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Experience of building thin wall structures and heat exchanger units using L-PBF

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Also to colleagues at UC Davis: Prof. Vinod Narayanan and Dr. Erfan Rasouli

Team for 8536: Additively-Manufactured Molten salt-to-supercritical Carbon Dioxide Heat Exchanger

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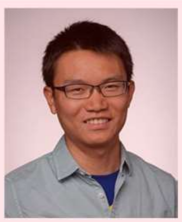


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METAL POWDER WORKS

Cost Share Partners

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HX Overall Design with 3D Printing

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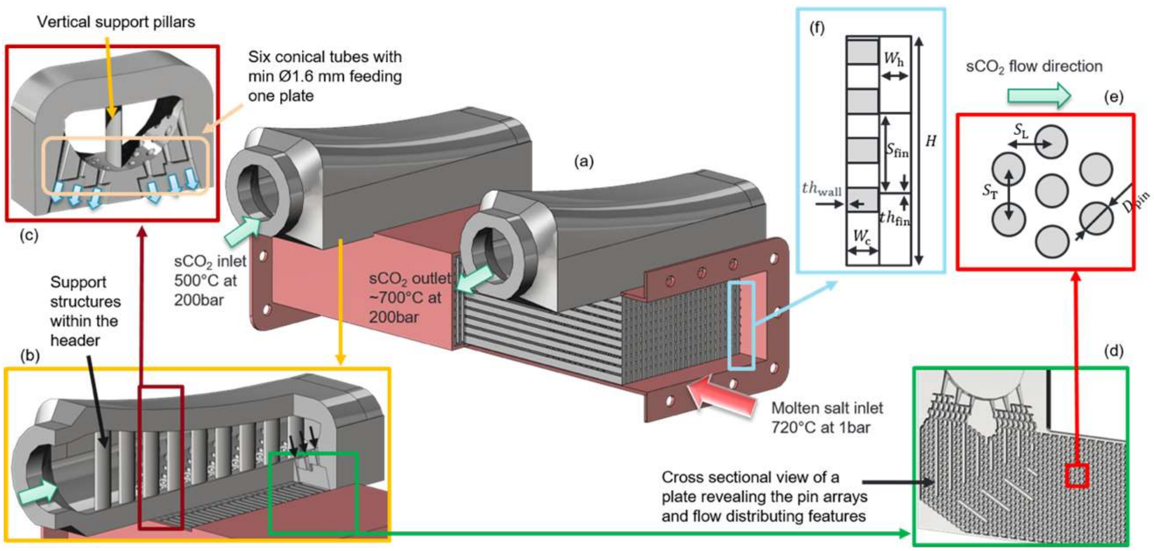
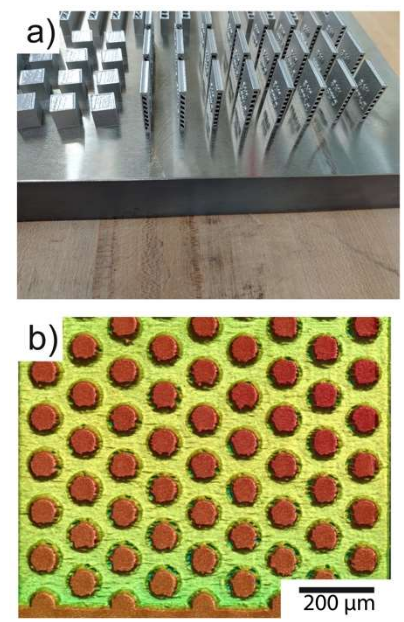
Mechano-thermal-fluidic Design
- Mechanical and CFD simulations
- Correlation-based thermofluidic model of the core

Metal Additive Manufacturing
- Porosity-based Process Map
- Surface Roughness
- Core Geometry Dimensional Tolerance

Process Based Cost Model





Laser Powder Bed Fusion (LPBF)

