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Optimizing the Surface Texture and Chemistry of Laser Powder Bed Fusion (LPBF) Haynes 282 for Increased Solar Absorptance

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Agenda

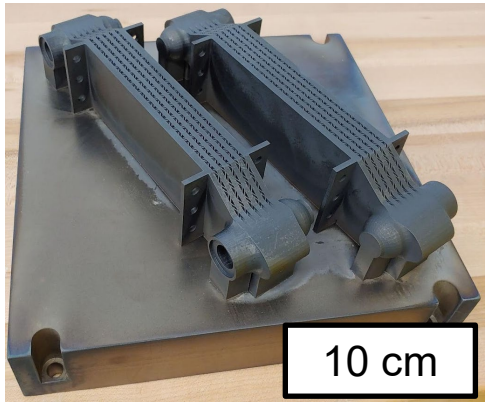
- Motivation
- Experiments
- Results & Discussion
- Conclusions

Motivation

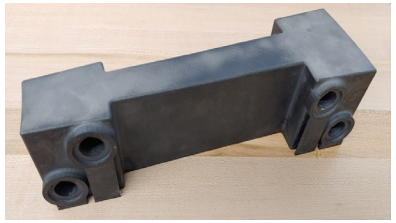
THE SURFACE OF LPBF AM PARTS

LPBF allows us to print complex geometries with a high surface-to-volume ratio.

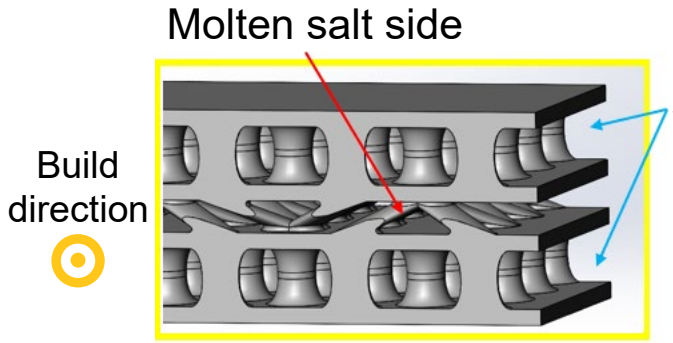
How much control do we have over the surface during printing?



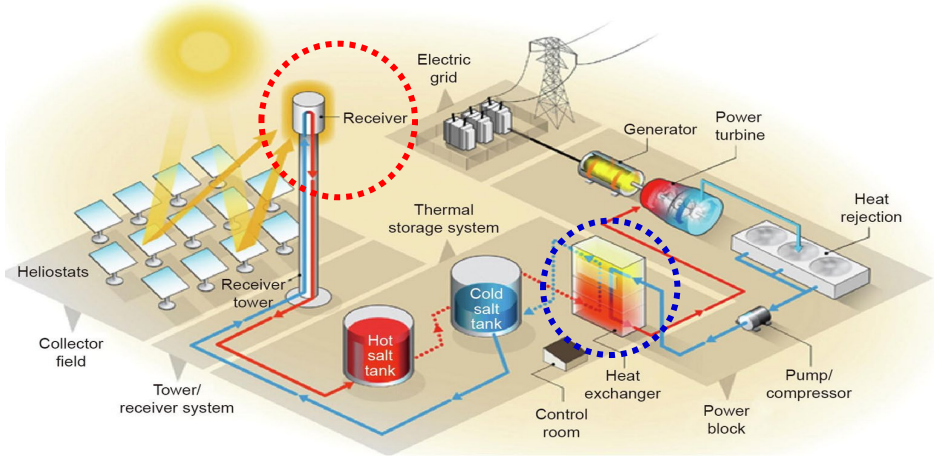
Haynes 282 MS-to-sCO_2 heat exchangers



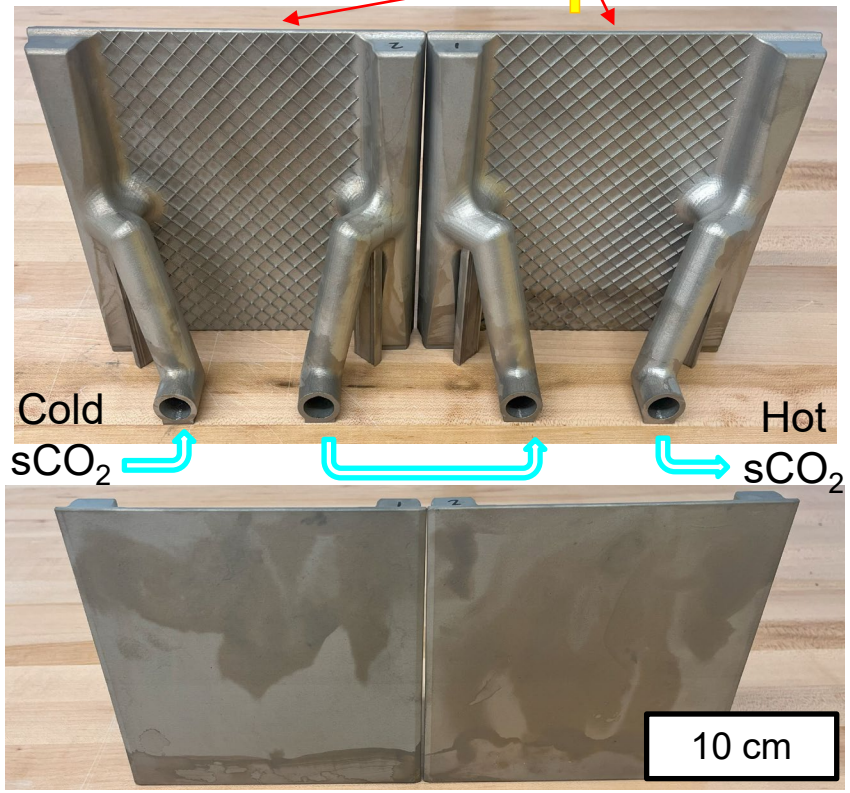
Haynes 282 stand-alone modular counter flow heat exchanger



MS-to-sCO_2 Heat exchanger internal geometry[1]



