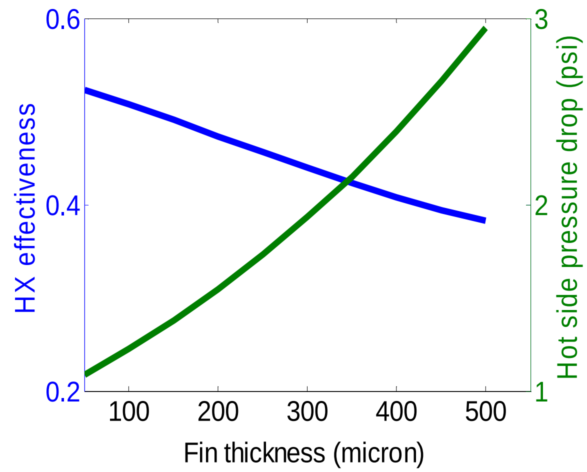
Design of Heat Exchanger

Trade-Off Study: Geometry

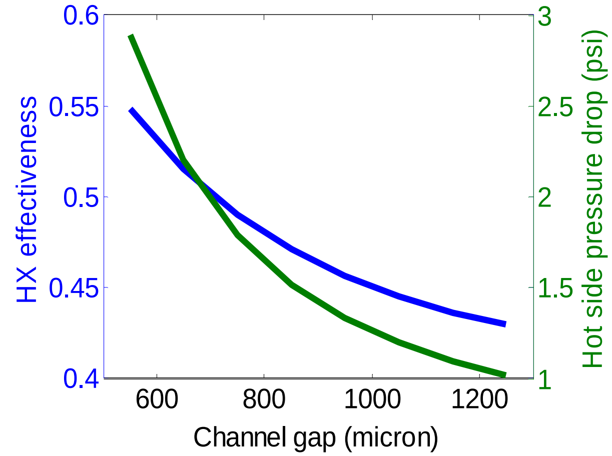
Thermal optimization



Effect of: Fin Thickness



Effect of: Channel Width



- TC > 30 W/mK, marginal returns
- Effectiveness increases with dP

- Thinner fins, higher fin density
  - Higher dP
  - Higher effectiveness

- Narrower channels
  - Higher dP
  - Higher effectiveness

➢ Thinner fins and smaller gaps give better effectiveness performance

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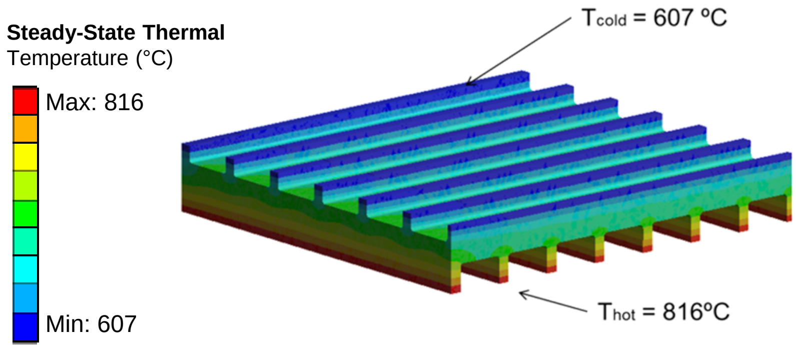
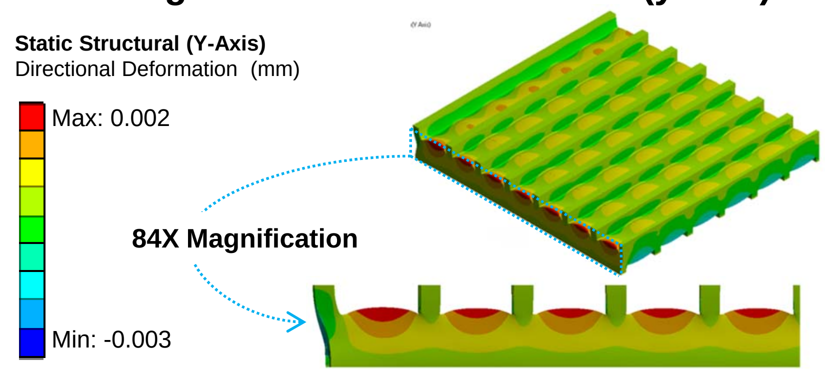
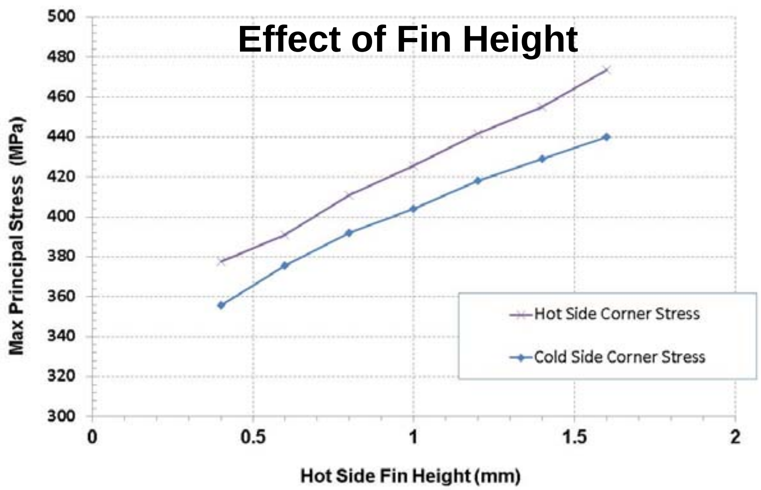
Thermal Stress Analysis

