FEW0233: Additive Manufacturing of New Structures for Heat Exchange

Crosscutting Research Program Portfolio Review Meeting

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Objective: develop a heat exchanger for sCO_2 power cycles with radically improved material efficiency and higher temperature tolerance than current technology.

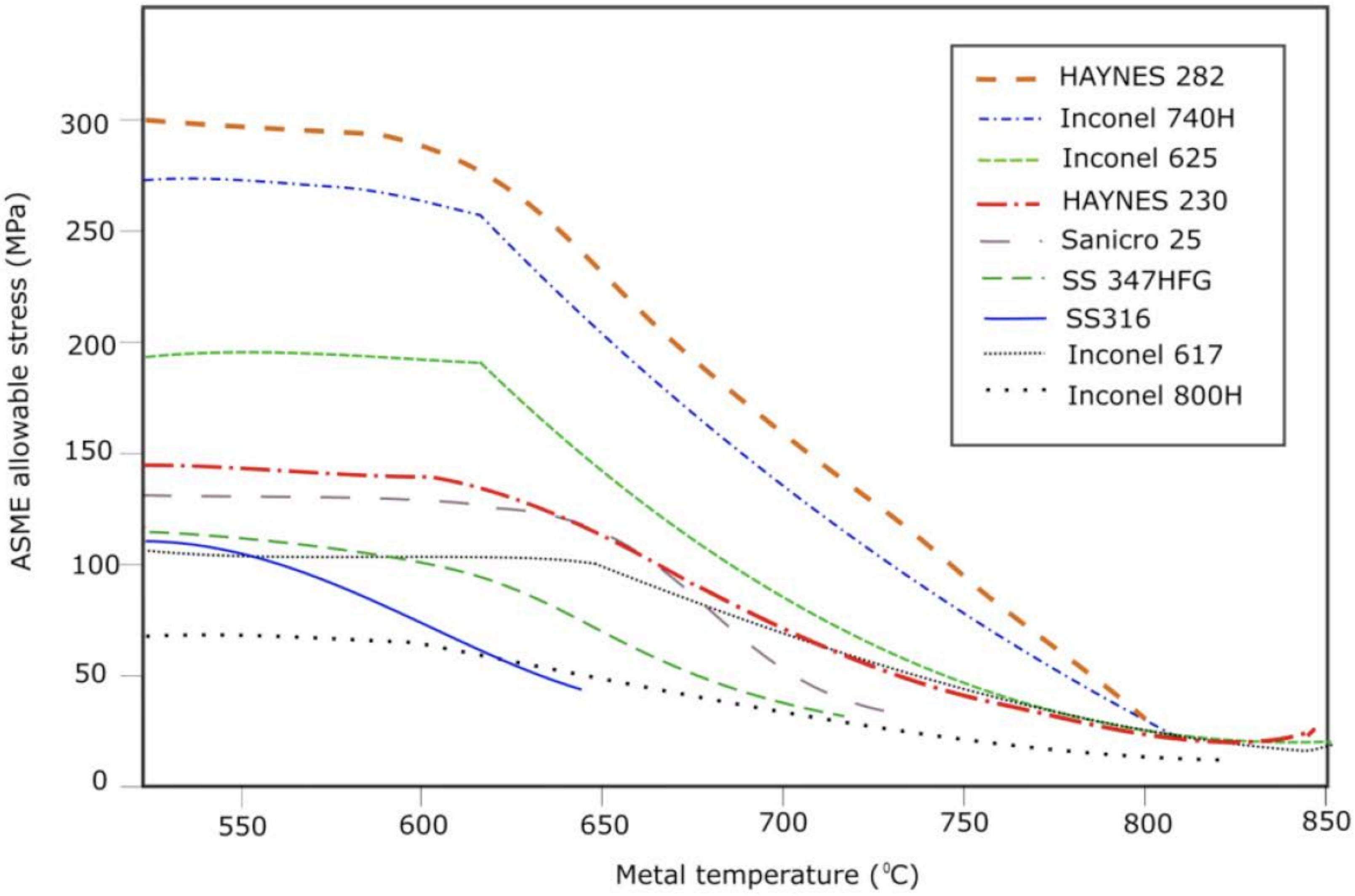
Approach: 3D-printing of nickel alloys in novel gyroid-like geometries.

Project target: working prototype heat exchanger operating at 700ºC, 300 bar ΔP

FY18	FY19	FY20	FY21
Phase I ($250k)→	Phase II ($250k) →	Phase III ($2.3M) →	

Currently 18 months, $400k into project.

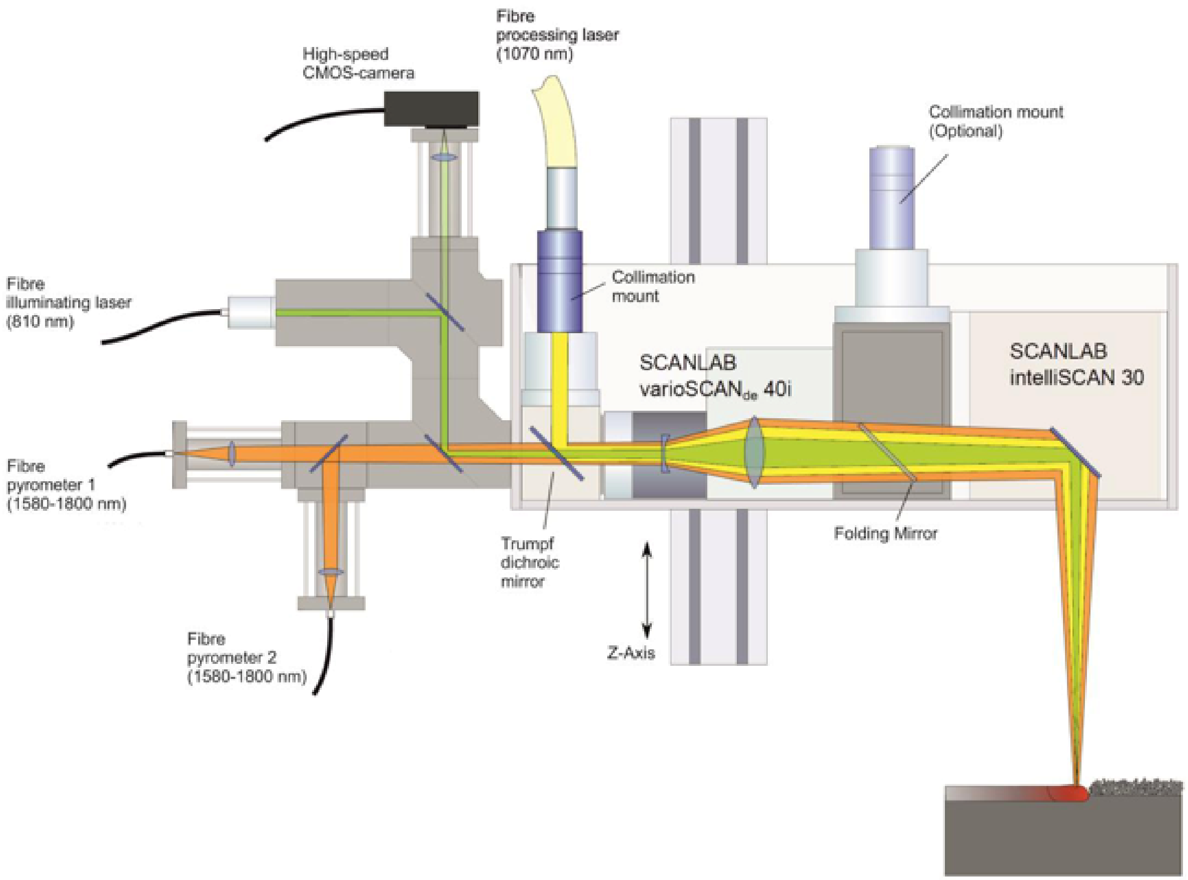
Nickel superalloys can maintain strength at high T…



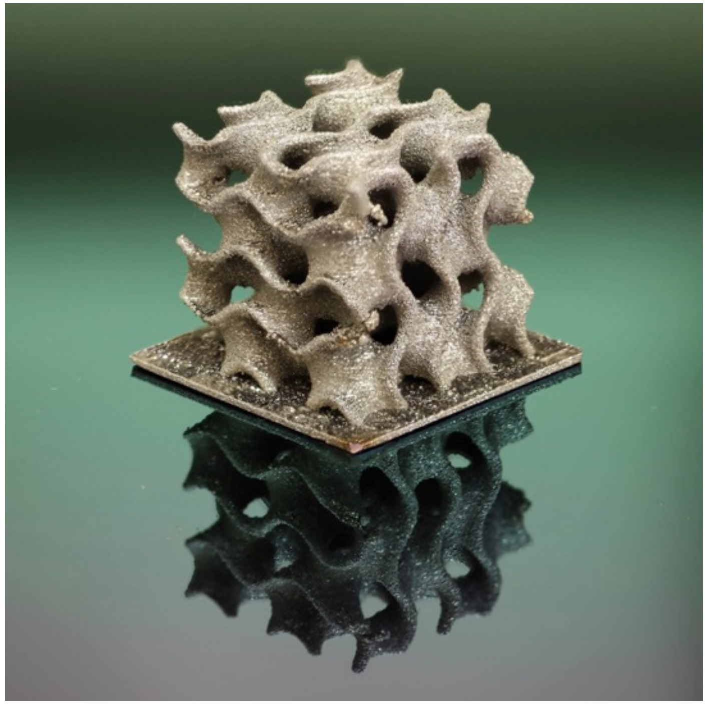
Source: ARPA-E, 2018

…but are expensive and hard to machine.

The project combines additive manufacturing of superalloys with new, efficient geometries.



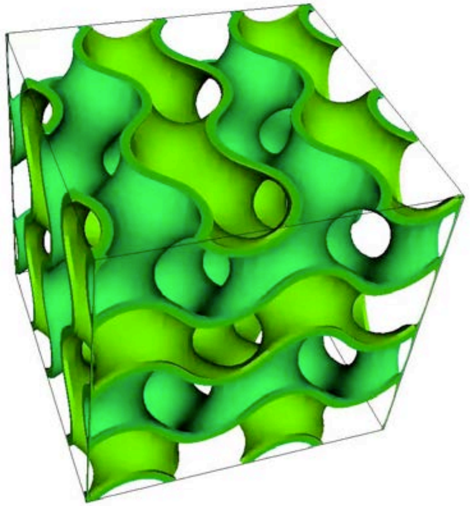
Powder Bed Laser Fusion

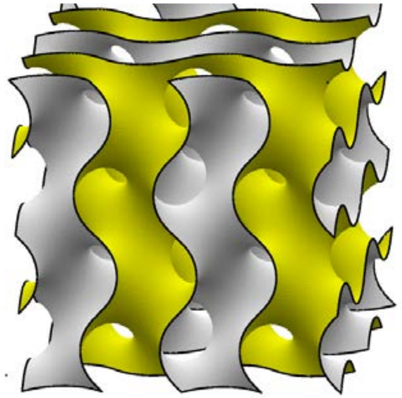


Gyroid-like geometries can make great heat exchangers

AKA: Triply Periodic Minimal Surfaces (TPMS)

Gyroid

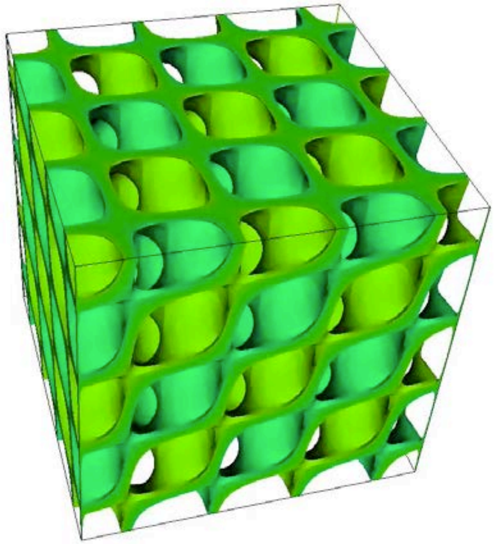




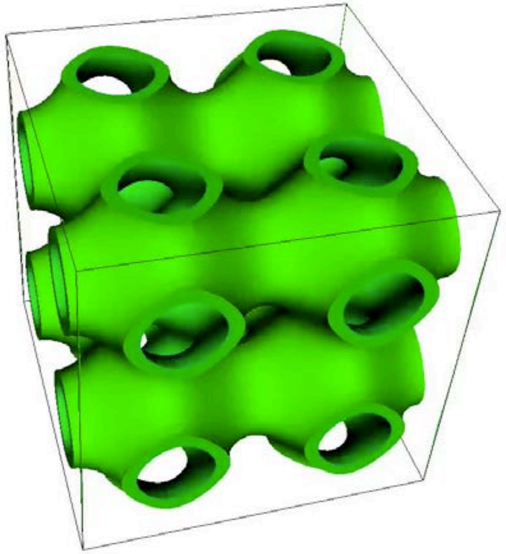
Surface defined by, e.g.:

$$\sin\left(\frac{2\pi}{L}x\right)\cos\left(\frac{2\pi}{L}y\right)+\sin\left(\frac{2\pi}{L}y\right)\cos\left(\frac{2\pi}{L}z\right)+\sin\left(\frac{2\pi}{L}z\right)\cos\left(\frac{2\pi}{L}x\right)=t$$