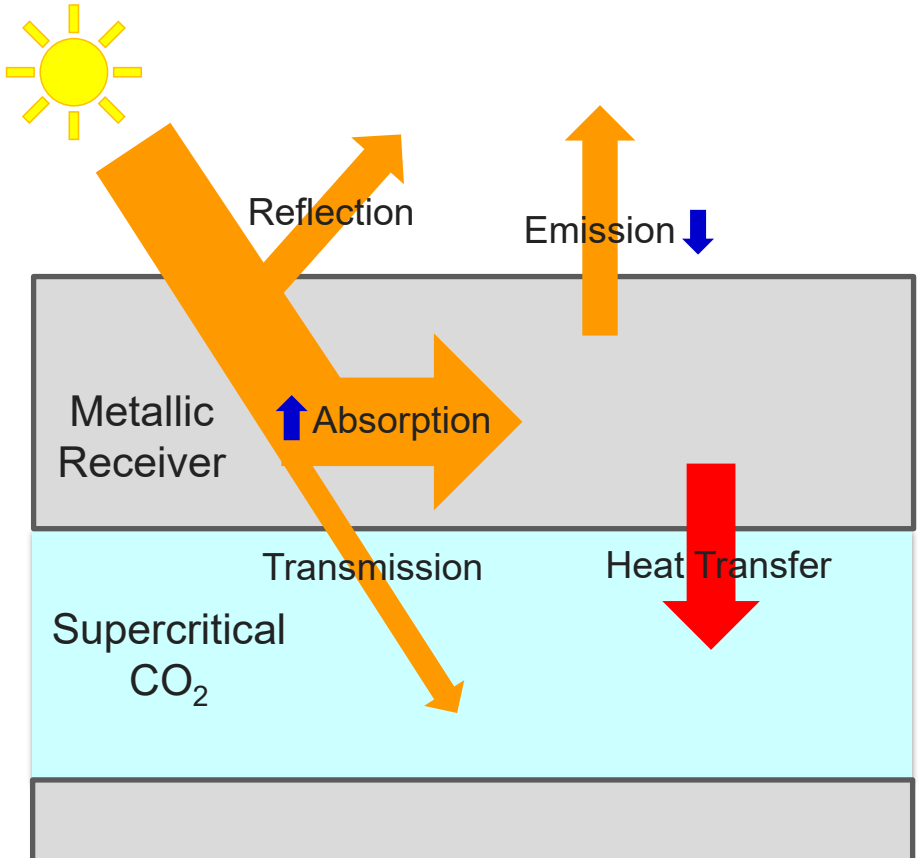
CSP power generation[2]



Haynes 282 sCO_2 solar receivers

[1]Tano, I.N., Rasouli, E., Ziev, T., Seo, J., Lamprinakos, N., Vaishnav, P., Rollett, A., Wu, Z. and Narayanan, V., 2022, July. In *Energy Sustainability* (Vol. 85772, p. V001T05A005). American Society of Mechanical Engineers.
[2]Ding, Wenjin, and Thomas Bauer. "Progress in research and development of molten chloride salt technology for next generation concentrated solar power plants." Engineering 7.3 (2021): 334-347.

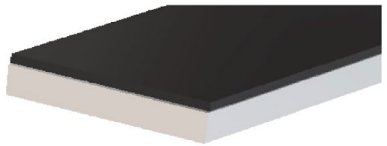
Can we control the surface to increase the absorptivity?



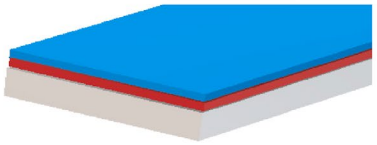
We want to maximize the absorptivity while minimizing the emissivity!

Figure of Merit: $\eta = \frac{\alpha_{solar} Q - \varepsilon\sigma(T^4 - T_{surr}^4)}{Q}$

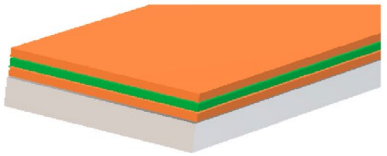
Intrinsic selective



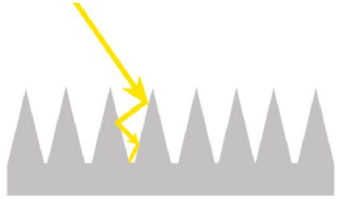
Semiconductor-metal tandems



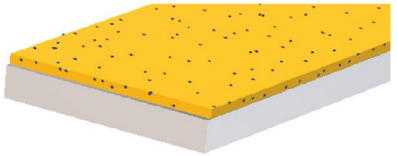
Multilayers

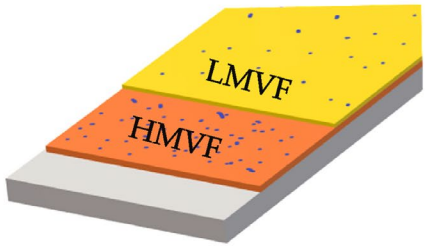


Textured surfaces

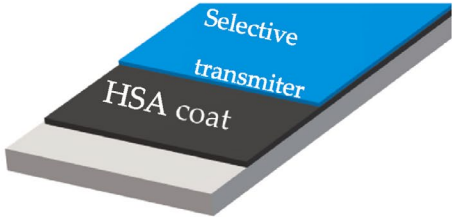


Cermet and double cermet





Selectively solar-transmitting coating on a blackbody-like absorber



Various ways to increase the absorptivity[3]

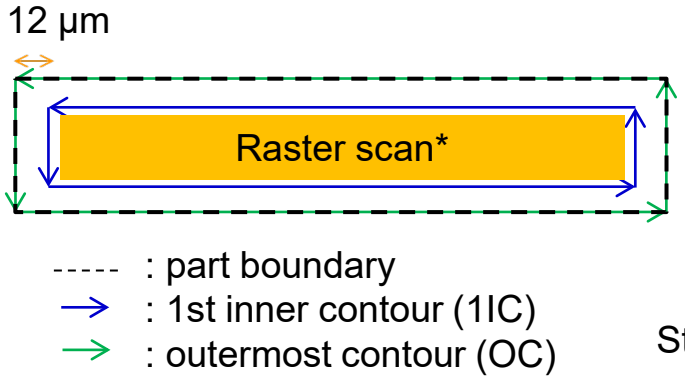
[3]Noč, Luka, and Ivan Jerman. "Review of the spectrally selective (CSP) absorber coatings, suitable for use in SHIP." Solar Energy Materials and Solar Cells 238 (2022): 111625.