1. CAD model is sliced into layers
2. Tool paths (laser scanning parameters) are chosen:

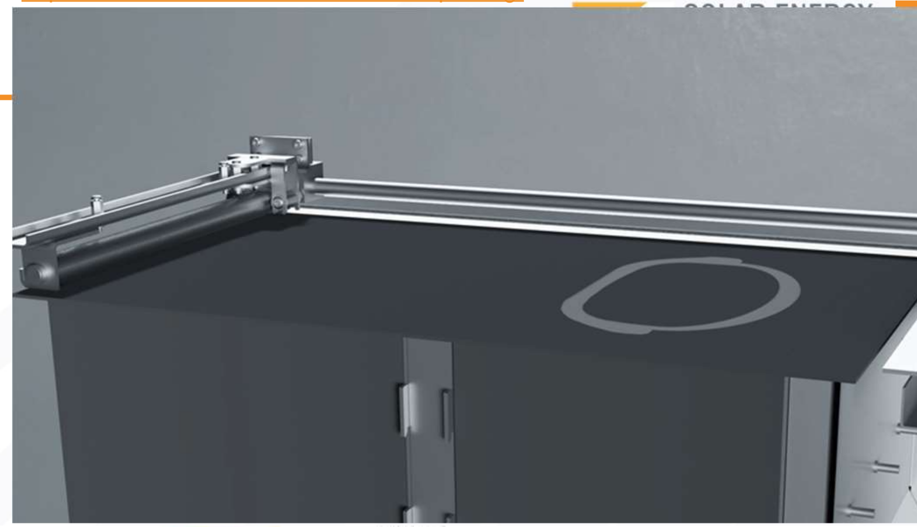
Scanning strategy
Support structure (for overhangs, etc.)
Laser Power, Scan Speed, etc.

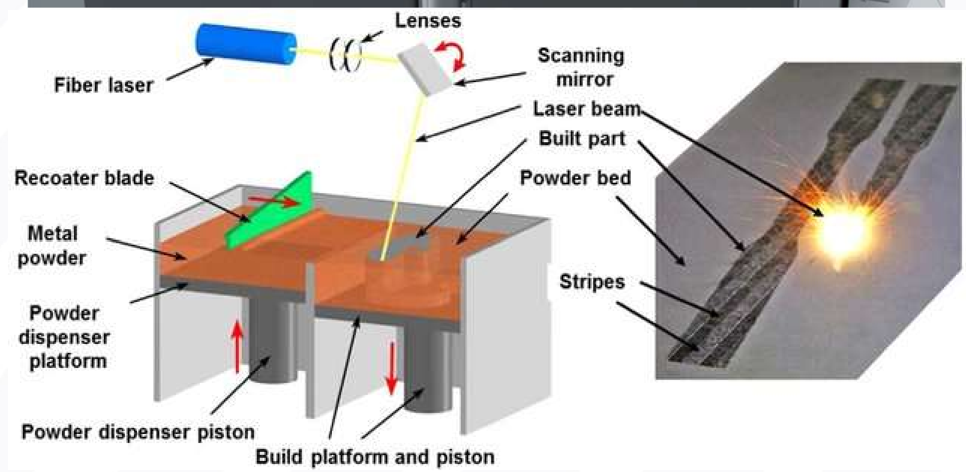
3. Machine spreads powder

layer thickness (20-60 μm)