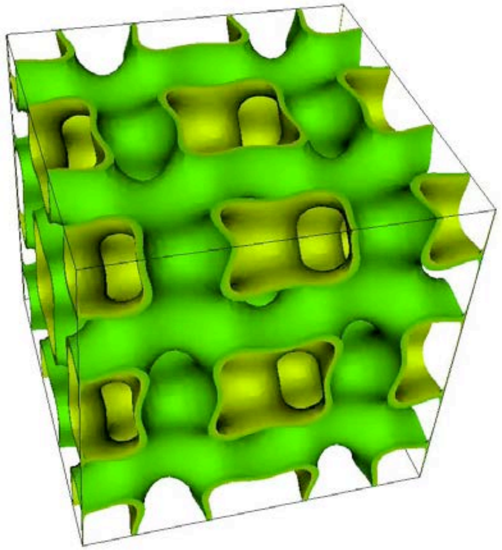
Schwarz-D



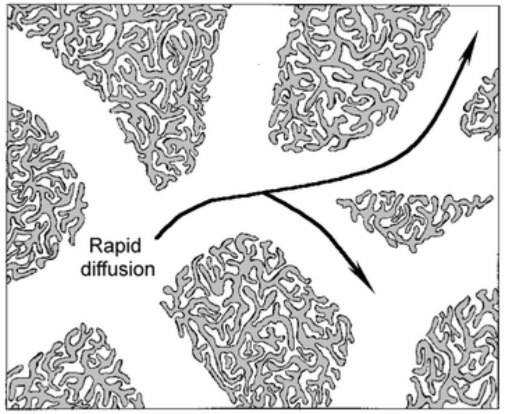
Schwarz-P

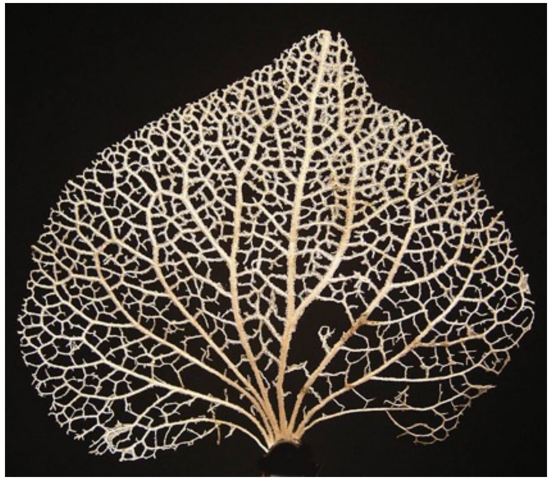


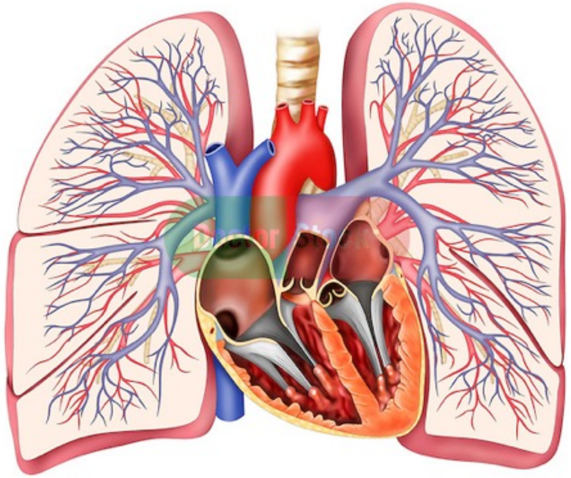
IWP



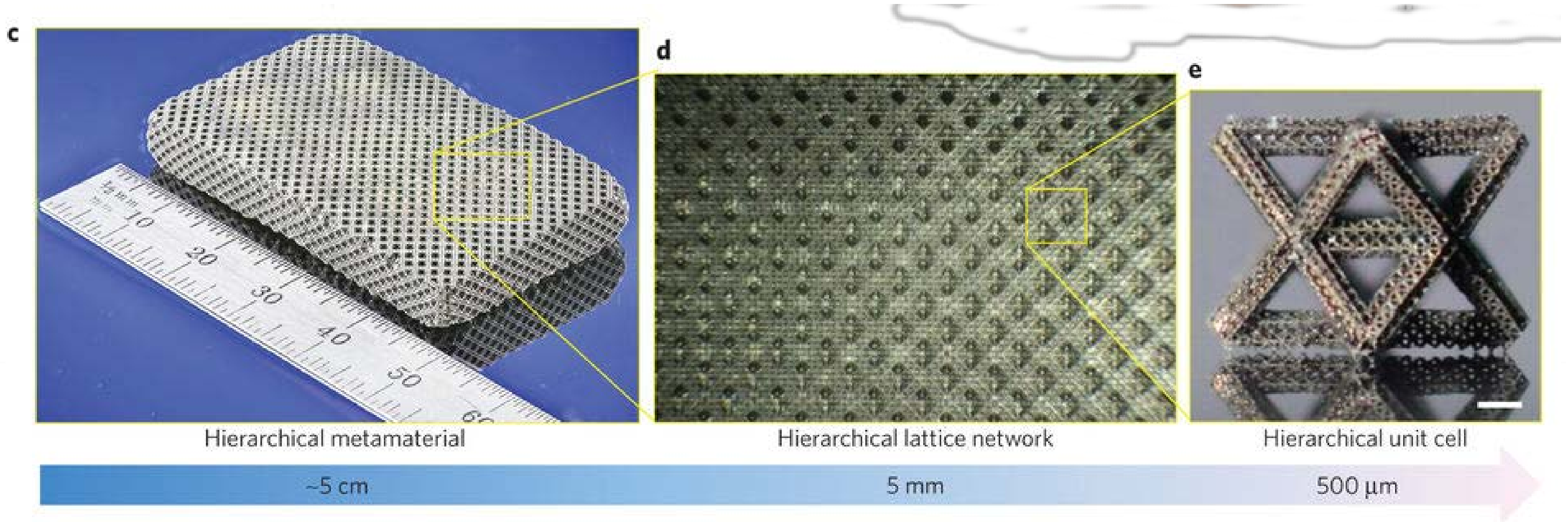
Hierarchies are common in nature for high interfacial area with low pressure drop



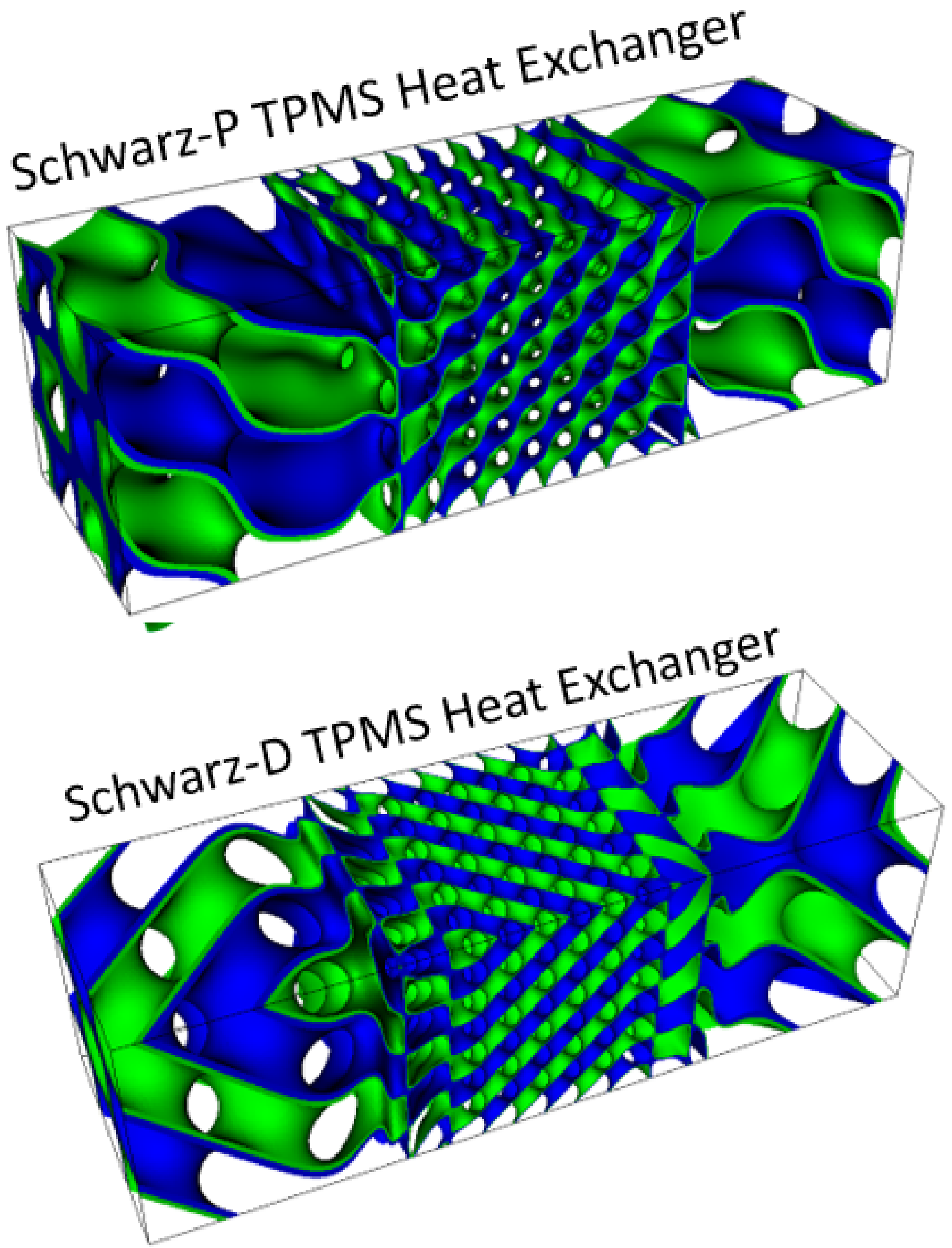


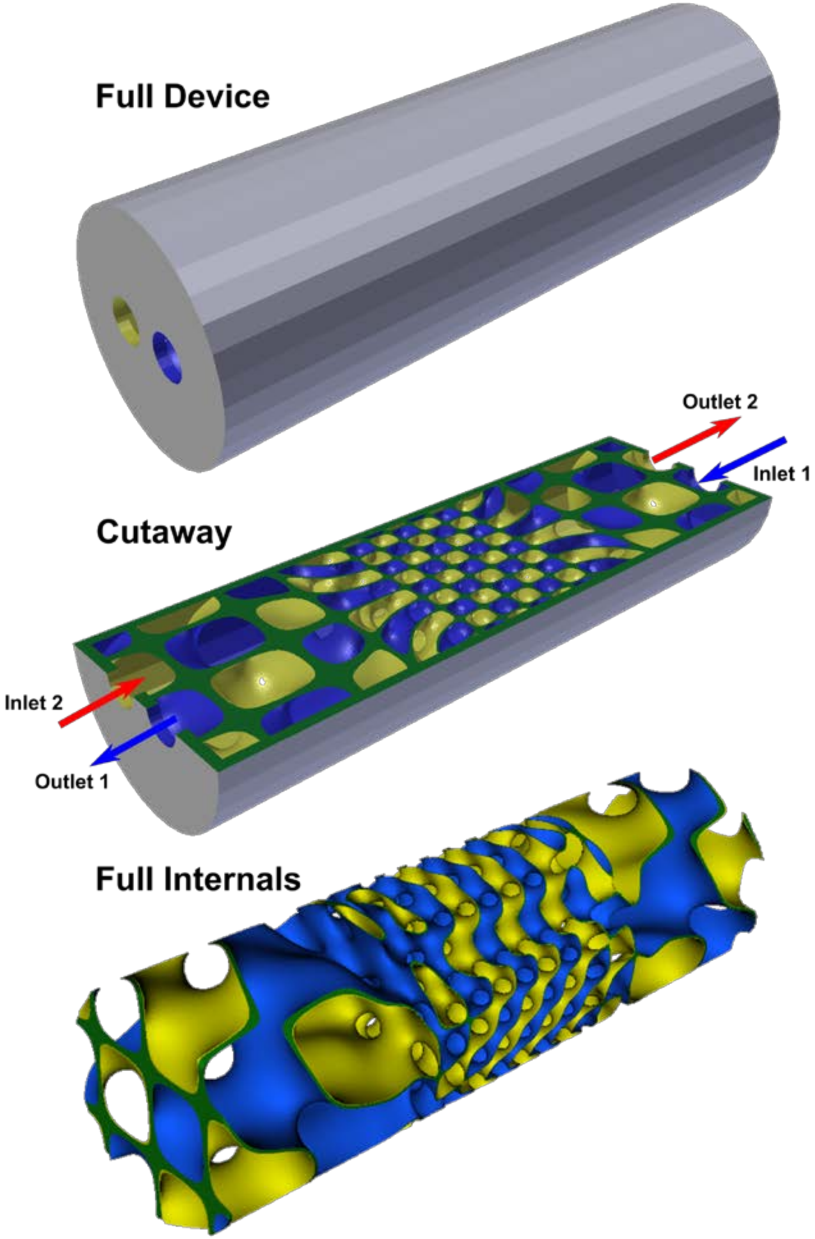


and are now achievable with AM.