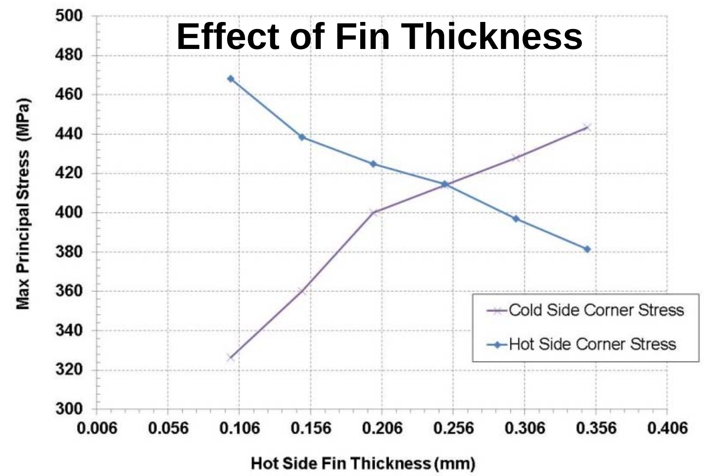
Temperature boundary conditions & gradient



Through Thickness Deformation (y-axis)







- *Thicker and shorter fins reduce thermal stress*
- *Unfavorable for thermal and pressure drop performance*

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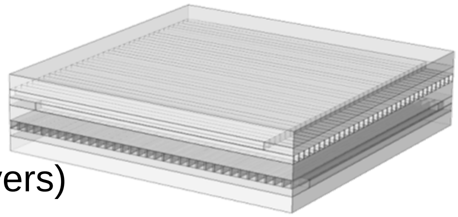
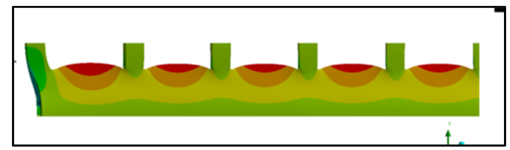
Heat Exchanger Design