4. Laser melts cross-section of part
5. Repeat 3-4 until part is complete
6. Cut off build plate, post process, etc.

https://www.sinterit.com/what-is-sls-3d-printing/





Criales *et al*. (2017) *International Journal of Machine Tools and Manufacture*

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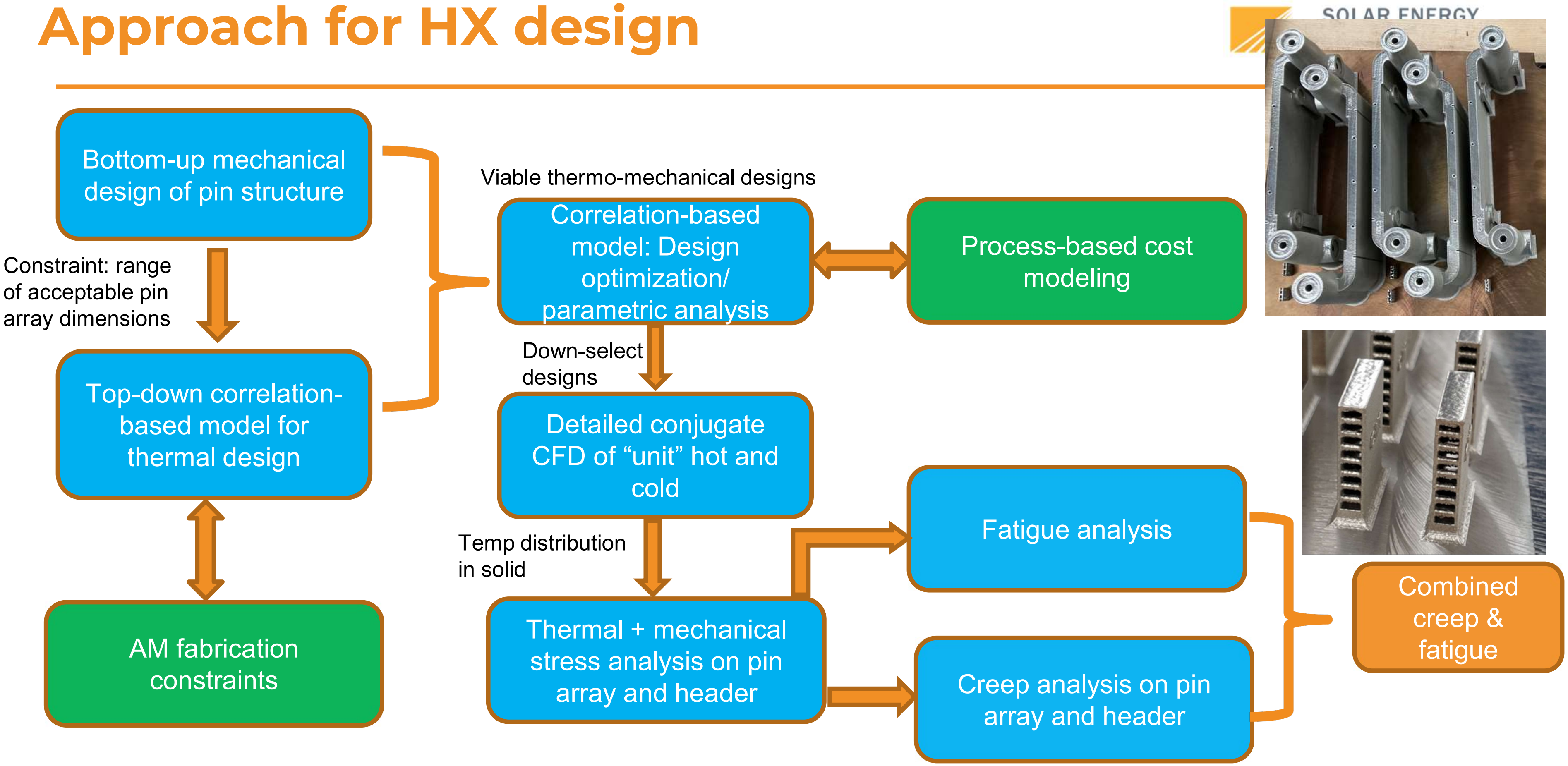
Approach for HX design



Materials used: Haynes 230, Haynes 282

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Materials

- Very few metallic alloys for high temperature service are supported by the LPBF manufacturers
- For Ni alloys, only IN625 and IN718 are available for 3D printing; our first experience in printing HXs was with IN718
- In general, alloys that have high creep strength are less weldable, which often translates to being unsuitable for printing
- The high operating temperatures, combined with corrosion issues, forced us to consider non-standard materials with higher creep strength
- We built on the experience of the power generation industry
- Started with Haynes 230 because of the experience base with corrosion resistance: made it work with higher pre-heat, even though it had a reputation for cracking
- Moved to Haynes 282, which was easier for printing
- Also have experience with a Co-based alloy, MHA 3300
- Our hypothesis has been that low defect content should maximize creep strength, just as it does for fatigue strength
- Accordingly, we have used the *defect-based process window* approach for developing process parameters