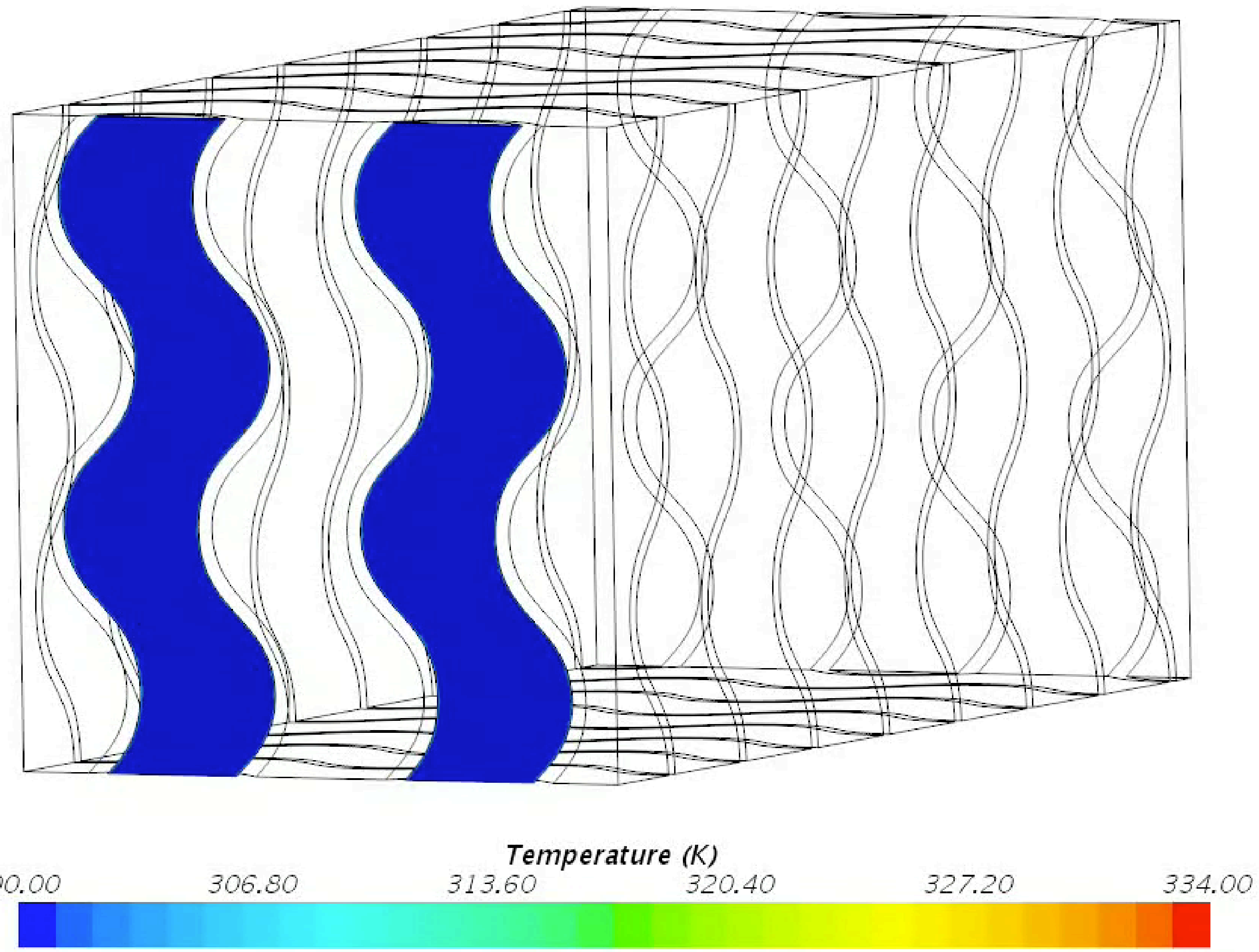


Various designs were created combining TPMS and hierarchy





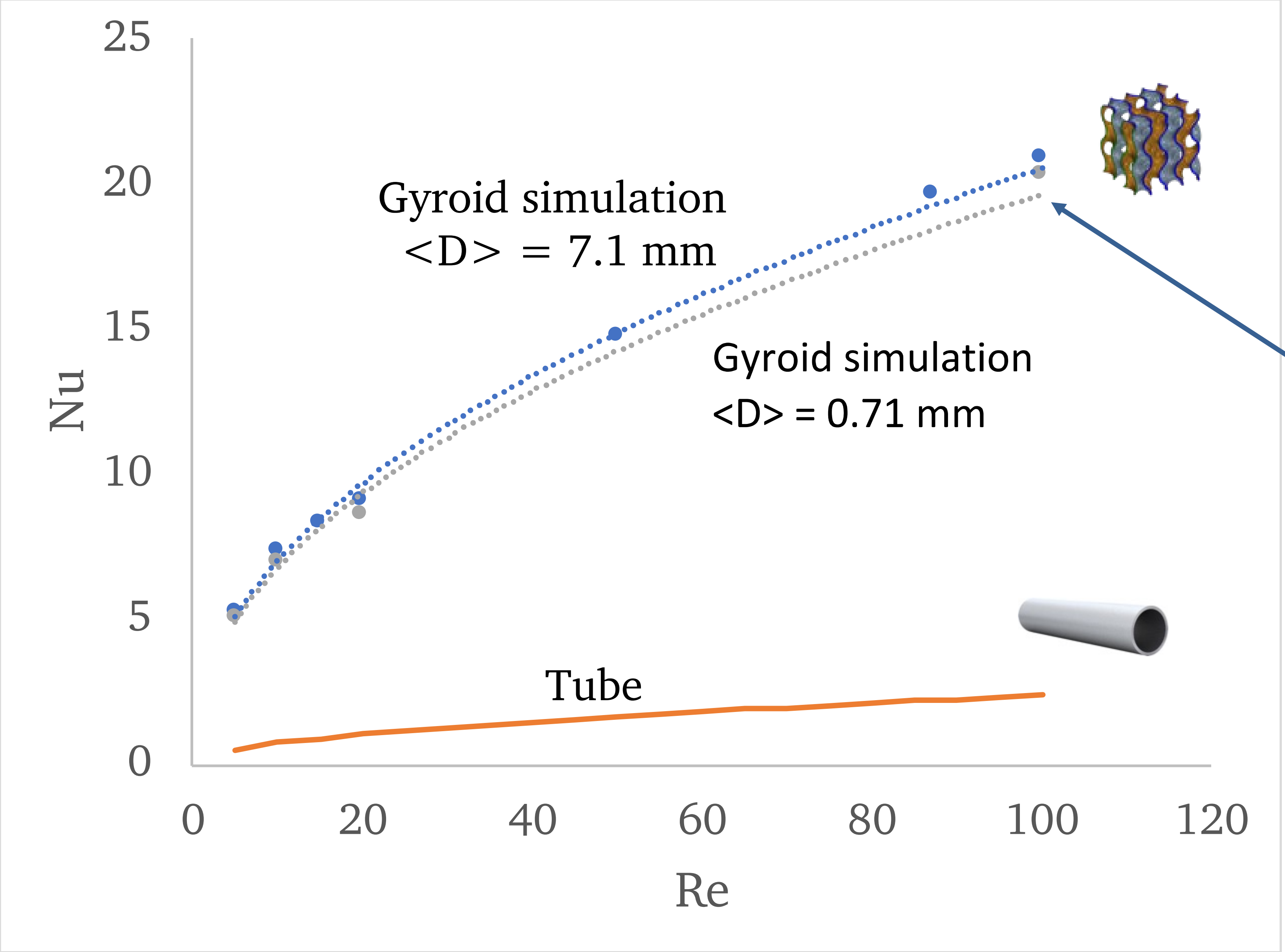
Our model shows that enhanced heat exchange comes from continual fluid movement to and from the wall.