Experiments

CO-DESIGNING, PRINTING, AND TESTING

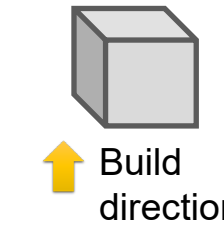
Co-designing and printing

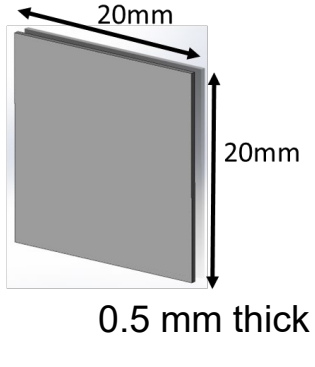
Approach 1: Contour variation



Sample	Outermost contour parameter		1st inner contour parameter	
	P (W)	V (mm/s)	P (W)	V (mm/s)
SP9	80	800	138	390

Standard contour parameters (for L = 40 µm, Inconel 718, EOS M290)





Sample	Name	Outermost contour			1st inner contour
		P (W)	V (mm/s)	E density (J/mm2)	
CS10	Removed contour	*OFF*			
CS11	Reduce P 2-fold	*40*	800	*1.25*	
CS12	Increase P 2-fold	*160*	800	*5*	
CS13	Increase P 4-fold	*320*	800	*10*	
CS14	Reduce V 4-fold	80	*200*	*10*	*OFF***
CS15	Reduce V 2-fold	80	*400*	*5*	
CS16	Increase V 2-fold	80	*1600*	*1.25*	
CS17	Max power	*370*	*959*	*9.65*	
CS18	Keyholing	*370*	*350*	*26.4*	
CS19	OC only	80	800	2.5	

Various contour parameters that were tried in this study

$$S_a = \frac{1}{A}\iint_A |Z(x,y)|\,dxdy$$

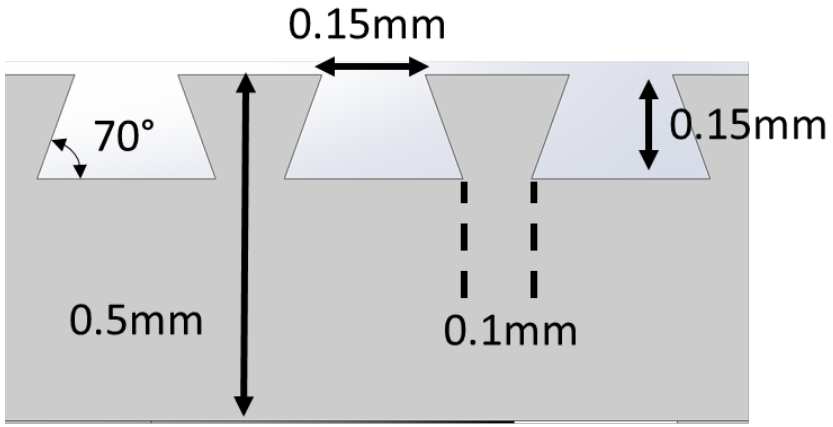
* The infill parameters were kept constant throughout the study.

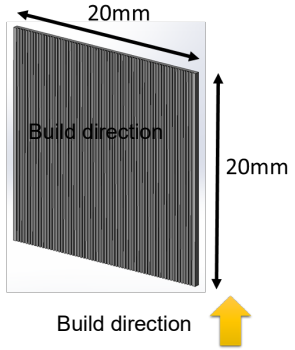
** Our previous study of varying 1IC parameters showed that the most significant increase in the S_a happened in parts without 1IC.

Co-designing and printing

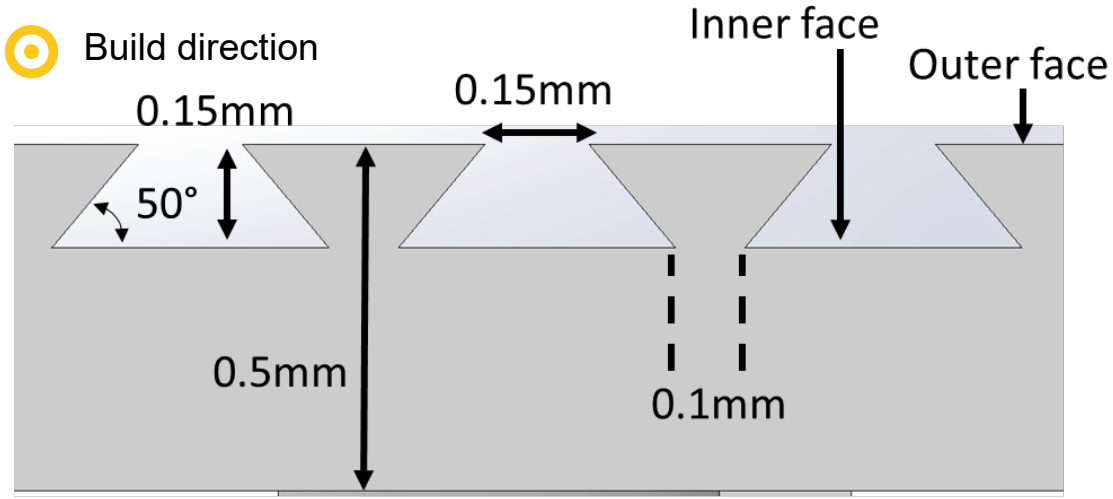
Approach 2: CAD file variation

Vertical grooves

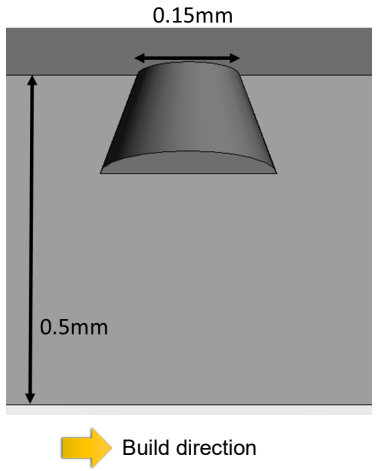


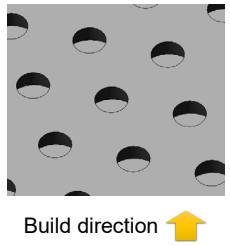


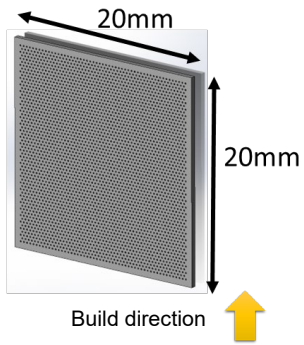
Build direction

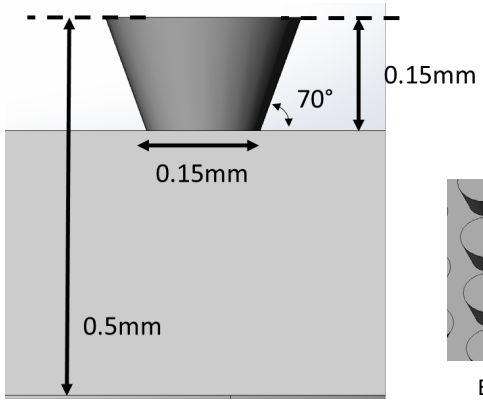


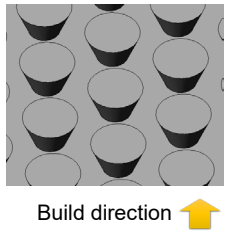
Divots and pegs











* Standard infill and contour parameters were used to print the samples for approach 2.