Physics-based 3D Printing via Process Windows

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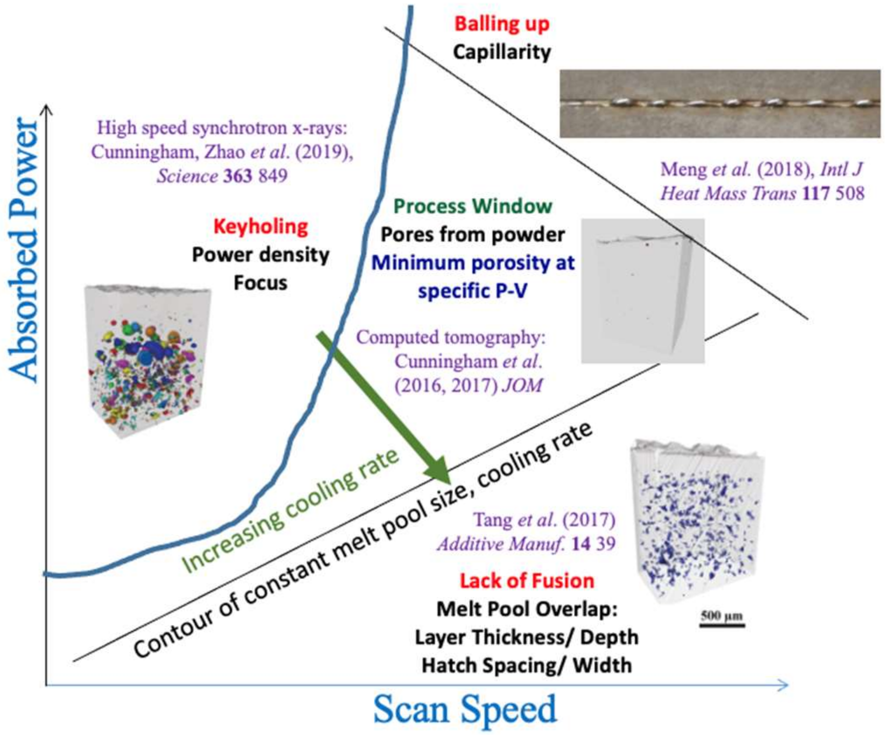
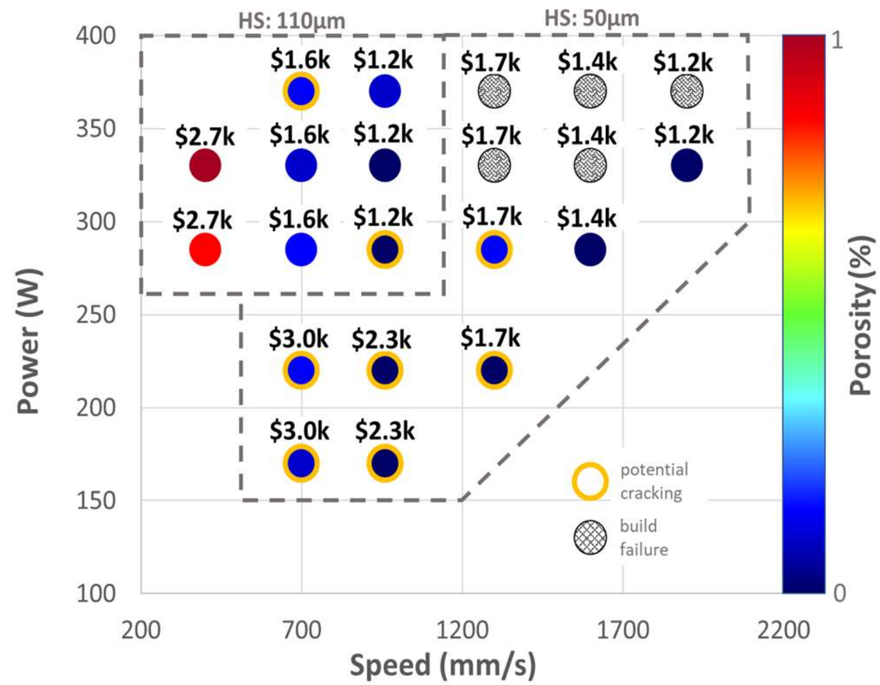


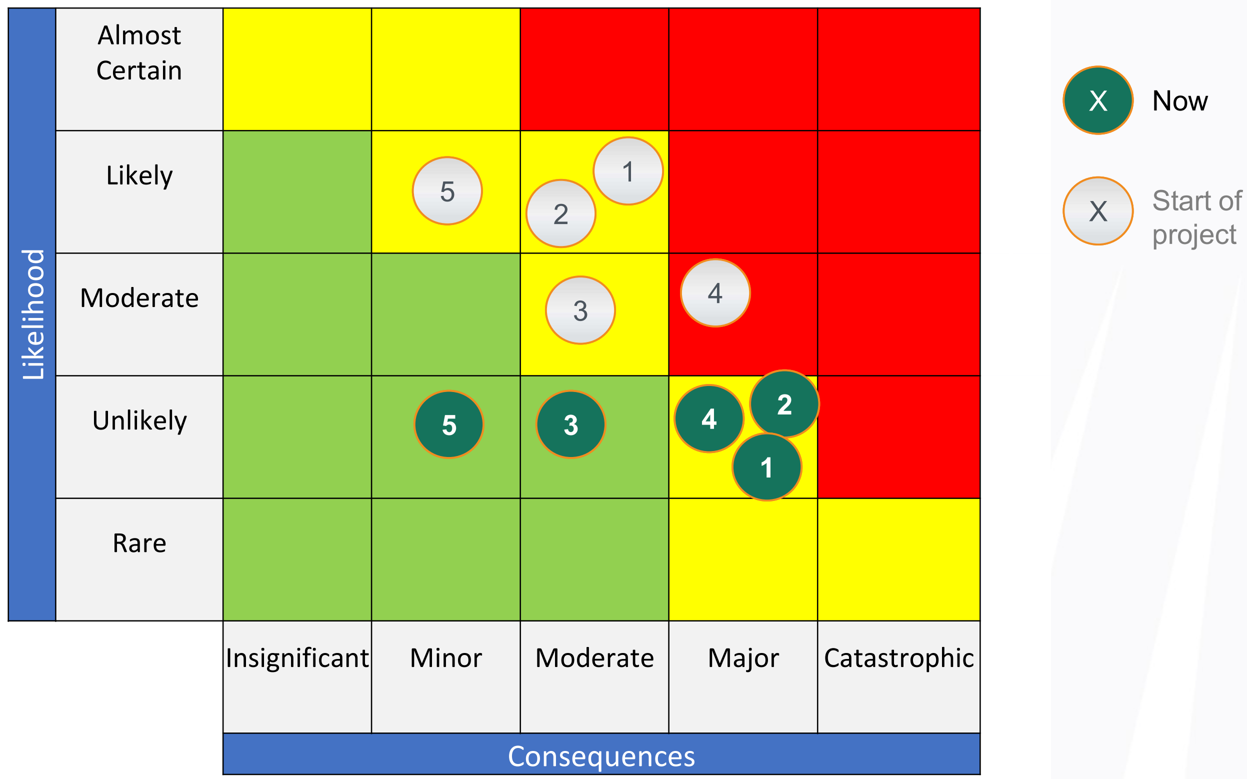
"Defect Structure Process Maps for Laser Powder Bed Fusion Additive Manufacturing", J.V. Gordon, S.P. Narra, R.W. Cunningham, H. Liu, H. Chen, R.M. Suter, J.L. Beuth, A.D. Rollett, *Additive Manufacturing*, **36** 101552 (2020)