U = 0.01 m/s
Re = 87
Pe = 521

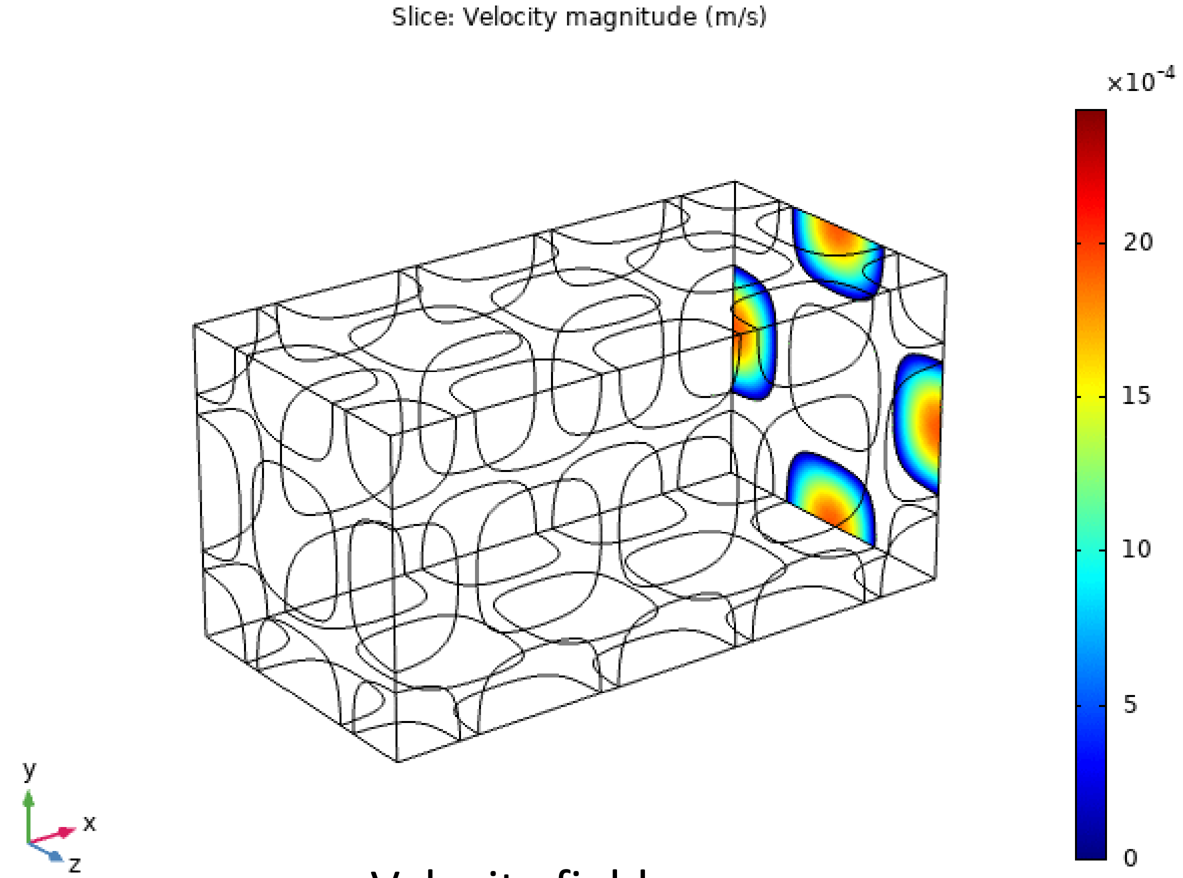
Steady-state temperature in cold fluid

Our modeling has confirmed advantages of TPMS geometries seen in literature

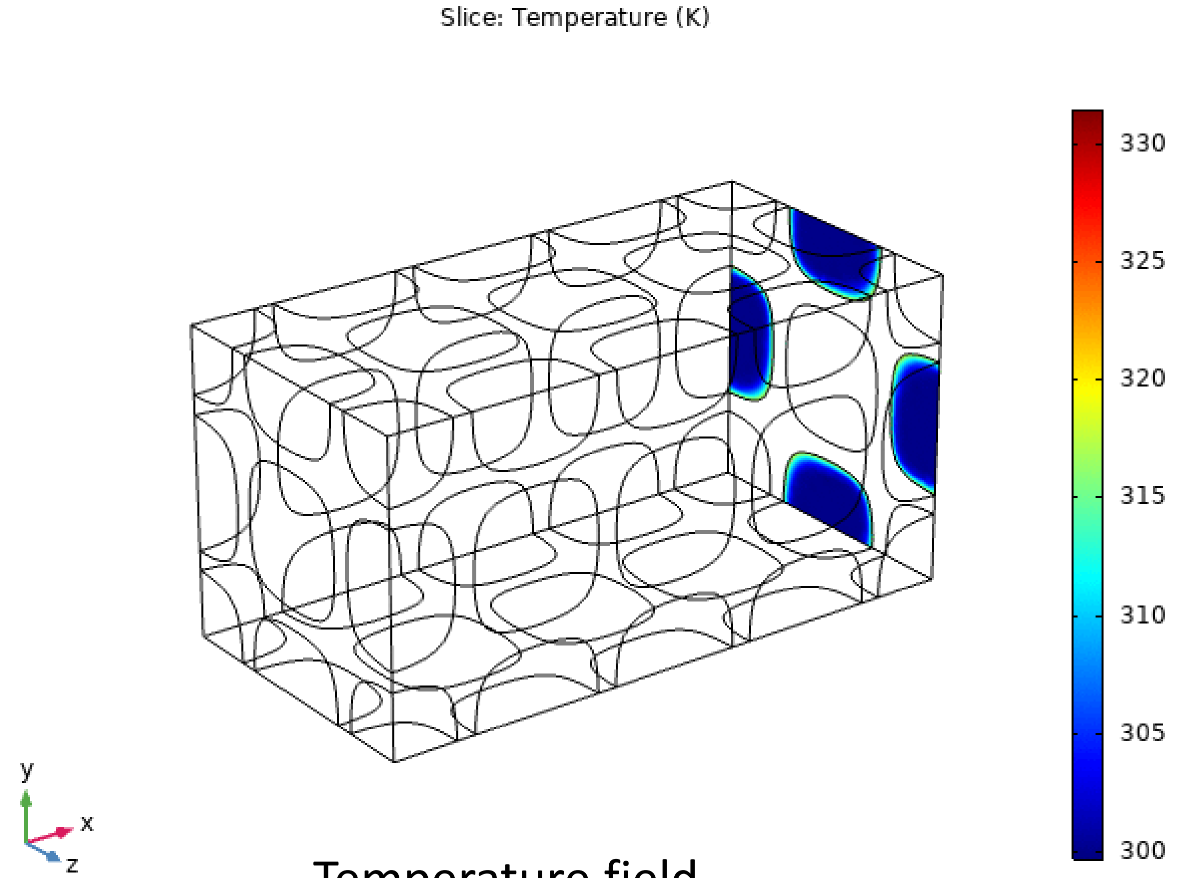


Nusselt Number correlation is consistent across channel sizes.

Simulations have been extended to other geometries.