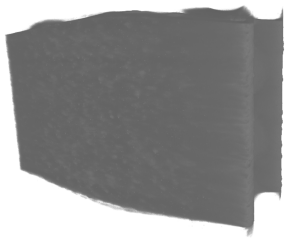
Surface evaluations

- Optical profilometry
  - Keyence VR-5000 Series

1. Reconstructs a height map.
   – Pixel size: 7.4 μm
2. Fast, wide-area scanning is possible.
   – ½ hour to image a 20 mm by 20 mm surface.

- Computed tomography
  - Zeiss Xradia CrystalCT

1. Reconstructs a point cloud.
   – Voxel size: 2.1 μm
2. Slow, but cavity features and porosity can be revealed.
   – 3 hours to image a 6 mm diameter 4 mm tall cylindrical region.
3. Voxel size and the field of view is limited by sample dimensions.



Heat treatment and solar simulator testing

LPBF process (0.1 % O_2)
followed by wire electrical discharge machining (EDM)

↓

Solution annealed at
1250 °C/2 h/Argon
Water quench

↓

1st aging at
899 °C/4 h/Argon
Air cool

↓

2nd aging at
788 °C/8 h/Air
Furnace cool

→

Solar simulator
up to 500 cycles
(surface: 800 °C)

Testing the stability of the optical properties over multiple cycles

Optical properties measurement
(absorptance, emittance)

MSE

Sandia National Laboratories

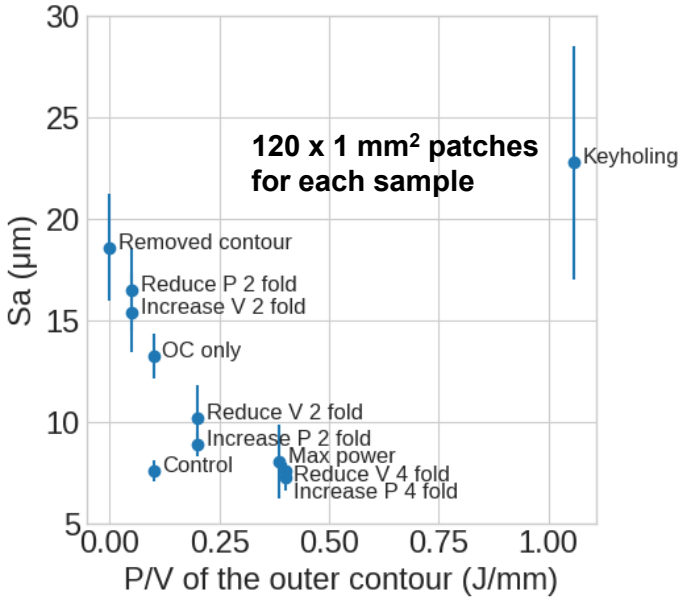
Results and Discussion

SURFACE AND OPTICAL PROPERTIES

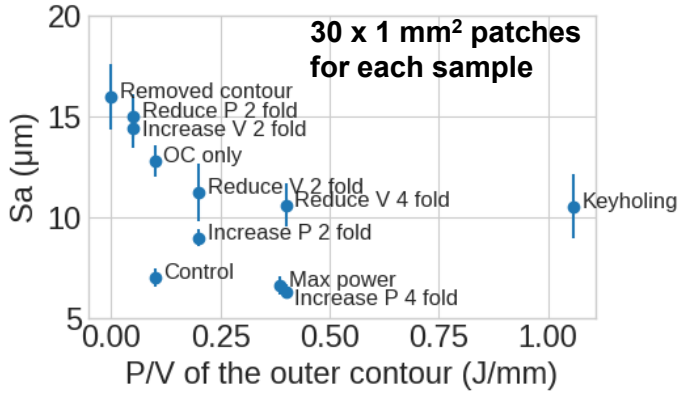
Contour variations

The surface roughness measured using the optical profilometer

Cubes

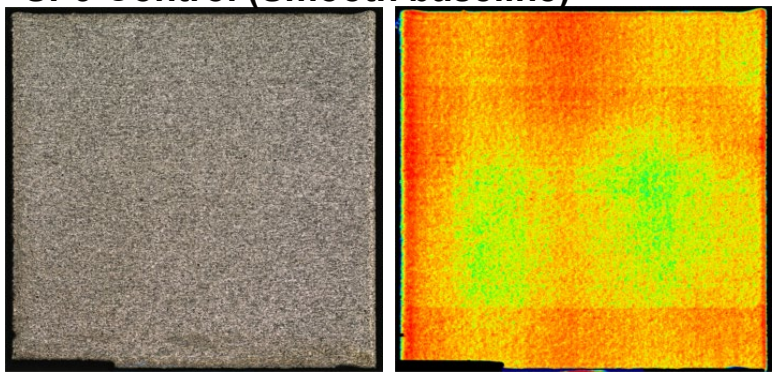


Thin walls

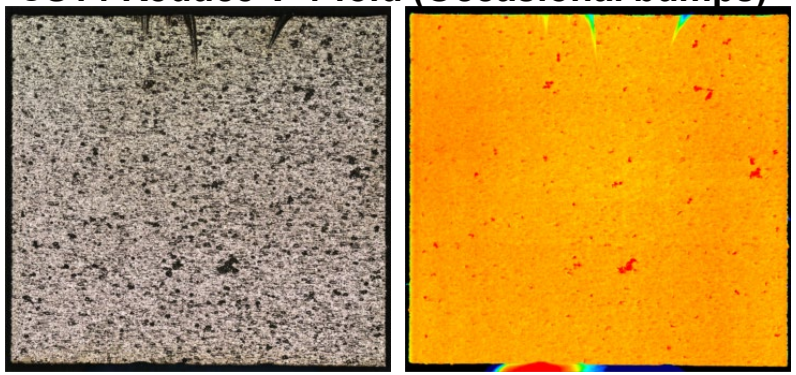


- The addition of contour scans generally makes the surface smoother.
- The Sa surface roughness shows a U-shaped curve when plotted against the outer contour P/V. (most of the literature shows only an increasing or decreasing trend with respect to P/V)
- CS18 with keyholing contour parameters showed rather distinct discoloration on the surface.