Unit cost for 2kW 3D printed heat sink overlaid on porosity data from Haynes 230 print testing.

Risk Update

Risk	#
Surface roughness ⇒ too much ΔP	1
Inadequate creep strength	2
Inadequate corrosion resistance	3
Powder retention ⇒ too much ΔP	4
Flow distribution among plates and within each plate	5



Minimum creep rate in H230

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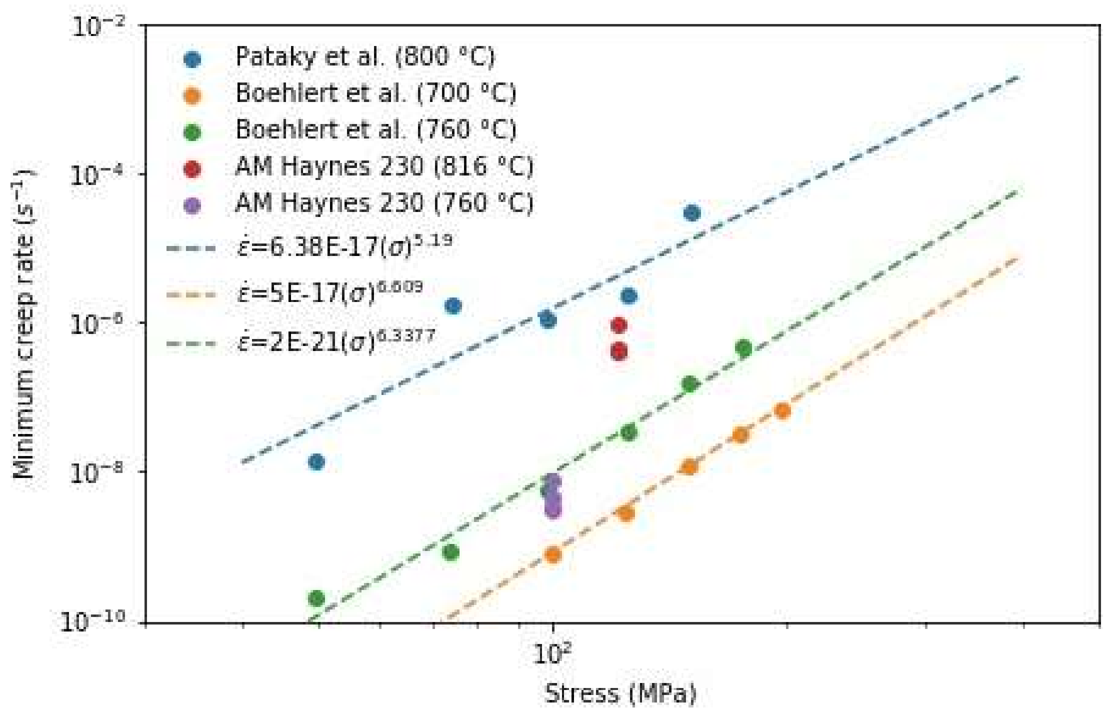
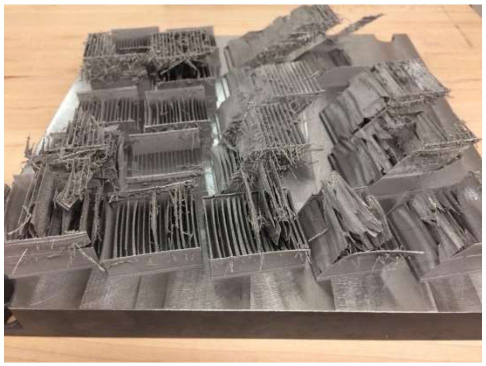