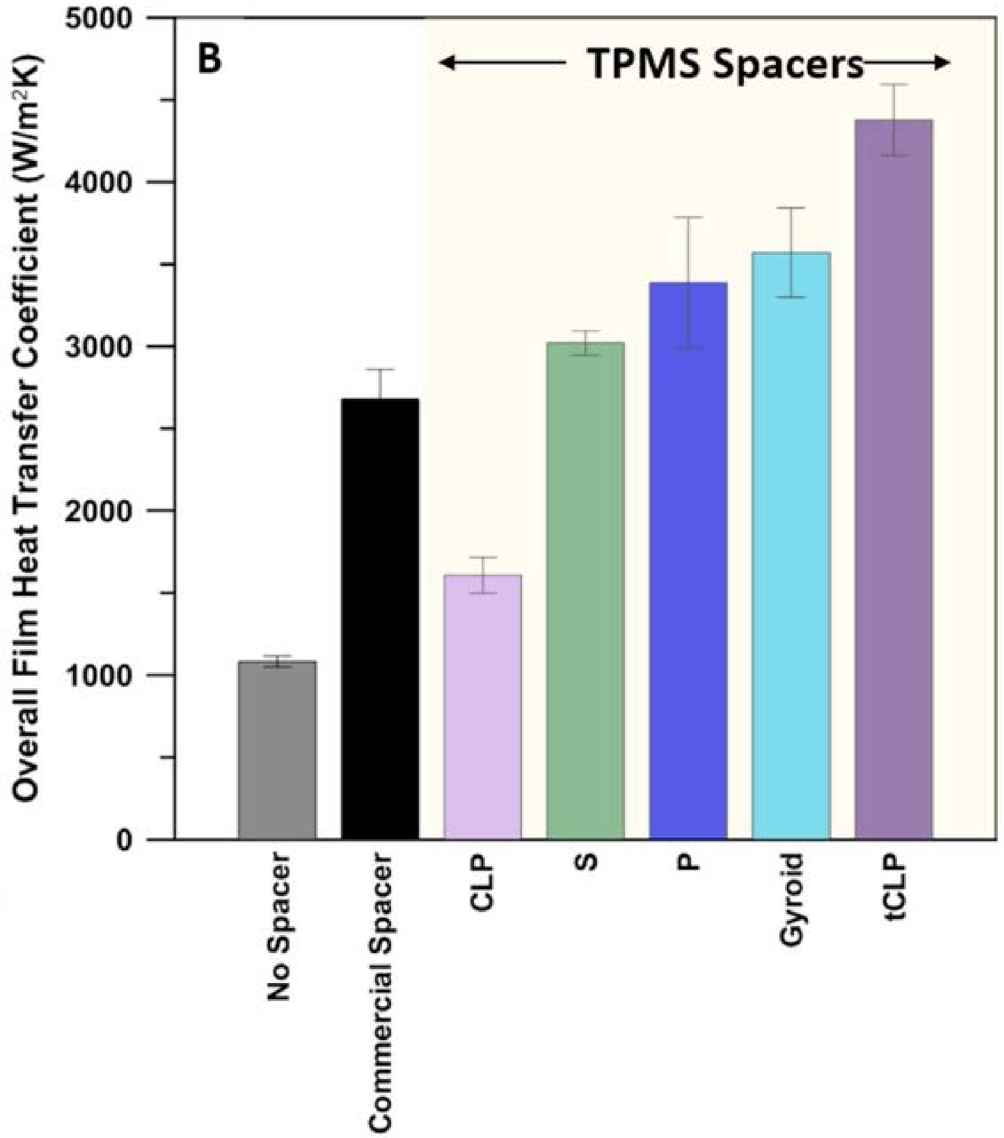
Velocity field

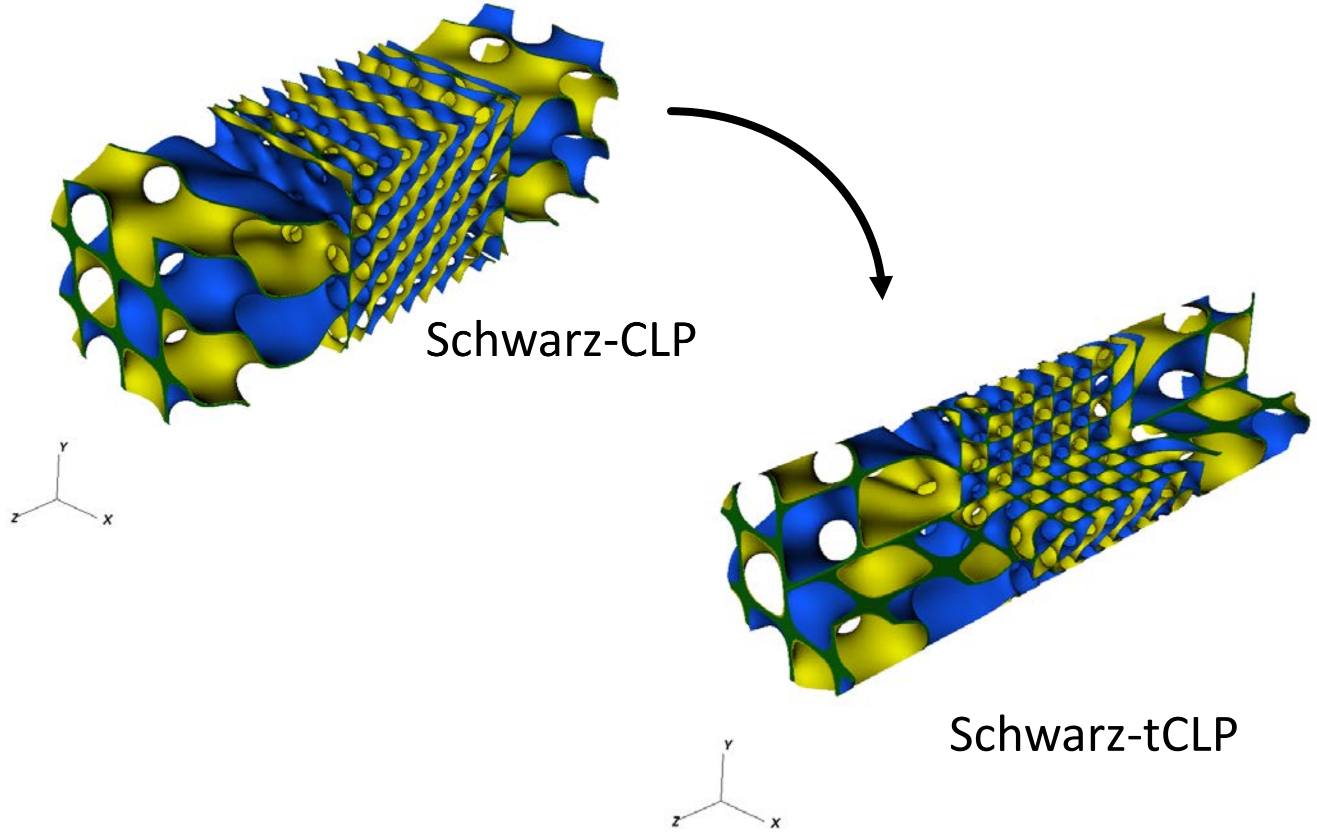


Temperature field

Schwarz-D cold fluid domain at stead state

Rotating a TPMS can dramatically change performance

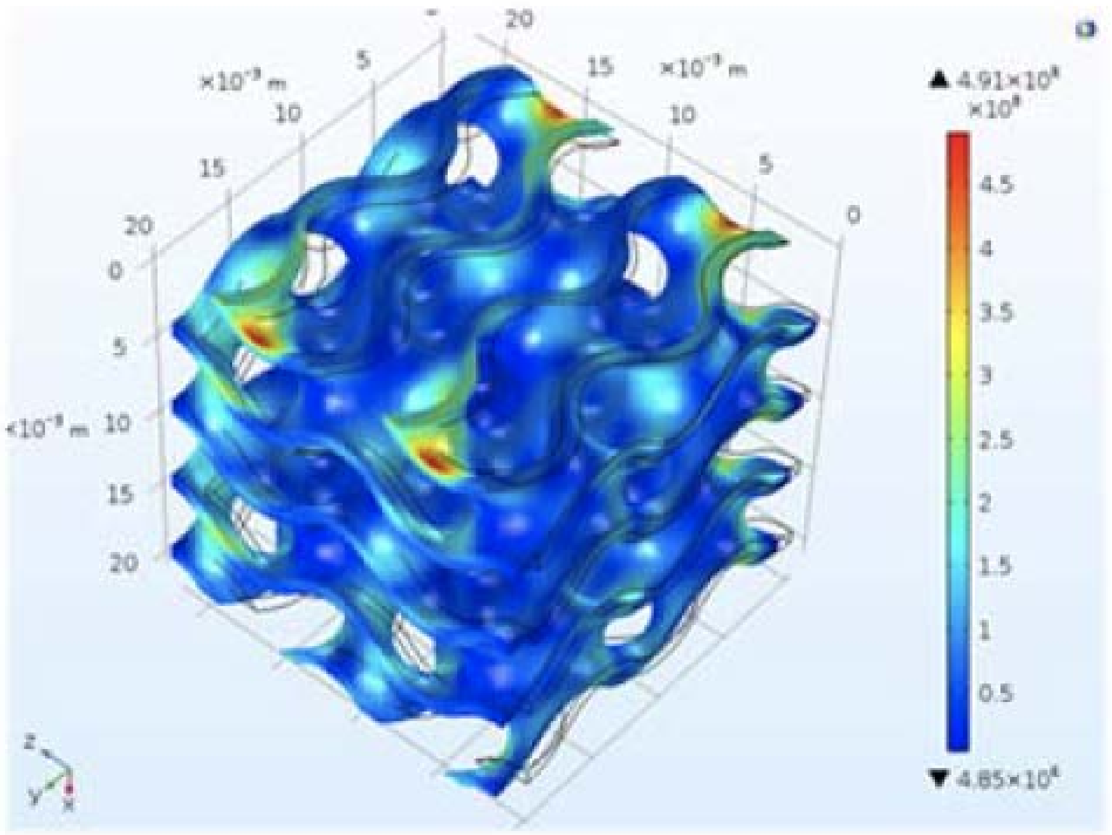




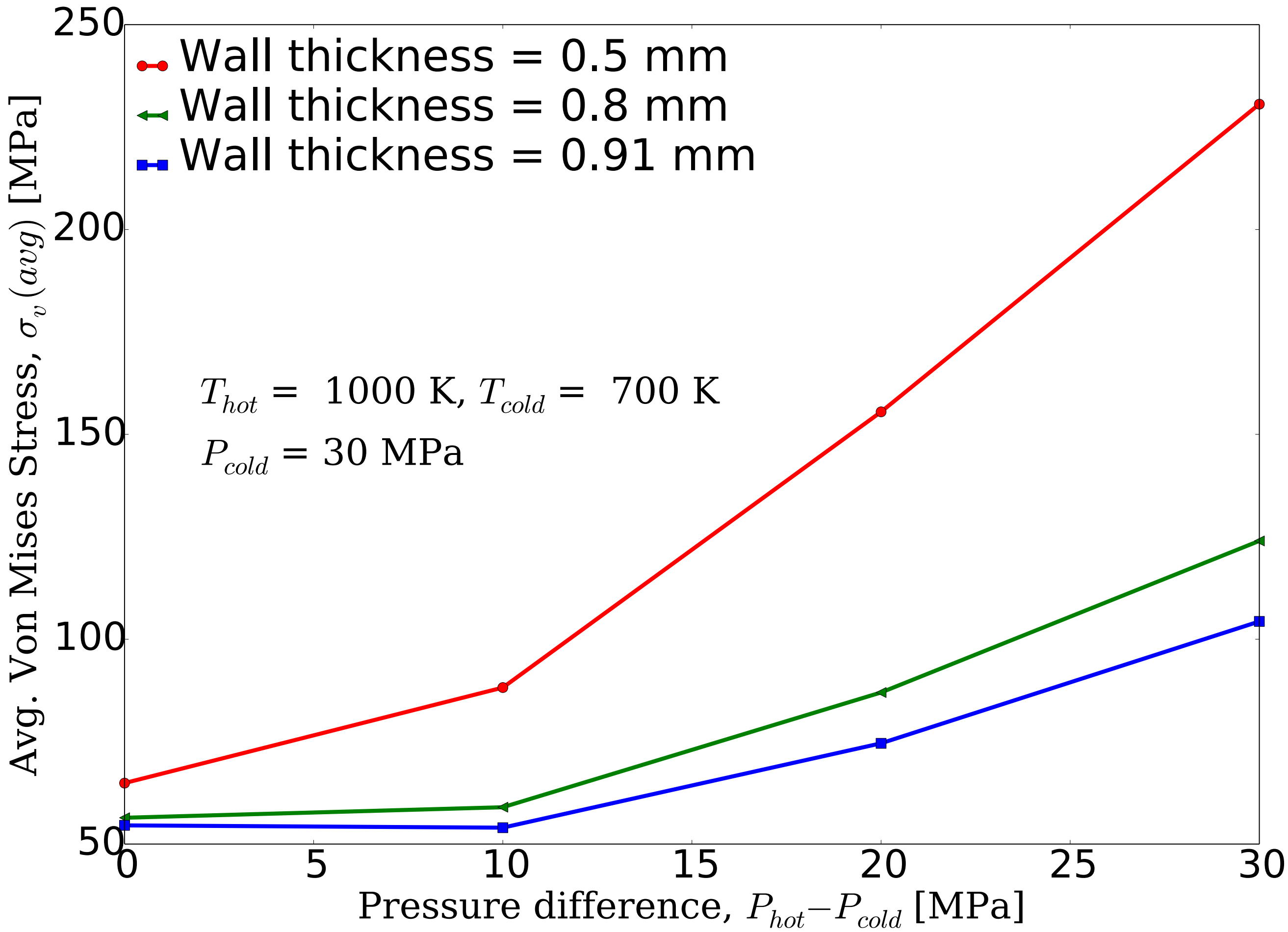
tCLP is the new most-promising candidate.

Source: Thomas et al. (2018). *Desalination, 443: 256—271.*

Solid mechanics model suggests pressure differential can be managed at reasonable wall thickness and material strength



Von Mises stress distribution in a gyroid



Fabrication

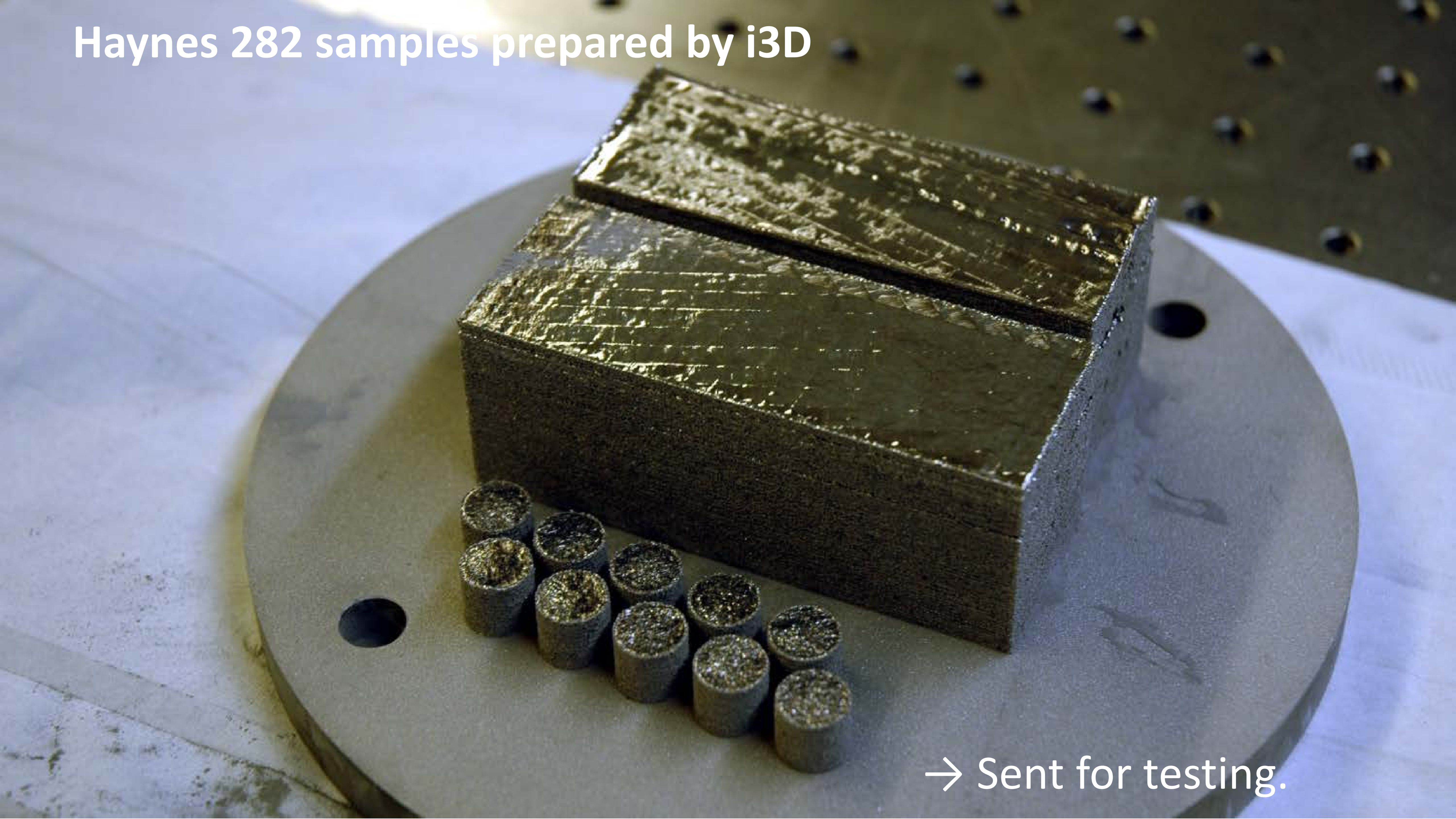
Five alloys considered, Inconel 625 most developed.

Alloy	Powder available	Printed in literature	Powder obtained	Coupons printed by LLNL/partners	Reactor printed by LLNL
Inconel 625	✓	✓	✓	✓	✓
Haynes 282	✓	✓	✓	✓	
Inconel 617	✓	✓	✓		
Haynes230	✓	✓			
Inconel 740H	✓				

We also considered Ultra-High Temperature Ceramics:

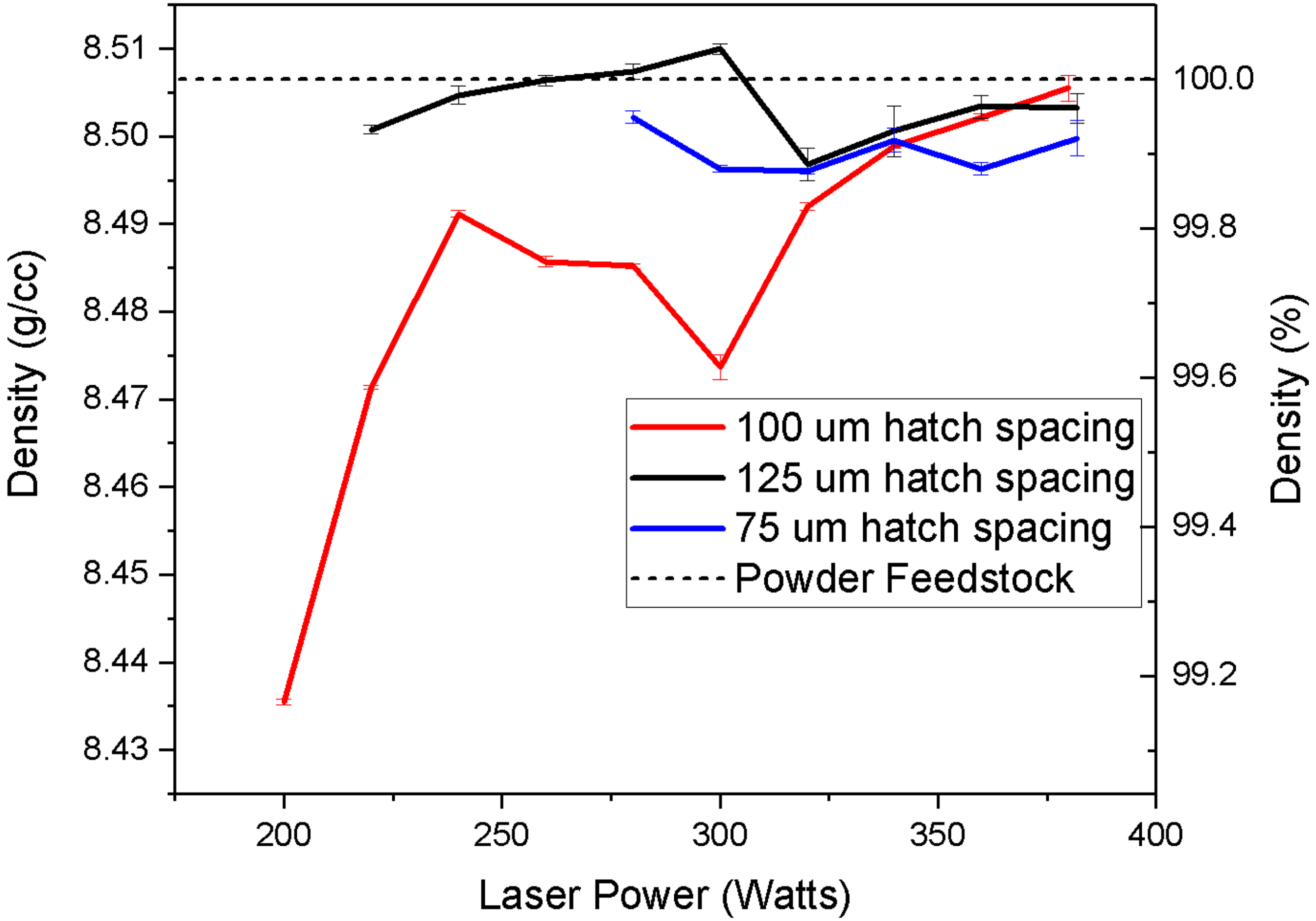
UHTC Composition	Additive Type	Additive (vol. %)	T_{sint} (°C)	Strength (MPa @ RT)	Strength (MPa @ 1200°C)
ZrB_2	C and or B_4C	0-5	1900	300-580	375-500
	$MoSi_2$	5-20	1900	520-1150	530-650
	SiC	20	2100	400-900	400-680
$80ZrB_2$ – 20SiC (vol. %)	B_4C	2-4	2200	470-760	450-610