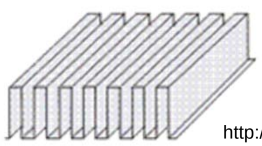
Refinement

3. Fin design modification
(fin strip connectivity in tape layers)



4. Fin design modification
(thicker, shorter fins – thermal stress modeling)



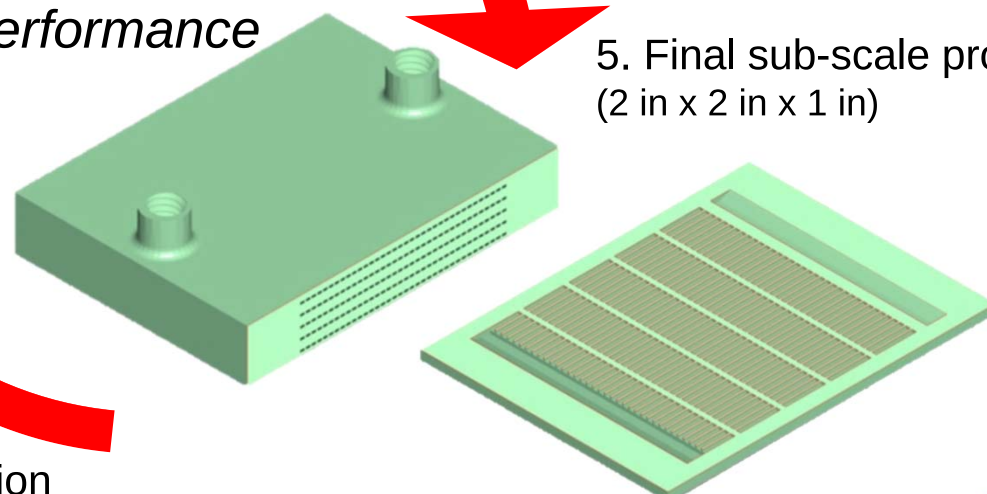


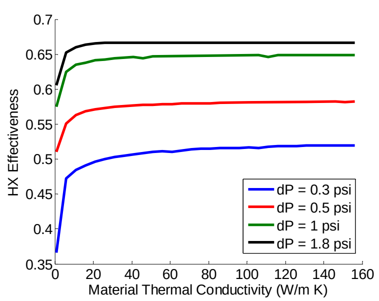
http://www.thermopedia.com/content/1036/

2. Fin design selection
(plain fins → manufacturability)

Design optimization for manufacturability and performance

5. Final sub-scale prototype
(2 in x 2 in x 1 in)





1. Material down-selection
(AlN/ ZTM/ ZTA)

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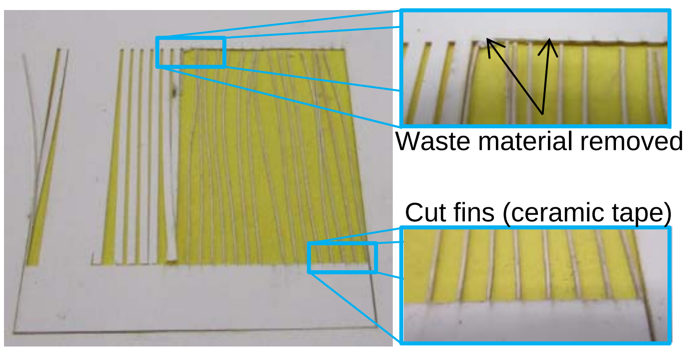
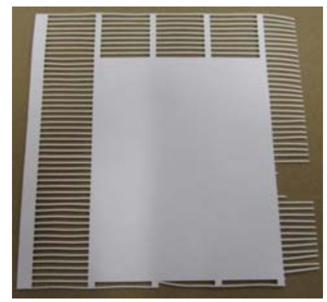
Prototype Fabrication

Design & Manufacturing Process Evolution

1. Long thin cantilever fins

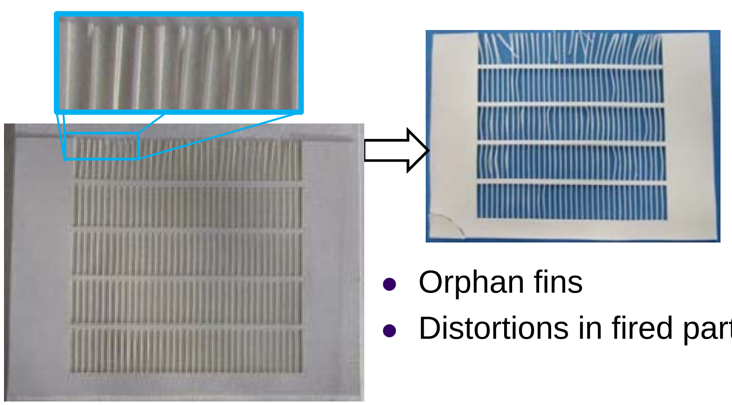


2. Straight supported fins



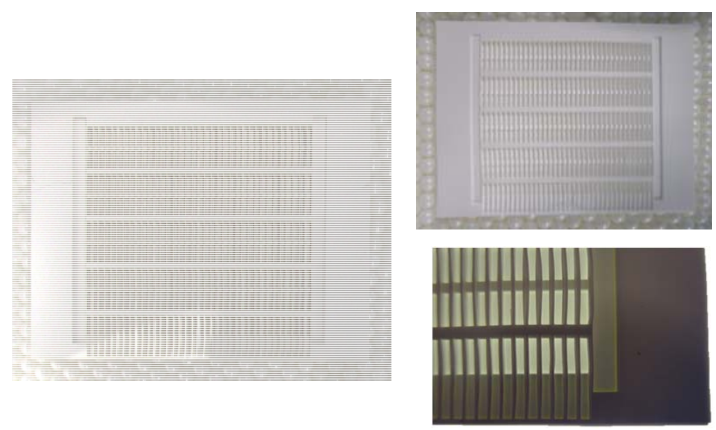
- Orphan fins
- No external support
- Distortion and tearing during:
  - Process handling
  - Cutting → aborted