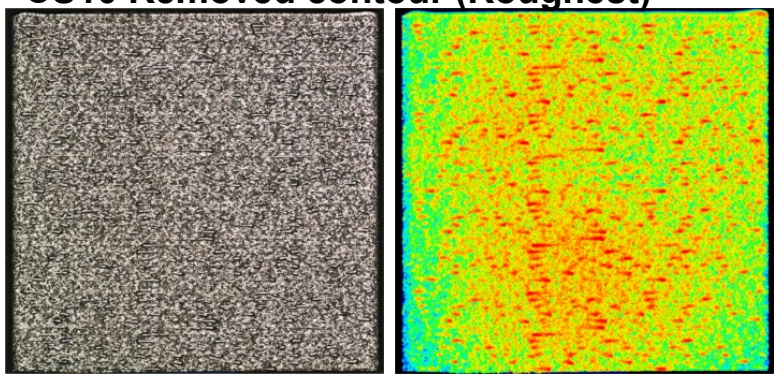
SP9 Control (Smooth baseline)



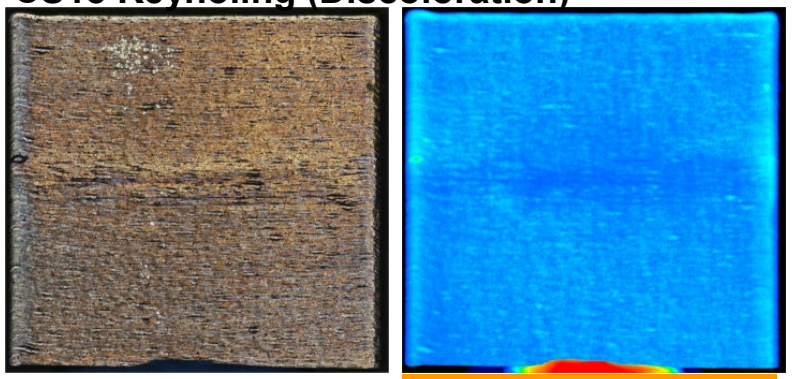
CS14 Reduce V 4-fold (Occasional bumps)



CS10 Removed contour (Roughest)

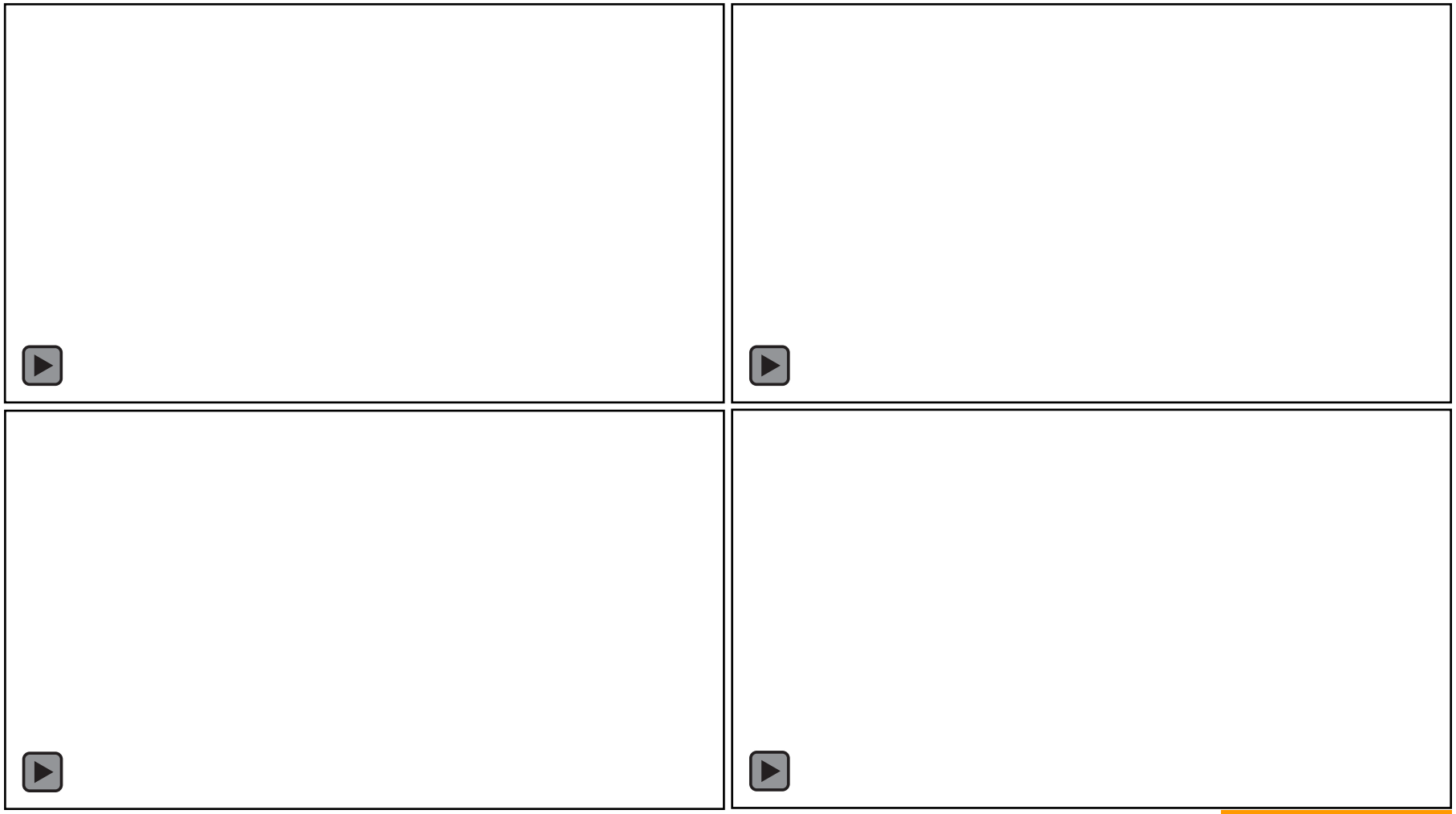


CS18 Keyholing (Discoloration)



CAD files variations

- **The surface features were printed, but the intended cavity structure was not achieved.**



Bright region: metal, darker region: void

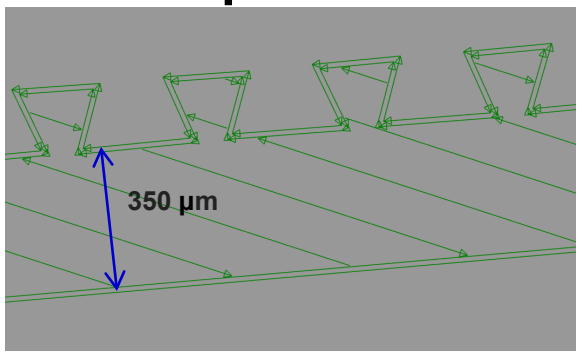
A group of spherical pores were observed around 300 µm depth into the sample.