Haynes 282 samples prepared by i3D



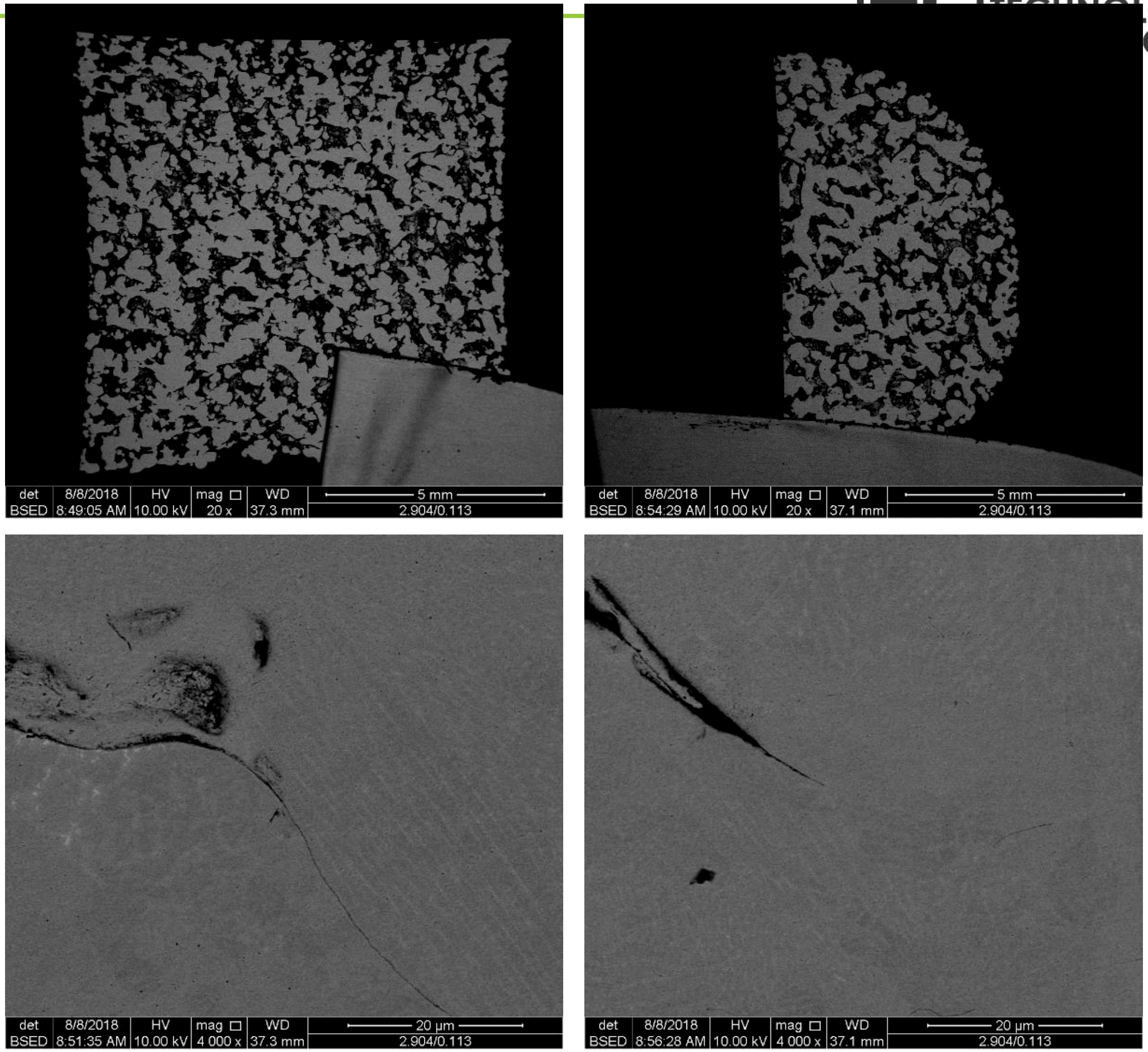
→ Sent for testing.

Initial density measurements were deceiving…



First prototype leaked through walls.

Analysis of coupons sent to NETL revealed massive porosity.

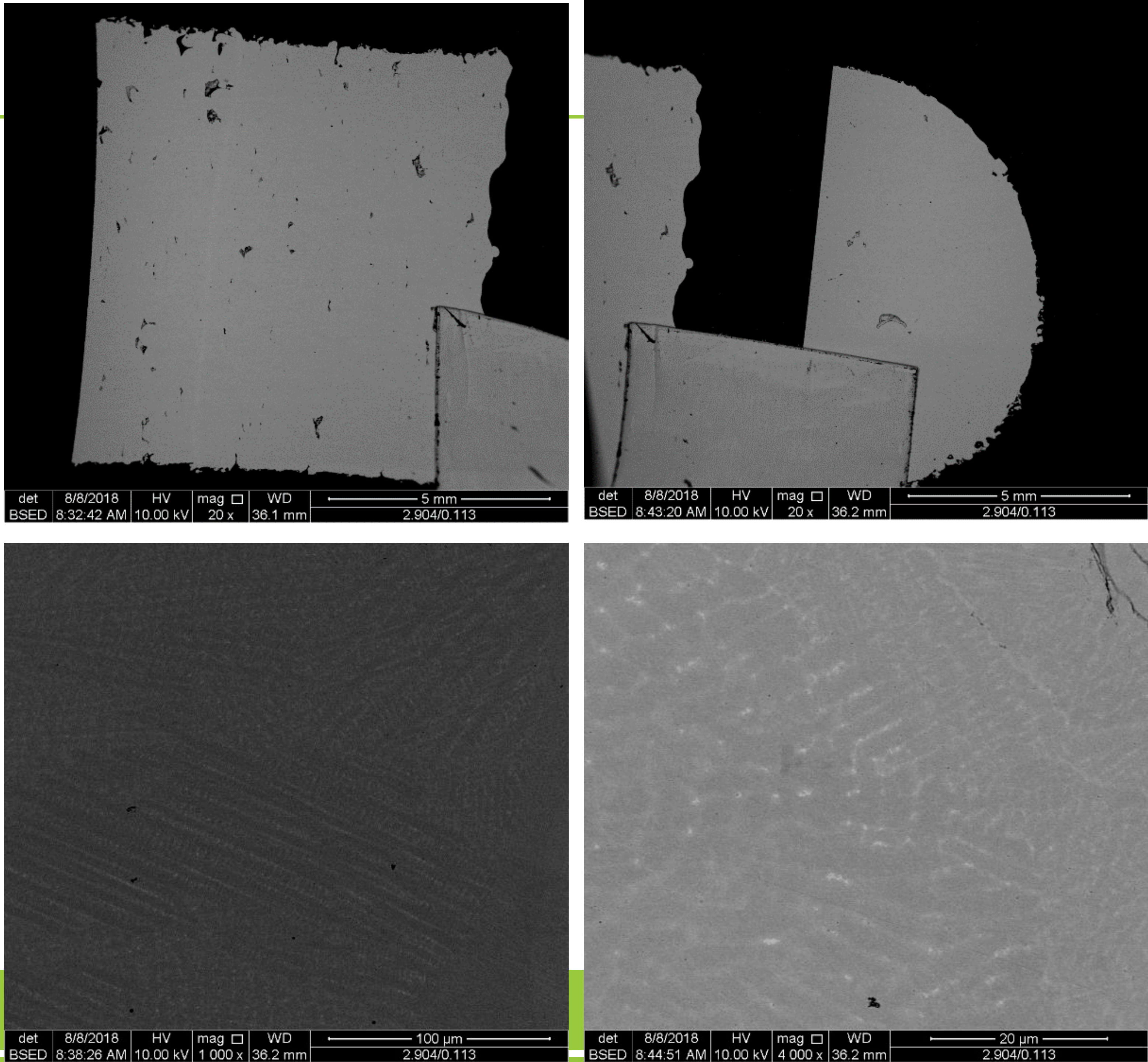


- **Square**
  - 37.4% voids / 62.6% solid
- **Half-circle**
  - 38.6% voids / 61.4% solid

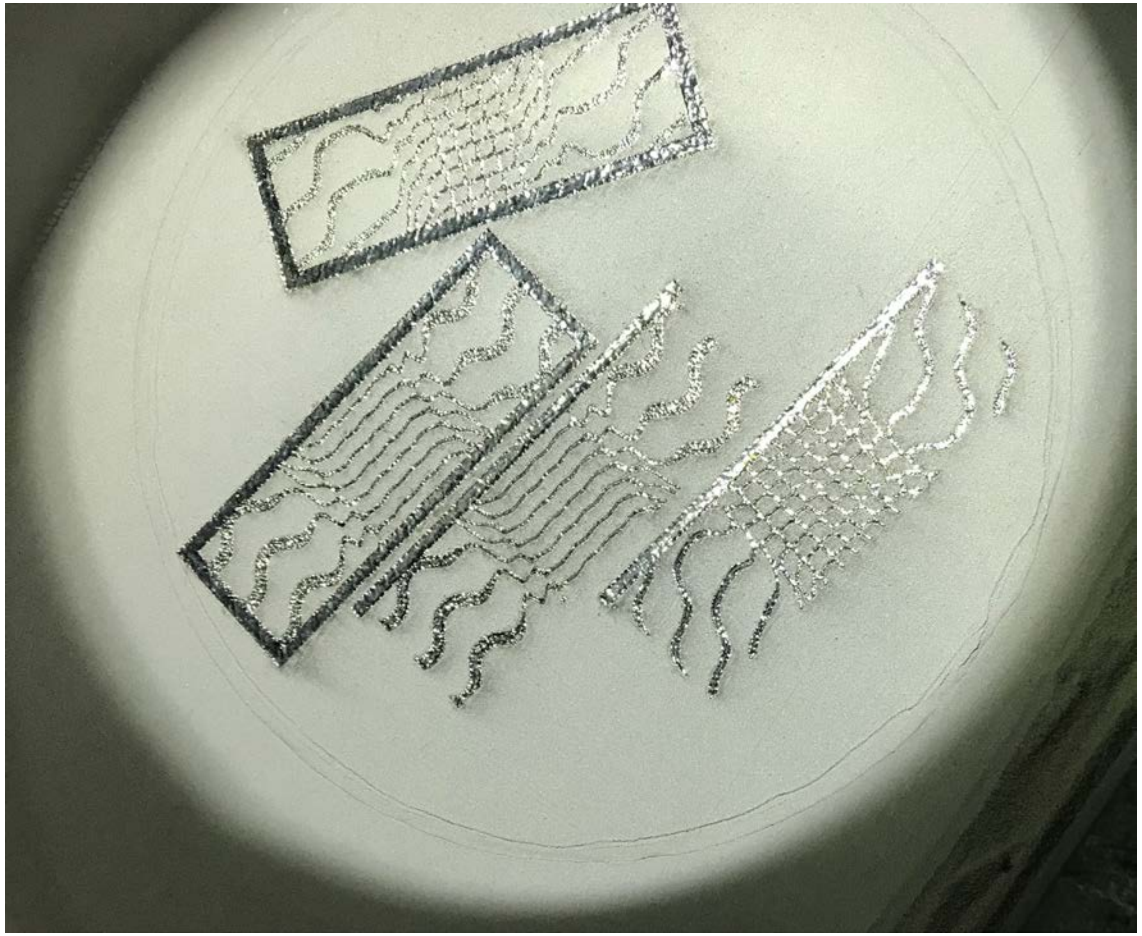
But not for all print parameters.

From these results, laser scan rate and power were adapted for subsequent builds.

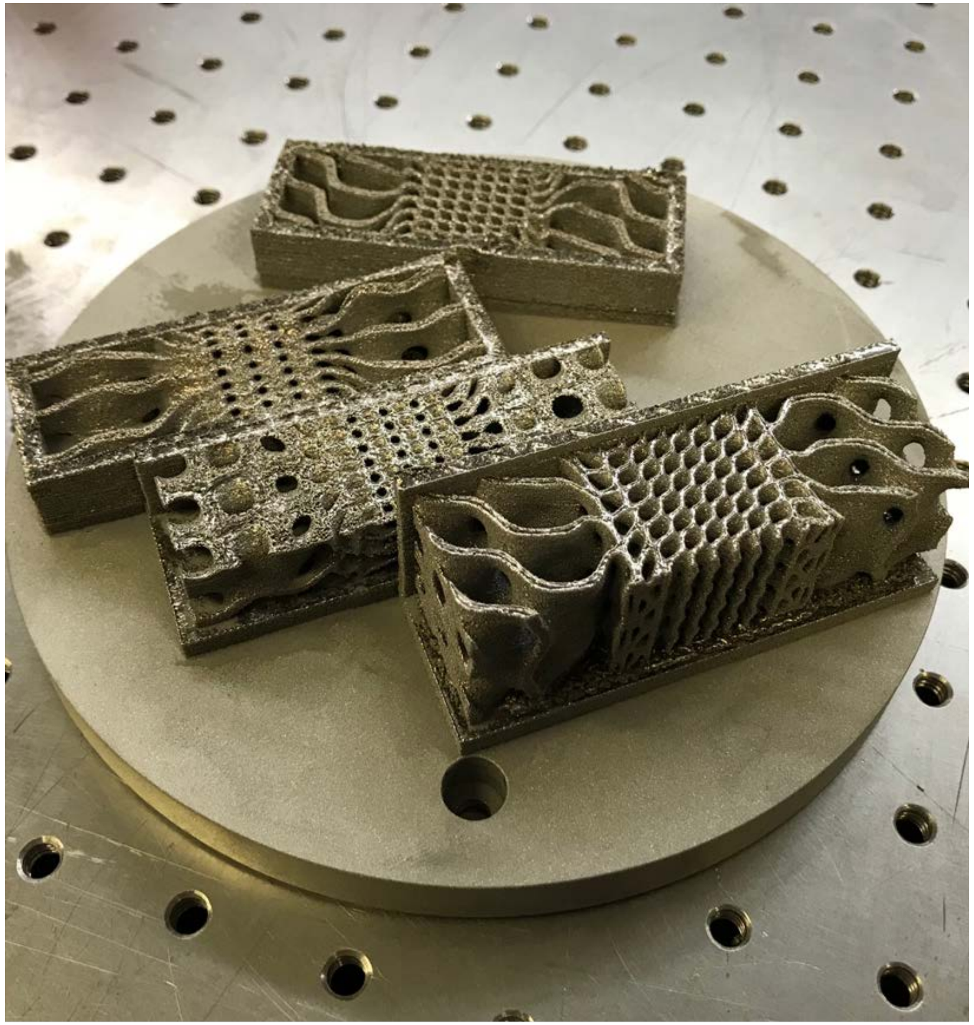
- **Square**
  - 1.6% voids / 98.4% solid
- **Half-circle**
  - 0.9% voids / 99.1% solid



Many builds attempted with new parameters.