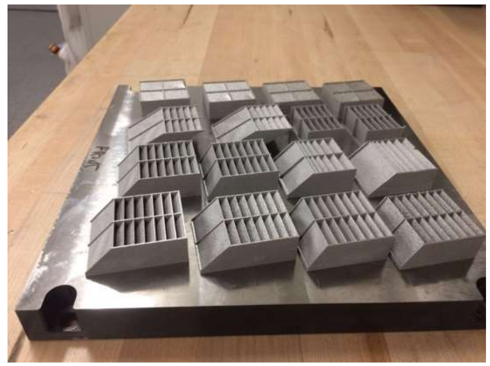
- The minimum creep rate of AM Haynes 230 is lower than that of wrought Haynes 230 even at a higher temperature and a lower stress level.
- The creep exponents suggest dislocation climb is the rate limiting creep mechanism between 700 °C and 800 °C.
- Essentially no "steady state creep" observed.

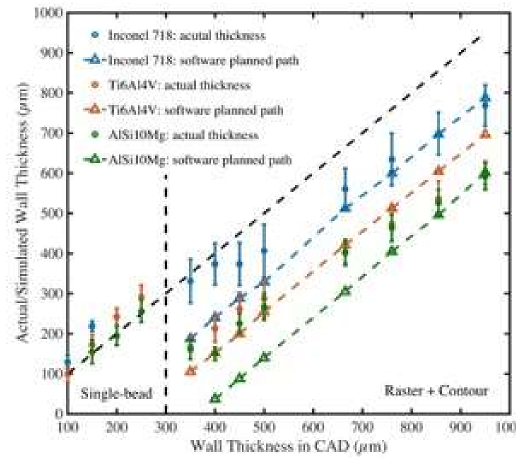
Journal of Nuclear Materials (2013), Pataky *et al.*

Materials Science and Engineering (2011), Boehlert *et al.*

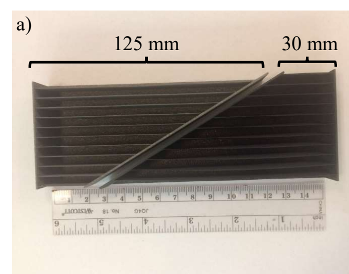
Residual stress, distortion: thin wall

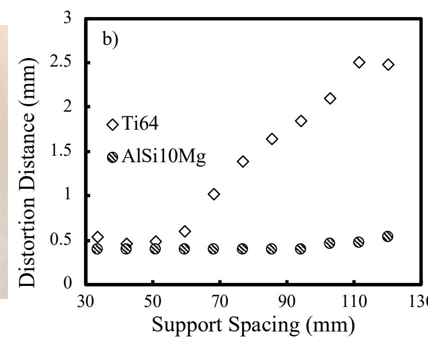






- As the feature dimension approaches the melt pool size (< 1 mm), the dimensional accuracy is significantly influenced by **melt pool size** (process parameters), **scan strategy** (raster vs. single-bead), **geometry** (e.g., inclination angle), and **materials**
- As the build height increases, the open ends of the thin wall should be anchored on the thicker components to prevent severe distortion
- EOS M290 uses single-bead mode to build features smaller than 350 µm where the wall dimension is mainly dictated by the melt pool size
- Thin walls with maximum inclination angle of 60° and minimum thickness 100 µm can be built but it is recommended to build wall with thickness > 500 µm