The samples suffered from cracks (moderate in SP-1, SP-2 and minor in SP-3, SP-4), which has never been observed in our bulk H282 parts printed with the same process parameters.

Why do we see the defects?

- **The surface features were printed, but the intended cavity structure was not achieved.**
  - **This is suspected to be due to the melt pool being larger than the sharp corners. (The melt pool is larger in thin walls due to heat build-up.)**

- **A group of spherical pores were observed around 300 µm depth into the sample.**
  - **This is suspected to be due to short melt pool turnarounds causing heat build-up. The identified pores look similar to keyhole porosity which is mainly due to excess energy input.**



- **The samples suffered from cracks (moderate in SP-1, SP-2 and rather minor in SP-3, SP-4) which has never been seen in our bulk H282 parts printed with the same process parameters.**
  - **We suspect there are a lot of variables of concern, such as residual stress. However, the complex patterning is responsible for the cracks since the thin walls without surface patterns did not show any cracks.**

* Chakraborty, Apratim, et al. "Micro-cracking mechanism of RENÉ 108 thin-wall components built by laser powder bed fusion additive manufacturing." *Materials Today Communications* 30 (2022): 103139.
** Shahabad, Shahriar Imani, et al. "On the effect of thin-wall thickness on melt pool dimensions in laser powder-bed fusion of Hastelloy X: Numerical modeling and experimental validation." *Journal of Manufacturing Processes* 75 (2022): 435-449.

Effects of the heat treatment

Images of the samples in crucible for the heat treatment

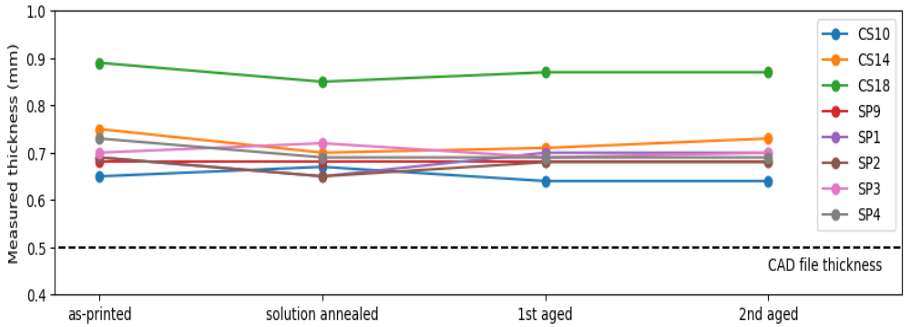
As-printed
(0.1 %O_2)

Solution annealed at
1250 °C/2 h/Argon
Water quench

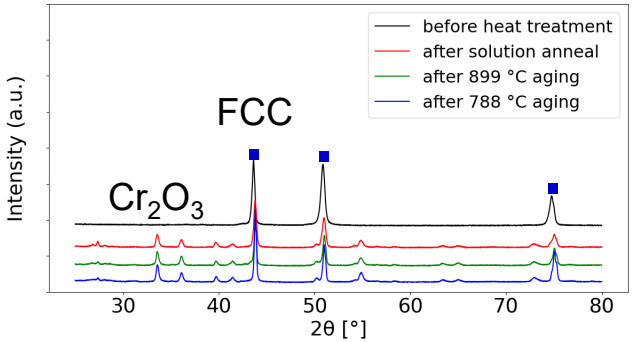
1st aged at
899 °C/4 h/Argon
Air cool

2nd aged at
788 °C/8 h/**Air**
Furnace cool

Thickness measurements (calipers)

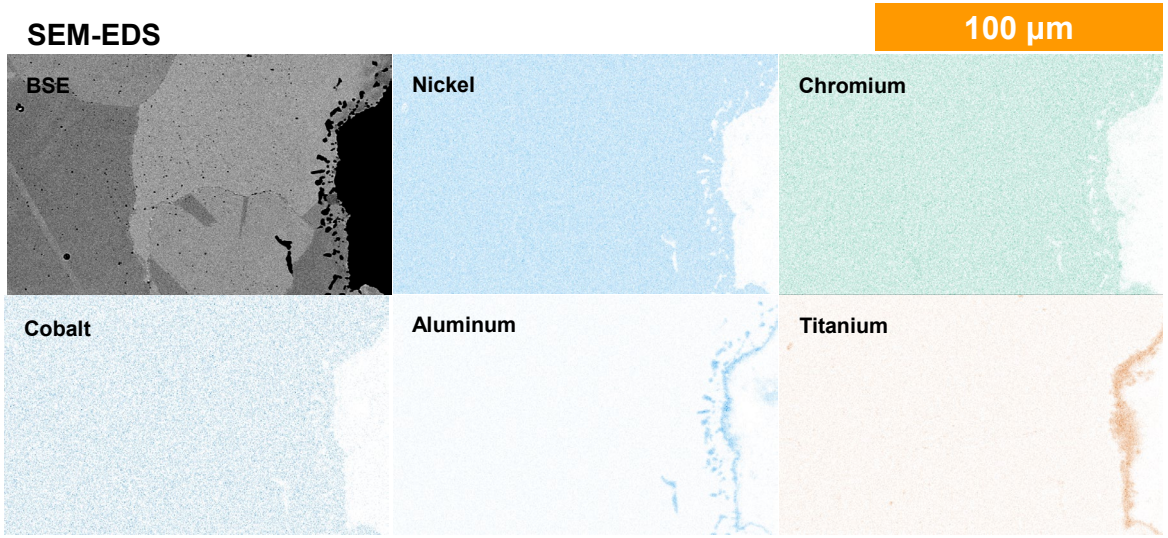


XRD measurements (surface 10 um)