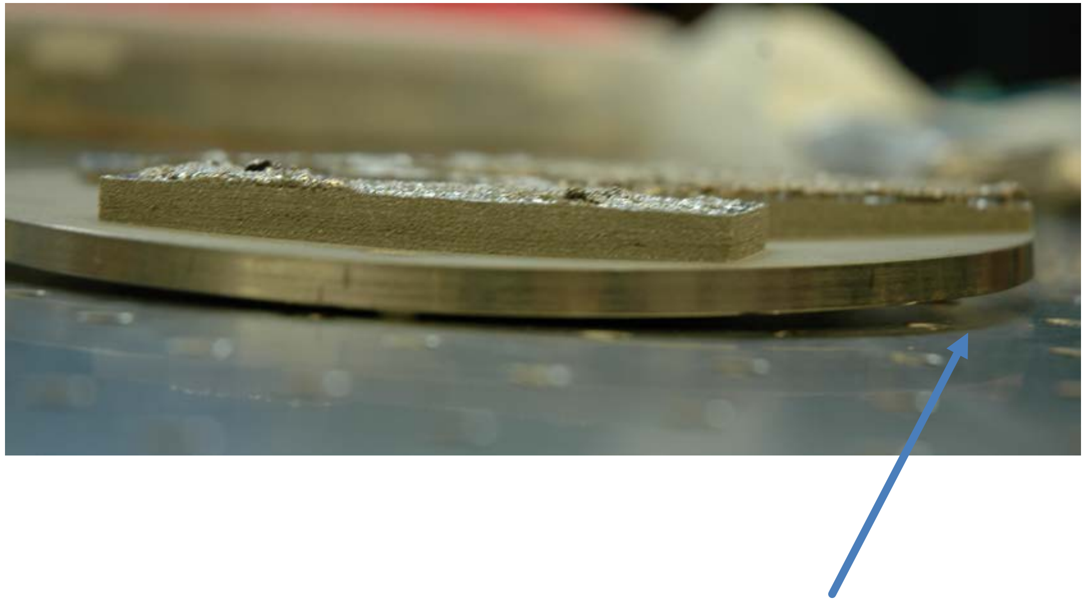


Single layer of a build

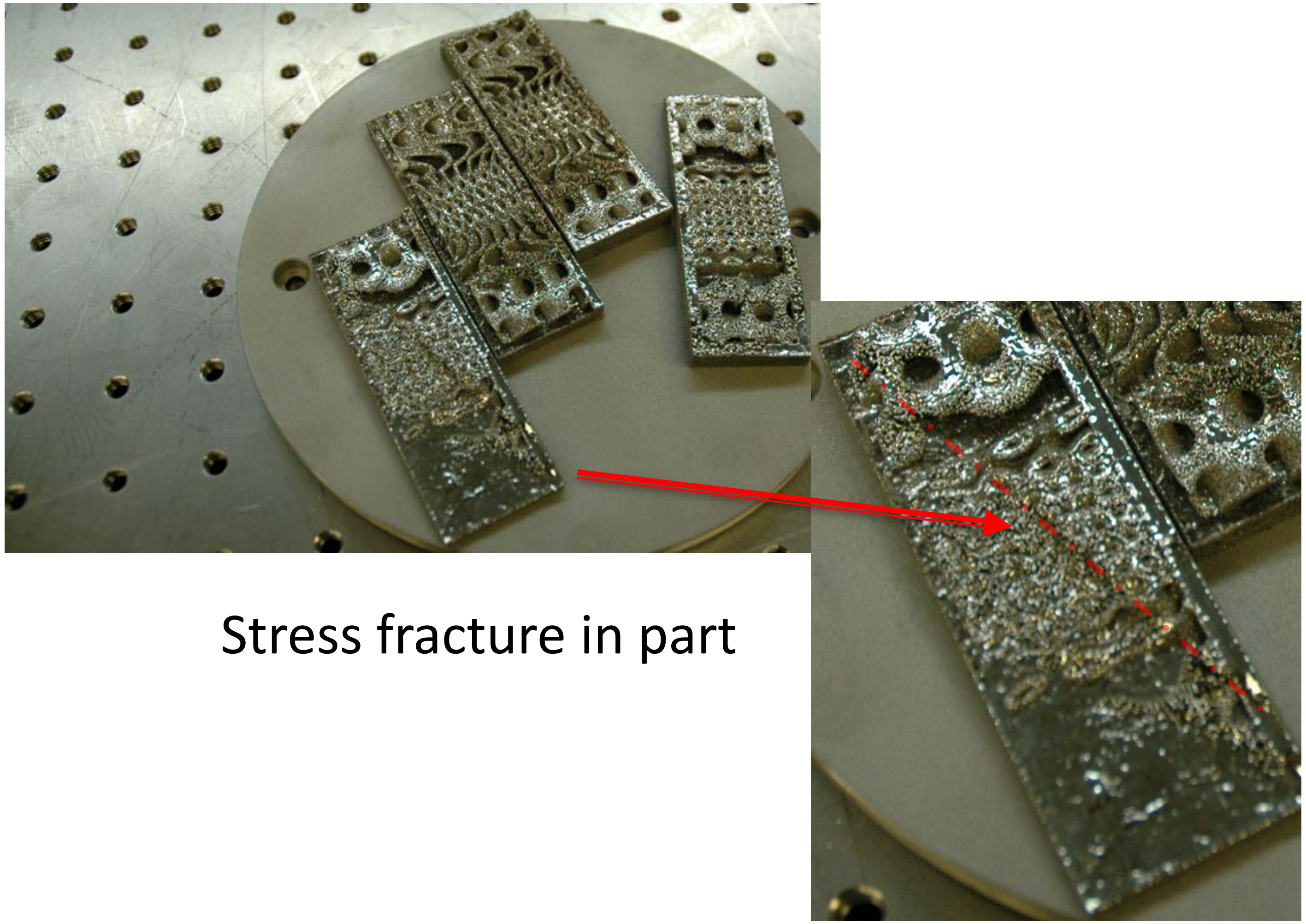


Some challenges remain...

Warping due to residual stress: bigger problem with Inconel 625 than other alloys.