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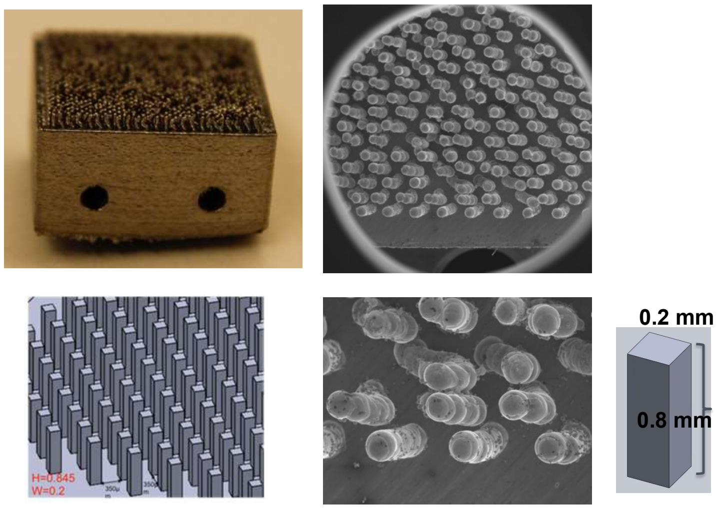
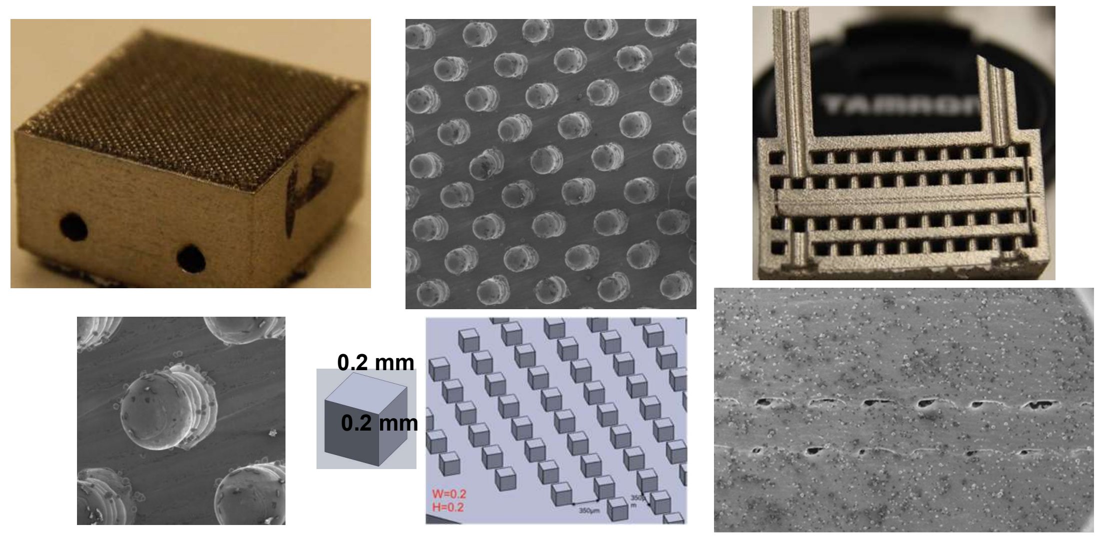
Residual stress, distortion: micro-pin





- Changing in P-V (power velocity) combination improved the surface finish but 4.2 aspect ratio was still not possible to fabricate.
- Aspect ratio of 1 when rectangular width is 200 μm was formed. However, when this dimensional feature was fabricated in a HX design, the pillars were indistinguishable from the walls
  - Regardless of the design (rectangular or tear drop) given, circular fins are formed
  - Cross-sectional diameter of 500 μm pillars were fabricated in a heat exchanger

Residual stress, distortion: micro-pin

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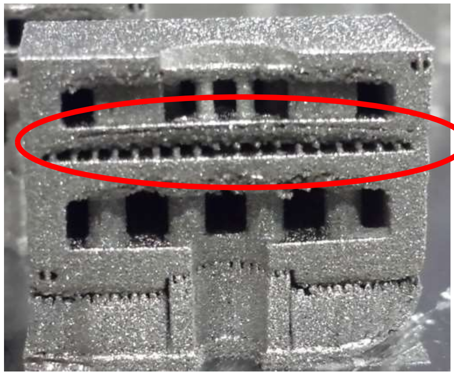
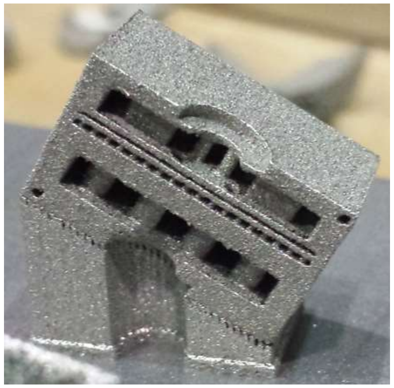
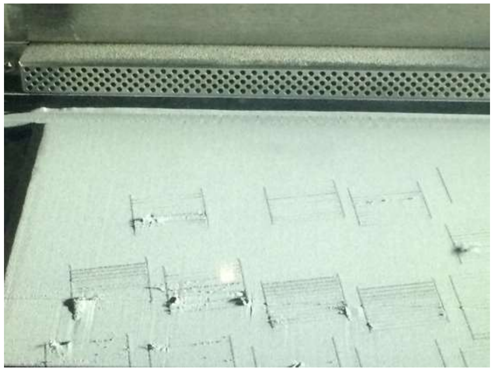


Titled 45°



Superelevation of unsupported thin walls caused collision with the hard recoater



- Tilted structures build with less distortion because of the self-supporting structures and smaller residual stress.