3. Straight supported fins + manifold



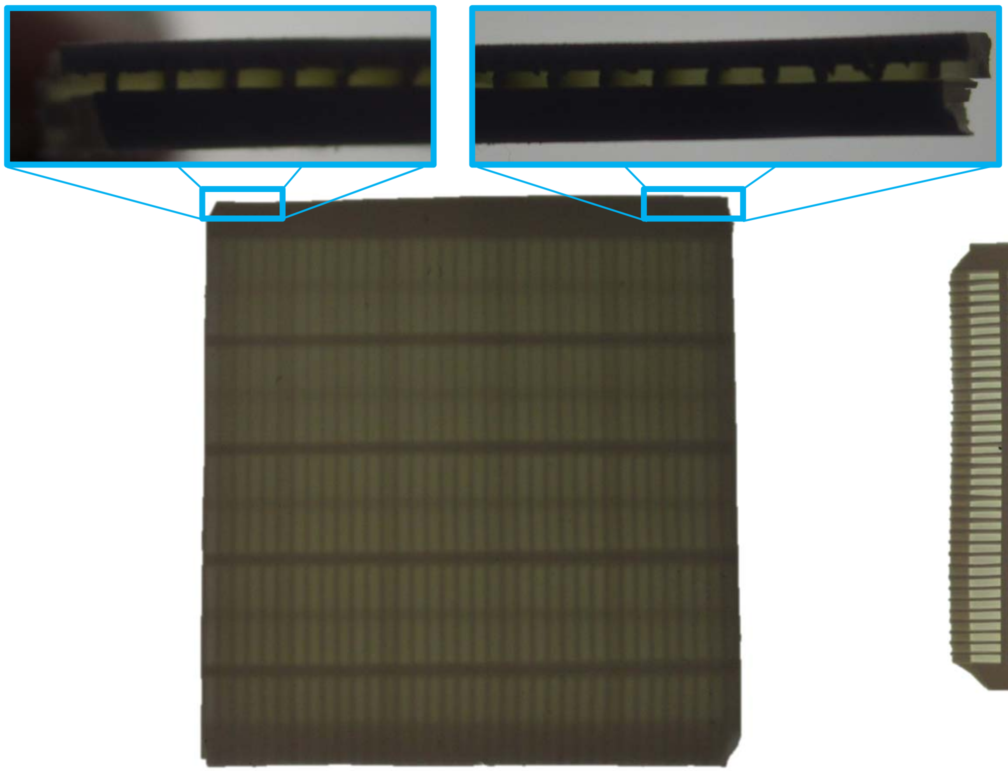
- Orphan fins
- Distortions in fired part

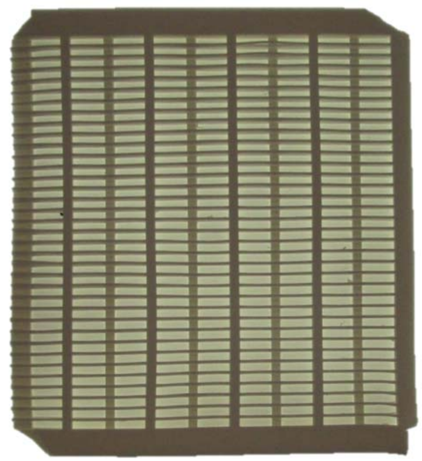
4. Supported fins with sacrificial strut



Prototype Fabrication

Sample Success and Learning





Summary

- Feasibility of LOM for highly complex ceramic heat exchangers demonstrated
- Material characterization was used in concert with design development
- Causes of delamination were eliminated by:
  - Decreasing binder burnout rate
  - Use of tape cleaning step
- Distortion of fine features was prevented:
  - 1) Unsupported heat exchanger fins → mitigated by design optimization
  - 2) Transport of cut tapes → minimized by design and process improvements
  - 3) Friction of part during shrinkage → solved by use of smooth firing surface

Acknowledgements

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- Naval Research Laboratory
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- Brian Matthewson, CAM-LEM