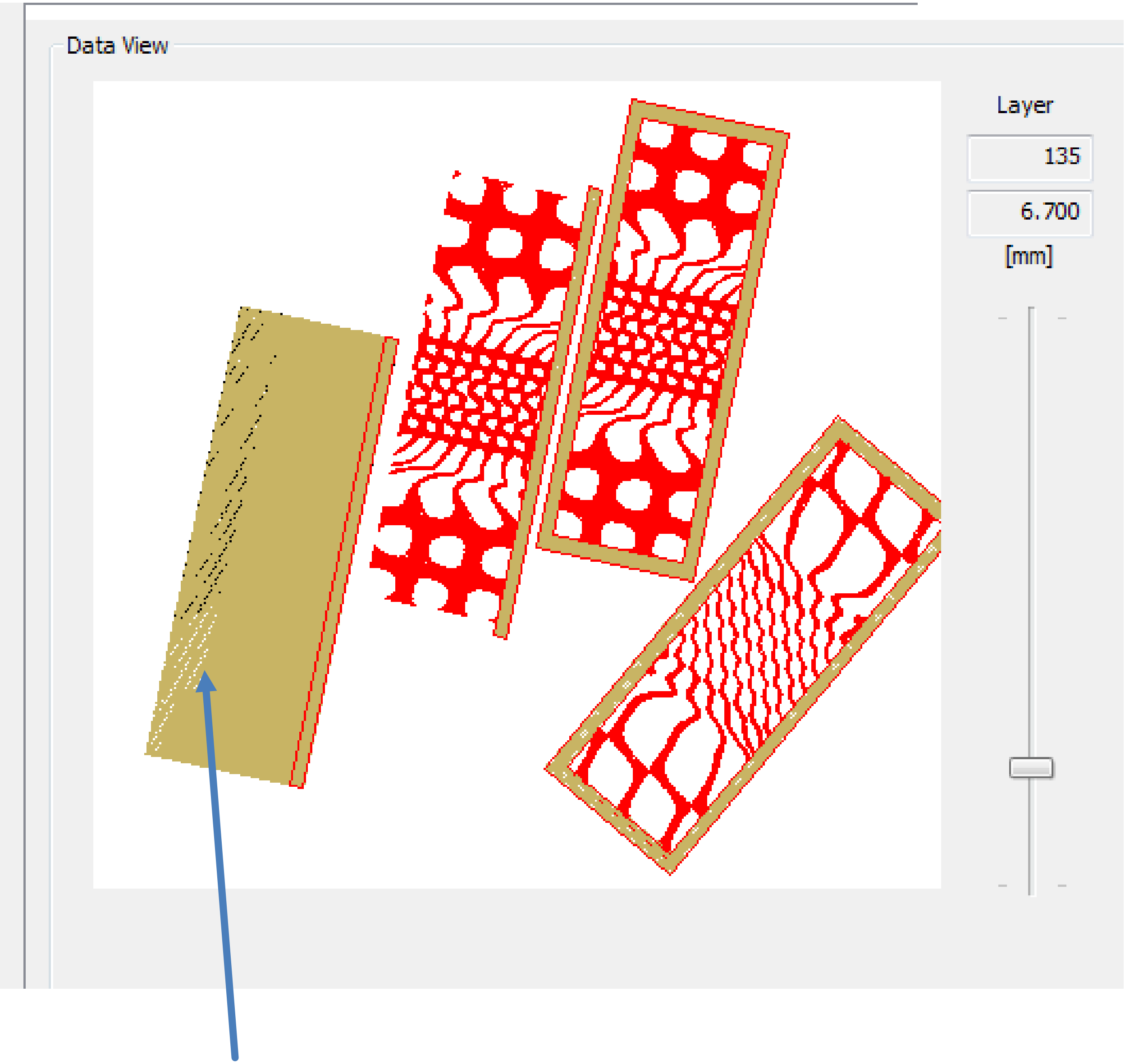


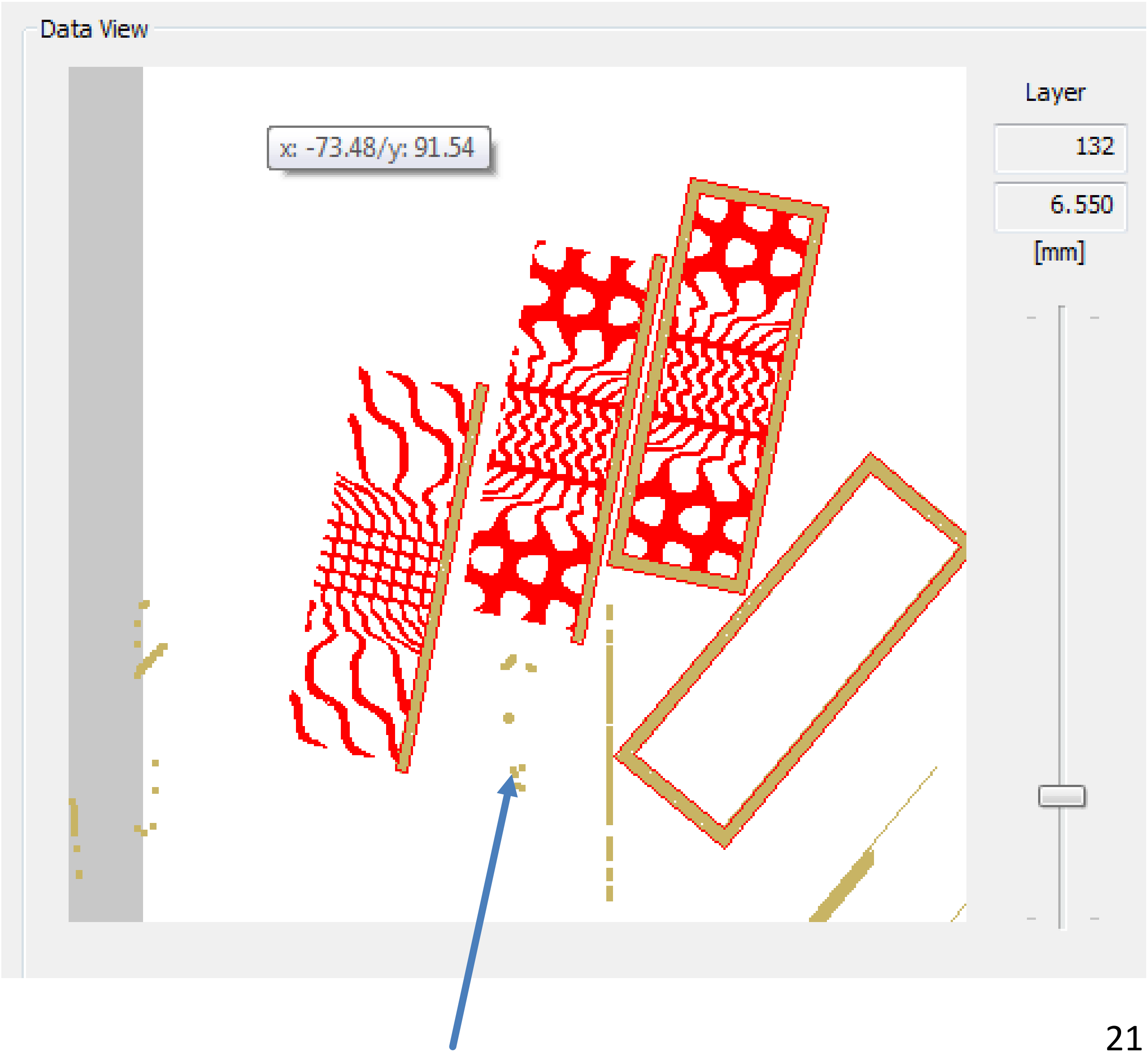
Build plate warps



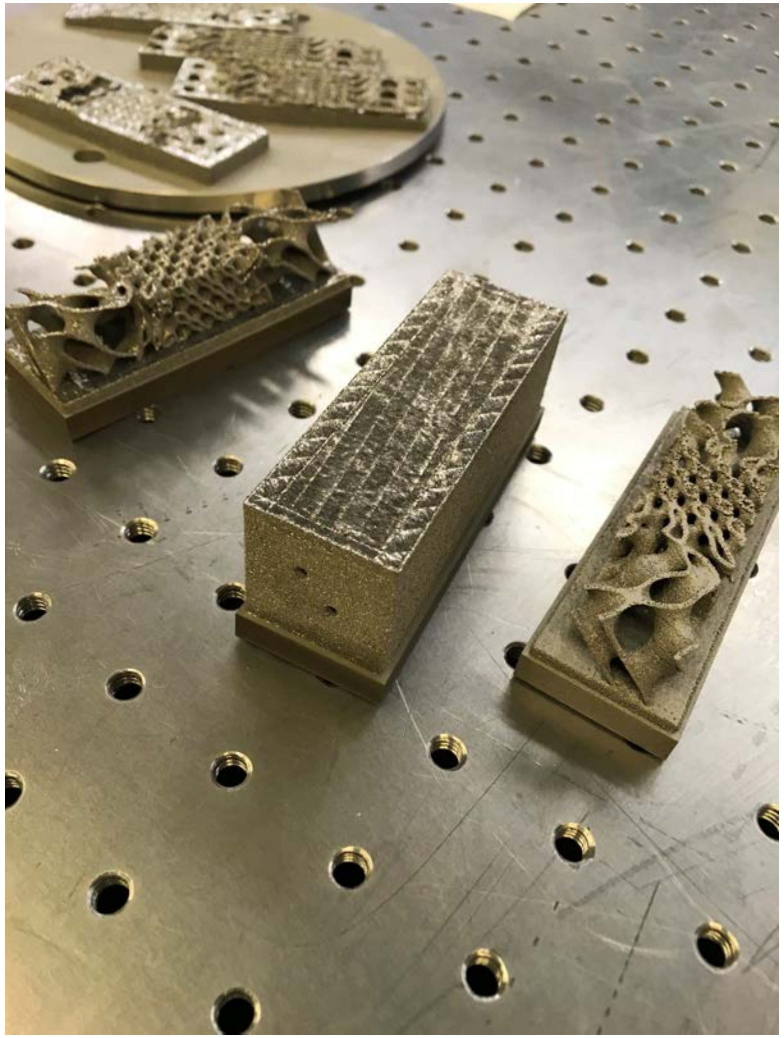
Stress fracture in part

Complex geometries lead to artifacts in the build files that must be managed.

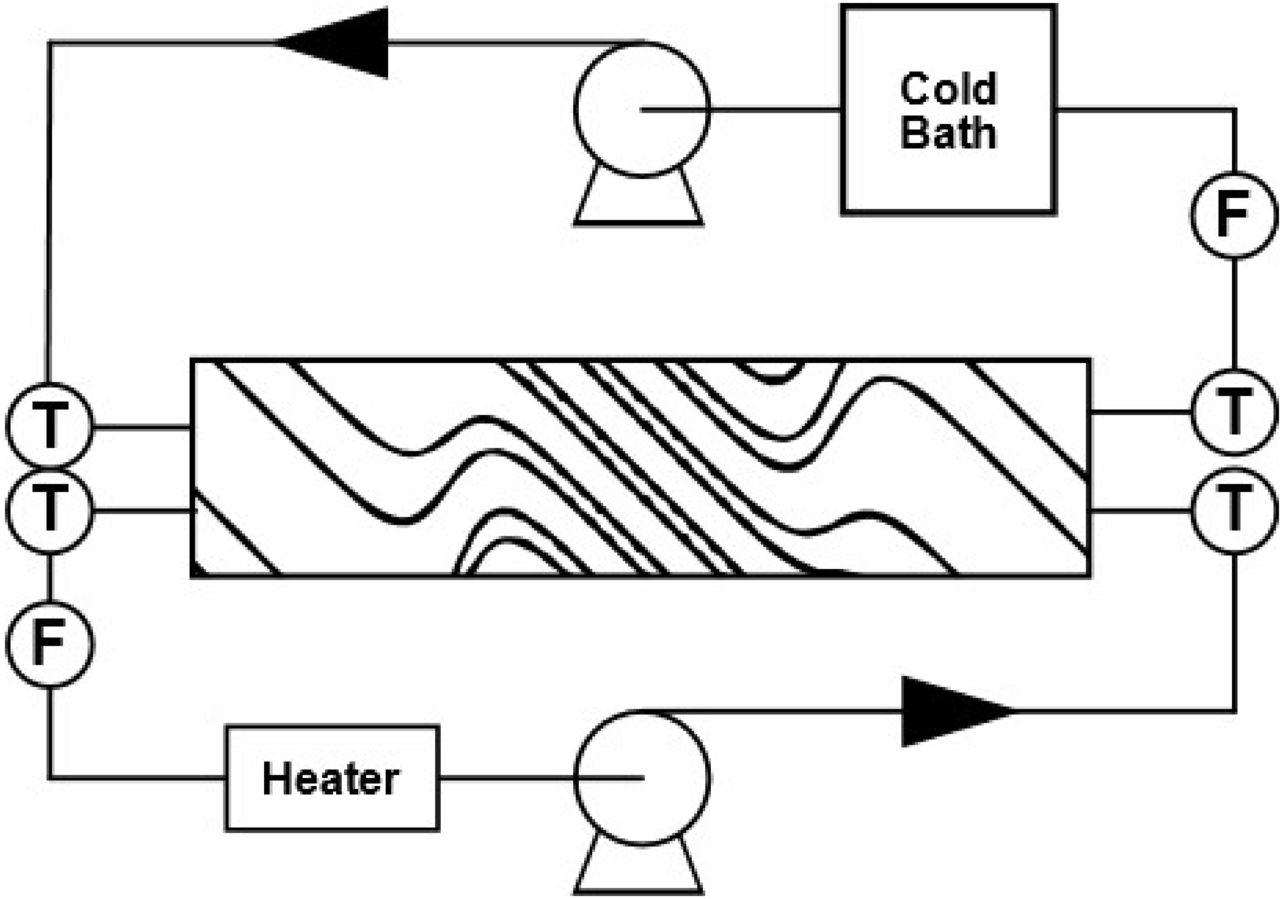




Although some warping is still present, one successful prototype was achieved.

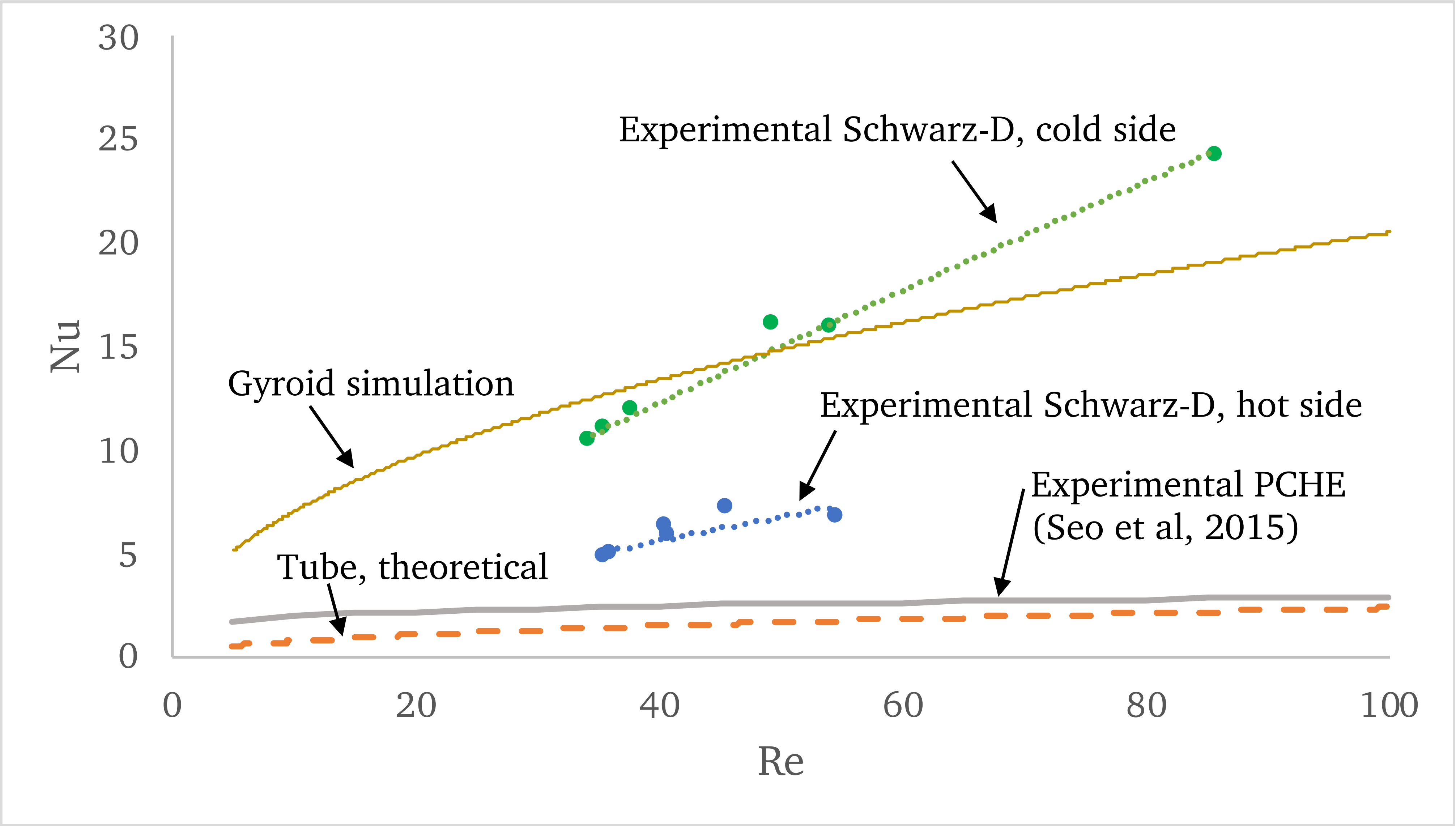


Schwarz-D Prototype tested in water/water heat exchange experiment



T_{hot} = 42°C
T_{cold} = 32°C

First experimental heat transfer measurements are encouraging.



Summary

- Enhanced heat transfer of the new geometries is confirmed by new simulations and early experiments.
- Stress simulations are in the right ballpark, but additional design and materials testing needed.
- Fabrication was more challenging than expected, but we are starting to find workable parameters.

Next steps

- Improved fabrication parameters
- Simulation of the full experimental domain
- Additional prototypes

→ Moving toward high T, high P performance testing.

Acknowledgements

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