What have we learned?

- **Change pin dimension**: build thicker micro-pins (> 1 mm) to avoid issues from dimensional accuracy and thermal distortion
- **Change build direction**: build pins as overhangs so they are always supported on both ends during melting
- Use brush recoater blade to reduce the risk of collision

Dimensional accuracy of micro-pins

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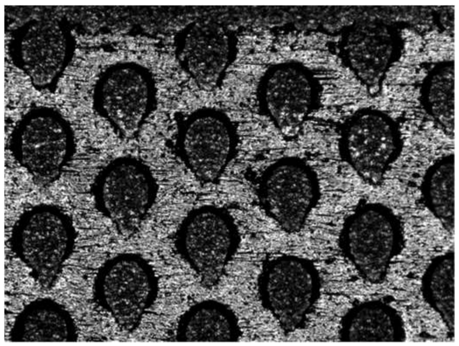
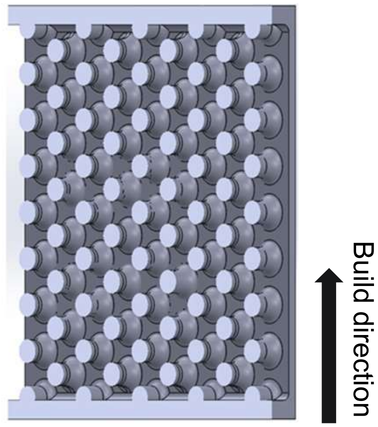
H230: overprinting with tear drop shape

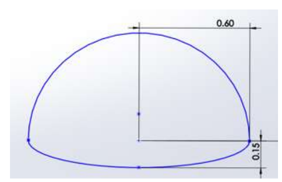


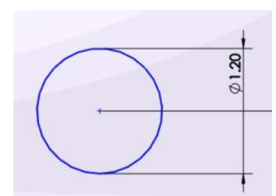


Pin diameter = 1.2 mm

H282

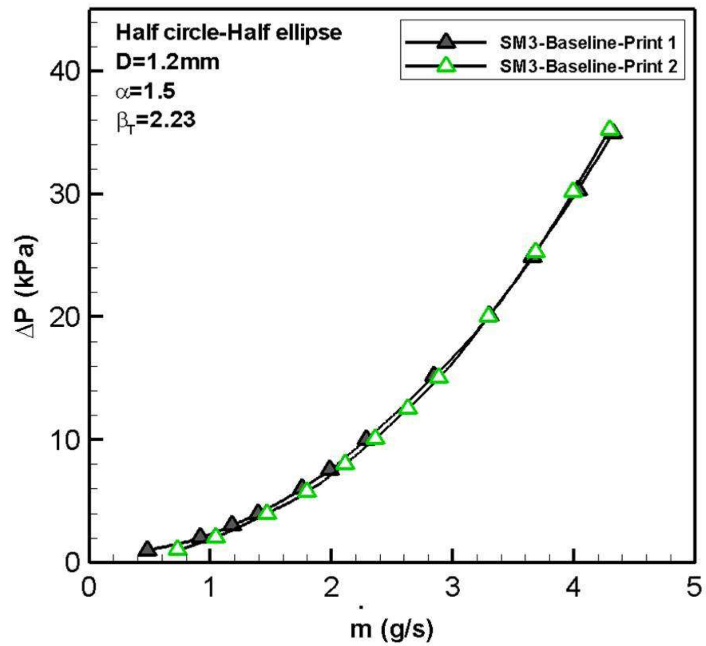
- To build the micro-pins as overhangs caused variations of pin dimensions especially along the build direction
- The dimension variation is materials dependent; different pin cross-sections can be used to build circular pins in different materials





Summary

- Printing of counter-flow HX units with non-standard nickel alloys is a robust manufacturing approach
- Graph of ΔP vs flow demonstrates reproducibility
- Integral headers are feasible but still in progress
- Creep properties of printed H230 are equivalent to standard version; in progress for other alloys
- Printing to 99.9 % dense is feasible with process window approach
- De-powdering can be done
- Many aspects of design adapted for 3D printing, i.e., co-design is crucial



Two different HX units (same design) printed at different times deliver identical ΔP versus flow rate

Questions Welcome