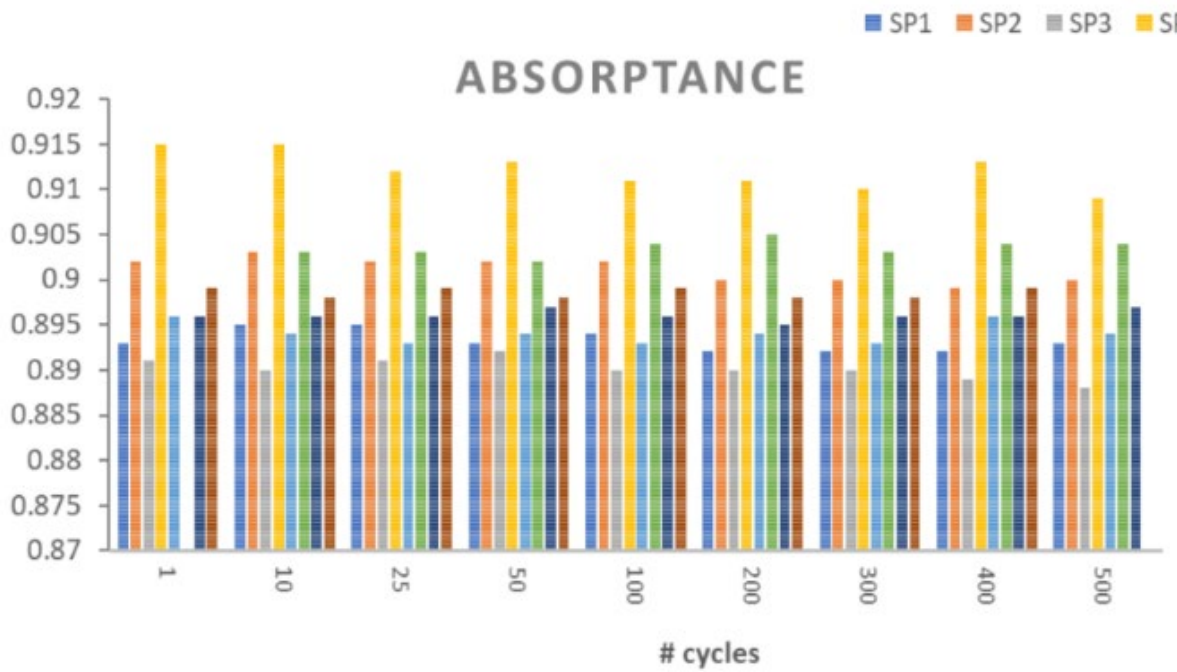
- Measuring the thickness with a caliper after each step did not show a significant trend (no severe oxide flake-off).
- CS18 (keyholing contour) and CS10 (contour removed) were the thickest and thinnest samples, respectively.

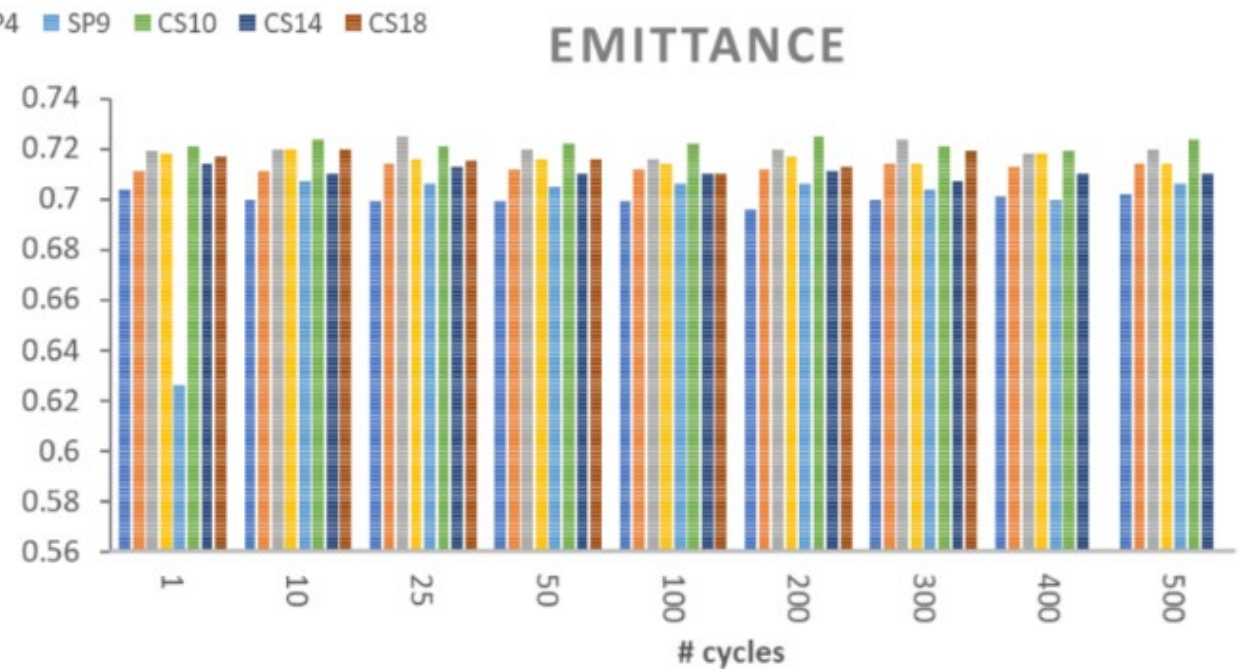
SEM-EDS



- EDS measurements after the full heat treatment showed a layer of 10 ~ 15 µm thick Al-and-Ti-rich oxide with occasional Al-rich oxide particles buried deeper (25 ~ 30 µm) into the bulk.
- The oxide layer giving the darkened surface improves absorptance.

Absorptance & emittance measurements



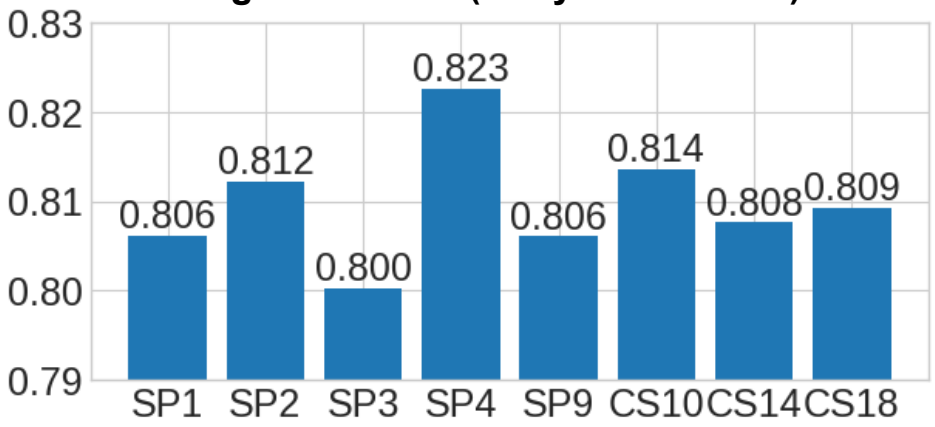


$$\eta = \frac{\alpha_{solar} Q - \varepsilon\sigma(T^4 - T_{surr}^4)}{Q}$$

$$\eta \cong \alpha_{solar} - \frac{\varepsilon}{8}$$

$when\ T = 1073\ K, T_{surr} = 293\ K,$
$\sigma = 5.67 * 10^{-12}\ W/cm \cdot K^4,$
$Q = 60\ W/cm^2$ (600 suns)

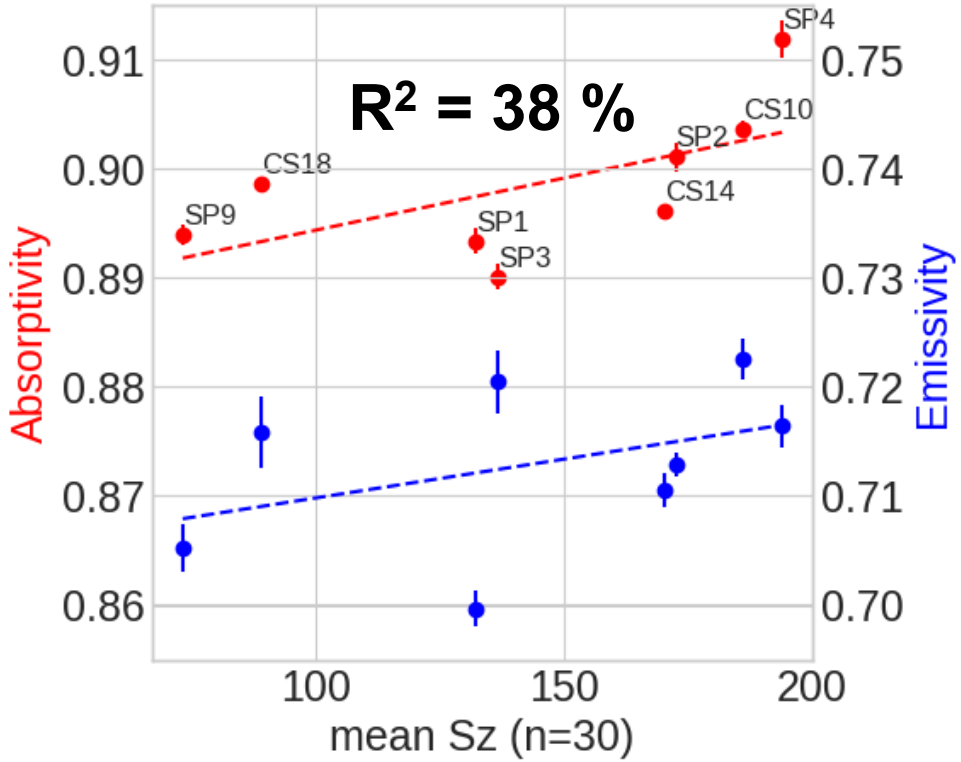
Figure of merit (10 cycles onward)

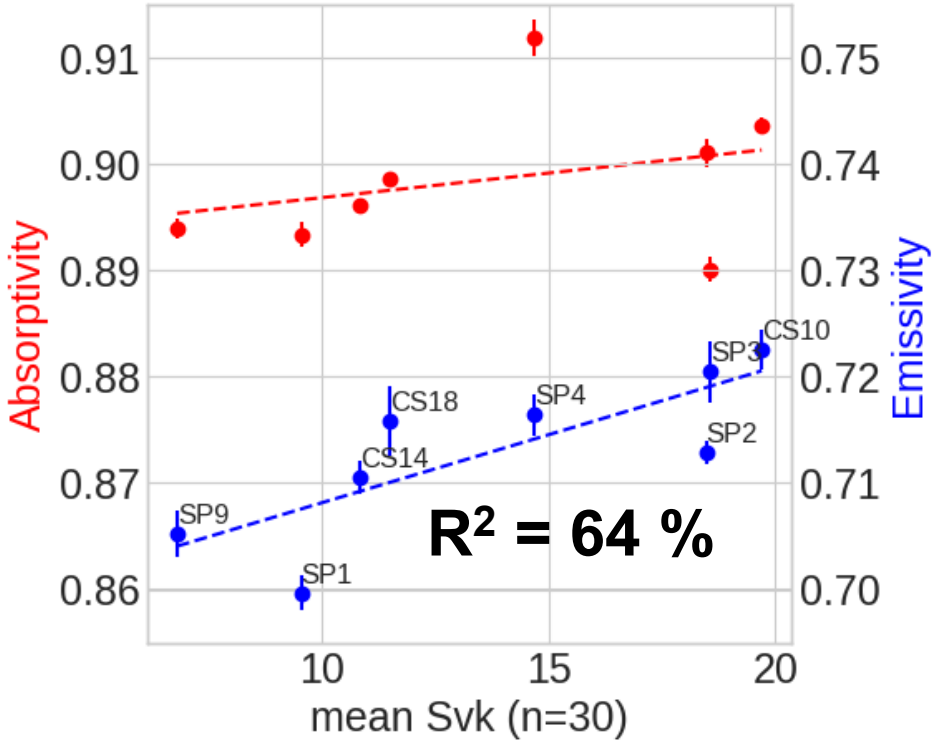


From 10 cycles onwards, the absorptance and emittance measurements stay relatively stable over cycles (advantages over some coatings techniques).

Over 500 cycles, SP-4 (pegs) has the best figure of merit followed by CS10 (contour removed) due to the high absorptance.

Surface roughness vs optical properties





Surface roughness parameter S_z and S_{vk} seems to be a better predictor of absorptivity and the emissivity , respectively, than S_a or S_v for this dataset. An optical ray tracing study will follow to provide better insight.

Conclusions & Future work

Conclusions

1. We show cost-and-time-efficient ways of inducing surface patterns during printing to tailor the optical properties.
2. Addition of a contour parameter generally reduces the roughness, and there seems to be an optimal P/V ratio for printing smooth surfaces.
3. Although the surface patterned samples failed to achieve cavity structures, two of them (SP-2 and SP-4) showed an improved absorptance that led to a higher figure of merit than the baseline.

Future work

1. The process will be modified to fabricate samples with better dimensional accuracy and density and further increase the figure of merit.
2. Additional experiments will follow to confirm our u-shaped process window in the surface roughness vs contour P/V space for thin walls and bulk cubes.
3. Optical ray tracing will be used to confirm that our surface patterns are causing the increase in absorptance.

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